The Environmental History of Silver Refining in New Spain and Mexico, 16c to 19c:

A Shift of Paradigm

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Abstract

The environmental history of silver refining in New Spain is the aggregate result of two refining processes, amalgamation and smelting, that emit two completely different sets of chemicals and impose two distinct levels of woodland depletion upon the environment. Over 60% of its silver was produced by amalgamation, a physical term that hides the complex and concatenated chemical reactions that transform silver sulphides into amalgamated silver and calomel. The chemical ratios and the historical levels of the *correspondencia* (mercury to silver weight ratio) are shown to mathematically restrict the possible level of physical losses of mercury during amalgamation to less than 15% on average, with mercury in calomel constituting the balance. Just under 40% of silver was refined by smelting in the presence of lead, with high emissions of lead fume and high energy requirements. Waterways would be the waste disposal channel for amalgamation, the air for lead fumes, and woodland depleted for smelting. A mass balance analysis is applied to each process to arrive at ratios of by-product emissions and energy input per kilogram of silver extracted. The raw data is derived both from historical sources and also from the nineteenth century accounts of the Hacienda de Regla, one of the major silver refining centres in nineteenth century Mexico. The choice of refining method in New Spain was determined by the chemical nature of the silver ores. The analysis of production costs at Regla and their projection back to the sixteenth century indicate that changes in the historical context could alter substantially the relative economies of both. The strategic decision by Spain to favour amalgamation over smelting was influenced by the fiscal importance of its mercury revenues. The main conclusion of this thesis is that a paradigm based on lead and calomel determined the material impact of the environmental history of silver refining in the New World.

Résumé

L'histoire environnementale du raffinage de l'argent à la Nouvelle Espagne est le résultat de l'agrégat de deux procédés, l'amalgamation et par la fonte, qui dégagent deux ensembles complètement différents de produits chimiques et produisent deux niveaux de réduction des bois. Presque 60% de l'argent a été produit par l'amalgamation, un terme physique qui cache les réactions chimiques complexes qui transformaient les sulfures d'argent en argent amalgamé et calomel. Les rapports chimiques et les niveaux historiques de la *correspondencia* réduisent mathématiquement le niveau possible des pertes physiques du mercure à moins du 15%, et calomel compris le 85% restante. À peu près de l'autre 40% de l'argent était produit par la fonte avec du plomb, avec grands émissions de la fumée au plomb et un très grand besoin d'énergie. Les cours d'eau seraient les voies pour jeter les déchets de l'amalgamation, l'atmosphère pour les fumées au plomb, et les bois épuisés par la fonte. Une analyse du bilan de masse de chaque procédé donne les rapports des émissions et de l'énergie requis par chaque kilogramme de l'argent produit. Les chiffres pour le calcul sont retrouvée des sources historiques et aussi des cahiers de comptabilité du dix-neuvième siècle provenant des opérations à la Hacienda de Regla, une des usines de raffinage de l'argent plus important au Mexique. Le choix du procédé de raffinage à la Nouvelle Espagne était déterminé para la nature chimique du minerai. L'étude des couts de la production à Regla et leur projections jusqu'au seizième siècle indique que les changes du contexte historique pouvaient changer le bilan entre les deux. La décision stratégique de l'Espagne qui a favorisé l'amalgamation sur le procédé para la fonte a été influencée par des raisons fiscales à cause des revenues de la vente du mercure. La conclusion principale de cette thèse propose qu'un paradigme fondé sur plomb et calomel a déterminé l'impact matérielle de l'histoire environnementale du raffinage de l'argent à la Nouvelle Espagne.

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To Adriana

Guide to the text

Chemical symbols

Ag: silver

Cl: chloride

Cu: copper

Hg: mercury

Na: sodium

O: oxygen

Pb: lead

S: sulphur

Units of measure

kg = kilogram

m = metre

m^2 = square metre

m^3 = cubic metre

Ma = million years

oz = ounce

t = ton (metric)

t/d = tons per day

t/m = tons per month

t/y = tons per year

lb = pound

y = year

Equivalence of units of measure

1 *quintal* = 46 kg

1 mark = 8 oz = 0.23 kg

1 *arroba* = 11.5 kg

1 *carga* = 12 *arrobas* = 138 kg

1 troy oz = 0.031 kg

1 lb = 0.454 kg

Tons (t) are metric tons = 1,000 kg

1 *fanega* maize = 1/2 *carga* of cereal = 52 kg

1 mark = 8.5 to 8.75 *pesos*

1 *vara* = 0.84 m

Monetary units

All calculations involving monetary units of *pesos*, *reales* and *tomines* have been rounded off on the basis of *peso*s only.

Translations

All translations are by the author unless otherwise indicated. Non-English words in the text and footnotes are inserted in italics, except for proper names and institutions.

Photographs, illustrations and drawings

All plots, tables, photographs and drawings by the author unless otherwise indicated. Digital images were taken by the author of original prints made public prior to 1920. Digital copies of other material were provided by the AHSLP, MMOB, AHUG and AHCRMyP. Satellite images from Google Earth have been reproduced for academic and non-commercial purposes, as well as single images from texts under 'fair dealing'. Where applicable, permission to reproduce is indicated in the captions to the figures.

Geopolitical terms

The geopolitical designations of New Spain and Mexico are used either separately or together, depending on the historical period being covered. New Spain covered a larger territory than republican Mexico, including territory in Central America, except for present day Panama that was assigned to New Granada.

Introduction

From the mid sixteenth century to the third quarter of the nineteenth century, Spain dominated the world production of silver. According to the data collated by TePaske, silver from the Hispanic New World constituted 40 % (sixteenth century), 74% (seventeenth century) and 71% (eighteenth century) of world production totals. The silver refining industry of New Spain came to produce on average nearly half of the world's silver during the eighteenth century.[1] Only the United States of America as of the 1870s overtook republican Mexico to become the world's leading producer of silver.[2] The historical impact of this wave of bullion from the New World on global trade and the future course of the European and Asian economies has been amply analysed within a global perspective.[3] The same silver is credited by Flynn and Giraldez with giving rise in 1571 to the first instance of truly global trade, the year Spain set up its entrepôt in Manila.[4] There is consensus that the mining and refining of silver in the New World changed the course of world history as of the mid sixteenth century.

The reverse side of the silver coin was the environmental legacy in the New World that was left in the shadow of this pivotal moment in history. Up to the end of the nineteenth century

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[1] John Jay TePaske and Kendall W. Brown, *A New World of Gold and Silver* (Leiden, Netherlands; Boston: Brill, 2010), 140.
[2] Charles White Merrill, *Summarized Data of Silver Production* (US Government Printing Office, 1930), 18.
[3] Modern historians of note such as the Chaunus, Braudel, Carla Rahn Phillips, de Vries and others have been cited in this regard, as in for example the analysis of the concatanated economic effects of New World silver flows as it made its way through Europe, the Ottoman Empire, Persia, India and ultimately to China, in Ronald Findlay and Kevin H. O'Rourke, *Power and Plenty. Trade, War and the World Economy in the Second Millenium* (Princeton: Princeton University Press, 2007), 212-26. John Kenneth Galbraith argues that it was not the silver per se that strongly assisted the birth of European capitalism, but its inflationary effect on prices of goods coupled with a decrease in wages, that led to increasing profits and capital accumulation, in John Kenneth Galbraith, *Money, Whence It Came, Where It Went* (London: Penguin Books Ltd., 1995), 10-11. Silver as a 'gift' to Europe, product of Spanish coercion, and its effects on Indian and Chinese economies is analyzed in Kenneth Pomeranz, *The Great Divergence. China, Europe, and the Making of the Modern World Economy* (Princeton, New Jersey: Princeton University Press, 2000), 269-74.
[4] Dennis O Flynn and Arturo Giraldez, "Cycles of Silver: Global Economic Unity through the Mid-Eighteenth Century," *Journal of World History* 13 (2002).

there is little in the way of published primary documents that comment on the collateral impact on communities and their habitat as a result of refining silver. One notable and very early exception was the following text by Inca Garcilaso de la Vega (1539-1616), the son of a Spanish *conquistador* and an Inca princess, which refers to the refining of mercury from its ore:

'The Inca Kings felt that [mercury] was harmful to the welfare of those who extract it and refine it, for they saw it caused tremors and the loss of consciousness. In view of which (as Kings that care so much for the welfare of their subjects, according to their name "Lover of the Poor") they prohibited by law its extraction, or any memory of it. So much did the Indians abhor it that they erased its name from their memory and language'.[5]

The early European sources from the Viceroyalty of Peru adopt a more business as usual approach to the workplace dangers of refining silver. Viceroy Toledo imposed larger heights of chimneys from smelting furnaces than their counterparts in amalgamation units.[6] Alonso Barba, author of the only major metallurgical work in the early seventeenth century to come from the New World, recommended that workers do not stand downwind during the heating of the amalgams to avoid the danger of mercurialism (becoming *azogado*) should an accident occur.[7] In the eighteenth century, de Gamboa would comment on the poisonous nature of smelters and amalgamation *haciendas*.[8] At least one lurid account of the deemed mortal effect of amalgamation on workers was penned by Sir William Rawson in England in the early

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[5] '*Los Reyes Inca … sintieron [que el azogue] era dañoso para la vida de los que lo sacan, y tratan, porque vieron que les causaba el temblar y perder los sentidos. Por lo cual (como reyes que tanto cuidaban de la salud de sus vasallos, conforme al apellido "amador de pobres"), vedaron por ley que no lo sacasen, ni se acordasen de él. Y asi lo aborrecieron los indios de tal manera, que aun el nombre borraron de la memoria y de su lenguaje'*. Garcilaso de la Vega and Aurelio Miró Quesada S, *Comentarios reales de los Incas* (Caracas: Biblioteca Ayacucho, 1976), 555.

[6] As quoted in Peter J. Bakewell, *Miners of the Red Mountain. Indian Labor in Potosí, 1545-1650* (Albuquerque: University of New Mexico Press, 1984), 150.

[7] Alvaro Alonso Barba, *Arte de los metales* (Barcelona: Editorial Labor, 1977), 170.

[8] Francisco Xavier de Gamboa, *Comentarios a las ordenanzas de minas dedicados al católico rey nuestro señor Carlos 111*, Madrid, Oficina de Joaquín Ibarra (1761), 462.

nineteenth century.[9] However the detailed accounts by European technical observers of this period do not mention any fatal environmental or workplace conditions as a consequence of the refining processes.[10] Concern over the depletion of woodlands was expressed throughout the colonial period within the context of the impact of mining in general, perhaps not so much in the modern sense of safeguarding the environment for future generations but more as a problem of sourcing new supplies of fuel so as not to impair the course of silver production.[11]

A generalized interest in the negative impact of human actions on the environment only arises after the middle of the twentieth century. As more information became available on the toxicity of chemicals, greater attention began to be paid to the environmental effect of industrial activity, with Rachel Carson's publication of Silent Spring in 1962 a significant milestone.[12] Her concern was triggered by the indiscriminate use of man-made pesticides, but in that same timeframe and context the devastating effects of mercury and its by-products on humans would become apparent to a world audience observing its effects on the fishing communities around Minamata Bay in Japan.[13] It cannot be said that the tragedy at Minamata immediately sensitized the historiography to the possible environmental impact from the use of mercury in the New World. The emphasis remained on the amounts of mercury produced or imported in relation to the refining of silver, not their environmental impact. Prior to public reaction to events at Minamata, Lohmann Villena had published in 1949 his detailed study on mercury production

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[9] William Rawson, "The Present Operations and Future Prospects of the Mexican Mine Associations Analysed, by the Evidence of Official Documents, English and Mexican, and the National Advantages Expected from Joint Stock Companies, Considered, in a Letter to the Right Hon. George Canning,"(London: J. Hatchard & Son, 1825), 19.

[10] Saint Clair Duport, *De la production des métaux précieux au Mexique, considérée dans ses rapports avec la géologie, la métallurgie et l'économie politique* (Paris: Firmin Didot Frères, 1843).;M.P. Laur, "De la metallurgie de l'argent au Mexique," *Annales des Mines, 6th series,* 20 (1871).

[11] For a recent review of historical texts on depletion of woodlands in New Spain and the Andes see D. Studnicki-Gizbert and D. Schecter, "The Environmental Dynamics of a Colonial Fuel-Rush: Silver Mining and Deforestation in New Spain, 1522 to 1810," *Environmental History* 15, no. 1 (2010).

[12] Rachel Carson, *Silent Spring* (Greenwich, Conn.: Fawcett, 1962).

[13] Shigeo Ekino et al., "Minamata Disease Revisited: An Update on the Acute and Chronic Manifestations of Methyl Mercury Poisoning," *Journal of the Neurological Sciences* 262, no. 1-2 (2007).

at the mine of Huancavelica, in present day Peru. Using his data, it is possible to calculate a yearly consumption of mercury for the refining of silver around Potosí of approximately 300 t per year for at least 74 continuous years.[14] The aggregate total of mercury consumed in the New World from 1556 to 1700, based in part of Lohmann Villena's data, was then estimated by Pierre Chaunu in 1959 at approximately 49,000 t (1,069,494 *quintales*), a yearly average for the refining centres of the New World of 340 t over 144 continuous years, that would increase in tandem with silver production in the eighteenth century.[15] One estimate on the total amount of mercury (and its compounds) discharged into Minamata Bay is from 260 t to 600 t of mercury over a period of 36 years, at an average of 7 to 17 t/y, part of which found its way into the human food chain as very toxic methyl mercury.[16]

Further refinements in these totals were published, but none of these magnitudes triggered a warning on the potential for major negative health and environmental issues for the communities of the New World arising from the amalgamation of silver ores.[17] The historical data represented an unprecedented major source of anthropogenic waste chemicals based on mercury voided into the communities and ecology of the New World. Quite the contrary, the technique of amalgamation, which needed to be supplied with such major quantities of mercury in order to function, was hailed in much of the modern historiography in quite positive terms. The importance of New World silver on world history was reflected onto the technique of

[14] Saúl Guerrero, "Chemistry as a Tool for Historical Research: Estimating the Contraband of Silver from Potosí and Oruro, 1576-1650," *Bulletin for the History of Chemistry* 37, no. 2 (2012): 75.
[15] Pierre Chaunu, *Seville et l'Atlantique (1504-1650). La Conjoncture* (Paris: SEVPEN, 1959), Tome VIII (2,2) 1975.
[16] Ronald Eisler, *Handbook of Chemical Risk Assesment: Health Hazards to Humans, Plants, and Animals. Volume 1: Metals* (Boca Raton, FL.: Lewis Publishers, 2000), 322.
[17] Richard L. Garner, "Long-Term Silver Mining Trends in Spanish America: A Comparative Analysis of Peru and Mexico," *The American Historical Review* 93, no. 4 (1988): 916-23.; D. A. Brading and Harry E. Cross, "Colonial Silver Mining: Mexico and Peru," *The Hispanic American Historical Review* 52, no. 4 (1972): 563. In the industrial world of the twenty-first century, average mercury emissions from global coal burning in 2013 are estimated at 474 t/y. Data from UNEP, "Global Mercury Assesment 2013 "(Geneva: United Nations Environmental Program), 9.

amalgamation.[18] The pioneering historians of silver refining would mention the danger posed by the use of mercury, but were limited by the fact there was no mention of widespread mercurialism in the primary documents spanning the complete span of amalgamation in the Americas.[19] Examples of the dangers of mercury in the refining of mercury ores were cited in Kendall Brown's study on Huancavelica (Peru).[20] In general, the absence of a strong commentary on this potentially serious issue as a direct consequence of amalgamation possibly led the environmental historian John F. Richards to state as late as the year 2003: 'as yet, the true environmental costs of silver [refining in the New World] have not been fully explored or acknowledged by scholars'.[21] Nicholas Robins, in his recent monograph on the ravages of mercury in the Andes of Huancavelica and Potosí, drew attention to the dangers of mercury but his strongest examples derive from the effects of refining mercury from cinnabar at Huancavelica, or from the dangers of mining and the attrition on local communities caused by the *mita* system of forced labour in the Vice-Royalty of Peru. His case is much weaker on the

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[18] '[amalgamation] stands out as a unique event in the annals of Spanish-American technology, up to the present time', Marcel Roche, "Early History of Science in Spanish America," *Science* 194, no. 4267 (1976): 807.; '[amalgamation] may rank ... as high as any other technical innovation made in the Americas since Europeans first went there', Peter J. Bakewell, *A History of Latin America*, 2nd ed.(Oxford: Blackwell Publishing, 2004), 185.;'in the refining of metals ... the americans contributed through amalgamation with perhaps the most important innovation of the period'- '*En el beneficio de los metales ... los americanos aportaban con la amalgamación la innovación tal vez más importante de la época'*. Bernd Hausberger, "El universalismo científico del Barón Ignaz von Born y la transferencia de tecnología minera entre Hispano américa y Alemania a finales del siglo XVIII," *Historia Mexicana* 59, no. 2 (2009): 614. 'Revolution', 'epoch-making' and 'the most transcendental event in the history of world metallurgy' are some of the other epithets that have been used to describe the implementation of amalgamation of silver in New Spain in the 1550s. For the respective quotes see Manuel Castillo Martos, *Bartolomé de Medina y el siglo XVI* (Santander: Servicio de Publicaciones de la Universidad de Cantabria, 2006), 75. ; Mervyn F. Lang, "Silver Refining Technology in Spanish America (patio y fundición) " in *5th International Mining History Congress*, ed. James E. Fell, P. D. Nicolaou, and G. D. Xydous (Milos Island: Milos Conference Center-George Eliopoulos, 2001), 139. ; Manuel Castillo Martos and M. F. Lang, *Metales preciosos--unión de dos mundos : tecnología, comercio y política de la minería y metarlurgia iberoamericana* (Sevilla: Muñoz Moya y Montraveta Editores, 1995), 99. Not all historians contribute to this panegyric on amalgamation. Portuondo dedicates just two lines to this refining process in her 20 page paper, María Portuondo, "Constructing a Narrative: The History of Science and Technology in Latin America," *History Compass* 7, no. 2 (2009): 505.

[19] In one of the most recent examples, in the second edition of the textbook on Latin American history, published in 2004, Bakewell dedicates two lines of text to the toxicity of mercury in relation to the use of amalgamation to refine silver in the New World. See Bakewell, *A History of Latin America*, 186.

[20] Kendall W. Brown, "Workers Health and Colonial Mercury Mining at Huancavelica, Peru," *The Americas* 57 (2001).

[21] John F. Richards, *The Unending Frontier: An Environmental History of the Early Modern World* (Berkeley: University of California Press, 2005), 366.

environmental impact of amalgamation per se, both on chemical grounds as will be argued in Chapter 3 and because he can only cite one primary source (Pedro de Oñate, a Jesuit priest) on the danger of mercury from the amalgamation process itself.[22]

When attention was finally focused on the environmental impact of silver refining, it was conditioned by a narrative that had been constructed to explain the uniqueness of a mercury amalgamation process that was only applied massively in the New World and not in Europe. This narrative posited that the richer superficial silver ores of the New World had been quickly exhausted by mid sixteenth century, and that smelting was incapable of refining at a profit the deeper ores with a low silver content. The implementation of mercury amalgamation was therefore the only viable technical and economic choice that allowed Spain to reap the wealth of silver from the 'other' poorer type of ore prevalent in the New World. No strategic choice was involved between two refining options, but rather a decision imposed by necessity. As a corollary to this narrative, smelting had to be relegated to a minor role in the production of silver, since 'rich' ores were not the average norm in the American continent. Thus amalgamation and mercury came to dominate the historical narrative on colonial silver refining, a modern yet unfiltered echo of the voices of colonial miners complaining of lower silver yields and clamouring for more and cheaper mercury as the key to silver production in the New World.[23]

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[22] N.A. Robins, *Mercury, Mining, and Empire: The Human and Ecological Cost of Colonial Silver Mining in the Andes* (Indiana University Press, 2011), 140.

[23] It is difficult to single out any specific historian as to the origin of this narrative, since it merges well with some of the primary documents from the colonial era. The Spanish historian of mining and silver refining Modesto Bargalló is a very useful source for extracts from early historical sources for mining and refining in New Spain and Peru. He presents in his book published in 1955 one of the first modern versions of this narrative, in Modesto Bargalló, *La minería y la metalurgia en la América española durante la época colonial* (Mexico: Fondo de Cultura Económica, 1955), 240-45. The same narrative is voiced by the most quoted of English language historians of colonial silver refining, as for example in: Bakewell, *A History of Latin America*, 184-89.; Brading and Cross, "Colonial Silver Mining: Mexico and Peru," 552-56.; Richard L. Garner and Spiro E. Stefanou, *Economic Growth and Change in Bourbon Mexico* (Gainesville: University Press of Florida, 1993), 111. An indication of their role as references to the history of silver refining is the fact the they are the historians cited for

The next step in the same direction came not from historians but from the discipline of environmental science. In attempting to interpret modern levels of mercury depositions world-wide, the residual contribution of historical silver refining activities needed to be assessed. In 1993 Jerome O. Nriagu published a one-page note in the journal Nature proposing that all the mercury used to amalgamate silver in the New World had been lost during the process through physical means, up to 65% during a heating stage of the amalgam, and the rest by spills or in waterways. Nriagu explicitly tied his line of reasoning to modern observations of artisanal gold mining in the Amazon.[24] His argument was taken up by successive authors, both environmental scientists and historians, with the latest proposal by Robins in 2012 stating that up to 85% of the mercury used in Potosí was ultimately volatilized.[25] In all these studies no mention is made of any chemical transformation of mercury during the refining process, nor is any other heavy metal mentioned as a source of environmental impact from the historical refining of silver ores.

This mainstream environmental narrative based on 'poor silver ores / amalgamation / volatile mercury loss' has faced major challenges in recent years on both fronts, by historians and indirectly by environmental scientists. The Spanish historian Lacueva, in 2010, questioned many of the tenets of this narrative. He begins by stressing that in the five year period prior to the implementation of amalgamation in New Spain, the shipments of precious metals to Spain (mainly silver) from the port of Veracruz had risen 70%. Thus the use of amalgamation was not a response to a crisis in silver production. He then argues that certain texts of the period from Zacatecas contradict the notion of 'poor' silver ores. He posits that in fact smelting was a more profitable refining method than amalgamation, though without a quantitative base to his

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the sections on silver refining in John Huxtable Elliott, *Empires of the Atlantic World : Britain and Spain in America, 1492-1830* (New Haven: Yale University Press, 2006).

[24] J. Nriagu, "Legacy of Mercury Pollution," *Nature* 363 (1993): 589.

[25] Robins, *Mercury, Mining and Empire*, 109.

argument. Finally, he recognizes that the increase observed in smelting in Zacatecas as of the mid seventeenth century cannot be readily explained by the 'poor ore / amalgamation' narrative.[26]

Bakewell had earlier recognized the potential contradiction of events in the seventeenth century to his narrative based on 'poor ores'. If smelting was held to be only viable for very rich silver ores, then only new sources of such an ore could justify the surge in smelted silver. He therefore proposed that gunpowder was helping miners find new pockets of ore with high silver content. The argument is weak but inevitable for Bakewell to remain consistent with his narrative. The weakness has been pointed out by Lacueva, who attempts to circumvent the contradiction trap by claiming that in fact smelting represented the lowest cost option for refining silver ores.[27]

The second challenge faced by the mainstream narrative has come indirectly from the results of recent studies (2011) from the field of environmental science. Cooke et al took measurements of mercury in deposits at the bottom of Lake Lobato, 6 km east of Potosí. When core samples of the sediments were measured for mercury, it resulted in a curve of mercury concentration that decreases during all the historical period amalgamation was practised at Potosí. In all, 70% of all the mercury deposited over Lake Lobato corresponded to periods before amalgamation was introduced by Spain. Pre-conquest levels of mercury in the sediment were higher than those of colonial Potosí.[28] This result pointed to a major flaw in the current

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[26] Jaime J. Lacueva Muñoz, *La plata del rey y de sus vasallos : minería y metalurgia en México (siglos XVI y XVII)* (Sevilla: Consejo Superior de Investigaciones Científicas, Escuela Superior de Estudios Hispano-Americanos; Universidad de Sevilla; Diputación de Sevilla, 2010), 93-107,147-228,259-68.
[27] Ibid., 133-34.
[28] C.A. Cooke et al., "Pre-Colombian Mercury Pollution Associated with the Smelting of Argentiferous Ores in the Bolivian Andes," *AMBIO: A Journal of the Human Environment* 40, no. 1 (2011).

narrative on colonial silver refining, with direct consequences for the way its environmental history should be studied.

The doubts raised by the current direction of the mainstream narrative, of which the above are just some of the salient objections, required a complete revision of the subject, starting with the most basic of questions. Why was Spain the only European power to come across the only major deposits of silver in the world? Why was amalgamation only used massively in the New World and not in Europe? Was amalgamation the only option available to Spain to refine the ores it found in the New World? How much silver was produced by amalgamation and how much by smelting, that is consistent with registered sale revenues of mercury? The balance of production by each refining method is the key to estimating two quite distinct sets of environmental impacts. What was the nature and amount of the chemicals voided to the environment from either refining process? Was mercury the only chemical of note to have an environmental impact in the New World as a result of silver refining?

The answers to these questions lie in a series of concatenated events that defined the environmental history of silver refining in the New World. It begins with the geology of silver deposits, which determine the different chemical nature of silver ores. The chemistry of the silver compounds then define their response to the two possible refining methods known in this period, smelting and amalgamation. While smelting can be applied to any silver ore with enough patience and lead flux, amalgamation of silver ores is in reality a misnomer for a complex set of chemical reactions that require the transformation of silver sulphides into silver chlorides (via the action of roasting with salt or through the reaction with copper sulphate), which are then reduced by mercury into elemental silver, which will only then amalgamate with the available mercury that has not been transformed into calomel (mercurous chloride). The presence of lead would impair the efficient use of mercury to amalgamate silver ores. Thus the choice of refining process for silver ores was determined in the first instance by the chemical nature of the ores.

What was the role of production costs and economics if chemistry was the gatekeeper to the two quite different paths of environmental impact? Under what economic scenarios of cost production could smelters derive a profit if the nature of their ores precluded the use of amalgamation? If lead fluxes were available to use with lead-poor ores, could refiners have turned to smelting and still made a profit during periods when mercury became too scarce or payment terms too onerous? Did smelting in fact compete on production costs with amalgamation? On the other hand, what exactly were the economic reasons behind the use of mercury, first in New Spain and then in the nineteenth century in republican Mexico?[29] For all that has been written on mercury and amalgamation, there is not a single detailed analysis of comparative production costs between amalgamation and smelting that can serve to answer this question, for lack of a suitable historical data base of production costs. What influence did the fiscal opportunity cost for the Spanish Treasury between amalgamation and smelting have as a result of Spain's ownership of the mines at Almadén and Huancavelica? Did the obvious value of mercury as a revenue stream to the Treasury tilt the balance towards the use of amalgamation in New Spain, and thus alter the course of its environmental history?

What follows is based on a chemical history of silver refining in the New World, using the tools from chemistry to interpret the historical documents, much as an economic history relies on applying principles of economy to decipher historical data. Following Occam's dictum I have sought the minimum number of variables that could explain the overall patterns

[29] While independence in the nineteenth century marks a clear historical boundary between New Spain and republican Mexico, the practice and environmental impact of amalgamation and smelting form a more continuous narrative that starts in mid sixteenth century and terminates with the introduction of the cyanide process at the end of the nineteenth century.

as reported in the historiography of silver refining. I have thus based my analysis on the chemical behaviour of the two main groups of silver compounds that were the source of silver production in New Spain and then Mexico: silver chloride with silver sulphides, and argentiferous galena. The following chapter explains how geology determined Spain's predominance in the silver market, and uses current theories on the evolution of silver deposits to interpret their composition and the manner in which this affected the course of silver refining in the New World. Geology also explains the fundamental chemical difference, and similarities, between silver ore deposits on both sides of the Atlantic. The conclusions reached in this chapter set the groundwork for the behaviour of the ores when subjected to either smelting or amalgamation in its various forms.

In the following two chapters I will weave between New Spain and the Vice-Royalty of Peru, because for the latter the extant documents provide a more continuous narrative on the state of smelting as inherited from Europe and a more detailed source on the critical evolution of amalgamation to an industrial-scale technique capable of refining sulphidic silver ores. For each process I establish its generic environmental footprint, which is intimately bound to the architectural legacy of every refining unit in the New World. Using the chemistry of the reactions I identify and quantify the separate set of environmental impact vectors generated by smelting and amalgamation.

I will then focus only on New Spain, where smelting competed more closely with amalgamation. An important key to interpret the historical trail of silver refining was found in the impressive architecture of the *Hacienda* de Santa Maria de Regla on the outskirts of Pachuca. It is very rare to find at present both the well-preserved physical remains of a major refining *hacienda* together with more than a decade of very detailed accounting records. What made Regla unique was the fact that detailed records for both amalgamation and refining processes were available. Chapter 4 provides a close-up view of the historical operation of a silver refining *hacienda* as seen through the mass balance of materials entering and leaving its walls. These accounts also serve to make up for the absence of historical measures of chemicals voided to the environment, since mass balances can be used to calculate the magnitude of the environmental impact of its operations. The simple tenet of the conservation of matter meant that what entered a refining compound had to be accounted for in what exited the compound, regardless of its chemical form. As a result it is possible to arrive at ratios of chemicals voided into the environment per kg of silver refined by amalgamation or smelting. In Chapter 5, the economic data from Regla give a very rare opportunity to analyse in depth the comparative production costs and structure of amalgamation and smelting. In turn these insights are used to explain why refiners in New Spain could have applied in a profitable way both amalgamation and smelting, subject only to the nature of the silver ore being refined.

The mass ratios for the main environmental impact vectors, calculated for each of the processes, complemented by the data on silver produced and mercury sold obtained from primary and secondary sources, are then used in Chapter 6 to project over the main mining districts of New Spain, or in total over Mexico, a gross estimate for the mass balances of the major waste products issued to the environment as a result of the historical refining of silver. It will quantify how the different chemical compositions of the ores being refined lead to totally different environmental impact vectors, thus highlighting the importance of the geochemistry of the silver ore deposits to the environmental history of silver refining in the New World. The results presented at the end of this research propose a major departure from the narrative that until now has dominated the studies on this topic. The quantitative data indicate it was lead and its compounds from smelting, not mercury from amalgamation, that was the only heavy metal to be issued to the air in major quantities. Calomel that exited as solid waste was the end result of the consumption of mercury during amalgamation. I will argue that the chemical and physical nature of the refining reactions mitigated the impact of mercury on the workers and communities, while exacerbating the environmental impact of lead and its compounds. Human choices were made in full knowledge of the toxicity of both lead and mercury, and the final environmental impact owed less to human foresight than to a fortunate attenuation of effects from a balance of refining processes dictated by fiscal reasons.

One final word of caution. The conclusions reached in this work only apply to the silver refining activity as carried out in New Spain and Mexico, and in no way represent the environmental impact of the mining and processing of mercury ores in Almadén or Huancavelica, nor to the overall environmental consequences of mining.

1 The genesis and nature of silver ores.

'It seemeth to me a thinge undecent to reade so much of golde and sylver and to know so lyttle or nothinge of the naturall generation thereof'' Richard Eden (1555)

'wherever the earth moves, metals are concentrated ... silver … a gift from the underworld sealed in cracks' Fortey, *Earth: An Intimate History* (2005)

1.1 Introduction

There is no Costa da Prata marked on maps of Africa alongside the Gold Coast and other shorelines that eponymously signposted each new class of trade goods for the expanding Europeans. From the fifteenth century to the seventeenth century, the Portuguese would hug the coasts from Africa to India and all the way to China with the fortified port-cities of the Estado da Índia, without having a single opportunity to become masters of a world-scale deposit of silver, and not for lack of searching for one.[30] The most they would achieve was to become middlemen in the Sino-Japanese trade of the sixteenth century, when Japan was known as the silver islands, and 'the profits made there by the Portuguese were the envy of sailors, merchants and adventurers from Amsterdam to Manila'.[31]

Unbeknownst to them, the Treaty of Tordesillas had effectively quarantined the Portuguese from ever adding to their wealth and possessions from new silver mines. In fact, with the exception of Spain and France, no other European power engaged in global expansion during the Early Modern Era would have as strong an option of coming across world-scale

[30] As for example the military campaign by Portugal in search for silver mines in Southern East Africa. A. R. Disney, *A History of Portugal and the Portuguese Empire : From Beginnings to 1807* vol. II (New York: Cambridge University Press, 2009), 145-71.; or the search for the 'islands east of Japan "*rricas de plata*"' as cited by Paul W. Mapp, *The Elusive West and the Contest for Empire, 1713-1763* (Chapel Hill; Williamsburg, Va.: University of North Carolina Press, 2011), 109.
[31] William S. Atwell, "International Bullion Flows and the Chinese Economy circa 1530-1650," *Past and Present* 95 (1982): 69,71.

deposits of silver ore.[32] The dearth of any major primary silver ore deposits in India or China raises the question as to why huge areas of the Earth remain barren to the present of any important '*criaderos'* (nurseries) of silver, to use the organic phrasing found in Spanish metallurgical tracts of the Early Modern Period. This lack of silver would drive part of the Asian transcontinental trade towards a Europe incapable as yet of producing the textiles, porcelain and spices that India, China and the Spice Islands could provide.[33] And yet it was no mean advantage for Europeans to have access to their own silver and gold mines and to have developed the necessary technology to extract the ores and refine these precious metals, supplemented by the gold bartered from Africa. By conquering the mountainous spine of the New World, Spain would have access to a source of silver of a magnitude beyond the powers of imagination of the European miners of the fifteenth century.

There is a sense of wonder at the unique triangulation of geological gifts that resulted from the trans-oceanic voyages due west of the Spanish mainland. The chemical context that defined the technical options for refining silver ores in the New World, and consequently its environmental history, belongs to the longest of the Braudelian cycles, that of geological time. Geology did not determine European imperial policy, but it did favour the Imperial ambitions of the Spaniards, who stumbled across the vast silver deposits found in Peru and New Spain to complement their own vast deposits of mercury of Almadén in Spain and Huancavelica in the Vice-Royalty of Peru. During the Early Modern Era, Portugal's name would be mostly associated with African and Brazilian gold, while Spain would fund its political aims to a great

[32] 'ore: any naturally occurring material from which a mineral or aggregate of value can be extracted at a profit'. L. J. Robb, Introduction to Ore-Forming Processes (Malden, MA: Blackwell Pub., 2005), 6.
[33] Dennis Flynn and Arturo Giráldez, "Latin American Silver and the Early Globalization of World Trade," in *National Identities and Sociopolitical Changes in Latin America* (London and New York: Routledge, 2001).; Andre Gunder Frank, *ReOrient: Global Economy in the Asian Age* (Berkeley: University of California Press, 1998).

extent based on New World silver from the highlands.[34] The same geological forces that also explain the dearth of silver deposits in India and China, or the brief silver bounty in Japan, configured the nature and direction of the first global flows of trade. Geology is the only path to provide an answer to Richard Eden's complaint quoted in the epigraph to this chapter.[35] What geology cannot explain is the luck of the draw that kept France from joining Spain as a major producer of silver of the Early Modern Era. Its colonists of New France were tantalizingly within reach of a source of silver in the Cobalt area of modern Ontario that equalled over 80% of the total silver extracted from Potosí by Spain.[36]

The environmental history of silver refining in the Americas is thus the end result of a chain of concatenated events that begins with the geological birth of each silver deposit. The geological genetic imprint defines the nature of the silver compounds contained in each ore,

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[34] Gold would be found on both sides of the Tordesillas Line, though geologists have remarked on the fact that silver and gold deposits tend to be dominated by one or the other (Frederick T. Graybeal, Douglas M. Smith, and Peter G. Vikre, "The Geology of Silver Deposits," in *Handbook of Strata-Bound and Stratiform Ore Deposits. Part IV*, ed. K. H. Wolf (Amsterdam: Elsevier 1986), 159. ; Walter Pohl, *Economic Geology : Principles and Practice : Metals, Minerals,Coal and Hydrocarbons - Introduction to Formation and Sustainable Exploitation of Mineral Deposits* (Chichester, West Sussex; Hoboken, NJ: Wiley-Blackwell, 2011), 227. This observation is made even by the non-specialist observer: 'one never has at the same time a high content in silver and gold' -'*on n'a jamais à la fois haute teneur en argent et en or'*, in Albert Bordeaux, *Le Mexique et ses mines d'argent* (Plon-Nourrit et cie., 1910), 291. In South America Colombia, Brazil and Venezuela are known more for their gold than for their silver.

[35] Richard Eden (1555) as quoted by Cyril Stanley Smith in his introduction to Vannoccio Biringuccio, *The Pirotechnia*, trans. Cyril Stanley Smith and Martha Teach Gnudi (Cambridge, Mass.: The M.I.T. Press, 1966), xxii. Richard Eden was the translator to English of Biringuccio's metallurgical text.

[36] Over 600 million ounces of silver [over 18,000 t] was produced from the Cobalt area in modern Ontario, according to Graybeal, Smith, and Vikre, "Geology Silver Deposits," 15. This amount represents 84% of the silver mined from Potosí up to the end of the eighteenth century (22,170 t, as reported in TePaske and Brown, *Gold and Silver*, 184. In monetary terms this would have provided a windfall of over 700 million *pesos* within the French colonial economy (at 40 pesos per kg of silver) or over 4,200 million livres (assuming 6 *livres* to the *peso* in the eighteenth century, according to Carlos Marichal, *Bankruptcy of Empire : Mexican Silver and the Wars Between Spain, Britain, and France, 1760-1810* (New York: Cambridge University Press, 2007), 54.). Annual values of sugar arriving in France from its Caribbean plantations went from 15 to 75 million livres per year from 1730 to 1790 (Robert Louis Stein, *The French Sugar Business in the Eighteenth Century* (Baton Rouge: Louisiana State University Press, 1988), 103.), so just the silver value of these deposits represented around 60 years of sugar imports from the French Caribbean to France at the highest range of sugar prices. If the French mining and refining establishment of the eighteenth century had the expertise to mine and smelt the Cobalt silver ores, the impact of silver from the area around modern day Cobalt throughout the French colonial economy of the New World, and the ripple effect on the overall French strategy towards its empire in the Americas, would have been substantial. The deposits were discovered in 1903.

and of any collateral metallic species. The chemistry of the silver compounds and the other metals present in the ore in turn defines the optimal refining process that can be applied to profitably extract the silver content of the ore, either smelting with lead or amalgamation with mercury. Each refining process finally produced a completely different set of environmental impact vectors that would create the environmental history of the local communities around refining centres and their landscape. The Spanish historian Castillo Martos has stated that when determining the reasons why mercury amalgamation became the method of choice in the New World and not in Europe, 'the difference in the nature of American and European [silver] ores is a fact not to be ignored; however other factors were more influential'.[37] I will argue throughout this thesis precisely the opposite, that the difference in the chemistry of the silver ores on both sides of the Atlantic is what defined at every step of the way the environmental consequences of silver refining in the Americas.

To understand what gave rise to the difference in the chemical composition of silver ores I will briefly review in the following sections the current geological explanations for the appearance of major silver deposits in the Americas and in Europe, based on present theories of metallogeny and plate tectonics.[38]

1.2 Subduction and the New World

Nine of the ten largest sources of primary silver ore known to humankind (those where at least 50% of their revenue is or was derived from the production of silver) lie on the

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[37] *'La diferente calidad de las menas americanas y europeas es un dato que no habría que despreciar; sin embargo, influyen más otras consideraciones*'. Castillo Martos, *Bartolomé de Medina*, 106.
[38] 'metallogeny [is] the study of the genesis of ore deposits in relation to the global tectonic paradigm ... a range of processes responsible for the formation of the enormously diverse ore deposit types found on Earth' Robb, *Ore-Forming*, vii.

mountainous spine of the New World (Figure 1 and Table I).[39] The only source of silver outside the New World to figure in this exclusive list are the Erzgebirge silver deposits in Europe. The combined silver endowment of Mexico (smaller now than New Spain) and Peru / Bolivia (the Vice-Royalty of Peru) continues to be the greatest known deposit of silver on Earth, with a total amount of silver (produced to date and remaining) to the year 1994 estimated at 441,405 t.[40]

It is a further measure of the uniqueness of the geological landscape that was conquered by the Spanish Crown that more than half of the mining locations listed in Table I would have been recognized by a miner in the New World of the late sixteenth century onwards.[41] Little did Charles V suspect there was no hyperbole in the motto granted under his reign to Potosí: 'I am the rich Potosí, treasure of the world, Lord of all the mountains and the envy of the Kings'.[42] At present Potosí remains what Laznicka terms the world's 'largest silver supergiant' ore reserve, a distinction all the more remarkable since the search for new deposits has continued since the sixteenth century, with the support of ever increasing technical sophistication.[43] The Spanish employed the word *bonanza* to denote a 'spectacularly rich precious metal zone', but

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[39] Graybeal, Smith, and Vikre, "Geology Silver Deposits," 2-32. Their listing published in 1989 includes only deposits that had yielded over 28 t of silver (one million ounces) to date, and does not include the Imiter silver deposit of Morocco, a deposit with an estimated 8,000 t of silver, as detailed in Alain Cheilletz et al., "The Giant Imiter Silver Deposit: Neoproterozoic Epithermal Mineralization in the Anti-Atlas, Morocco," *Mineralium Deposita* 37, no. 8 (2002). As of the twentieth century the majority of silver produced is a by-product from the mining and refining of other metals (for example, copper), which explains why the Lubin Kupferschiefer district in Poland is now listed as the single largest deposit of silver, even greater than Potosí, even though the silver content of the ores is a paltry 4 grams per ton, Peter Laznicka, *Giant Metallic Deposits : Future Sources of Industrial Metals* (Berlin: Springer, 2006), 54. Sources for Table I: a) Graybeal, Smith, and Vikre, "Geology Silver Deposits." b) Laznicka, *Giant Metallic Deposits*. c) TePaske and Brown, *Gold and Silver*.

[40] D.A. Singer, "World Class Base and Precious Metal Deposits; A Quantitative Analysis," *Economic Geology* 90, no. 1 (1995): 91.Table 2.

[41] Graybeal, Smith, and Vikre, "Geology Silver Deposits," 2-32.

[42] '*Soy el rico Potosí, del mundo soy el tesoro, el rey de todos los montes y la envidia de los reyes*' quoted in Pedro Cunill Grau, "El paisaje andino: Punas, Salares y Cerros," in *Potosí: plata para Europa* ed. José Villa Rodríguez(Sevilla: Universidad de Sevilla, 2000), 81.

[43] Laznicka, *Giant Metallic Deposits*, 108. The terms giant and supergiant are based on a relative scale determined by the scarcity of each metal and the size of the endowment in each deposit, thus the more scarce a metal the lower the threshold in endowment size required to classify it as a giant or supergiant deposit. See ibid., 38-54.

it could as well describe the whole geological panorama that opened up to them in the New World.[44] It has been estimated that of the total 337 'giant metal deposits' discovered until now, only 13 were known prior to 1492, and only an additional 12 would be found up to 1800.[45]

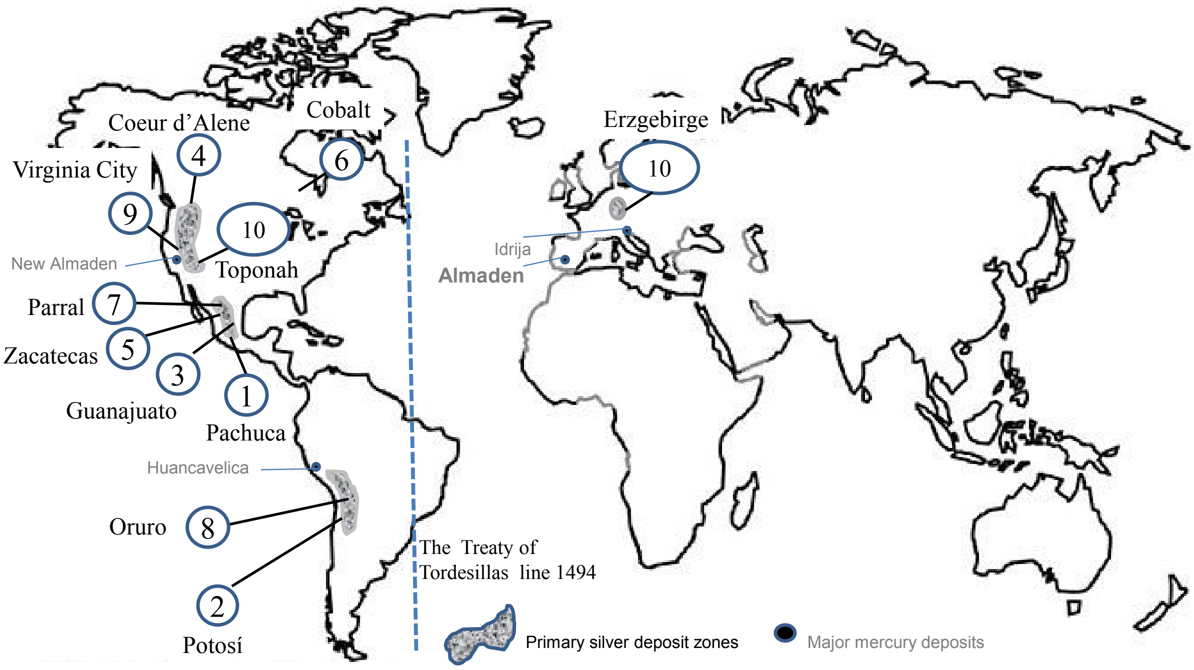

Figure 1-1. Top ten silver deposits ranked by aggregate production and main mercury sources up to the late twentieth century. Data from Table 1-I.

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[44] Graybeal, Smith, and Vikre, "Geology Silver Deposits," 1. According to the *Diccionario de la lengua española* (http://www.rae.es), *bonanza* was a Spanish term originally applied to sailing, and denoted a calm (favourable) sea.

[45] Peter Laznicka, "Discovery of Giant Metal Deposits and Districts," in *Proceedings of the 30th International Geology Congress: Energy and Mineral Resources for 21th Century: Geology of Mineral Economics* ed. Pei Rongfu(VSP, 1997), 356-357.

ranking by aggregate production	country	location	aggregate production		production dates		endowment/reserves+production/contained			
			metric tons	source	years	source	ore million tons	source	silver metal tons	source
1	Mexico	Pachuca	36,400	a, 17	1528-1976	a, 17	35	a, 17	42,452 (production plus reserves)	b, 137
2	Bolivia	Potosí	> 28,000	a, 9	1545-1950	a, 9	100	a, 9	86,000 (endowment)	b, 131
3	Mexico	Guanajuato	31,700	b, 137	to 1984	b, 137	8	a, 17		
4	United States	Coeur d'Alene	26,180	a, 22	1884-1980	a, 22	50	a, 22	34,000 (contained)	b, 364
5	Mexico	Zacatecas	23,236	b, 138						
6	Canada	Cobalt, Ontario	ca. 18,000	a, 44	1903-1967	a, 15				
7	Mexico	Parral	13,496	a, 16	1631-1982	a, 16	50	a, 16		
8	Bolivia	Oruro	7,588	a, 8	1595-1962	a, 8	27	a, 8	12,000 (production plus reserves)	b, 146
9	United States	Virginia City	5,376	a, 28	1859-1950	a, 28	19.1	a, 28		
10	United States	Tonopah	4,878	a, 28	1900-1950	a, 28	8.8	a, 28		
	Germany	Erzegirbe (including Freiberg)	4,788	a, 12	1163-1910	a, 12	20	a, 12	7,000 (Freiberg, contained)	b, 364

Table 1-I. Major silver deposits ranked by aggregate production. For sources see footnote 39.

Spain would find three of the dozen in the first fifty years after starting their conquest of the New World, including the two major epithermal deposits of primary silver ore. Six of the ten ore deposits that appear in Table I would be under control of the Spanish Crown for a space of some 250 years. The scale of the *bonanza* found in the Spanish silver mines in the New World is highlighted by the fact that ‘Pachuca [in New Spain, present day Mexico, is] the world's second largest epithermal accumulation [of silver known up to the year 2006] after Potosí'.[46]

In its westward thrust of conquest and expansion Spain had stumbled without knowing across 'the Andean and Cordilleran orogens of the western Americas [that] contain the greatest concentration of metals on Earth, and are pervasively mineralized from one end to another'.[47] According to Evans, the mineralization observed in the continental margin arcs of the Andes and Cordillera is unique in the variety and magnitude of its metal endowment.[48] The explanation for the mixture of bounty and scarcity of silver deposits in Figure 1-1 had to wait for recognition of the dynamic nature of global plate tectonics, the new paradigm in the field of geology that as of the late 1960s would radically change the view held until then of Earth as a 'static, rigid sphere'.[49]

Subduction is a word that does not appear in the historiography of Spanish America and New World silver, and yet subduction is the geological script that determined the history of Spain's role in the New World.[50] In 1972 Richard Sillitoe published a paper in which he

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[46] *Giant Metallic Deposits*, 137. The difference between the top tier deposits in Table I and the remainder of known silver deposits in the world is very large. Over 115 primary silver deposits in the world (excluding the ex-USSR) were reported in 1980 which had produced over their lifetime over 1 million ounces (oz), equivalent to 28 t. Graybeal, Smith, and Vikre, "Geology Silver Deposits," 6-30. To place this threshold in perspective, 28 tons of lifetime production corresponds to approximately a quarter of just one year's output in Potosí averaged over 250 years continuous production during the Early Modern Era. World-class silver deposits that have accounted for 79% of all silver discovered and produced are those that contain over 2,400 t of silver (the top ten percent of all known deposits), while supergiant deposits of silver contain over 22,000 t of silver, and account for 37% of total silver endowment. Singer, "Precious Metal Deposits," 10.

[47] Robb, *Ore-Forming*, 338.

[48] Anthony M. Evans, *Ore Geology and Industrial Minerals : An Introduction* (Oxford; Boston: Blackwell Scientific Publications, 1992), 331.

[49] R. W. Carlson, "Introduction," in *Treatise on Geochemistry : The Mantle and Core.*, ed. R. W. Carlson (Oxford: Elsevier-Pergamon, 2004), 15. There is an interesting account of the paradigm change brought about by plate tectonics, and a discussion in terms accessible to the non-geologist as to why deposits of silver arise from movements within the Earth, in Richard A. Fortey, *Earth : An Intimate History* (London: Harper Perennial, 2005), 202, 253.

[50] The theory of subduction as the explanation for the silver wealth exploited nearly exclusively by Spain has not yet received attention in recent histories of the region to explain the uniqueness of its silver deposits, for example: Kendall W. Brown, *A History of Mining in Latin America : From the Colonial Era to the Present* (Albuquerque: University of New Mexico Press, 2012).; Robins, *Mercury, Mining and Empire*.; Elliott, *Empires Atlantic World*.; Manuel Castillo Martos, "Plata y revolución tecnológica en la América virreinal," in *Historia de las Ciencias y*

proposed an explanation as to why the western area of the New World has been privileged with metallic richness.[51] According to Sillitoe, the metallogeny of silver ore deposits of the American continents begins at the mid-ocean ridges within the Pacific Ocean, extended gashes on the sea-floor where ocean crust is being continually issued forth from material that rises from the mantle, and where metal rich solutions are vented and precipitated minerals fall on the newly created and spreading ocean floor. The new ocean crust spreads on either side of each ridge until the eastern portion reaches first the continental crust of the Americas (Figure 1-2). Instead of a head-on-collision, a subduction of the oceanic crust takes place as it slides under the thicker continental crust, a very slow motion version of the last step of a mechanical escalator sliding continuously under the more static landing stage. In so doing it entrains with it all surface metallic deposits vented from the mid-ocean ridge and also accumulated during its travel under the Pacific Ocean, together with quantities of sea-water. As the subducting ocean crust slides deeper under the continental crust it enters a zone where, in Forley's powerful and succinct summation, whenever the Earth moves metals are indeed concentrated.[52] In the case of silver, hydrothermal processes will play a major role: 'The most efficient metal transport in ore formation is by aqueous fluids [in which] metals dissolve … through simple

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de las Técnicas, ed. Luis Español González , José Javier Escribano Benito, and María Ángeles Martínez García (Spain: Universidad de la Rioja, 2004).; Bakewell, *A History of Latin America*.

[51] R.H. Sillitoe, "Relation of Metal Provinces in Western America to Subduction of Oceanic Lithosphere," *Geological Society of America Bulletin* 83, no. 3 (1972): 815. For a more recent discussion on subduction and the American continent see Suzanne Mahlburg Kay, Víctor A. Ramos, and William R. Dickinson, *Backbone of the Americas : Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision* (Boulder, Colo.: Geological Society of America, 2009).Other possible processes that have been proposed involve the scraping off of certain metal content from the base of the overriding plate during subduction; inhomogeneous distribution of metals below the solid crust of the Earth, scavenging of pre-existing concentrations at depth, and accretion from large meteorites that fell at an early stage of Earth's history. For a more detailed discussion see A. H. G. Mitchell and M. S. Garson, *Mineral Deposits and Global Tectonic Settings* (London; New York: Academic Press, 1981), 191,324-326. For an approach based on melt generated by subduction then zoned magma chambers leading to volatile stripping of copper and silver via magmatic vapour phases followed by extended fractional crystallization of metals and hydrothermal activity see B. Lehmann, A. Dietrich, and A. Wallianos, "From Rocks to Ore," *International Journal of Earth Sciences* 89, no. 2 (2000): 287-292.

[52] Fortey, *Earth : An Intimate History* 253.

ions ... or complexes'.[53] Hydrothermal processes involve the action of water to transport metals under the Earth in concentrated solutions akin to the strong metal-rich soup of a hot mineral spring. Epithermal deposits is the term used for the resulting hydrothermal ore deposits formed at shallow depths (less than 1500 meters) and fairly low temperatures (50-200ºC).[54]

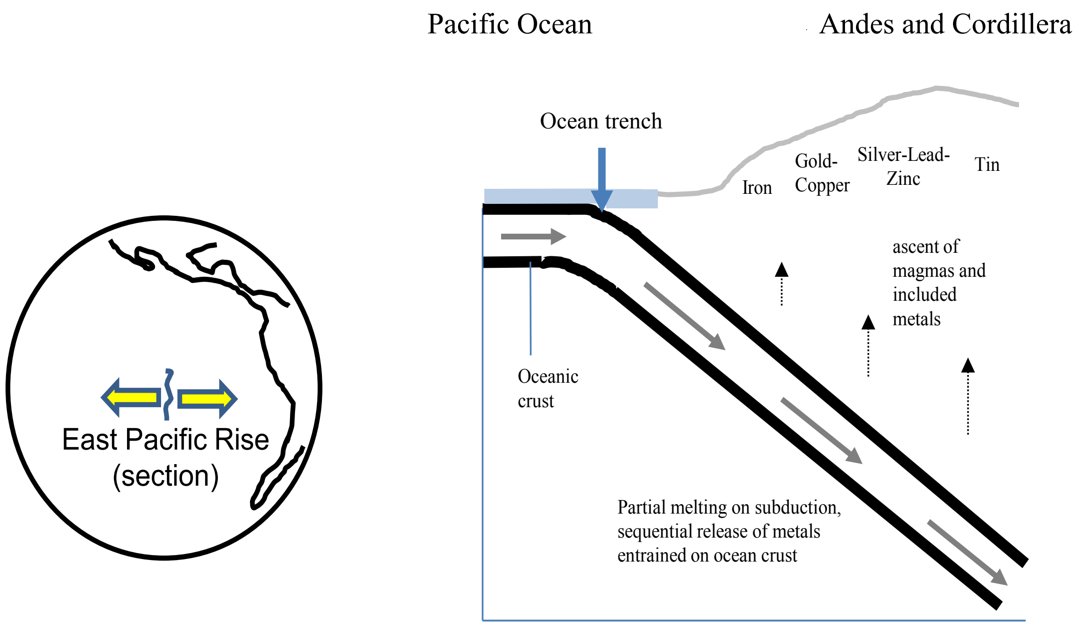

Figure 1-2. The spreading ocean floor subducts under the continental crust of the Americas (illustration based on Sillitoe in footnote 51).

Silver and its compounds are among the metals that have been deposited in major amounts via subduction processes along the mountainous spine of the Americas. Figure 1-3 is of great help in visualizing the role of subduction in defining the location of major primary silver deposits in the New World. It also shows why the history of silver refining in Japan has

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[53] Lehmann, Dietrich, and Wallianos, "From Rocks to Ore," 285.
[54] Robb, *Ore-Forming*, 7.

the same geological roots as that for New Spain.[55] In the Pacific coast of the Americas subduction started in the Mesozoic [201 to 66 Ma] and early and middle Cenozoic [66 to 2.5 Ma] and is still very much active beneath Central and South America.[56] I have already mentioned that the Andes have been described by modern geologists as the single most important concentration of metallic ore deposits to be found in the world.[57] According to plate theory the reason for this distinction is the 'singular longevity of the convergent plate boundary of the eastern Pacific rim', so that even as these words are written a section of oceanic crust that was formed some 55 million years ago at the mid-ocean ridge is now sliding continuously under the South American plate in an on-going process of subduction.[58] Nowhere else on earth has such persistent and active subduction occurred so close to a large and inhabitable landmass. This proximity is crucial for historical events of the Early Modern Era to have been influenced by this geological process. To quote a strangely disturbing Freudian turn of phrase: 'Latin America was, in comparison with other regions in which mineral wealth was potentially to be extracted, eminently penetrable'.[59] Long- term and active subduction is what distinguishes the Spanish silver mines of the New World from the blank spaces in Figure 1-1.

Not all subduction zones are created equal as far as silver is concerned. The cornucopia of New World metals, including silver, 'may' be related to its proximity to the East Pacific Rise, as metals keep being added to the spreading oceanic crust. 'The whole Eastern Pacific

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[55] William R. Dickinson, "Anatomy and Global Context of the North American Cordillera," in *Backbone of the Americas : Shallow Subduction, Plateau Uplift, and Ridge and Terrane Collision*, ed. Suzanne Mahlburg Kay, Víctor A. Ramos, and William R. Dickinson (Boulder, Colo.: Geological Society of America, 2009), 2.
[56] Sillitoe, "Metal Provinces in Western America," 815. Ages in parenthesis throughout are expressed in million years (Ma) and correspond to the classification as published in the 2011 version of the International Stratigraphic Chart (www.stratigraphy.org).
[57] One important exception relevant to the history of silver refining in the Americas is iron.
[58] Pohl, *Economic Geology*, 222.; Mitchell and Garson, *Global Tectonic Settings*, 186.; F. T. Graybeal and D.M. Smith Jr, "Regional Distribution of Silver Deposits on the Pacific Rim," in *Silver - Exploration, Mining and Treatment*(Mexico City: Institution of Mining and Metallurgy, 1989), 7.
[59] Peter J. Bakewell, "Introduction," in *Mines of Silver and Gold in the Americas* ed. Peter J. Bakewell (Aldershot (UK): Variorum, 1996), xxii.

continental margin arcs from British Columbia to Chile are well endowed with major silver deposits while the Western Pacific continental margin has virtually none'.[60] According to Graybeal and Smith the shorter the time interval to subduction, as applies to the eastern side of the Pacific Ocean crust, the more evident the effect of 'enrichment of silver in young ocean crust at spreading centres', which is why the western areas are silver-poor in comparison.[61]

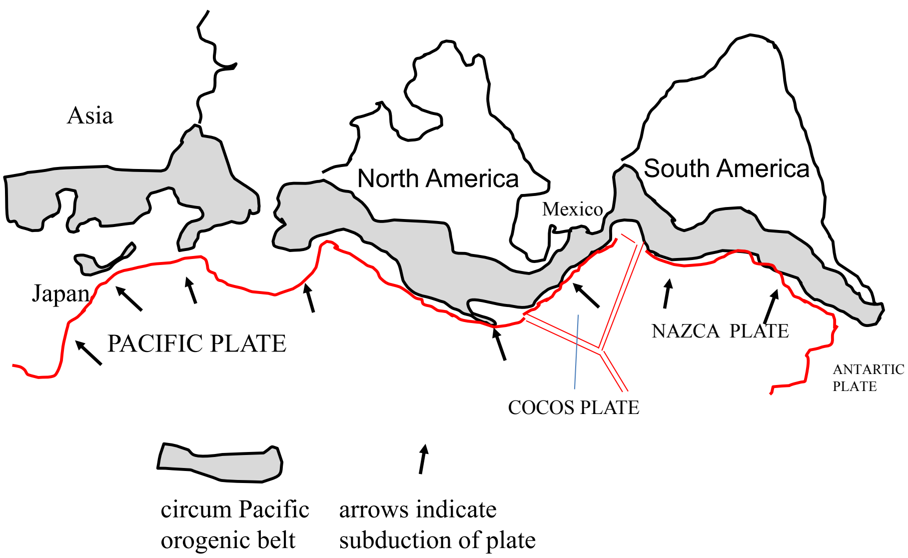

Figure 1-3. Subduction along the Andes, Cordillera and Japan (based on illustration in footnote 55).

Even if subduction is the fundamental geological process that gave rise during different geological eras to silver deposits both in the Americas and Europe, the resulting chemical nature of the silver compounds and accompanying metals varied substantially in each location, as I will discuss in the following sections.

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[60] Evans, *Ore Geology*, 330-331.
[61] Graybeal and Smith Jr, "Regional Distribution of Silver Deposits on the Pacific Rim," 3.

1.3 The geological difference in New World silver deposits

New World silver did not arise from a single type of metallogeny, since there is a distinct genesis to silver ores in the Andes compared to those of New Spain, even if both are the ultimate product of subduction processes. It has long been evident that the two silver refining industries proceeded along different historical lines, and historians have proposed this arose from differences in the silver content of the ores and from the tax burden imposed upon refiners.[62] In geographical terms the silver in the Andes has been concentrated in few and large deposits at very high altitude, such as Potosí. In the case of New Spain, the geographical dispersion of silver deposits is much more pronounced, and none has reached the magnitude of Potosí. As to the geological difference between the two, according to Sillitoe:

"It should be noted that **the Bolivian silver deposits are parts of tin systems** formed in a back-arc setting by chemically reduced magmas dominated by a crustal source. In contrast, **the main Mexican silver deposits are accompanied by lead, zinc and subordinate gold** and are associated with chemically oxidized magmas of combined mantle plus crustal origin that were formed in an arc setting above a shallowly inclined subduction zone. Hence, **the two regions differ substantially in both their tectonic and magmatic settings** [emphasis added]'.[63]

There is as yet no work that relates directly the geological difference of both areas to the geographical concentration, dispersal and size of silver deposits. However, the greater probability of finding both lead and gold together with silver in the deposits of New Spain (Mexico) compared to the Andean locations is extremely relevant in the light of the importance of smelting in New Spain compared to the Andes. The presence of lead is a necessary condition

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[62] Brading and Cross, "Colonial Silver Mining: Mexico and Peru."
[63] Dr. Richard Sillitoe, private communication. The mention of crustal or mantle sources of magma indicate the origin of the magma from where metals and their compounds are ultimately leached from by hydrothermal processes. Chemical reduction or oxidation will determine the final chemical profile of these metals and compounds. Subduction processes of a different nature are indicated, back-arc setting (inland side of the Andes), or shallowly inclined subduction zones in the case of Mexico.

for smelting, and the added cash flow from gold would assist in making this process economically viable. I will return to both issues in the chapters that follow.

1.4 The chemistry of the sources of silver in New Spain / Mexico

It is virtually impossible to obtain a wide sampling of the ores found by Europeans at each of the mining sites developed during the first centuries of silver mining in the New World.[64] In one location even the historical mines have been physically erased from the face of the earth by modern day mining techniques in search of parts per million of gold.[65] The problem is compounded by the fact that silver is extracted from a greater number of different ores than any other metal: over 200 varieties of silver ore have been reported.[66] The complexity of the multiple sources of silver is captured in its bewildering visual array by the early historical observers:

‘it is common to find some [silver] clean and purified, that does not need to be refined … it has waxed sometimes as glitter; other times, wrapped around a stone like a thin piece of string made of fine silver ... silver that arises in minerals encrusted in stones ... is a marvellous thing to see in how many ores it is nurtured ... because some are black; others, yellow, grey-brown, light-brown, light-coloured or of many shades of colour; some, extremely hard and thus stubborn, and others soft, tender ... some ores are earthy, others leaden, others are laced with iron pyrites; and others are mixed with gold, copper, tin, lead, caparrosa [ferrous or copper sulphate], to sum it up, there is hardly any [silver] that can be found that is not mixed in various ways’.[67]

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[64] ‘No specimens of silver minerals survive from the original mines [of Potosi]’. T.C. Wallace, M. Barton, and W.E. Wilson, "Silver & Silver-Bearing Minerals," *Rocks & Minerals* 69, no. 1 (1994): 35. While there are reports of samples collected and sent back to Spain from the New World, the fate of these samples is unknown.

[65] The whole Cerro San Pedro on the outskirts of San Luis Potosí is at present being levelled to the ground through open-pit mining operations by the Canadian mining company New Gold. The historical mines dating from the late sixteenth century onwards have disappeared literally into thin air.

[66] Claudia Gasparrini, "The Mineralogy of Silver and its Significance in Metal Extraction," *CIM Bulletin* 77, no. 866 (1984): 99.

[67] ‘*se suele hallar alguna limpia y acendrada, que no tiene necesidad de beneficiarse … cuajase algunas veces como escarcha; otras, revuelta a una piedra como un delgado hilo de plata fina … la plata que nace en minerales incorporada en piedras … es cosa de maravilla ver cuán diferentes son los metales en que se cría. Porque unos son negros; otros, amarillos, pardos, de color castaño, rubio y de todos colores; unos, durísimos y por extremo empedernidos, y otros blandos, tiernos … unos metales hay terrosos, otros plomizos, otros margajitosos; y otros tienen mezcla de oro, cobre, estaño, plomo, caparrosa; y, en suma, casi no se halla ninguno que no tenga varias mixturas*’. Bernabe (S.J.) Cobo, Historia del Nuevo Mundo, ed. Francisco (S.J.) Mateos, vol. 91, Biblioteca de Autores Espanoles (Madrid: Atlas, 1964), 141.

In the absence of physical historical evidence it is necessary therefore to turn to modern research on the main chemical compounds from which the major part of silver production has been obtained, and the current state of knowledge on the chemical transformations that are known to take place in deposits of silver ore. I have expressly avoided addressing each of the historical silver deposits of New Spain in the formal terminology of geology that categorizes ore deposits of different genetic types according to all the metals present, the host rocks that ultimately make up the gangue or waste mineral material, and the mechanisms by which these metal compounds were deposited in the host rocks.[68] This would require detailed historical knowledge of the geological genetic type of silver ore deposit for each mining district (*Real de Minas*) of New Spain, which according to Humboldt numbered around 500 in the 1800s.[69] On the contrary, I will base my analysis of the environmental impact of historic silver refining on the one factor common to all the *Reales*, that the silver produced in New Spain came from basically just two chemical groups of silver compounds distributed among these deposits: 1) silver sulphide compounds (simple to complex), that via weathering as described below could give rise to surface concentrations of silver halides (mainly silver chloride) and also metallic silver and 2) argentiferous galena (lead sulphide, PbS, that contained silver compounds).[70]

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[68] As one example, these descriptive models have been published by the United States Geological Survey for deposits such as currently found in Pachuca (Model 25 b, Dan L. Mosier et al., "Descriptive Model of Creede Epithermal Veins," in *U.S. Geological Survey Bulletin 1693*, ed. Dennis P. Cox and Donald A. Singer (Washington: U.S. Geological Survey, 1987), 145-49.) There is an updated level of description that now also takes into account the environmental consequences of the various chemical compounds that make up the deposit, under the term 'geoenvironmental models'. For model 25 b see Geoffrey S Plumlee et al., "Creede, Comstock, and Sado Epithermal Vein Deposits," in *Preliminary Compilation of Descriptive Geoenvironmental Mineral Deposit Models, Open File Report OFR-95-0831* ed. E. du Bray (Denver, CO: US Geological Survey, 1995), 152-61.

[69] Alexander von Humboldt, *Essai politique sur le royaume de la Nouvelle-Espagne* (Paris: Chez F. Schoell, 1811), Tome III, 310.

[70] In contrast to gold, the main primary source of silver was not the native metal but the chemical compound silver sulphide (Ag_2S). V. M. Goldschmidt, *Geochemistry* (Oxford: Clarendon Press, 1954), 189. Sulphur is not one of the most common elements on Earth (around 0.05% of the crust) but its role in the movement of metals underground might explain its unmistakeable presence around active volcanoes as a yellow efflorescence of elemental sulphur on the crater walls or via the rotten-egg smell of hydrogen sulphide (H_2S). Silver is classified as a calcophile metal, one that prefers to react with sulphur, as anyone eating a boiled egg with a silver spoon can quickly ascertain. Pohl, *Economic Geology*, 208,356. Silver sulphide presents itself at ambient temperature as the

1.4.1 Silver sulphide and silver chloride

Nearly one hundred years ago, Emmons explained that a silver ore deposit is not an inert mountain of material but a constantly evolving chemical reactor in which over time the composition of the original (hypogene) silver compounds is constantly changing.[71] Because the surface layer of the deposit is a zone where oxygen plays an important role, the term ‘oxidized zone’ has led to the erroneous statement in some of the historiography that silver oxide is generated in this surface layer.[72] It is not silver that is oxidized but other chemical species present in the ore deposit: the ferrous ions to ferric ions, or the sulphide ions to sulphate. Quite the opposite, any silver ion will be reduced to elemental silver, or be solubilized by the sulphate ions and later precipitated as chlorides, and other halides.[73]

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mineral acanthite, the most common of all silver ores, so soft that it can be cut with a knife, with a colour range ‘from black to mirror white silver’. Acanthite is the low temperature (< 173 ° C) form of argentite, and in some of the literature both terms appear to be readily interchanged. Wallace, Barton, and Wilson, "Silver-Bearing Minerals," 25,27. Acanthite would be found in most mines of New Spain and Peru in huge quantities, as the main hypogene (original) silver mineral. It can also be found as part of the silver content in galena, the sulphide of lead.

[71] William Harvey Emmons, *The Enrichment of Ore Deposits* vol. 625 (Washington: United States Geological Survey, 1917), 264.

[72] ‘the interaction between mercury and the surface of gold is easier than with the surface of silver, and this may be the reason why the Romans did not amalgamate silver. The latter [silver] oxidizes when exposed to air and, sometimes, appears with a film of silver oxide (Ag_2O) that impedes contact between the metals [silver and mercury]’- ‘*La interacción entre el azoque y la superficie de oro nativo es más fácil que con la de plata y ello puede ser motivo por el cual los romanos no amalgamaron plata. Esta última se oxida en el medio ambiente y, a veces, aparece recubierta de una capa de óxido de plata (Ag_2O) ... que impide el contacto entre los metales*.’ Castillo Martos, *Bartolomé de Medina*, 74.; mention of finely ground silver ores (oxides, chlorides and sulphides) in Bakewell, "Introduction," xvi. The chemical texts are quite clear on this topic: ‘silver oxide could not accumulate in oxidizing zones, because it is soluble in acid and also [to a limited extent] in water ... it is unknown as a natural mineral [of silver]’ S.A. Cotton, *Chemistry of Precious Metals* (Bristol: Blackie Academic & Professional, 1997), 282.; Emmons, *The Enrichment of Ore Deposits* 625 255.; ‘other naturally occurring silver compounds, including oxides … are either rare or unknown’, in Richard H. Sillitoe, "Supergene Silver Enrichment Reassessed," in *Supergene Environments, Processes and Products*, ed. Spencer R. Titley (Society Economic Geology, 2009), 22.; ‘neither metal [silver and gold] is attacked by oxygen, but silver reacts with H2S in town air forming a black tarnish of Ag_2S.’ Cotton, *Chemistry of Precious Metals* , 275.

[73] Although it is an older paper, Emmons provides detailed chemical reactions that take place in the oxidation zone, and serves as a guide to a correct interpretation of the chemical changes in this region. Emmons, *The Enrichment of Ore Deposits* 625 157-62,252-74.

Sillitoe has published an extensive review of the research up to the year 2009 on the changing nature of the chemical composition of silver ore deposits.[74] He states there is a fundamental difference between copper deposits, where enrichment has been studied and confirmed even down to levels below the water table, and the behaviour of deposits of silver sulphide, which are the ones that predominate in the New World. The revisionist proposal by Sillitoe that ‘supergene sulphide enrichment is an economically unimportant process’, being absent in most examples of major extant silver deposits he reviews in his paper, leads to a conclusion of great relevance in the interpretation of the early subjective reports by miners in the New World. The first generation of Spanish refiners in the New World found a text-book example of an undisturbed deposit of silver sulphide, in which superficial levels had undergone weathering to silver chloride and silver in the zone above the water table. According to Sillitoe, the absence of supergene enrichment means that on average the silver content found at the more superficial levels is indicative of the silver content as a whole for the deposit. In other words the major change as extraction proceeded within most mines in the New World was not so much in total silver content as in the nature of the silver compounds within which it was to be found (Figure 1-4).[75]

Not all the silver sulphide deposits or even all the veins of a major deposit necessarily undergo any process of chemical change at all. When it does take place, the first segment a

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[74] Sillitoe, "Supergene Silver Enrichment," 21-23. In this paper Sillitoe provides a more detailed geological description of major silver deposits in the world, including an estimate of their reserves of silver. An earlier overview of silver sources based on the type of deposit in the Americas is provided in D.M. Smith Jr, "Geology of Silver Deposits along the Western Cordillera," in *Silver - Exploration, Mining and Treatment* (Mexico City: Institution of Mining and Metallurgy, 1989).

[75] There is no doubt that miners came across pockets of extremely rich silver content, as in this description: ‘I have seen in the mine of Zacatecas such a rich vein of silver that, on placing it in the fire, it spit out pieces of silver the size of a broad bean’ - ‘*yo he visto en la mina de Zacatecas una vena de metal tan rico que, quemando en el fuego, escupía pedaços de plata como habas*’ Agustin de Sotomayor, as quoted in Julio Sánchez Gómez, *De minería, metalúrgica y comercio de metales : la minería no férrica en el Reino de Castilla, 1450-1610* (Salamanca: Universidad de Salamanca : Instituto tecnológico geominero de España, 1989), 34. According to Sillitoe’s argument these bonanza zones are not the end product of weathering but the high concentration level of silver was present from the origin of the deposit.

Spanish miner would have found close or at the surface would have provided him initially with an ore mainly in the form of native silver and silver chloride (chlorargyrite), for the most part generated by oxidation-reduction reactions above the water table.[76] As the Spanish miners continued to extract silver ores at deeper levels down to and below the water table, these would revert to the original and primary (hypogene) silver sulphide, native silver, and more complex sulfosalts such as pyrargyrite that contain antimony, an element that interferes in all silver refining processes.[77]

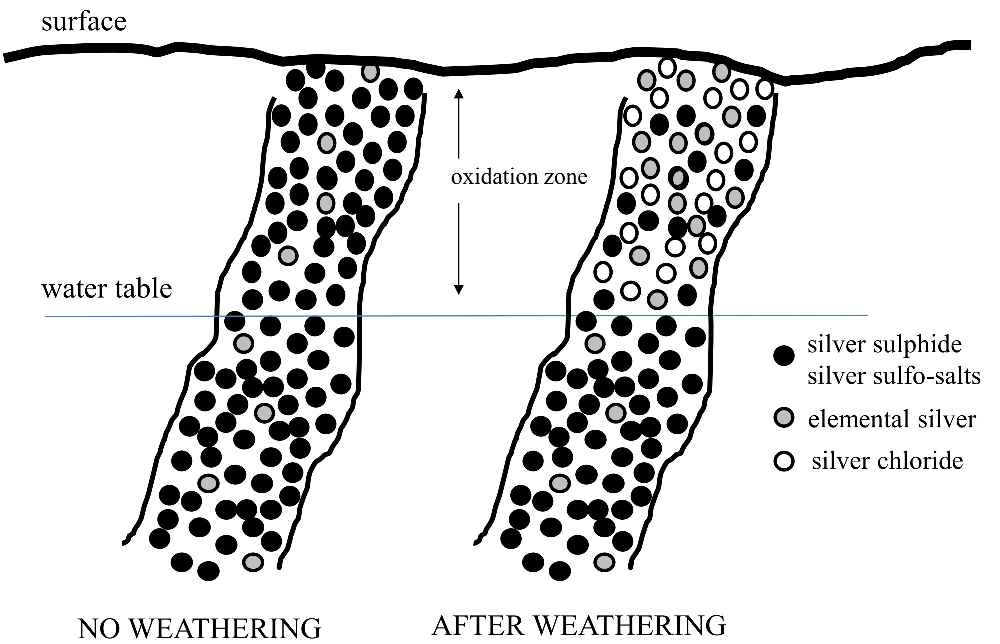

Figure 1-4. A simplified representation of Sillitoe's interpretation of the effect of weathering on an original (hypogene) non-weathered sulphidic silver deposit. Drawing based on interpretation of Sillitoe in footnote 74.

The earliest historical texts that reflect the mining practices of the Spanish conquerors of the sixteenth century reflect from the first moment the main classes of silver compounds

[76] Blanchard has identified silver chloride as the main silver compound that differentiates silver ores of the New World from those known in Europe up to the sixteenth century. Ian Blanchard, *Russia's "Age of Silver". Precious-metal Production and Economic Growth in the Eighteenth Century* (London; New York: Routledge, 1989), 3.
[77] Sillitoe, "Supergene Silver Enrichment," 22,30.

indicated in the discussion based on Sillitoe's review. A useful guide is found in the dictionary by De Llanos from 1609, which describes three main visually distinct classes of silver ores:

a. Very rich silver ore or native metal that could be worked directly with a hammer was called respectively *tacana* or *machacado.*[78]

b. Ores found from the surface down to the water table were called *colorados* in New Spain and *pacos* in Peru. In some areas the presence of reddish iron oxide-hydroxide minerals such as limonite-haematite in this zone (gossan is the term used in geology texts) or the mixture of oxidized iron pyrites and enriched silver minerals found near the surface gave rise to the term of 'coloured' ores in Spanish. By inference these ores would be made up primarily by native silver and silver chloride, other silver halides, and some silver sulphide.[79] The depth of the oxidized zone will vary according to each deposit and its climatic conditions. According to Burkart the *colorados* in certain mines of New Spain reached down to 150 metres, in others the *negros* (see below) reached the surface, testimony to the fact that the degree of weathering

[78] Garcia de Llanos, *Diccionario y maneras de hablar que se usan en las minas y sus labores en los Ingenios y beneficios de los metales (1609)* (La Paz, Bolivia: MUSEF, 1983), 79-80. Even if 'it is noteworthy that in many well-known mining districts there is very little of the native metal', native silver can constitute either an important hypogene or secondary source of the metal. Emmons, *The Enrichment of Ore Deposits* 625 263. With the exception of Cobalt, Ontario, it is claimed that it was more common to find native silver in Europe than in the New World. For example, at Schneeberg (Erzgebirge area) a solid mass of native silver measuring 1x2x4 metres was found in 1477 from which a table was made for the Duke Albrecht of Saxony, which weighed around 20 tons. Wallace, Barton, and Wilson, "Silver-Bearing Minerals," 20-22.

[79] Garcia de Llanos, *Diccionario*, 79-80. For a description of how gossan is formed see Pohl, *Economic Geology*, 85. and Robb, *Ore-Forming*, 239. Silver chloride, AgCl, is found as the mineral cerargyrite (chlorargyrite, horn silver). Cerargyrite is very soft, white or transparent when fresh; on exposure to light, it immediately darkens and becomes opaque. Typically, specimens are brown. Wallace, Barton, and Wilson, "Silver-Bearing Minerals," 28. 'Cerargyryte [in modern texts written as cerargyrite] (horn silver, AgCl) is probably unknown as a primary constituent of ores deposited by ascending hot waters but is commonly developed by weathering, alteration … at or near outcrops of silver-bearing sulphide lodes... its occurrences include nearly all sulphide deposits ... in arid undrained areas it is an important ore mineral, so important that the term "chloriding" is generally used in such regions for pocket hunting near the surface. It is fairly stable at the surface, particularly in arid countries'. Emmons, *The Enrichment of Ore Deposits* 625 272-73. Silver halides in general would give the mines of Catorce in the province of San Luis Potosí a special distinction with regards to the refining process they would adopt at the end of the eighteenth century.

is not necessarily the same in every silver ore deposit.[80] The greater the aridity, the greater the amount of silver chloride (cerargyrite or chlorargyrite) to be expected in a deposit.[81]

c. Darker and deeper ores found above and below the water table called *negros* or *negrillos*, the silver sulphide and sulfo-salt ores.[82]

As the knowledge of the nature of the different silver ores advanced in tandem with chemical theory, the information on silver ores in the historiography converges on the average chemical profile of a silver sulphide ore deposit as described in Sillitoe's summary above.[83]

The lack of scientific knowledge of the indigenous workers at the mine was more than compensated by the skill to pursue a vein underground based on the visual and tactile evidence under the tenuous flicker of a yellow flame. However, what would have posed a greater challenge to the Spanish miner-refiner aboveground was the ability to recognize that ores could contain the same overall silver content but require completely different levels of refining skills to extract the same amount of silver from them. The historical consequence was the waste of

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[80] J. Burkart, "Du filon et des mines de Veta-Grande, près de la ville de Zacatecas, dans l'état du même nom, au Mexique," *Annales des Mines, 3eme série* 8 (1835): 66-67.

[81] Emmons, *The Enrichment of Ore Deposits* 625 , 256; Pohl, *Economic Geology*, 222.

[82] Garcia de Llanos, *Diccionario*, 86. Another sulphur containing hypogene silver mineral of commercial importance is pyrargyrite, Ag_3SbS_3, a sulphide containing both silver and antimony. Pyrargyrite is an important silver mineral in the mines of Zacatecas, Guanajuato and Pachuca of New Spain. Emmons, *The Enrichment of Ore Deposits* 625 276. 'The name comes from Greek, fire and silver ...dark ruby silver, is more common than proustite [see below] and is an important ore of silver; a deeper red than proustite and less sensitive to light; in mining lore, high grade pyrargyrite ore is known as "blood mining" in reference to the color and texture of a freshly excavated face'. The presence of compound silver sulphide salts together with other metals would lead them to be branded as rebellious, since they did not respond in a straightforward manner to amalgamation or smelting. Another sulphide hypogene silver mineral is proustite, Ag_3AsS_3, which contains both silver and arsenic. 'Known as ruby silvers due to their translucent red colour when fresh, lighter than pyrargyrite. perhaps the most vivid color in all the mineral kingdom is the scarlet-vermilion of proustite ... [though] exposure to light darkens it'. Wallace, Barton, and Wilson, "Silver-Bearing Minerals," 29.

[83] Humboldt identifies by name silver sulphides, horn silver (silver chloride) and antimony/arsenic compounds of silver among the main silver ores of Mexico, in Humboldt, *Essai politique*, Tome III, 354-61.; by mid nineteenth century silver chloride is identified as one of the main components in *pacos* or *colorado*s, together with descriptions of silver and antimony sulphides, among others in Edward Pique, *A Practical Treatise on the Chemistry of Gold, Silver, Quicksilver and Lead, Tracing the Crude Ores from the Mines Through the Various Mechanical and Metallurgic Elaborations, Until the Pure Metal is Obtained* (San Francisco: Towne & Bacon, printers, 1860), 81-84.; by the turn of the century Emmons was publishing his research on the chemistry of silver ore deposits.

good silver ores from silver sulphide deposits, since the absence of adequate refining skills resulted in the complaint by Spanish miners of the apparent sudden onset of poor silver content relatively soon after mines started to be exploited.[84] The miners and authorities did not have the knowledge base at the time to recognize that the real poverty lay not in the silver content of the deeper ores but in the range of refining skills they could bring to bear on silver sulphide ores during the early years of silver production.

1.4.2 Argentiferous galena

The other major source of silver in New Spain was argentiferous galena, which contributed an important fraction of the close to 40% of silver that would be refined by smelting (Chapter 6). These deposits were found in the region of San Luis Potosí, Durango, Sombrerete, Chihuaha and Zimapán in New Spain. This was the silver compound familiar to silver refiners in Europe up to the conquest of the New World that will be described in section 1.5. The economic consequences of the weathering of deposits where galena is the main silver ore has not received as much attention as the case for silver sulphides presented above.[85]

1.4.3 The silver belt in New Spain / Mexico

The silver belt of New Spain lies at the edge of the North American continental shelf, and is traversed by the Volcanic Belt of Mexico (Figure 1-5). The Mexican metallurgist

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[84] In Chapter 3 I will comment in detail on this issue, since the early amalgamation process cut its teeth on the ore recovered from mountains of tailings. In the mid eighteenth century women would still be combing through 200 year-old tailings in search of useful silver ore. Manuel Jose Dominguez de la Fuente, *Leal Informe Politico-Legal (Observaciones sobre la maniobra de las minas, hechas en el Real de Guanajuato en 1774)* (Guanajuato, Mexico: Ediciones La Rana, 1999), 79.

[85] The literature on weathering of galena deposits is much more limited than for deposits of hypogene silver sulphide. An early discussion that questioned the current opinion at the time that no great supergene enrichment of galena deposits is observed can be followed in John Stafford Brown, "Supergene Sphalerite, Galena, and Willemite at Balmat, New York," *Economic Geology* 31, no. 4 (1936). Formation of supergene silver chloride in deposits such as Slocan, British Columbia, are generated from the fraction of silver sulphides also present in a deposit that also contains galena. See the description of the genetic type model 22c, in Dennis P. Cox, "Descriptive Model of Polymetallic Veins," in *U.S. Geological Survey Bulletin 1693*, ed. Dennis P. Cox and Donald A. Singer (Washington: U.S. Geological Survey, 1987).

Guillermo Salas has classified the locations of deposits of Mexico into six metallogenic provinces, of which two are of special interest to the history of silver refining. The first is the *Sierra Madre Oriental*, an extension of the North American Rocky Mountains that is the link between the Cordilleras of the north to the Andes of the south, where the main deposits contain lead, silver (in galena or silver sulphide ores), zinc and copper. It encompasses the historic mining districts of San Luis Potosí, Guanajuato, and Zacatecas. According to Salas this metal province is rich in argentiferous lead, lead-zinc and lead deposits. The second is the *Provincia del Eje Neovolcanico Mexicano* (also known as the Volcanic Belt of Mexico) which contains the mining districts of Pachuca and Real del Monte and Taxco, also producing both silver (in galena or silver sulphide deposits) and lead.[86] The more recent monograph by Coll-Hurtado et al mentions that gold-silver and argentiferous lead deposits are to be found in Zacualpan, Sultepec and Taxco, as well as in Pachuca and Real del Monte, all areas historically known as pioneers in the mining and refining of silver. Other argentiferous lead deposits are found in Guanajuato, Zacatecas and Fresnillo.[87]

1.5 The chemistry of the sources of silver in Europe

The silver ore of the New World was to be refined on the basis of the accumulated experience of Europe and Asia of mining and metallurgy dating back at least two thousand years.[88] To understand the challenge faced by the miners of the sixteenth century when confronted for the first time with the type of silver ores found in the New World, it is necessary

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[86] Guillermo P. Salas, *Carta y Provincias Metalogenéticas de la República Mexicana* (Mexico: Consejo de Recursos Minerales, 1980), 69-73. The work includes a detailed fold-out map of the regions.

[87] Atlántida Coll-Hurtado, María Teresa Sánchez-Salazar, and Josefina Morales, *La minería en México: geografía, historia, economía y medio ambiente* (Mexico: UNAM, 2002), 16-22. A metal province has been defined as an area 'characterized by an abnormal concentration of large deposits of a particular metal or metals, by numerous occurrences of a metal, or both' as distinct from the term metallogenic belt which 'shows the types of deposit of a metal or metals formed within a narrow time range, ideally not more than 10 to 20 million years ... or less'. Mitchell and Garson, *Global Tectonic Settings*, 5-6.

[88] An overview is presented in Ian Blanchard, *Mining, Metallurgy and Minting in the Middle Ages. Continuing Afro-American Supremacy 1250-1450.* , vol. 3 (Munich: Franz Steiner Verlag Stuttgart, 2005).

to understand how the different geological roots on both sides of the Atlantic determined the nature of the silver ore in the deposits. Subduction processes had also given rise to the Variscan

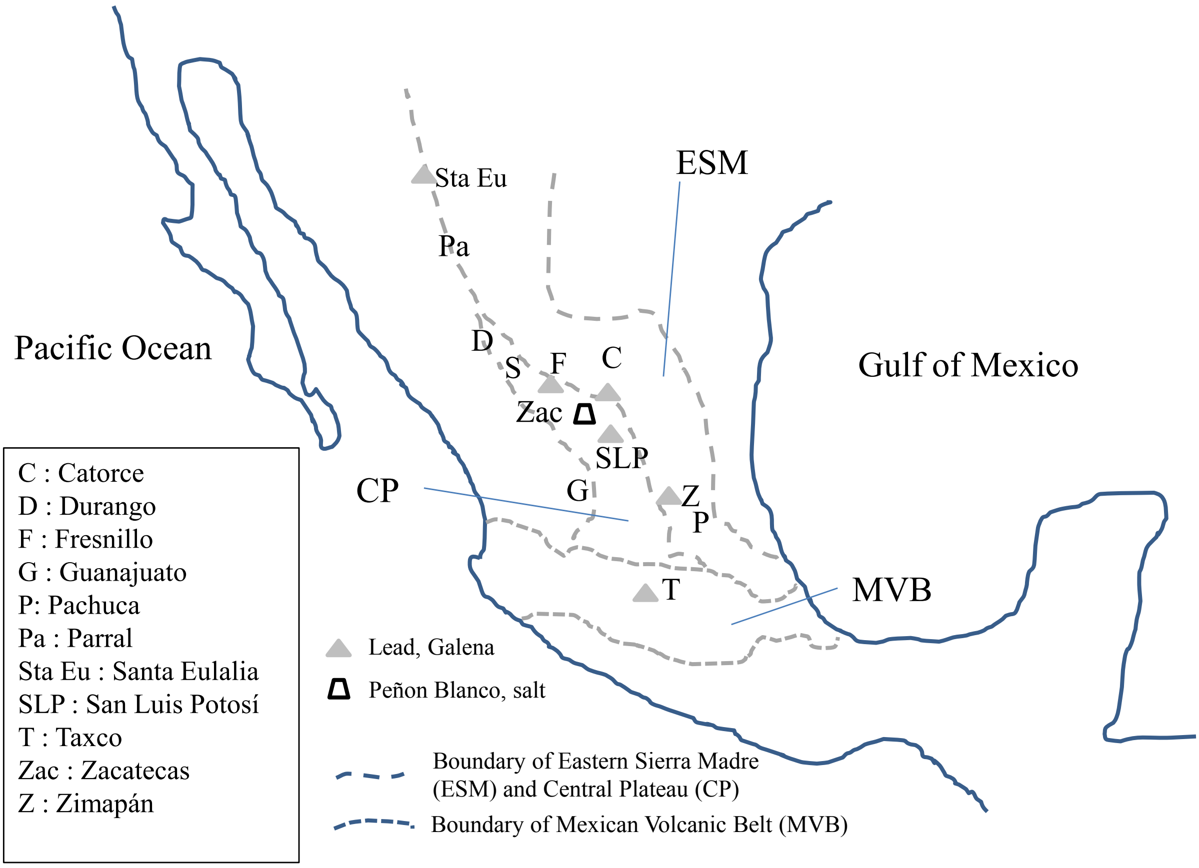

Figure 1-5. The main historical silver, lead and salt deposits of New Spain / Mexico (based on footnote 86).

orogen, the geological process of rock deformation and mountain building in Europe that took place during the Carboniferous to Permian, 359 to 252 Ma. It gave rise to silver-bearing polymetallic ore deposits stretching from Devon/Cornwall to Spain and the modern day Czech Republic.[89] The first major difference on both sides of the Atlantic is that the European silver ores were deposited over 250 Ma ago while the silver ores in the mines to be worked by the

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[89] 'Variscan and Hercyninan orogenies are essentially synonymous terms' Robb, *Ore-Forming*, 110, 334-38.

Spaniards are as young as 12 Ma.[90] The different metallogenic epochs led to a fundamental change in the way silver ore deposits were generated, thus in their chemical make-up. This is a critical difference that sustains the main arguments of this thesis, so I will quote at length on this topic:

‘The principal historic source of silver in Precambrian and Paleozoic mineral deposits [European ores] has been as a by-product or co-product of base metal ores. Most of this silver was concentrated by syngenetic [concurrent] or diagenetic [transformation in time of existing deposits] processes ... the principal historic source of silver in Mesozoic and Cenozoic mineral deposits [New World] has been as a coproduct or major economic component of ores. Most or all of this silver was epigenetically concentrated [ores deposited in cracks formed after the host rocks were created] **... the increased abundance of relatively young deposits in which silver is the principal economic component reflects a fundamental evolutionary change in the abundance of silver in the crust and/or in the processes which concentrate silver into ore** [emphasis added]’.[91]

In other words, in Europe the main silver source known to generations of miners up to the early sixteenth century were ores in which silver was secondary to metals such as lead or copper. The first silver deposits to be exploited in Europe were argentiferous galena. The silver within this lead ore has been reported as consisting of ‘minute crystals of the silver sulphide … rather evenly spaced through massive lead sulphide, even when only a little silver is present’.[92] The silver content can range from 0.01% to over 1%.[93] These are the lead-silver sources that funded the Athenian Empire, which provided the silver and lead of Rome, and from the Middle Ages the silver of the Harz and some of the Erzgebirge mines of Germany, of Kutna-Hora and the lead and silver of England.[94] Lead would gift to European silver refiners

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[90] Laznicka, *Giant Metallic Deposits*, 150.; There is an interesting graph that shows the clear division in time between the formation of the silver deposits at Erzgebirge and those of the Americas in Graybeal, Smith, and Vikre, "Geology Silver Deposits," 39.
[91] "Geology Silver Deposits," 163-64.
[92]Emmons, *The Enrichment of Ore Deposits* 625 367.
[93] Pohl, *Economic Geology*, 195-97.
[94] For example, in the sixteenth century Agricola wrote: ‘In the same region is found Goslar, where one finds so much galena from which lead is extracted that one could say the whole mountain is made of lead’ - ‘*Dans la même région se trouve Goslar, ou l’on rencontre tant de galène dont on tire le plomb que l’on peut dire que toute cette*

an in-built key for the extraction of metallic silver via smelting, but lead could also interfere by amalgamating with mercury. These are the lead based silver ores that had served to generate European mining and refining expertise on silver over many centuries.

When from the fifteenth century the argentiferous lead ores of Europe began to be exhausted or required deeper mines subject to flooding, it was the expertise in a metallurgy based on lead smelting that was now adapted to extract secondary silver from copper ores found at Erzgebirge (Joachimsthal), in the Tyrol (Schwaz) and in Hungary (Neusohl). This was the new generation of silver bearing ores that would make the Fuggers an extremely rich banking family based on their large scale approach to refining operations.[95] The silver in the copper ore is inserted in complex copper minerals such as tetrahedrite. It cannot be discerned as solid discrete particles as in the case of argentiferous galena.[96] In both cases silver is not the primary economic target in the ore, in total contrast to the silver-bearing ores found in the Spanish mines of the New World. This secondary role of silver, and the fact metallurgy of silver in Europe cut its teeth on argentiferous lead ores, is what separates the average European silver ore from its counterpart in the New World.

Figure 1-6 situates the main silver historic mining areas within Europe. The earliest mining in Central Europe took place in the Harz region around Goslar, including Rammelsberg and Freiberg, known for their argentiferous galena as source of its silver. The Erzgebirge, the Ore Mountain region straddling Germany and the modern day Czech republic, rose to prominence as a major source of silver rich copper ores such as made Joachimstahl (present

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montagne n'est que galène.' Georgius Agricola, *Bermannus*, trans. Robert Halleux and Albert Yans (Paris: Belles Lettres, 1990), 18.

[95] J.U. Nef, "Silver Production in Central Europe, 1450-1618," *The Journal of Political Economy* (1941): 578-85. The evolution of silver refining techniques in Europe will be treated at greater depth in Chapter 2. The pivotal role of the Fuggers in the history of silver refining in the New World will be discussed in Chapter 5.

[96] Gasparrini, "The Mineralogy of Silver," 99-100.

day Jachymov) famous; it is the only European silver deposit to figure in Table I. The English deposits of Devon and Cornwall have been more important for tin and lead than for silver but played a historic role in supplying lead to the silver smelters of Europe and New Spain.[97] The copper ores that contained silver of the Hungarian mines at Neusohl would supply the major silver and copper refining centres units set up by the Fuggers both at Neusohl (Hungary) and

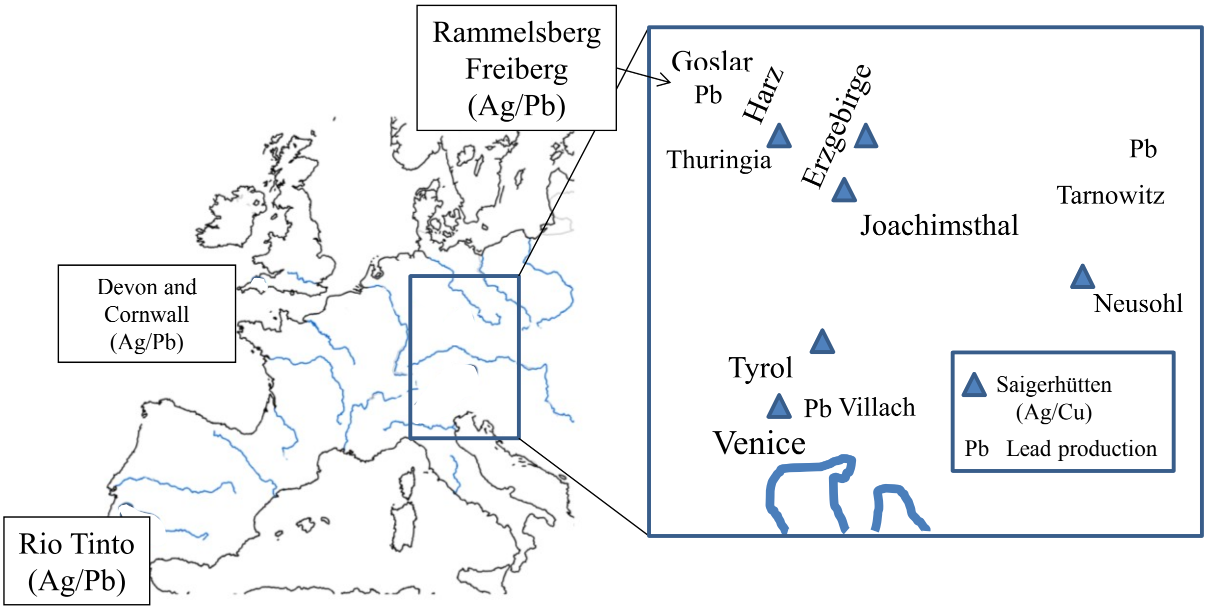

Figure 1-6. Location of main historic silver mining regions in Europe by mid sixteenth century. Adapted from Blanchard in footnote 98. Map and inset not to scale.

also at Vilbach to process the ores from the Tyrol region.[98] Finally the Rio Tinto and Guadalcanal mines in Spain were the sources of jarositic and argentiferous galena ores.[99]

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[97] Mitchell and Garson, *Global Tectonic Settings*, 280.; Stephen Rippon, Peter Claughton, and Chris Smart, *Mining in a Medieval Landscape: The Royal Silver Mines of the Tamar Valley* (Exeter: Univ of Exeter Press, 2009), 13-52.

[98] Ian Blanchard, "England and the International Bullion Crisis of the 1550s," in *Precious Metals in the Age of Expansion: Papers of the XIVth International Congress of the Historical Sciences* ed. Hermann Kellenbenz (Stuttgart: Klett-Cotta, 1981), 87-93.; Nef, "Silver in Europe," 584.

[99] On the composition of silver ores at Rio Tinto: 'Jarosite is the lead-silver equivalent to fahl, by degradation of pyrites, formed a potassium iron sulphate rich … and is found in the Rio Tinto silver deposits at Huelva, Spain, formed at junction between weathered pyrites and primary pyrites'. P. T. Craddock, *Early Metal Mining and Production* (Washington, D.C.: Smithsonian Institution Press, 1995), 29. South-west Spain is the only place where silver has been extracted from jarositic earths according to Leonard U. Salkield, "Ancient Slags in the South West

The map is important because the history of silver refining in New Spain and then Mexico is woven from threads of technical experience spooled from each of these areas. German smelting know-how based on lead would migrate from the mines of *MittelEuropa* to New Spain in the early sixteenth century, as I will narrate in Chapter 2. Venice will play a leading role in the development of the amalgamation refining process in Europe, as I will explain in Chapter 3. Cornish miners expert in dressing tin ores and English smelters raised on lead ores will immigrate to Mexico in the nineteenth century, where I will catch up with them in Chapters 4 and 5. The Fuggers will lend unwillingly their considerable wealth obtained from smelting European argentiferous copper ores to the initial supply of mercury to New Spain, as I will argue in Chapter 5.

Figure 1-7 visually summarizes the differences in the nature of ore deposits on both sides of the Atlantic. The geological youth of the New World silver deposits is reflected in the altitude at which they are found, compared to the historical silver deposits of Europe.[100] In

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of the Iberian Peninsula," in *La minería hispana e iberoamericana. Ponencias del I coloquio internacional sobre historia de la minería* (León: Cátedra de San Isidro, 1970), 94.

[100] Figure 1-7 is a simplified picture of complex geological forces at work. For example, the silver deposits at Cobalt (Ontario) were unrelated to subduction processes operating on the western seaboard of the continent. Altitude is a fickle guide, since the Himalayas are quite barren of silver deposits. Aridity is a condition that can change over millions of years, so current conditions may be quite different from those existing when the deposits were formed (see Laznicka, *Giant Metallic Deposits*, 172.) Sources: treeline range, Christian Körner, "A Re-Assessment of High Elevation Treeline Positions and Their Explanation," *Oecologia* 115, no. 4 (1998): 446-47.; maximum altitude Potosí (Cunill Grau, "Paisaje andino," 79.); Porco (C.G. Cunningham et al., "Relationship between the Porco, Bolivia, Ag-Zn-Pb-Sn deposit and the Porco caldera," *Economic Geology* 89, no. 8 (1994): 1833.); Pasco (Laznicka, *Giant Metallic Deposits*, 127.); Oruro (José De Mesa and Teresa Gisbert, "Oruro. Origen de una villa minera.," in *La minería hispana e iberoamericana. Ponencias del I coloquio internacional sobre historia de la minería.*(León: Cátedra de San Isidro, 1970).); Zacatecas (Burkart, "Mines de Veta-Grande," 60.); Real del Monte (José J. Galindo y R, *El distrito minero Pachuca-Real del Monte* ([Pachuca?]: Cia. de Real del Monte y Pachuca, 1957), 2.); Catorce (Rafael Montejano y Aguiñaga, *El Real de Minas de la Purísima Concepción de los Catorce, SLP* (San Luis Potosi: Editorial Universitaria Potosina, 1993), 169.); Cerro San Pedro (Alvaro Sánchez-Crispín, Eurosia Carrascal, and Alejandrina de Sicilia Muñoz, "De la minería al turismo: Real de Catorce y Cerro de San Pedro, México. Una interpretatión geográfico-económica," *Revista Geográfica*, no. 119 (1994): 85.); Guanajuato (Yann René Ramos-Arroyo, Rosa María Prol-Ledesma, and Christina Siebe-Grabach, "Características geológicas y mineralógicas e historia de extracción del Distrito de Guanajuato, México. Posibles escenarios geoquímicos para los residuos mineros," *Revista Mexicana de Ciencias Geológicas* 21, no. 2 (2004): 273.); Parral (Robert C. West, *The Mining Community in Northern New Spain: the Parral Mining District* (Berkeley and Los Angeles: University of California Press, 1949), 9.); central European mines (Humboldt, *Essai politique*, Tome III, 333.).

practical terms this meant that erosion had not worn down and dispersed the topmost layers of silver compounds, a task that would be accomplished by the Spaniards, who on the back of indigenous labour in a few centuries achieved what would otherwise have taken place over millions of years of geological

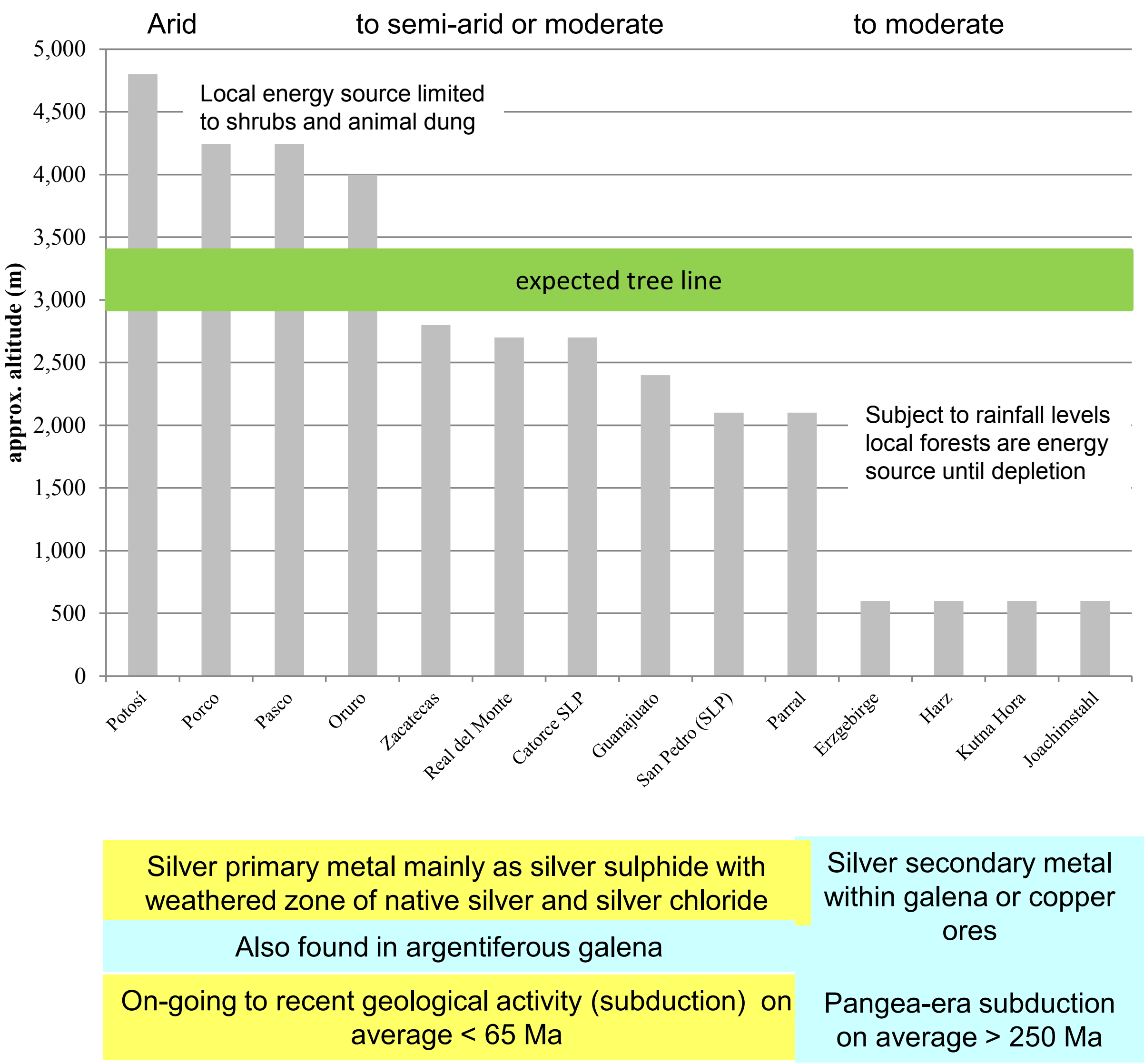

Figure 1-7. Altitude of the main historical silver ore deposits found in the Hispanic New World and in Europe. For sources see footnote 100.

time. It also meant that in the case of the Andean deposits, most were at or above the treeline, which would have immediate consequences on the sourcing and pricing of fuel:

'[Silver] is generated usually in sparse and sterile lands, in paramos and punas [Andean highlands with very scarce vegetation, usually above the tree line] of great cold, hills and snowy ranges ... the most highly regarded are the mines in high mountains and places, the mountains with mines are bare, treeless, with no vegetation'.[101]

1.6 The silver content of New World ores

The current narrative on the history of colonial silver refining has been built upon the notion that the average silver content of the ores in the New World was very poor, which in turn is claimed to have limited their refining to just one viable technique, amalgamation.[102] The roots of this line of thought can be traced to the earliest years of silver refining in the New World, when for example in the 1550s in New Spain it was claimed that: 'the ore that only had three marks [1.5 % by weight] was considered poor'.[103] On the other hand claims can also be found for a high level of silver in these ores, as stated in the early 1600s:

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[101] '*criase [la plata] de ordinario en tierras ásperas y estériles, en paramos y punas de riguroso frio, en cerros, lomas y sierras nevadas ... estímanse mas las minas de cerros y lugares altos.. son los cerros de minas rasos y pelados, sin arboleda*'. Cobo, *Historia del Nuevo Mundo*, 91, 141.

[102] Among the most recent examples in the modern historiography are the following: 'the vast quantities of ore with a low to medium silver content' - '*las inmensas cantidades de mineral de ley baja y mediana*' in Hausberger, "El universalismo científico del Barón Ignaz von Born y la transferencia de tecnología minera entre Hispano américa y Alemania a finales del siglo XVIII," 607.; 'low-yield ore, characteristic of South America' in Lang, "Silver Refining Technology in Spanish America (patio y fundición) " 140.; 'the low [silver] content of the silver deposits'-'*la baja ley de las menas de plata*', Peter Bakewell, "La transferencia de la tecnología y la minería hispanoamericana, siglos XVI y XVII: algunas observaciones," in *Hombres, técnica, plata : minería y sociedad en Europa y América, siglos XVI-XIX*, ed. Julio Sánchez Gómez, Guillermo Mira Delli-Zotti, and Francisco A. Rubio Durán (Sevilla: Aconcagua Libros, 2000), 365. The major exception is Blanchard, who bases his analysis on the different types of ore found on either side of the Atlantic, and not on any deemed difference in silver content. He explains the adoption of refining methods not on a deemed poverty of the ores but rather on their lead content. Blanchard, *Russia's "Age of Silver". Precious-metal Production and Economic Growth in the Eighteenth Century* 3-31.

[103] *'el que era de tres lo tenían por pobre*'. Juan Suárez de Peralta, *Tratado del descubrimiento de las Indias : (noticias históricas de la Nueva España)* (México, D.F.: Consejo Nacional para la Cultura y las Artes, 1990), 164.

'we understand, that minerals are mined in the provinces of Germany and metals are refined from them though with little benefit, and we have been told … that ours have much more silver content'.[104]

In the early nineteenth century Humboldt stated that Mexican silver ores were deemed much richer than European ores. However 'it is not thus … by the intrinsic richness of the ores, but rather by the great abundance in which they are found in the ground ... that distinguishes the mines of America'.[105] In the late nineteenth century Burkart would claim from his own first-hand experience: 'Mexican silver ores are not in general inferior in silver content to those of other mines: on the contrary, they are richer than those from the majority of other mines and locations in Europe'.[106] Historical judgements of this nature need to be judged with care. Even by the nineteenth century the assaying of silver ores in Mexico prior to refining was the exception and not the rule.[107] This problem of the absence of analytical information does not seem confined to the New World, since Burkart complains of the difficulty of finding sufficient data to calculate the silver content of European ores.[108] In addition, sampling of large ore masses was a major challenge, and silver content when reported was based on the silver that could be extracted, which was never necessarily the silver actually present in the ore.[109]

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[104] '*habemos ... entendido, de que en las provincias de Alemania se labran minerales y se benefician los metales dellos que son de muy poco aprovechamiento, y nos han afirmado ser de la misma suerte que los negrillos que tratamos y que estos tienen mucha mas ley y plata*' Marcos Jimenez de la Espada, Relaciones Geograficas de Indias - Peru II, ed. Jose Urbano Martinez Carrera vol. 184, Biblioteca de Autores Espanoles (Madrid: Atlas, 1965 (1588)), 126.

[105] '*ce n'est donc pas ... par la richesse intrinseque des minerais, c'est plutôt par la grande abondance dans laquelle ils se trouvent au sein de la terre .. que les mines de l'Amerique se distinguent*' Humboldt, *Essai politique*, Tome III, 371.

[106] 'los minerales de plata mexicanos no son inferiores por cuanto a su ley tomada en general, a los de otras minas: por el contrario, son más ricos que los de la mayor parte de las demás minas o distritos [de Europa]'. Johann Burkart, "Memoria sobre la explotación de minas de los distritos de Pachuca y Real del Monte de México," *Anales de la Minería Mexicana (Revista de Minas)* I (1861): 97.

[107] Duport, *Métaux précieux au Mexique*, 138-39. By mid nineteenth century no assaying of ores was carried out in Catorce, Sombrerete, Fresnillo, Zacatecas and Guanajuato, according to Laur, "De la metallurgie de l'argent au Mexique," 182.

[108] 'the majority [of European silver mines] do not possess the necessary data to calculate the silver content of the ores'- *'las mas de ellas no contienen los datos necesarios para calcular la ley de los frutos'* Burkart, "Memoria Real del Monte," 92.

[109] Laur, "De la metallurgie de l'argent au Mexique," 49. See Chapter 4 for examples of problems in sampling with respect to data of silver content even by the late nineteenth century.

There are three ways to address this issue. Brading and Cross question the statements on operational grounds:

‘various problems confront the historian who attempts to come to a closer view of colonial refining... on many occasions both miners and royal officials claim that ore levels had fallen; they then provide an average figure, let us say, of one ounce silver per hundredweight of mineral. The historian then has to decide: did these refiners know how much silver their ores really contained?’[110]

To their observation I would add the following question: could the inability to extract silver from an ore that has suddenly changed its chemical structure so as to place it outside the scope of the refining method being used have been misinterpreted as a sudden impoverishment of the silver content of the ore?

Finally, what exactly is meant by a ‘low’ silver content? There is no atemporal and absolute threshold that determines when an ore is low or high in silver.[111] What exists is a location-specific set of human skills and a total production cost in each historical period that determine how much silver is extracted from a given ore, which in turn is a function of silver content, chemical nature of the ore, variable and fixed costs of production, and the option to market any metallic co-products from the refining process. Therefore the only number that is relevant is the minimum value of extracted silver that is required to meet the cost of production, a value that changes with technology, location and historical period. An orphaned number designating a silver content, devoid of context, can mislead rather than assist in deciphering the events that determined the environmental history of silver refining in the New World.

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[110] Brading and Cross, "Colonial Silver Mining: Mexico and Peru," 555.
[111] To highlight how relative the terms ‘poor’ or ‘rich’ are in relation to the silver content of silver ores, in modern times the typical range reported for silver ore deposits is between 10 to 1,000 grams of silver per ton, 0.001% to 0.1%, the latter being now considered a ‘rich’ silver ore. Wallace, Barton, and Wilson, "Silver-Bearing Minerals," 18,30.

In view of the weight placed upon the notion of 'poor ores' in the historiography (see Introduction) I have nevertheless reviewed a selection of the historical numerical data on silver content as reported in primary and secondary sources, though the exercise has to be interpreted with caution. First of all the source of much of this information is sometimes unclear, whether it was hearsay, assumptions or actual assays. Second, there is no histogram available up to the end of the nineteenth century that segments total quantities of ore in New Spain or Mexico according to their silver content. At the most the data reported in the historiography can be grouped approximately by period, and a strong aggregation of values may be representative of the average of silver content during a certain period. Since they are reported in a variety of units, I have calculated where necessary their value as a weight percentage.[112] The data plotted in Figures 1-8, 1-9 and 1-10, represent a non-exhaustive sampling of the published values of silver content in ores from New Spain/Mexico, Peru and Europe, excluding bonanza values (those above 2.5% silver content by weight).

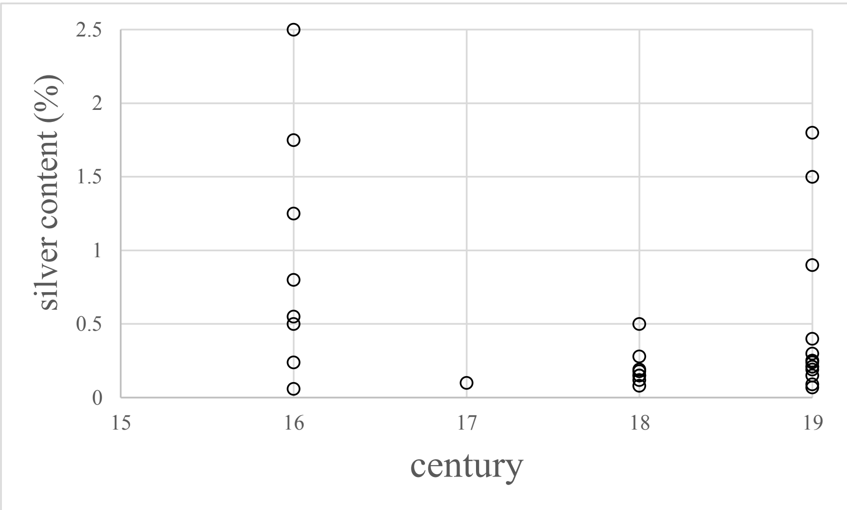

Figure 1-8. Plot of average silver content in ores of New Spain / Mexico grouped by century, data from Table 1-II.

[112] In modern geological texts the grade of an ore (silver content) is expressed as grams per ton.

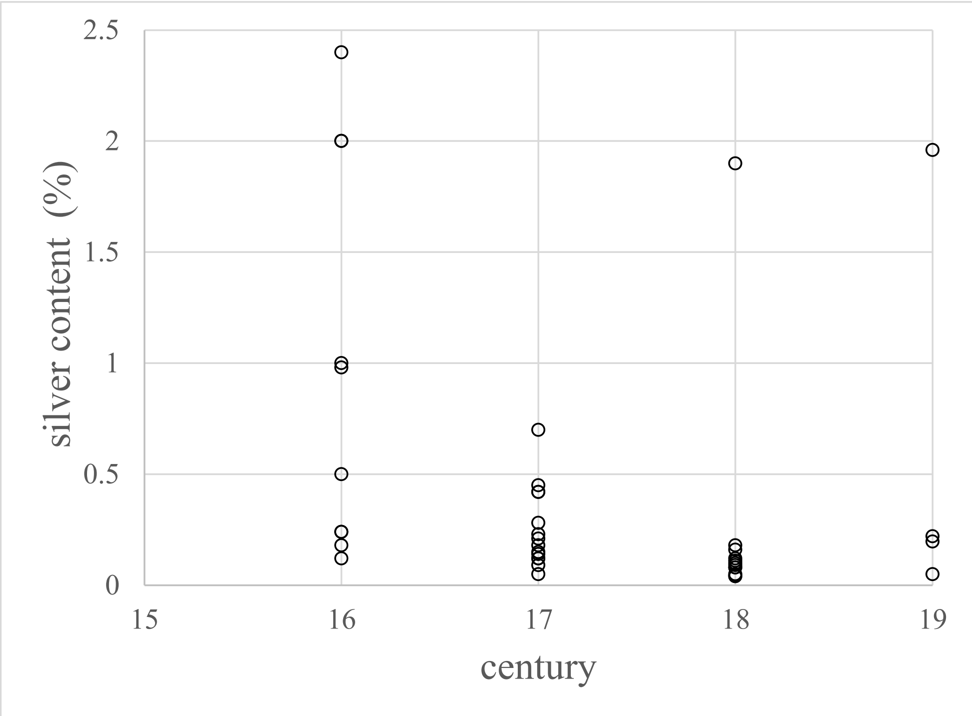

Figure 1-9. Plot of a selected range of data for the silver content in ores of the Vice-Royalty of Peru / Bolivia, as per Table 1-III, grouped by century.

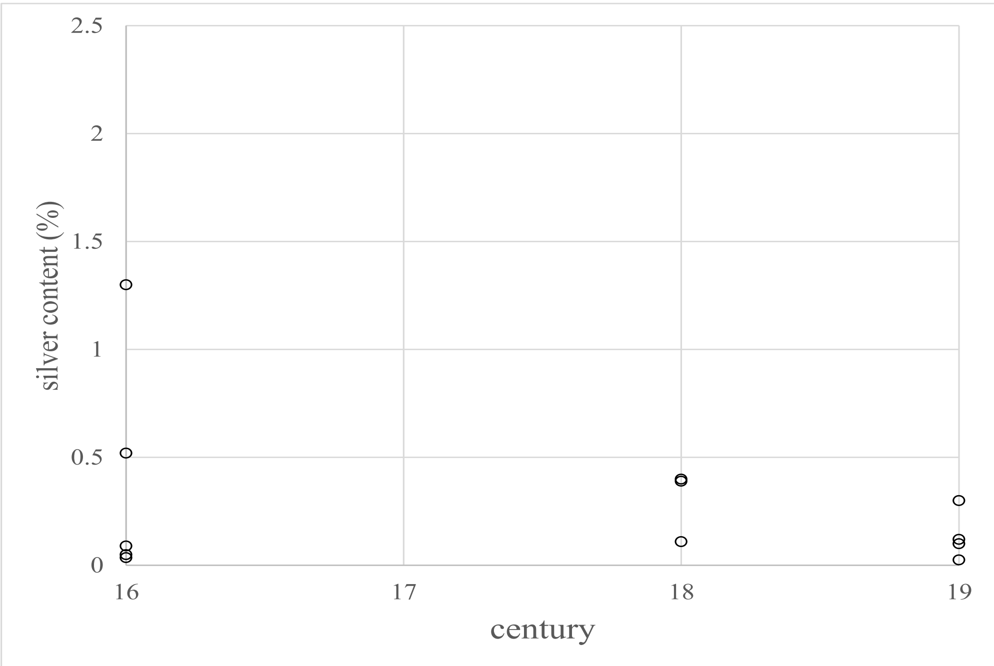

Figure 1-10. Plot of published data for the silver content in ores of Europe, as per Table 1-IV, grouped by century.

Tables 1-II and 1-III include the sources of the data for the New World.[113] Table 1-IV corresponds to the data for some mines of Europe.[114] The statistical significance of each data

[113] Sources: a) Miguel Othon Mendizábal, *La minería y la metalurgia mexicanas (1520-1943)* (Mexico: Centro de Estudios Históricos del Movimiento Obrero, 1980). b) Jaime García Mendoza, "La administración de las minas de plata y haciendas de beneficio de la familia Sandoval en Taxco (1562-1564)," in *La plata en Iberoamérica: Siglos XVI al XIX*, ed. Jesus Paniagua Pérez and Nuria Salazar Simarro (Leon: Universidad de León, 2008). c) Gonzalo Gómez de Cervantes, *La vida económica y social de Nueva España al finalizar el siglo XVI* (Mexico: Antigua Librería Robredo de José Porrúa e hijos, 1944). d) Linda A. Newson, "Silver Mining in Colonial Honduras," *Revista de Historia de América*, no. 97 (1984). e) Ciriaco Pérez Bustamante, "Las minas en los grandes geógrafos del periodo hispánico," in *La minería hispana e iberoamericana. Ponencias del I coloquio internacional sobre historia de la minería* (León: Cátedra de San Isidro, 1970). f) José Antonio Fabry, Compendiosa demostracion de los crecidos adelantamientos, que pudiera lograr la real haciencda de su Magestad mediante la rebaja en el precio del azogue que se consume para el laborio de las minas de este reyno ... con una previa impugnacion à las reflexiones del contador Joseph de Villa-señor y Sanchez ... Añadese un breve modo de reducir, ligar, y alear el oro, y la plata à la ley de 22. quilates (Mexico: Impressa por la viuda de J.B. de Hogal, 1743). g) Dominguez de la Fuente, *Leal Informe Politico-Legal*. h) Garner, "Long-Term Silver Mining."i) D. A. Brading, "Mexican Silver-Mining in the Eighteenth Century: The Revival of Zacatecas," The Hispanic American Historical Review 50, no. 4 (1970). j) Enrique Tandeter, "Forced and Free Labour in Late Colonial Potosi," Past & Present, no. 93 (1981). k) D.A. Brading, Miners and Merchants in Bourbon Mexico 1763-1810 (London: Cambridge University Press, 1971). l) Bargalló, *Minería y metalurgia colonial*. m) Joseph Garcés y Eguía, Nueva teórica y práctica del beneficio de los metales de oro y plata por fundición y amalgamación que de órden del rey nuestro Señor Don Carlos Quarto (Mexico: D. Mariano de Zúñiga y Ontiveros, 1802). n) Humboldt, Essai politique. o) Clara Elena Suarez Arguello and Brígida Von Mentz, Epístolas y cuentas de la negociación minera de Vetagrande, Zacatecas, 1791-1794, 1806-1809 (Mexico: Centro de Investigaciones y Estudios Superiores en Antropologia Social (CIESAS), 2008). p) Burkart, "Mines de Veta-Grande." q) Duport, *Métaux précieux au Mexique*. r) Laur, "De la metallurgie de l'argent au Mexique." s) T. 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Ramírez, "La minería y la metalurgia nativa en el norte peruano (siglos XVI-XVII)," Anuario de estudios americanos 64, no. 1 (2007). D) W. E. Wilson and A. Petrov, "Famous Mineral Localities: Cerro Rico de Potosi, Bolivia," Mineralogical Record 30 (1999). E) Carlos Serrano Bravo, "Historia de la minería andina boliviana (siglos XVI al XX) " http://www.unesco.org.uy/phi/biblioteca/archive/files/370d6afed30afdca14156f9b55e6a15e.pdf. F) Wallace, Barton, and Wilson, "Silver-Bearing Minerals." G) Arthur F. Wendt, "The Potosi, Bolivia, Silver District," Transactions of the American Institute of Mining Engineers XIX (1891). H) María del Carmen Martínez Martínez, "Plata y mineria en la correspondencia privada de las Indias," in Ophir en las Indias. Estudios sobre la plata americana. Siglos XVI-XIX, ed. Jesus Paniagua Perez and Nuria Salazar Simarro (Leon: Universidad de Leon, 2010), 30. I) Luis Capoche, "Relación General de la Villa Imperial de Potosí," in Biblioteca de Autores Españoles, ed. 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point varies and cannot be quantified. The visual impression from the three sets of data points to similar ranges of silver content on ores on both sides of the Atlantic, within the limitations of the comparison, grouped around a value of 0.25% from the seventeenth century onwards.[115]

This is as much as can be said on this matter, without incurring the mistake that the silver content of ores of the New World could be compared simply on absolute value with those of the ores of Europe. As will become more evident in the subsequent chapters, a silver ore containing 0.25% of silver in the presence of major amounts of lead or copper in Europe cannot be compared on the same basis as a silver ore containing 0.25% of silver in the form of silver sulphide in New Spain. The only straightforward conclusion from this analysis is that the concept of a 'poor' silver ore is too simple and devoid of context to be of use in the analysis of

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[114] Sources: a) George Papadimitriou, "Mining and Metallurgical Activities in Ancient Laurium and its Impact on the Golden Era of Athens " in *5th International Mining History Congress*, ed. James E. Fell, P. D. Nicolaou, and G. D. Xydous (Milos Island: Milos Conference Center-George Eliopoulos, 2001). b) Wallace, Barton, and Wilson, "Silver-Bearing Minerals." c) R. F. Tylecote, "Roman Lead Working in Britain," *The British Journal for the History of Science* 2, no. 1 (1964). d) Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 e) Lynn Willies, "Introduction" (paper presented at the Boles and Smeltmills: Report of a seminar on the History and Archaeology of Lead Smelting, Reeth, Yorkshire, United Kingdom, 15 to 17 May 1992). f) P. Braunstein, "Innovations in Mining and Metal Production in Europe in the Late Middle Ages," *Journal of European Economic History* 12 (1983). g) William Jacob, *An Historical Inquiry into the Production and Consumption of the Precious Metals*, vol. 1 (New York: Augustus M. Kelly, 1968; repr., 1831). h) Georgius Agricola, *De re metallica*, trans. Herbert Clark Hoover and Lou Henry Hoover (New York: Dover Publications, 1950). i) Hermann Kellenbenz, "Final Remarks: Production and Trade of Gold, Silver, Copper and Lead from 1450 to 1750," in *Precious Metals in the Age of Expansion: Papers of the XIVth International Congress of the Historical Sciences*, ed. Hermann Kellenbenz (Stuttgart: Klett-Cotta, 1981). j) Christoph Bartels, "The Production of Silver, Copper and Lead in the Harz Mountains from Late Medieval Times to the Onset of Industrialization," in *Materials and Expertise in Early Modern Europe : Between Market and Laboratory*, ed. Ursula Klein and E. C. Spary (Chicago: University of Chicago Press, 2010). k) Arduz Eguía, *Minería altoperuana*. l) Mikuláš Teich, "Born's Amalgamation Process and the International Metallurgic Gathering at Skleno in 1786," *Annals of Science* 32, no. 4 (1975). m) Antoine-Marie Héron de Villefosse, *De la richesse minérale considérations sur les mines, usines et salines des différens états, et particulièrement du Royaume de Westphalie, pris pour terme de comparaison* (Paris: Levrault, 1810). n) Louis Edouard Rivot, *Description des gites métallifères, de la preparation mecanique et du traitement metallurgique des minerais de plomb argentiferes de Pontgibaud* (Paris1851). o) *Principes généraux du traitement des minerais métalliques traité de métallurgie théorique et pratique* (Paris: Dalmont et Dunod, 1859).

[115] According to Blanchard, by the sixteenth century the silver content in European ores was below 0.2%: 'During the first [silver] long-cycle [1125-1255] output had peaked on the basis of argentiferous lead ores containing in excess of 100 oz of silver/ton [this is equivalent to 0.28% silver]. During the second long-cycle [1250-1392/1412] the best quality ores contained no more than 40 oz [0.11%] of silver per ton. Finally during the third long-cycle [1425-1560] whilst in the Balkans ores of 20-40 oz silver content were exploited, elsewhere 12 ½ oz [0.03%] ores, the minimal amount which could be processed by the prevailing cupellation method were the norm'. Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 xvi.

New Spain		original units	g/t	oz / quintal	marks / quintal	mark / arroba	kg/ton	arrobas de plata por quintal de tierra	pesos/ ton	oz / carga	source
		conversion factor to % weight	0.0001	0.063	0.50	2.00	0.1	25.0	0.003	0.02	
mine location	period	% weight calculated									
Zacatecas	1550s	5 to 15			10 to 30						a, 40
Zacatecas	1550s	50						2			a, 40
New Spain	1564	1 to 1.5			2 to 3						b, 48-49
New Spain	16c	0.5			1						c, 150
New Spain	16c	0.06		1							c, 151
Honduras	16c	0.5 to 0.6		8 to 10							d, 48
Honduras	16c	0.7 to 0.9		12 to 14							d, 48
Honduras	16c	2 to 3			4 to 6						d, 48
Honduras	16c	1.5 to 2			3 to 4						d, 48
Honduras	16c	0.24		4							d, 48
New Spain	1620s	8 to 10			16 to 20						e, 301
Zacatecas	17c and 18c	0.09 to 0.12		1.5 to 2							d, 48
New Spain	1740s	0.06 to 0.5		1 to 8							f, 1-5
Guanajuato	1774	over 0.08%									g, 90-91
Honduras	18c	2 to 16				1 to 8					d,48
Honduras	18c	0.50			1						d,48
New Spain	18c	0.12 to 0.18		2 to 3							h,914
New Spain	18c	0.18		3							i, 668
New Spain	mid to late 18c	0.15			0.3						j, 100
Zacatecas	1775	0.12		2							k, 672
Zacatecas	1801	0.19									l, 153-154
New Spain	1800s	0.18 to 0.24		3 to 4							m, 241
New Spain	1802	0.25									n, 144-146
Guanajuato	1800s	0.24		4							o, 413
Zacatecas	1808	0.4								20	p, 699
Zacatecas	1835	3			6						q, 81
Zacatecas	1835	1.5			3 1/6						q, 81
Zacatecas	1835	0.9			1 7/8						q, 81
Zacatecas	1835	0.21		3 1/2							q, 81
Mexico	1840s	0.2 to 0.3									r, 83, 85, 236, 279-280, 351
Mexico		0.1 to 0.5									s, 57-62, 254
Zacatecas	1854-1868	0.15					1.48				t, 4
Zacatecas	1876	0.07					0.73				u, 4
Pachuca	1870-1888	0.19									v
Pachuca	1870-1888	1.8									v
Mexico	1860s	0.09									w, 471
Santa Barbara, near Parral	1900s	0.025 to 0.05	250-500								x, 208-209
Zacatecas	~1910	0.21							70		y, 278
Real del Monte	~1910	0.12	1200								y, 275
others near Pachuca	~1910	0.10 to 0.15	1000 to 1500								y, 275
Zacatecas	1980s	0.012	120								z, 1680
Pachuca	20c	0.018	180								aa, 137

Table 1-II. Silver content of ores reported for New Spain / Mexico. Sources are listed in footnote 113.

Vice-Royalty Peru		original unit	g/t	oz / quintal	marks / quintal	oz / ton	weight %	pesos / quintal	mark / pound	pounds / cajón (5000 lbs)	marks / cajón	ducats / hundred weight	source, page
		conversion factor to %	0.0001	0.063	0.50	0.003	1	0.06	51	0.02	0.01	0.05	
mine location	period	% weight calculated											
Potosí	1545	40 to 45			80 to 90								A, 241
Potosí	early 1550s	49			100								B, 124
Potosí	1550s	49							1				C, 175
Potosí	1550s	24										480	D, 11
Potosí	1560s	2											E, 44
Potosí	mid 16c	20					20						E, 43
Potosí	mid 16c	25					25						F, 36
Potosí	1545-1572	25					25						G, 75
Potosí	1568	1			2								B, 124
Potosí	1573	2			4								H, 30
Potosí	1574	4 to 4.5			8 to 9								A, 241
Potosí	1580s	0.2 to 0.4		2 to 3				3 a 6					I, 122
Potosí	late 16c	12 to 15						200 to 250					J, 109
Potosí	late 16c	2 to 3						30 to 50					J, 109
Potosí	late 16c	0.1 to 0.4						2 to 6					J, 109
Potosí	late 16c	0.50									50		K, 50
Potosí	1588	1			2								L, 126
Potosí	16c	30 to 40					30 to 40						M, 374
Potosí	16c	5									500		M, 40
Oruro	1605	0.2						3 to 4					N, 563
Oruro	1605	0.4						6 to 8					N, 563
Oruro	1605	0.7			1.4								N, 564
Potosí	1600s	0.4 to 0.5								20 to 25			O, 81
Potosí	1600s	0.2								10 to 12.5			O, 81
Potosí	1600s	0.1								2.5			O, 81
Potosí	1607	0.1		1.5									A, 241
Potosí	1618	0.20				52							G, 76
Potosí	1636	0.10				50							G, 77
Potosí	1600 to 1630s	0.1 to 0.4				50 to 150							D, 12
Potosí	1600 to 1650	0.1									12 to 13		M, 51
Potosí	1660	0.40				150							G, 77
Cerro Pasco	1700s	0.1									10 to 12		P, 33
Potosí	1740	0.1								5			O, 81
Potosí	1700 to 1750	0.04									4		M, 51
Cerro Pasco	1700 to 1750	0.1									8		M, 110
Peru	mid 17c	0.1 to 3	800 to 30,000										E, 59
Cerro Pasco	1790s	0.1									8		P, 33
Potosí	late 18c	0.10		0.75									Q, 48
Peru	late 18c	0.03 to 0.06									3 marks 1 ounce to 6 marks 2 ounces		R, 62
Cerro Pasco	late 18c	0.06 to 0.25									6 to 25		P, 31
Potosí	late 18c	0.04 to 0.06			0.08 to 0.12								S, 100
Potosí	18c	0.06 to 0.12		1 to 2									T, 914
New World	16c to 18c	0.12 to 0.24		2 to 4									U, 661
Potosí	16c to 18c	0.005 to 0.02	50 to 200										V, 83
Cerro Pasco	1820s	4									400		Q, 36
Potosí	1886	0.20				70							D, 13
Potosí	late 19c	0.04 to 0.06				15 to 20							G, 89
Potosí	late 19c	1.96				700							G, 91
Potosí	late 19c	0.21 to 0.24				75 to 80							G, 102

Table 1-III. Silver content of ores in the Vice-Royalty of Peru. Sources are listed in footnote 113.

the environmental history of silver refining in the New World.

Silver deposits by themselves do not explain the dominance and choices exercised by Spain over silver production. Geology would also provide the Spanish Crown with the ownership of vast deposits of the three chemical substances that subsequent chapters will show were indispensable for the refining of the silver ores: mercury, salt and lead.

Europe		original units	troy ounce / ton	oz / ton	weight %	g / 100 kg	oz / 100lb ore	pound silver / talent of ore	marks /cajon	marks / hundredweight	page
		conversion factor to % weight	0.0031	0.0029	1	0.001	0.06	1.76	0.01	0.5	
mine location	period	% weight calculated									
Laurion	BCE	0.04			0.04						a, 34
Laurion	BCE	0.12 to 0.26		40 to 90							b, 18
Laurion	BCE	1.9	600								c, 26
average European silver ores	1125-1225	0.29		100							d, xv
England	12 c	0.07-0.28		25-100							e, 1
average European silver ores	1250-1392/1412	0.12		40							d, xv
minimum quality European	1425-1566	0.036		12.5							d, xv
Balkans	1425-1566	0.058 to 0.12		20 to 40							d, xv
Eisleben, Schwaz	1480	0.79				790					f, 589
Eisleben, Schwaz	1494	1.38				1380					f, 589
Austrian mines	1460s	0.12 to 1.32					2 to 22				g, 242
Goslar? Erzgebirge?	1520s	0.88 to 1.76						0.5 to 1			h, 36
Europe	1526	0.52								1.053	i, 316
Rammelsberg	16c	0.03 to 0.07			0.03 to 0.07						j, 80
Rammelsberg	16c	10			10						j, 80
Cornwall/Devon	<18c	0.4	130								c, 26
Freiberg, Saxony	1750s	0.16 to 0.625							16 to 62.5		k, 110
Slovakia	18c	0.09 to 0.12					1.5 to 2				l, 312, 314
Harz	1805	0.01 to 0.04			0.01 to 0.04						m, 102
Pontgibaud, France	1840s	0.1			0.1						n, 193-197
Flintshire	1850s	0.03			0.03						o, 317-319, 386-388
Cornwall/Devon	19c	0.08 to 0.12	25 to 40								c, 26

Table 1-IV. Silver content of ores in Europe. Sources are listed in footnote 114.

1.7 Mercury

During the Early Modern Era there were only three sources of mercury in the world for all practical purposes, of which the two most important ones would be under the direct control of the Spanish Crown, one on each side of the Atlantic (see Figure 1-1). Nearly 80% of all the mercury produced in this period was owned by Spain. The mercury mine in Almadén, Spain, remains the doyen of the group even after over one thousand years of production. In Europe only Idrija achieved important and sustained levels of exploitation, but always inferior to those of Almadén. Spain would find in the New World the second most important source of mercury of the world of that time at Huancavelica, in present day Peru. As Table 1-V shows, there were no other known major deposits of mercury during this period, since China never materialized as a viable supplier of mercury to the New World in spite of repeated attempts by the Spanish authorities to find Chinese supplies.[116]

There is a sense of incredulity at the scale and variety of geological deposits at the service of the Spanish Crown during this period. Not only had Spain conquered exclusive access to the main silver depository on Earth, it was already in possession of a mercury deposit that even modern geologists address in mystified terms:

‘Almadén ... is a most enigmatic mineral system ... [with an endowment of ca. 271 thousand metric tons] it is the largest Hg [mercury] “supergiant” that stores close to 30-40% of mercury of the world’s endowment. It is also the number 1 deposit in terms of geochemical magnitude of accumulation, of all metals. Despite this, there is no satisfactory explanation where this mercury had come from, and why it had accumulated in this geologically almost “normal” setting’.[117]

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[116] Sources: a) S.M. Cargill, D.H. Root, and E.H. Bailey, "Resource Estimation from Historical Data: Mercury, A Test Case," *Mathematical Geology* 12, no. 5 (1980). b) Lars D. Hylander and Markus Meili, "500 Years of Mercury Production: Global Annual Inventory by Region until 2000 and Associated Emissions," *Science of The Total Environment* 304, no. 1–3 (2003). c) Laznicka, *Giant Metallic Deposits*.

[117] *Giant Metallic Deposits*, 356-58. A similar sentiment, ‘possibly the largest geochemical anomaly on the planet’, is expressed in Cris M. Hall et al., "Dating of Alteration Episodes Related to Mercury Mineralization in the Almadén district, Spain," *Earth and Planetary Science Letters* 148 no. 1-2 (1997): 287.

ranking	country	location	aggregate production		production to 1800		production period	source
			metric tons		metric tons			
1	Spain	Almadén	271,000	a, 492			1499-1975	a, 493
		country total	304,666	b, 16	67,966	b, 15	1501-2000	b, 16
2	Italy	Monte Amiata	104,000	a, 492	n/a		1850-1975	a, 493
			104,473	b, 16			1851-1982	b, 15
3	Slovenia	Idrija	102,200	a, 492	35,609	b, 15	1495-1975	a, 493
			107,311	b, 16			1501-1997	b, 16
4	Peru	Huancavelica	52,000	a, 492	50,321	b, 15	1566-1810?	a, 493
		incl. Yanacocha after 1993	57,962	b, 16	n/a		1551-2000	b, 15
5	United States	New Almaden	38,000	a, 492	n/a		1847-1975	a, 493-94
		New Idrija	20,000	a, 492			1854-1975	a, 493
		country total	131,106	b, 16			1801-2000	b, 15
6	Ukraine	Nikitovka	33,700	c, 359	n/a		not indicated	
	ex- USSR	Nikitovka, Kyrgyzstan and Tajikystan	77,788	b, 16	n/a		1881-2000	b, 15
7	China	country total	45,978	b, 16	> 5	b, 15	1601-2000	b, 15
8	Mexico	country total	32,250	b, 16	n/a		1891-2000	b, 15
9	Africa	continent total	17,212	b, 16	n/a		1921-2000	b, 15

Table 1-V. Major deposits of mercury through history. Sources indicated in footnote 116.

Up to 1977 the Almadén mine has produced about one-third of the world's mercury, with extraction commencing prior to the arrival of the Romans in Spain.[118] Spain would be further awarded in the New World with the mercury mine at Huancavelica, which would provide the majority of the supply of mercury to the amalgamation processes carried out in the Vice-Royalty of Peru until its exhaustion at the beginning of the nineteenth century.

[118] Cargill, Root, and Bailey, "Resource Estimation from Historical Data: Mercury, A Test Case," 492.

1.8 Salt, sodium chloride (NaCl)

'Without salt there was no silver. Without silver another would have been the history of New Spain'.[119] Salt was as critical an ingredient for the refining of the silver ores in the New World as mercury. Yet again the size of the natural deposits of salt that were gifted by geology to Spain at locations close to the main silver deposits could only have strengthened their belief in Divine Intervention. The largest salt deposit in the Americas, Uyuni, lies in the Andes, and the other nearby salt deposit of Yocalla was harvested by amalgamation refiners of Potosí, who were thus spared the cost and logistics of bringing salt from the sea.[120] While New Spain did not have a single deposit of salt of the scale of the Andean Uyuni, Peñon Blanco (Figure 1-4) among others satisfied the industrial demand for salt:

'from the 16c to the 19c Southern and Central Mexico relied mainly on their own inland resources, besides importing salt from either coast. Colima salt came to the altiplano via Guadalajara and was sold as far away as Guanajuato... salt came from Campeche via Veracruz and then packtrain to the capital and neighbouring mines. The salinas del Peñon Blanco supplied all the mines from northern central Mexico up to Durango … Peñon Blanco would also sell as south as Pachuca ... [in contrast to the monopoly on mercury] free market economy regulated trade'.[121]

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[119] '*Sin sal no había plata. Sin plata, la historia de la Nueva España habría sido otra*.' Juan Carlos Reyes, "Introducción," in *La sal en México* ed. Juan Carlos Reyes (Colima: Universidad de Colima,Consejo Nacional para la Cultura y las Artes, 1995), vii.

[120] Cunill Grau, "Paisaje andino," 77. The Uyuni salt deposits are clearly seen as a white patch on satellite images taken from a height of 64,000 km as appear on Google Earth© images of the central Andes.

[121] Ursula Ewald, *The Mexican Salt Industry, 1560-1980 : A Study in Change* (Stuttgart; New York: G. Fischer, 1985), 202-203.; Coll-Hurtado, Sánchez-Salazar, and Morales, *La minería en México*, 26. Apart from Peñon Blanco, other salt mines are mentioned as belonging to Ocotlan, Piaxtla, Chila, Tehuacan, Cuzcatlan, Omitlan, Chiautla, Acatlan, Jasco and Sinaloa, in Ewald, *Mexican Salt Industry*, 20.; Mendizábal, *La mineria mexicana*, 80.; Jaime J. Lacueva Muñoz, "Nueva Vizacaya y sus yacimientos minerales hasta el descubrimiento de San José del Parral," in *Ophir en las Indias. Estudios sobre la plata americana. Siglos XVI-XIX*, ed. Jesús Paniagua Pérez and Nuria Salazar Simarro (León: Universidad de León, 2010), 106. Salt came from many more smaller locations than Peñon Blanco, and a good case study of local multiple sources of supply for the silver mines in the Taxco area is given in Margarita Menegus Borneman, "Las comunidades productoras de sal y los mercados mineros: los casos de Taxco y Temascaltepec," in *Minería regional mexicana. Primera reunión de historiadores de la minería latinoamericana*, ed. Dolores Avila Herrera and Rina Ortiz (Mexico: Instituto Nacional de Antropología e Historia, 1994).

1.9 Lead

It is important to insist on the fact that lead was present in important quantities in New Spain, for geological reasons previously pointed out by Sillitoe. The argentiferous lead mining districts are (among others) Sombrerete, Veta Grande in Zacatecas; Catorce, Matahuela in San Luis Potosí; Taxco in Guerrero; Santa Eulalia, Hidalgo del Parral in Chihuahua; Temascaltepec and Sultepec in Mexico, Zimapán close to Pachuca. Lead deposits are found in Chihuahua (Santa Eulalia among others), Coahuila (Sierra Mojada), Nuevo León (Sombrerete, Ojo Caliente) and Zacatecas.[122] Mendizábal draws attention to the important fact that even though it was known that lead deposits existed in New Spain no effort was made to develop them:

> 'Lead ... was present in great abundance ... as well as in argentiferous galena … it seems that lead was never the aim of any special exploitation, except in the mines of El Cardinal and Zimapán (Lomo del Toro) in the state of Hidalgo, which produced some fifteen thousand cargas annually (4,140 tons), sufficient quantity to meet the industrial demand for lead ... at the end of the eighteenth century lead mines are exploited in Sultepec'.[123]

The location of the principal lead resources in the northern provinces that took longer to pacify may have delayed their discovery (for example the deposits at Santa Eulalia were only discovered in 1704) but Mendizábal points to an absence of clear directives from the Spanish Crown to search for lead mines as diligently as for silver or mercury sources.

The lead endowment of Mexico as calculated to 1994 was of 11,062,988 t, just below that of Germany at 12,150,180 t.[124] Up to the Early Modern Era both Germany and England

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[122] Teodoro Flores, *Yacimientos minerales de la República Mexicana, con algunos datos relativos a su producción* (México: Instituto Geológico de México, 1933), 18,28. Also in Coll-Hurtado, Sánchez-Salazar, and Morales, *La minería en México*, 16.

[123] *'[El] plomo ... existía en gran abundancia ... como en la composición de la galena argentifera y [aunque se aplicaban los impuestos del rey desde el siglo XVI] parece ser que el plomo no fue objeto de explotación especial, sino en las minas de El Cardonal y Zimapán (Lomo del To) en el estado de Hidalgo, que producían unas quince mil cargas anuales (4140 toneladas), cantidad suficiente para las necesidades industriales del plomo ... a finales del siglo XVIII se explotan minas de plomo en Sultepec*'. Mendizábal, *La mineria mexicana*, 71.

[124] Singer, "Precious Metal Deposits," 94.

had based their refining of silver ores on the use of their endogenous lead deposits and the application of smelting technology. From a geological point of view there was no lack of local deposits of lead available to refiners in New Spain.

1.10 Final remarks

Portugal had enforced a no-sail zone down the Atlantic seaboard of Africa by the end of the fifteenth century, all the while whetting the appetite of Europe by returning with African gold loaded onto its ships. The only unopposed expansion route by sea for other European powers lay to the West, and Spain was the first to back the leap into the unknown. As a result of this decision by the *Reyes Católicos*, Spain stumbled onto a continent with an active and extended subduction zone along all its western coastline. It colonized first the narrowest portion of what is now North America, endowed with a very rich metallogenic zone, and would thread the rest of its conquest and colonization along the metal-rich spine of the Andes. Spain thus came to control a unique monopoly of mineral resources that would allow it to corner the market of silver production for nearly three centuries, a geological-political conjunction that has not been repeated for any other metal up to the present. It would only be in the nineteenth century that the new United States of America would join Spain in profiting from the silver and gold bonanza of its own politically controlled subduction area.

Spain would control in just 50 years the two major deposits of primary silver ore known to man, together with the major mercury deposit of Huancavelica to complement its Spanish mine of Almadén, the salt deposits of Uyuni and the polymetallic deposits that contained lead and gold in New Spain. The diversity of this geological bonanza meant that Spain had at its disposal all the raw materials needed to make possible the refining of the silver ores of the New World. The term 'silver ore' however is too generic, and implies a uniformity that does not exist. The silver ores of Europe, the Andes of the Vice-Royalty of Peru and the Silver Belt of

New Spain do not share an identical geological genesis, though all are the product of subduction processes. The different roots in geological time may be the reason why silver ores found in Europe were extracted in order to profit from their content of lead or copper, with silver as a collateral benefit. In contrast, in the New World it was only the silver content that sustained all mining and refining production costs, in the chemical form of silver sulphides or argentiferous galena. This was the fundamental and relevant difference on both sides of the Atlantic, not the silver content in each ore.

Once geology determined the embarrassment of mineral riches of the New World, it was up to the Spanish miners and authorities to make a conscious choice as to which technical route to follow in their pursuit of silver. The environmental history of the refining of silver in the New World was not the unavoidable consequence of ores poor in silver content. Sillitoe's proposal that there is no major supergene enrichment above the water table in sulphidic silver deposits, shores up the strong suspicion that the early decrease in the production of silver, as mines clawed deeper into the mineral veins of the New World, was a technical issue unrelated to silver content. I have argued in this chapter that it was the consequence of the change in the chemical profile of these deposits, from superficial elemental silver and silver halides to a deeper and much more intractable silver sulphide ore. The reasons why silver halides and argentiferous lead were easy to refine for the early Spanish miners, yet silver sulphides posed initially an insurmountable challenge, and the very distinct environmental consequences of the refining method applied to each type of ore, now lead this narrative into the next two chapters.

2 The dry refining process: smelting of silver ores.

'The most general and proper way, better adapted to the nature of metals, to separate them from the earth and stones where they are raised so as to reduce them to their purity and perfection … is through the fire of the furnaces, which to this end are called smelting ovens'. Alvaro Alonso Barba, *Arte de los metales* (1637)[125]

'in those times there had come from Castille and the islands many Spaniards poor and greedy, curs hungry for wealth and slaves'. Bernal Díaz, *Historia verdadera de la conquista de Nueva España* (ca 1568)[126]

2.1 Introduction

The Spanish priest Alvaro Alonso Barba (born 1569) is a singularity amongst the early Spanish refiners of silver ores in the New World. He wrote the only extant metallurgical text of the early period that is sourced in the practice of the New World, which provides a first-hand guide to the mind-set and skill level of the time. He also proposed the last original refining method for silver ores based on mercury, the *cazo* process that will be described in the following chapter. As a historical figure he is firmly entrenched in the historiography on amalgamation of silver ores in the Americas. Thus at first sight it might seem odd that he would exalt smelting as the 'most general and proper way' to extract silver from its ores.[127]

In fact, the major part of Barba's much cited book, *Arte de los Metales,* is dedicated to the smelting of ores (approximately 68 pages of Books IV and V, out of a total of 198 pages), longer than his discussion on what he terms ordinary amalgamation (Book II, 36 pages) or even

[125] '*El modo más general, más propio, y más conforme a la naturaleza de los metales, para apartarlos de la tierra, y piedras con que se crían, y reducirlos a la pureza y perfección … es mediante el fuego en los hornos, que para este efecto se llaman de fundición*'

[126] '*en aquel tiempo vinieron de Castilla y de las islas muchos españoles pobres y de gran codiçia e caninos y hambientos por aver riquezas y esclavos*'.

[127] Barba, *Arte de los metales*, 130. The metallurgical term 'smelting' is confusingly close to the word 'melting'. The latter implies the use of heat to change the physical state of a crystalline substance from solid to liquid. The former is only applied to metallic ores, and is an operation that requires both heat and chemical reactions to bring about the extraction of a metal from its ore. For a definition of smelting see Manuel Eissler, *The Metallurgy of Argentiferous Lead* (London: Crosby Lockwood & Son, 1891), 33.

the description of his new *cocimiento* (cooking) process (25 pages of Book III). And yet forty years before this manuscript was sent to Madrid for printing (1637), the practice of smelting silver ores in New Spain had suffered a fate similar to Mark Twain's news of his early demise:

'and with respect to smelting, I say that it is very much forgotten since 35 years have passed since it was last used, so if new ores with sufficient silver tenor for smelting were to be discovered, no man would still be alive who knew how to smelt them, nor would there be a smith to make the tools required for smelting; and there may come a time when this work may be held of some interest and of great curiosity by the fact that it [knowledge on smelting] should have been preserved in writing'.[128]

The author of this premature obituary for smelting was Gómez de Cervantes, a commentator at the end of the sixteenth century on events unfolding in the New World, and not a *minero*.[129] He was claiming that smelting had long since disappeared in New Spain in the face of the success of mercury amalgamation. The notion that amalgamation swept its way past smelting to become virtually the sole refining process in the New World still percolates its way through the modern historiography.[130] Yet the view expressed at the time by Gomez de Cervantes contains two important errors of fact. First, towards the end of the sixteenth century not enough mercury was being imported into New Spain to amalgamate all its silver ores.

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[128] '*y en cuanto a la fundición, digo que esta tan olvidada por haber más de 35 años que no se usa, que entiendo que si se descubriesen metales de ley, que se hubiesen fundir, no habría hombre que los supiese fundir, y aun dudo si habría herrero que supiese hacer las herramientas de fundición; y quizás, vendrá tiempo que se tenga en algo esta relación y por muy gran curiosidad esta prevención haberlo escrito*' in Gómez de Cervantes, *Nueva España siglo XVI*, 156-157.

[129] The term *minero* is applied in the early documents both to the person that owned and/or operated the mines and the person who owned and/or operated the refining haciendas. It was only by the eighteenth century that the business of refining could be regarded as separate from that of mining, with the introduction of the *maquila* or toll (Chapter Five). The use of the masculine does not mean women were excluded from the business of mining and refining, but they do not appear in documents as much as the men. The following extract shows an interesting exception since women are involved on both sides of the business: 'Doña Francisca de Paz minera of this village [San Luis Potosí] declares before Your Eminence one hundred and fifty cargas of ore from my mines to be processed in the refining hacienda of Doña Ysabel de Adriansen which she owns in Los Pozos' - '*Doña Francisca de Paz minera en este pueblo manifiesto ante Vmd [Vuestra Merced] ciento y sinquenta cargas de metal de mis minas para beneficiarlas en la hacienda de minas de doña Ysabel de adriansen que la susodicha tiene en los posos'*, AHSLP, Fondo de Alcaldía Mayor 1635.3, expediente 19, 11 July 1635. Many widows undersign documents relating to sales or rental agreements of refining haciendas in New Spain.

[130] For example, the recent claim that more than 95% of all silver was produced by amalgamation in Manuel Castillo Martos, "Alquimia en la metalurgia de plata y oro en Europa y America " in *Informes para obtener plata y azoque en el mundo hispánico* (Granada: Universidad de Granada, 2008), xxiv.

Second, not all of New Spain's silver ores could be refined via the amalgamation process applied at that time, since as indicated in the previous chapter argentiferous lead also constituted an important part of the silver sources in New Spain. Very relevant in this regard were the deposits of silver rich galena discovered towards the end of the sixteenth century in the mines of the Cerro San Pedro close to the town of San Luis Potosí, towards the north of Ciudad de México.

Barba is definitely one of the strong and credible voices of the late sixteenth century on silver refining in the New World, and his evidence gives a contemporary lie to the report by Gómez de Cervantes. The overall impression in Barba's text is that amalgamation is never taken for granted as being a better refining method than smelting. Time and again he cautions his contemporary readers against being led astray by the limitations of mercury amalgamation, which could not even be used to provide a true assay of silver in an ore. 'Whoever deals with ores without knowing how to assay them by fire to learn correctly their silver content ... runs a great risk ... do not trust the assay by mercury, which is very deceitful'.[131] Deceitful mercury is certainly not a part of the mainstream historiography on colonial silver refining. Barba knew first-hand that mercury amalgamation was not a process that would extract silver efficiently from every ore. In his words:

'a certain *minero* … extracted a lot of very rich ore, but did not realize this; he assayed it by mercury [amalgamation] and measured four or five pesos per quintal [0.24 to 0.3%]… he abandoned the mine, because he deemed it without profit ... [later I found the ore and] assayed it by fire [smelting with lead] and it had nine hundred pesos per quintal [approx. 54%]'.[132]

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[131] '*Muy a riesgo esta ... el que tratando en metales no supiere ensayarlos por fuego para enterarse con certidumbre de la ley que tienen ... no se fien del ensayo de Azogue, que es muy engañoso'*, Barba, Arte de los metales, 151.

[132] '*cierto Minero ... saco cantidad de metal riquísimo, aunque no lo conoció; ensayolo por Azogue, a cuatro o cinco pesos por quintal ... desamparo la Mina, porque no le era de provecho ... [luego yo halle del metal y] ensayelo por fuego, y tenía a novecientos pesos por quintal'*. Ibid., 71. Metal is the word used in Spanish texts to denote both the metallic element as well as the ore. Halleux provides the etymology of the Latin word metallum, derived from the Greek metallon, which initially referred to the mine, the 'underground cavity of extraction'. After the first century CE it came to designate the minerals in the mine, the ores, whether metallic or not. It was only at the end of Antiquity that it was applied to seven specific bodies: gold, silver, copper, iron, tin, lead, and

Barba's windfall profits were the result of a confusion still found to the present day that amalgamation of silver in ores was of the same nature as the amalgamation of gold. Mercury amalgamation was one of the tested methods to assay gold ores in Europe in the sixteenth century, and amalgamation did not require the skills of assaying with lead using a cupel and a furnace.[133] The clue to explain the great discrepancy between assaying with mercury or by smelting can be deduced from the similar experience of another priest that was a friend of his:

'In the Cerro de Santa Juana … ores like Soroche [galena, lead sulphide] were extracted, that when assayed with mercury showed little or no silver; they were thrown away by the *mineros* [until I assayed them by smelting] and found they had sixty or more *pesos* per *quintal* [3.6% silver] ... on my advice he collected many [and] extracted much wealth from them'.[134]

The chemical explanation to both priests' profit-taking is that lead is the main metal present in galena or *soroche* [as it was called in the Andes] and it forms an amalgam with mercury, thus competing and interfering with the extraction of silver. The silver extracted from a *soroche* ore by amalgamation can therefore be a minor fraction of the real amount of silver present. This is the reason why argentiferous lead was never refined efficiently by amalgamation. The limitations of simple amalgamation also extend to non-lead silver ores rich in silver sulphide or sulfo-salts, the *negrillos*. Mercury alone will not reduce silver sulphide to silver metal, as I will explain in greater detail in the next chapter, so simple assaying of

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either mercury or electrum. The concurrent use of metallum to designate both these seven bodies and also the ore of a mine is the reason why the Spanish texts use the word 'metal' for both purposes as well. Robert Halleux, "La nature et la formation des métaux selon Agricola et ses contemporains," Revue d'histoire des sciences (1974): 212.

[133] L. Ercker, *Treatise on Ores and Assaying*, trans. Anneliese Grünhaldt Sisco and Cyril Stanley Smith (Chicago: University of Chicago Press, 1951), 57-60, 96-97. Any of the metallurgical texts of this period provides details on how to make cupels from crushed bones, hollow receptacles in which ores and lead could be melted in a furnace.

[134] '*En el Cerro de Santa Juana ... se sacaban unos metales como Soroches, que por el ensaye ordinario de Azogue mostraban ninguna o muy poca plata: echabanlos por ahí los Mineros [hasta que los ensaye al fuego] y halle que tenían a sesenta, y mas pesos por quintal ... recogió con mi aviso cantidad de ellos [y] mucha riqueza de ellos saco'*. Barba, Arte de los metales, 71. The fact there is an earlier tale in the historiography of a skilled priest buying cheaply an ore wrongly classified as poor in silver and then refining its true worth to his profit underlines the ubiquity of technically proficient Spanish priests with a good eye for wealth in the mining landscape of the New World. See Juan de Peralta, late sixteenth century New Spain, as quoted in Henry R. Wagner, "Early Silver Mining in New Spain," Revista de Historia de América, no. 14 (1942): 61-62.

negrillos by mercury amalgamation without the required chemical pre-treatment would again have given false low values.

Smelting never disappeared as a major contributor to the production of silver in the New World, regardless of reports to the contrary.[135] The attention paid by Barba in his metallurgical text on the technical merits of smelting indicates this was a topic of current interest to the mining community from whose experience this text was sourced. The handful of German, Siennese or Spanish authors who wrote texts on mining and refining in the sixteenth and seventeenth century reflected the most relevant practices of the mining district from where the authors drew their experience.[136] A case in point is the fact that Agricola does not address the technique of refining silver ores by amalgamation with mercury. He was writing about techniques applicable to the silver ores found in the Erzgebirge and Harz mountains, argentiferous copper or lead for which amalgamation was not an option.[137] In contrast, both Agricola and Ercker mention in detail the amalgamation of gold ores, a reflection on the

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[135] This perception is shared by the English historian Mervyn F. Lang: 'All descriptions and accounts of South American mining emphasise the amalgamation technique giving the impression that smelting was totally discarded. This was not true' in Lang, "Silver Refining Technology in Spanish America (patio y fundición) " 140. Two further examples in-between Gómez de Cervantes and Castillo Martos of the notion that amalgamation dominated over smelting are cited as follows. In his monograph promoting the use of a mineral additive (*tequesquite*) to facilitate the smelting of silver ore, Garcés y Eguía pays the following compliment to amalgamation: 'the master key that has made possible the extraction of the prodigious sums of silver with which the Americas have astounded the world' - '*la llave maestra que ha facilitado la extraccion de las prodigiosas sumas de plata conque las Américas han asombrado al mundo*', in Garcés y Eguía, *Nueva teórica del beneficio de plata*, 76. Sonneschmidt, a firm believer in amalgamation as practised in New Spain, said around the same turn of the eighteenth century: 'this refining by mercury … has produced the greatest part of the enormous quantity of silver that is circulating in the world' - '*este beneficio por azogue ... ha producido la mayor parte de la enorme cantidad de plata que esta girando por el mundo*' in F.T. Sonneschmidt and J.M. de Fagoaga, *Tratado de la amalgamación de Nueva España* (Galería de Bossange (padre), 1825), 160. In Chapter Six I provide quantitative evidence as to the historical importance of smelting in New Spain, where it produced 40% of all the silver.

[136] 'Agricola's ... outlook is severely local to Germany and the topics considered are almost completely restricted to the activities current within regions in and around the Harz mountains and the Erzgebirge... De Re Metallica gives a picture of the best practices of the age, practices that had made Germany lead Europe in non-ferrous metallurgy and which caused the services of German metallists to be sought by the rulers of many other countries'. Leslie Aitchison, *History of Metals* (London: Macdonald & Evans, 1960), 373.

[137] An alternate interpretation advanced in the historiography is that Agricola's silence on mercury amalgamation of silver ores proves that Biringuccio's instructions for the amalgamation of silver ore were quickly forgotten and never put in practice. Bargalló, *Minería y metalurgia colonial*, 111.

importance of this new process as of the fifteenth century in the Rhennish workings of Europe.[138] Biringuccio, a Siennese and not a German, is the only metallurgist and author of the sixteenth century to mention in detail the use of mercury to refine silver ores by amalgamation, in a book that was published in Venice, because he was addressing a Venetian mining audience already conversant with the amalgamation of silver ores, as I will explain in the following chapter.

2.2 Smelting of silver ores : the human context.

The early history of smelting silver in the New World is defined by the profile of the Spanish actors who arrived in the newly conquered lands in search of a wealth they could never attain back in their homeland. When Spain reached the New World it turned its attention very early to mining activities. It is claimed that some ten percent of the 1,500 strong contingent that came on the second voyage of Columbus was made up of 'workers ... to take gold out of the mines' on Hispaniola.[139] Precious metals were not the only target:

'On September 18, 1505, Fernando, having heard good reports about the possibility of finding copper in La Española, dispatched three caravels from Seville with all equipment needed for such an enterprise. He sent not only equipment, but a hundred African slaves'.

Five years later the King would add another 250 slaves destined to mining. It was mining, and not sugar, that marked the start of African slavery to the New World.[140]

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[138] 'Agricola was the first writer to give a comprehensive account of the metallurgy of gold and his most extensive recordings deal with that subject [including amalgamating gold with mercury]'. Aitchison, *History of Metals*, 385. According to Cyril Stanley Smith 'there are no books on metallurgy among the incunabula'. The most prominent mining texts published in the sixteenth century and early seventeenth centuries are: the anonymous German *Probienbuchs* (early sixteenth century), the Siennese Biringuccio's *De Pirotechnia* (1540), the German Agricola's *De Re Metallica* (1556) and Ercker's *Treatise on Ores and Assaying* (1574) and the Spaniard Barba's *Arte de los Metales* (1637). See the introduction to Biringuccio, *The Pirotechnia*, x-xix.

[139] '*gente trabajadora ... para sacar oro de las minas*', as quoted in J.E. Pérez Sáenz de Urturi, "La minería colonial americana bajo la dominación española," *Boletín Millares Carlo*, no. 7 (1985): 55.

[140] Hugh Thomas, *Rivers of Gold : The Rise of the Spanish Empire* (New York: Random House, 2005), 256-257. 291.

The Spanish contingent that swarmed over New Spain on the heels of the conquest was described by Bernal Diaz, one of the original band of *conquistadores* of New Spain under Hernán Cortés, as 'poor and greedy, curs hungry for wealth and slaves'.[141] Oviedo describes well the predatory, rags-to-riches mentality of many of these *mineros*:

'And in particular, those in these parts that have no intention of remaining nor wish anything from this land other than to ravish it and return to their homes, turn to trading or to the mines ... or any other activity that will allow them to get rich quickly and leave ... for most who are here treat this land as a step-mother, even though many have fared much better here than in their own motherland'.[142]

Part of the problem faced by Spain was the very small pool of home-grown talent from where the early miners could be sourced, with no generational experience on any type of silver ore. Two historical texts that refer to the early period, ca 1550, attest to the very low level of skills prevalent at the time:

'this way of extracting silver [smelting] was not learnt from the indians, nor did men go from here who knew about it, because they did not know how to smelt, and they were also ignorant of refining over a bed of ash … previously they used to disinter the dead and burn their bones, so as to benefit from the ash alone to make the cupels in which they refined, and in a similar manner there were other primitive actions that point to the ignorance of that time'.[143]

'the Spaniards did not have the experience of the ancient asturianos [from Asturias], or Portuguese, or Gallegos [from Galicia] gained in antiquity working the mines of the provinces ... of Spain, from where the Romans had taken great treasures'.[144]

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[141] '*pobres y de gran codiçia e caninos y hambientos por aver riquezas y esclavos*'. Bernal Díaz del Castillo, *Historia verdadera de la conquista de la Nueva España : Manuscrito "Guatemala"* (Mexico: Colegio de México : Universidad Nacional Autónoma de México, 2005), 834.
[142] '*Y en especial, los que en estas partes no tienen pensamiento de permanecer ni quieren desta tierra sino desfructalla e volverse a sus patrias, danse a la mercaduria o a las minas ... e a otras cosas con que presto alleguen hacienda con que se vayan ... porque los mas que por aca andan, tienen esta tierra por madrastra, aunque a muchos hales ido muy mejor que en su propia madre*'. Gonzalo Fernández de Oviedo y Valdés, Historia general y natural de las Indias (Madrid: Ediciones Atlas, 1959), 80.
[143] '*este género de sacar plata no se aprendió de los indios, ni de acá fueron hombres que lo supieran, porque no sabían fundir, y también ignoraban el afinar sobre cendrada de ceniza ... antes solían desenterrar a los muertos y quemar los huesos, cuya ceniza sola decían que aprovechaban para hacer la capella en que afinaban, y asimismo había otras rusticidades en que se conoce bien la ignorancia de aquel tiempo*' from a letter from Agustín de Sotomayor to the King, dated 20 April 1573, as quoted in Tomas González, Noticia histórica documentada de las célebres minas de Guadalcanal, desde su descubrimiento en el año 1555, hasta que dejaron de labrarse por cuenta de la Real Hacienda, vol. II (Madrid 1831), 409.
[144] '*los españoles no tenian aquella esperiencia de los antiguos asturianos, e lusitanos, e Gallegos tuvieron antiguamente en este ejercicio de las minas en las provincias ... de España, de donde los romanos tan grandes tesoros hobieron*' Fernández de Oviedo y Valdés, Historia natural de Indias, 47.

Even by the early seventeenth century Barba was sufficiently worried by the overall lack of skills he observed in Peru to propose that only those who passed an official exam to demonstrate their ability to assay ores by smelting should be allowed to refine silver ores, such had been the waste incurred by ignorant refiners in the past.[145] Modern historiography shares the judgement on the poverty of metallurgical skills:

> 'the number of expert miners that were available was very small and their knowledge very rudimentary, since except for the mines of Vizcaya, and those of mercury at Almadén, exploited by the German bankers the Fuggers, there was no exploitation of important mines at that time in Spain, given that the famous silver mines of Guadalcanal, in the Sierra Morena [some 110 km north of Seville] were not discovered until 1555'.[146]

The Spanish historian of mining, Julio Sánchez Gómez, argues that from Roman times up to the sixteenth century it became common practice in mining deposits of argentiferous lead (galena) in Spain to only work the most easily accessible surface deposits, abandoning the mine as soon as it required deeper levels of mining.[147] By the middle of the sixteenth century the contribution of Spanish mines, with the exception of Almadén, to the revenues of the Crown was on average less than 0.4%, which gives an indication of how little mining and refining know-how would have figured among its subjects.[148] From a metallurgical point of view the working of iron ores in Asturias and the Basque country (part of the Kingdom of Castille at the

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[145] Barba, *Arte de los metales*, 70-71.

[146] '*el número de mineros expertos de que se disponía era muy pequeño, y sus conocimientos muy rudimentarios, pues salvo las minas de Vizcaya, y las de mercurio de Almadén, explotadas por los banqueros alemanes Fugger, no se trabajaban entonces minas importantes en España, dado que las famosas minas de plata de Guadalcanal, en la Sierra Morena, se descubrieron hasta el año de 1555'*. Mendizábal, *La mineria mexicana*, 19. Silver ore from the mines at Guadalcanal was smelted, since it was argentiferous galena as is evidenced in the following extract: 'in this month [January 1559] three thousand six hundred and eighty eight marks of silver were extracted; refining goes well, with the care that has been taken in assaying the lead' - '*en este mes [enero 1559] se saco tres mil e seiscientos e ochenta e ocho marcos de plata; las afinaciones andan buenas, y con el cuidado que se ha tenido de ensayarles el plomo'*. González, Noticia histórica minas de Guadalcanal, II 17.

[147] Sánchez Gómez, *Minería no férrica en el Reino de Castilla*, 47. The Mexican historian Mendizábal shares the view that 'due to the imperfection in mining techniques and metallurgy the miners abandoned their works at the first sign of impoverishment [of the ore]' - '*debido a la imperfección de la técnica de laboreo y la metalurgias los mineros abandonaban los trabajos al primer indicio de empobrecimiento*' in Mendizábal, *La mineria mexicana*, 21.

[148] Sánchez Gómez, *Minería no férrica en el Reino de Castilla*, 269.

time of the conquest of the New World) would have provided some background on furnaces and smelting but little in the way of providing prior experience for the majority of silver ores to be found in the New World.[149] The technology employed in the iron works of the Basque country is claimed to have been too simple to be of use in the refining of silver in the New World.[150]

The Spanish colonial authorities recognized the technical deficiency in the field of mining and refining silver ores and turned to German technical expertise for New Spain from the 1520s and for Peru in the 1570s.[151] 'Tradition holds that the Germans or <alamans> had a [mining and refining] know-how that was much sought after'. The term German encompassed those originally from Germany but also included Swiss, Bohemians, Slovaks, Austrians and other Middle Europeans.[152]

'at the forefront of [metal refining] were the German master miners. Having gained experience in the Harz and Saxony, these men travelled to the new mineral fields across Europe, transferring knowledge and skills ... their skills in operating smelters was much sought after'.[153]

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[149] The role of Basque families as owners of mining investments in Zacatecas has been described in E. Fernández de Pinedo y Fernández, "Influencias recíprocas de las técnicas extractivas entre la minería vasca y la americana en la Edad Moderna," *Areas*, no. 16 (1994): 36. The Basque (*Vascongados*) fraction in Potosí has been made famous thanks to the description of their ongoing fights in Bartolomé Arzáns de Orsúa y Vela, *Historia de la villa imperial de Potosí*, ed. Lewis Hanke and Gunnar Mendoza L (Providence: Brown University Press, 1965).

[150] Fernández de Pinedo y Fernández, "La minería vasca y la americana," 38. English language historians are equally dismissive, see Peter J. Bakewell, "Mining in Colonial Spanish America," in *The Cambridge History of Latin America*, ed. Leslie Bethell (Cambridge: Cambridge University Press, 1984), 111.;R.C. West, "Early Silver Mining in New Spain, 1531-1555," in *In Quest of Mineral Wealth. Aboriginal and Colonial Mining and Metallurgy in Spanish America.* , ed. Alan Craig and Robert C. West (Baton Rouge: Geoscience Publishers, 1994), 122.

[151] Instructions to Toledo as cited in C. Salazar-Soler, "Innovaciones técnicas, mestizajes y formas de trabajo en Potosí de los siglos XVI y XVII," in *O trabahlo mestigo. Maneiras de pensar e formas de viver séculos XVI a XIX*, ed. Eduardo Franca Paiva and Carla Maria Junho Anastasia (Sao Paulo: UFMG, 2002), 149. The authorities in Madrid did not hesitate in turning to whichever foreign expertise they considered could assist the mining and refining effort in the New World, since in the next chapter I will refer to similar instructions being given in the case of amalgamation.

[152] '*La tradition veut que les Allemands ou <alamans> aient des compétences très recherchées. Sous ce terme générique, on désigne des personnages originaires d'Allemagne, mais aussi de la grande province germanique incluant la Suisse, la Bohème, la Slovaquie, l'Autriche, etc.*' Marie-Christine Bailly-Maître, L'argent : du minerai au pouvoir dans la France médiévale (Paris: Picard, 2002), 143.

[153] Martin Lynch, *Mining in World History* (London: Reaktion Books, 2002), 17. For similar references to the migration of German skilled miners within Europe see John U. Nef, *The Conquest of the Material World* (Chicago: University of Chicago Press, 1964), 12.

From the thirteenth to the seventeenth century German miners would be employed in England, France, Sardinia, Norway, and in the Serbian Brskvo mines, among others.[154] The presence of German miners in the New World came about either through individuals circumventing the initial restrictions on emigration for non-Castillians, or later in the sixteenth century as part of technical teams sent by either the Welsers (1529) to assist in the extraction of gold, or by the Fuggers at the request of the Spanish authorities, once travel was allowed after November 15, 1526 to subjects of the Holy Roman Empire under Charles V (Germans, Flemish).[155]

The need for technical assistance in smelting the ores of New Spain arose quite soon after mines started to be exploited. According to a document dated June 6th 1571 by the *Cabildo de México* to the *Concejo de Indias,* less than ten years had passed between the start of mining in 1532 and the observation that by 1542 ores had declined in silver content and in ease of smelting, '*minas comenzaron a perder la ley y la Buena fundición'*. This is a very significant pairing of concurrent events in a sixteenth century document that strengthens the line of argument that the difficulty in smelting the deeper silver sulphides triggered the conclusion that silver content had suddenly decreased substantially. Then, according to this account, a German dubbed with the generic name of Juan Alemán advised the Vice-Roy on German

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[154] German miners in Sardinia and Serbia, Lynch, *Mining in World History* 17.; in England, Jacob, *An Historical Inquiry into the Production and Consumption of the Precious Metals*, 1 292.; in Norway, Wallace, Barton, and Wilson, "Silver-Bearing Minerals," 32.

[155] Demetrio Ramos, "Ordenación de la minería en Hispanoamérica durante la época provincial (siglos XVI, XVII y XVIII)," in *La minería hispana e iberoamericana. Ponencias del I coloquio internacional sobre historia de la minería. Cátedra de San Isidro* (León: Cátedra de San Isidro 1970), 381-382.; Hugh Thomas, *The Golden Empire. Spain, Charles V, and the creation of America* (New York: Random House, 2010), 113. The ill-fated expedition of eighty miners sent by the Welsers came mainly from the Erzegirbe area, where the main mining activity was focused on argentiferous copper ores that were being refined by the liquation process with lead in the early sixteenth century. All except a few would die in the New World, with little support for their endeavours. Juan Friede, "La introducción de mineros alemanes en América por la compañía Welser de Augsburgo," *Revista de Historia de América*, no. 51 (1961): 99-104.

smelting techniques using lead and litharge with rich ores.[156] Events seem to have taken place even earlier. Bargalló places the arrival in New Spain of the German smelters Juan Enchel and others in 1536, sent by the factors of the Fuggers in Seville,

> ‘with tools and techniques to smelt metals from silver mines that until then had not been understood, and they set up grinding and refining facilities [most likely in Sultepec, according to Icazbalceta], from where came great benefit to the republic and great service to your Majesty’.[157]

The Germans were not the only source of smelting skills to aid the initial wave of Spaniards. The technical role of African slaves within a smelting *hacienda* is an intriguing facet to the history of smelting in the New World. They are mentioned as of the mid-sixteenth century by Bartolomé de Medina: ‘And so I have seen how such ores are processed in many places using *greta* and *cendrada* and with great cost to the owners of the mines and with great risk to the life and health of those involved in their processing, both of indians and negroes’.[158] The seventeenth century records of Zacatecas make frequent mention of the African slaves that are sold or rented together with the physical assets of a refining *hacienda*. The level of skills of some of these slaves is indicated by the following notations: ‘a black called domingo smelter from the land of angola; another black called juanito … smelter from the land of angola’.[159] Since all the slaves in the inventory are identified according to their place of origin in Africa, most probably as an indicator of their behavioural and physical nature, the fact that the smelters

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[156] Henry R. Wagner, "Early Silver Mining in New Spain," ibid., no. 14 (1942).; Bargalló, *Minería y metalurgia colonial*, 91. For a review on German miners in the New World see West, "Early Silver Mining," 16.

[157] ‘*con aparejos e yndustria para fundir los metales de las mynas de plata que hasta entonces no se entendían, e hyzieron yngenios de moler i fundir los metales (seguramente en Sultepec, según Icazbalceta) de donde se siguió mucho provecho para la rrepublica y gran servizio a Su Magestad’*. At least one Spaniard, Alonso Carreño, is said to have established an ‘*ingenio de fundicion’*, a smelting refinery, in Sultepec by 1543. Bargalló, Minería y metalurgia colonial, 58, 95.

[158] ‘*Y así he visto como se benefician los dichos metales en muchas partes con greta y cendrada y la muy grande costa de los dueños de las minas y el mucho riesgo de las vidas y salud de los que en el beneficio de elas entienden, así de indios como de negros’* as quoted in Castillo Martos, *Bartolomé de Medina*, 112.

[159] ‘*otro negro llamado domingo afinador de tierra de angola; otro negro llamado juanillo … afinador de tierra de angola*’ in a rental agreement for a smelting and refining hacienda between Pedro de Medina and Andrés Pereira, 20 March 1608, AHEZ, Notaria-Colonia, Numero 01 (Pedro Venegas, 1608), expediente 1.

came from Angola may not necessarily indicate a premium being placed on the level of skills originally brought by the slave. Slaves would persist in silver mining duties, and Mendizábal has pointed out the great number of slaves that worked in refining *haciendas* of Zacatecas, though according to the quote provided from the Bishop Alonso de la Mota y Escobar (1602) the indigenous workforce was better skilled than the African slaves or the Spaniards for both smelting and amalgamation.[160]

A picture emerges of a stage from early to mid sixteenth century with a very limited resource of refining skills in the New World, given the possible exception of some literate clergy who refined silver ores, together with pockets of German, Andean and African know-how of smelting methods. Bargalló also refers to this period as a proto-smelting period in New Spain where the lack of knowledge of German smelting techniques led to many trial and error processes.[161] In Chapter 3 I will return to this scenario, since it may have been an important factor in the fast adoption of an alternate refining process, one more amenable to such a large group of unskilled refiners of silver ores.[162] The contrast with the evolution of the mining and refining work-force of Europe remains to be studied. The technical complexity of the smelting operations carried out on a large scale has been used to argue that it led in Europe to the

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160 Mendizábal, *La mineria mexicana*, 32, 36.

161 '*el desconocimiento de dichas técnicas [las europeas alemanas de minería del siglo 16] hubieran evitado la serie de tanteos de los primeros mineros que por cierto han merecido severas críticas ... de cuantos han estudiado ese periodo inicial de la metalurgia hispanoamericana*' Bargalló, Minería y metalurgia colonial, 23. It is interesting to note the assertion that at the other end of the historical period studied in this thesis : 'The dependence on Spanish mining methods was so great on the American [United States of America] frontier that by the 1880s mining men were literally relying on Spanish techniques hooked up to a steam engine'. The author argues that the Spaniards had a strong mining and refining experience before arriving in the New World. Otis E. Young, "The Spanish Tradition in Gold and Silver Mining," Arizona and the West 7, no. 4 (1965): 299. It can be counter argued that the rich experience applied north of the Mexican border in the late nineteenth century was the product of three centuries of experience in the New World, not from Europe.

162 Even by the nineteenth century in Europe the high level of skill required for an efficient use of smelting to refine silver ores is remarked upon in the preface to Schlutter's classic textbook by M. Hellot. He points out that among the lead mines in France are those that give six ounces of silver per quintal [under 0.4%], 'their smelting and refining very amenable … that have been abandoned due to a lack of intelligence and [management]' – '*sa fonte et l'affinage très-asaisés ... qui ont été abandonnées faute d'intelligence & de conduit*'. Christophe-Andre Schlutter, *De la fonte des mines, des fonderies, etc.* , trans. M. Konig, vol. 2 (Paris: Jean-Thomas Herissant et Jacques-Noel Pissot, 1853), xiii.

development of a high degree of organization and literacy within the mining work-force, beginning as early as the eleventh century in Goslar (Harz Mountains). Bartels presents a persuasive argument that since smelting involved careful and consistent control of many process variables (temperature, exact knowledge of the silver content to be able to monitor the extraction process, consistent batches prepared for each furnace charge) therefore:

'assaying, precision measurement, data collection, the use of mathematics, attempts at standardization, the writing of technical instructions, the writing of technical books to be published – all this contributed to the practice of mining and metallurgy'.[163]

The fact that profit levels could not depend on contingent bonanza ores but on the careful monitoring of all the process variables, required:

'extensive written communication ... in mines, ore processing, and smelting works not only the experts ... but even every foreman had to be able to write and to do basic calculations from the mid-sixteenth century onwards. By the seventeenth century the vast majority of Harz miners were literate, and it was no longer possible to enjoy respected status in the community without being able to read and write'.[164]

Even when Spain found an alternative refining route in the New World, it still applied smelting in a major way in many mining districts, as will be detailed in Chapter 6. The level of smelting skills of the indigenous workforce or the African slaves, and their technical hierarchy within a smelting *hacienda* of New Spain is as yet an unexplored topic, and Bartel's conclusions raise the question if a similar path of development was ever observed at any level for the smelting labour force of the silver refining industry of the New World.

One final topic is the size of the work-force required for smelting, and whether this was a factor that was adversely affected by the epidemics that ravaged the indigenous communities after the arrival of the European diseases. Berthe has argued that a major reason why the Crown was looking so enthusiastically for an alternative to the tried and true smelting method was the

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[163] Bartels, "Production of Silver in Harz Mountains," 73, 98.
[164] Ibid., 98-99.

shortage of manpower after the epidemics among the indigenous population in 1545.[165] Medina in his promotional report on the advantages of amalgamation does focus expressly in the mid-sixteenth century in New Spain precisely on the size of the workforce of the rival process to amalgamation, claiming that :

'since [for] a horse-powered *ingenio* [smelting *hacienda*] working with one sound furnace … it is necessary to have four smelters and four carriers and two Spaniards that will need rooms and people to handle the horses of the *ingenio* and their rooms and two to refine and to grind the *greta* and *cendrada* another two persons and to make the furnaces and work the stones another two and to work the *cendradas* for every time they refine six persons are required because at the end of two days per week it will come to two persons each day and at night twelve negroes, and more to cover and take out such charcoal'.[166]

The impression left by both texts is that amalgamation required a smaller workforce than smelting, though no quantitative figures are proposed to establish man-hours per kg of silver refined by both processes. This exercise will be carried out in Chapter 5.

2.3 The chemistry of smelting and the nature of the ore

Smelting of silver ores is a complex operation for two reasons: in most cases it takes place at temperatures that require a furnace and not a simple cooking fire, and second, it requires a high degree of empirical skill to guide the silver in the ore through at least two major changes before isolating it in a pure state. However, the early history of silver refining in the New World hinges on the fact that the only exception to this statement is for an ore rich in silver chloride, like those found in the weathered section of a silver sulphide deposit. The

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[165] Jean Pierre Berthe, "Le mercure et l'industrie mexicaine au XVIéme siècle," in *Ciencia, vida y espacio en Iberoamérica: trabajos del programa movilizador del C.S.I.C., "Relaciones científicas y culturales entre España y América".* ed. Jose Luis Peset Reig (Madrid: Consejo Superior de Investigaciones Científicas, 1989), 144.

[166]'*porque un ingenio de caballos que trae un horno andando bueno … ha menester cuatro fundidores y cuatro cargadores y dos españoles que se muden por sus cuartos, y por personas que anden con los caballos del ingenio por sus cuartos, y más dos afinadores, y para moler la greta y cendrada otras dos personas, y para hacer los hornos y labrar las piedras otras dos, y para hollar las cendradas cada una que afinan, son menester seis personas, porque al final de dos días a la semana que vendrán a ser dos personas cada día y de noche doce negros, y más para cubrir y sacar dicho carbón*' as quoted in Castillo Martos, Bartolomé de Medina, 112.

highest accessible temperature range to a person with no special training is that of an ordinary camp fire, in the range of 600 to 650° C.[167] Native silver melts at 962° C, silver sulphide at 825 ° C, so this temperature would not be high enough to cause these compounds trapped in a mineral matrix to flow and be recovered as a puddle in the ashes of the fire. However silver chloride, with a melting point as low as 455° C, does soften and liquefy under these conditions.[168] Furthermore, in the presence of charcoal (carbon) lying at the base of the fire it will be reduced to elemental silver at these relatively low temperatures.[169]

The weathering that chemically transformed the more superficial veins of silver sulphide deposits in the New World therefore gifted the early mass of untrained Spanish *mineros* with silver chloride, the easiest of silver compounds to refine by smelting, with virtually no skills required. All they needed was to avoid overheating the silver ores so as to avoid losing silver via volatilization, and even this level of care may have been beyond them. The downside to such an easy operation was that no effort was made to refine the silver to its highest possible level.[170] It is no surprise that as soon as these silver halides were depleted, and more silver sulphide was present in the ore, the gaggle of Spanish dilettante refiners would find less and less silver coming out of their primitive operations, regardless of the true silver content of their ores.

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167 Aitchison, *History of Metals*, 34.

168 Cotton, *Chemistry of Precious Metals* 277.

169 Wallace, Barton, and Wilson, "Silver-Bearing Minerals," 17. Reduction in this thesis, except when it appears within a quotation, refers to the modern chemical term as applied to redox equations, whereby the metal in its ionic state gains electrons from another element that in turn is being oxidized (losing electrons), so that the metal is transformed to its elemental state. When the word appears in historical quotations prior to the nineteenth century it is used in in accordance with the Latin original of the word, *reducere* – "to lead back" to an original state. 'Reduction had the more specific sense ... of the isolation or extraction of a metal from ... an ore'. William Royall Newman, *Atoms and Alchemy : Chymistry and the Experimental Origins of the Scientific Revolution* (Chicago: University of Chicago Press, 2006), xiii.

170 'it is not likely that for a long time anything but very impure silver was shipped' in Wagner, "Early Silver Mining in New Spain," 61.

For all other silver compounds contained in ores the process requires a much greater level of skill, such as was supplied through the German artisans in the New World. Europe by mid fifteenth century had been refining its silver mainly from argentiferous galena, lead sulphide ores.[171] In contrast to most metal ores, silver will not form silver oxide on heating in air, and heating silver ores to high temperatures over 1000° C can simply lead to major physical losses of silver in the smoke of a furnace. It is estimated that at some point prior to 2500 BCE a major breakthrough in smelting occurred, possibly invented by tribal people on the southern shore of the Black Sea: silver could be processed as a by-product of smelting lead from galena.[172] The lead obtained by heating galena absorbs in its melted state any silver present in the ore, either as native silver or silver that has also been reduced at high temperature from any silver compounds present (silver sulphide, silver sulfo-salts, argentojarosite). The process from a chemical point of view is the same whether lead is present in the ore (as in argentiferous galena) or whether lead is added to the 'dry' silver ore.[173] The difference only lies in the economics of production, as analysed in Chapter 5.

Figure 2-1 represents the two main stages involved in the refining of silver from either of these two starting minerals. The diagram is based on the description by Craddock of a two-step refining process, where the first step is a smelting process under high temperatures and reducing conditions that creates a silver rich lead. In Spanish historical texts this is called *fundición*. The second step is sometimes called the cupellation stage, or *afinación* in Spanish texts. The silver-enriched lead, *plomo rico* in Spanish, is heated in a cupel to around 1,000° C

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[171] Craddock, *Early Metal Production*, 211.
[172] Galena is one of the easier ores to smelt, since at temperatures as low as 800° C lead oxide (litharge) is formed from the lead sulphide at the upper, more oxidizing zone, while the reduction of the oxide to metallic lead (which melts at 327° C) takes place in the presence of unburnt charcoal or carbon monoxide. In addition a further quantity of lead is produced by the reaction between the lead oxide and the lead sulphide. N. H. Gale and Z. A. Stos-Gale, "Cycladic Lead and Silver Metallurgy," *The Annual of the British School at Athens* 76(1981): 178.
[173] It was known by the sixteenth century that to avoid losses via volatilization even native silver or silver chloride benefit from the addition of lead prior to smelting. Agricola, *De re metallica*, 400.

under oxidizing conditions, achieved by blowing air (oxygen) onto the surface of the molten lead so that litharge (lead oxide) is formed as a surface scum that entrains with it the oxides of the majority of other metals present except gold.[174] The litharge (*greta* in Spanish texts) is skimmed off to be recycled. The litharge is also absorbed by the material of the cupel (porous crushed bone in many cases) which is then also recycled (*cendrada* in Spanish texts). Recycling did not require reducing lead from litharge, and had the added advantage of recovering any silver entrained in the litharge.[175]

Simply heating efficiently and uniformly to the right temperature (in itself a major technological breakthrough) is not enough: in the first step it must be done under conditions that reduce the silver compounds (chlorides, sulphides or more complex sulphosalts) to metallic silver, to assure maximum recovery of the silver content of the ore. Silver has to be absorbed by the lead and not lost in the slag or volatilized if the temperature is too high. The second step requires quite the opposite, a careful oxidation of the surface of the molten lead avoiding spatter or other physical loss of silver into the litharge that is being continually scraped off, within a furnace that has to be kept at or over one thousand degrees centigrade.[176] As a historian of silver refining in the New World and mining engineer has written, after describing smelting of silver ores:

'litharge fluxed everything ... smelting furnaces fell apart in a week ... refining furnaces ... lasted a little longer ...This [his description of the process] is so oversimplified that it may appear anyone could do it. If so, blame this narration, because it is a very complicated and difficult process which taxed the skill of experienced furnacemen'.[177]

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[174] Craddock, *Early Metal Production*, 210-223.; Gale and Stos-Gale, "Cycladic Lead and Silver Metallurgy," 180. To observe the other possible inputs to the two stages of smelting see F. Ströbele et al., "Mineralogical and Geochemical Characterization of High-medieval Lead–Silver Smelting Slags from Wiesloch near Heidelberg (Germany)—An Approach to Process Reconstruction," *Archaeological and Anthropological Sciences* 2, no. 3 (2010): 212.

[175] Biringuccio, *The Pirotechnia*, 172.

[176] Ibid., 163.

[177] Alan Probert, "Bartolome de Medina: the Patio Process and the Sixteenth Century Silver Crisis," *Journal of the West* 8, no. 1 (1969): 96.

Smelting is not 'a relatively simple affair', 'much more simple ... than amalgamation'.[178] On the other hand, smelting can be applied to any silver ore, though the operation becomes more technically demanding according to the nature of the ore. When dry, polymetallic ores are smelted, the two-stage process of Figure 2-1 can become an iterative sequence of multiple stages of smelting, as has been reconstructed for the way jarositic earths containing silver of the Rio Tinto mines in Spain were refined by smelting in Phoenician times, using lead imported from Carthage.[179] The silver sulphide and complex silver sulfo-salts of the silver ores in the New World represent the intermediate spectrum of smelting complexity between the beginner's luck of silver chloride and the unique challenge of the jarositic silver compounds of Rio Tinto. Smelting was always the refining workhorse for ores that could not be refined by amalgamation in the New World, such as those containing lead or antimony.[180]

In Europe as of the mid fifteenth century, silver refining techniques had been forced to adapt to a new type of silver source, the argentiferous ores rich in copper.[181] The technical challenge these new ores posed and the impact on silver production once the new refining process had been mastered has been considered a pivotal moment in the history of mining in Europe:

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[178] Brading, *Miners Bourbon Mexico*, 137.; '*el proceso de fundición era mucho más simple ... que el de amalgamación*', Lacueva Muñoz, *La plata del Rey*, 89.

[179] Craddock, *Early Metal Production*, 220.

[180] Antimonial ores were being efficiently smelted together with iron or copper pyrites by 1604. West, *The Parral Mining District*, 30.; 'when smelting ores from hard sulphidic veins, or with antimony, it would have been enough to mix them with lead ores, or *greta*, or *cendrada*' – '*Al tratar de fundir las menas de sulfuros duros, o antimoniosos, hubiera bastado con mezclarlos con menas plomizas, o greta o cendrada*' in Bargalló, *Minería y metalurgia colonial*, 91.; argentiferous lead, copper or zinc ores rebellious to amalgamation required smelting according to Thomas Egleston, *The Metallurgy of Silver, Gold, and Mercury in the United States* (London; New York: J. Wiley & Sons, 1887), 40-41. For detailed technical descriptions of how smelting was carried out up to the nineteenth century see for example Laur, "De la metallurgie de l'argent au Mexique," 240-255.; Bargalló, *Minería y metalurgia colonial*, 92-98, 249-251.; *La química inorgánica y el beneficio de los metales en el México pre-hispánico y colonial* (Mexico: Universidad Nacional Autónoma de México, 1966), 109-110.; West, "Early Silver Mining," 26.

[181] Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 1071.

'An invention of the mid-fifteenth century ... was of even greater importance ... it was discovered that the separation of silver from the argentiferous copper ores, which abounded in Central Europe, could be effectively accomplished with the help of lead ... the rich copper ores had been little exploited before this time because of the difficulty of extracting silver from them ... no other invention had so stimulating an effect … upon the development of the mining and metallurgical industries in Central Europe on the eve of the Reformation'.[182]

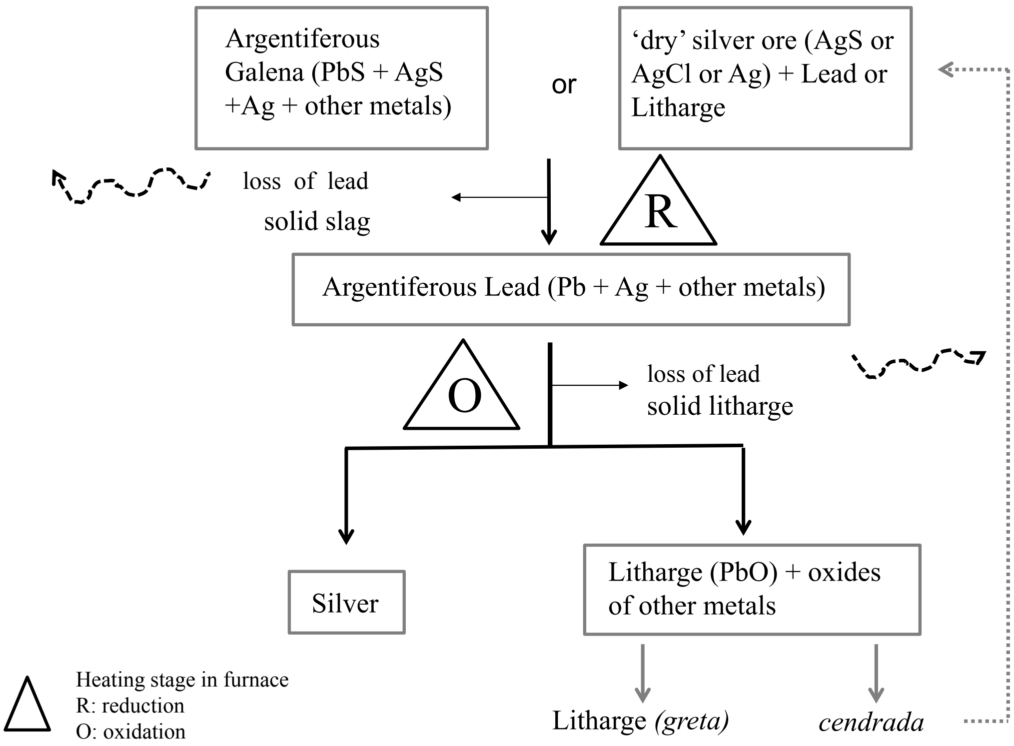

Figure 2-1. Schematic diagram of two stage refining of silver ores using lead, adapted from Craddock, footnote 179.

The new copper liquation process (*Saigerprozess*) also made use of the capacity of liquid lead to absorb silver. Silver was then recovered from the lead by the traditional cupellation method.[183] The increase in percentage terms of silver production in Europe was the same order of magnitude as that which would be experienced in the New World with the

[182] Nef, *Conquest of the Material World*, 36.
[183] Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 973.; Aitchison, *History of Metals*, 385.

introduction of amalgamation.[184] 'More than any other invention, this accounts for the great prosperity of mining and metallurgy during the century which followed'.[185]

Even though this new refining breakthrough was not applied in the New World, I cite it for two reasons. First, to emphasize that mining and refining are human activities that continually respond to new challenges, so that events in the New World are not exceptional in the sense that refining technology was already on a wave of large-scale innovation even before Columbus sailed to his West. Second, because the banking dynasty of the Fuggers, who will become a vital part of the early history of amalgamation in New Spain, owed their wealth in part to this new technology. The Central European mining industry evolved into 'a major industrial complex' thanks to the symbiotic production and sale of copper and silver, a pairing essential for the commercial success of the new technology. It also incorporated into the pricing of silver the costs associated with external sourcing of lead, since the argentiferous copper was in general lead-poor. That it resulted in a very profitable venture can be judged from the success of the Fuggers, who built their fortune on being able to coordinate 'a complex chain of raw materials, technical expertise and parallel marketing of two and even three metals, one noble and two base'.[186]

The level of smelting skill developed in Europe allowed its refiners to extract silver from ores with as low as 0.04% silver content.[187] This technical threshold should not be

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[184] From 1470 to 1490 production of silver with the new process increased over five times to 22,794 kg and in a further 20 years to 34,563 kg, .Bruce T. Moran, *Patronage and Institutions : Science, Technology, and Medicine at the European Court, 1500-1750* (Rochester, NY, USA: Boydell Press, 1991), 11.

[185] Nef, "Silver in Europe," 576.

[186] Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 974.; Aitchison, *History of Metals*, 317.

[187] Approximately 12 oz of silver per short ton of ore, Agricola, *De re metallica*, 388. A threshold of 0.02% for smelting as practised in Saxony in the late eighteenth century is mentioned in Francisco Javier de Sarria, *Ensayo de metalurgia* (Mexico: D. Felipe de Zuniga y Ontiveros, 1784), 105. In Poland argentiferous lead ores containing just 0.02% were smelted, according to D. Molenda, "Silver Production in Poland, XVIth to XVIIIth Century " in *Hombres, Técnica, Plata. Minería y sociedad en Europa y América, Siglos XVI-XIX* ed. Julio Sánchez Gómez and Guillermo Mira Delli-Zotti (Sevilla: Aconcagua Libros, 2000), 23. A minimum value of 0.03% is given in in Phillips, *Metallurgy Silver*, 433.

confused with the profit threshold determined by the balance between production costs and total revenues obtained from refined silver and all other major metals present in the ore (gold, lead or copper).

2.4 The infrastructure of smelting in New Spain

Though smelting was carried out in many locations and different periods within New Spain, the region around the town of San Luis Potosí became a major producer of silver during the seventeenth century on the strength of its smelting of silver ores. The silver deposits in the vicinity of San Luis Potosí began to be exploited by the Spanish conquerors of the northern Chichimeca territory by the end of the sixteenth century (1592). The most prominent were the deposits of the Cerro San Pedro, but due to the lack of sufficient water at the site some of the smelting *haciendas* were built in Monte Caldera, some 7 km from the mines and 25 km from the town of San Luis Potosí.[188] Others were located in the town itself. The presence of lead in most of the ores found in the vicinity of the town of San Luis Potosí made smelting the only viable refining process right from the start.[189] In the absence of technical documents written by refiners of this region, it is the historical legal documents of San Luis Potosí that provide an indirect guide to the way smelting was practised by its major exponent in New Spain.[190] The

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[188] For the location of the main sites around San Luis Potosí mentioned in this chapter see Figure 2-14.
[189] Even by 1744, by which time the use of mercury in some haciendas of the region has been documented, a committee of miners including the local mayor (*Alcalde Mayor*) set up to test a new amalgamation recipe at the request of the Crown made the observation that 'what is generally processed are ores by fire [smelting], and at this time none by mercury … the ores for mercury are of low silver content, with no stability [of supply] … but to demonstrate their obedience to the Crown they will set up the test' - *'que lo que generalmente se benefician en este mineral, son metales de fuego, y en estos tiempos ninguno de azogue … los de azogue, de cortissimas leyes, de ninguna estabilidad, … pero para mostrar su obediencia a la Corona montaran el ensayo'* AHSLP, Fondo Alcaldía Mayor 1744.1, expediente 35, dated 13 December 1744. Not all the ore was rich in lead, at least by 1622, when there are references both to *metal plomosso* (lead ores) and to *metal seco* or *sequillo* (dry or dryish ores) in AHSLP, Fondo Alcaldía Mayor 1622.6 expediente 15, receipts for ores dated 1622 and 1623.
[190] The Spanish refiners did not find in New Spain the same advanced level of metallurgy their counterparts would find in the Andes, where the indigenous craftsmen had been smelting silver ores in *huayras*, small tube furnaces riddled with holes so that the blast was provided by the force of the wind on hillsides, well before the arrival of the Spaniards. For studies on pre-hispanic smelting practice in the Andean region see Colleen M Zori and Peter Tropper, "Late Pre-Hispanic and Early Colonial Silver Production in the Quebrada de Tarapaca, Northern Chile.," *Boletín del Museo Chileno de Arte Precolombino* 15(2010): 68,82,85.; Pablo Jose Cruz and Jean-Joinville Vacher,

operational stages of the smelting process have been described at length in the historiography.[191] I will only focus on those areas where some further light can be shed:

a) The introduction of *molinos*: a common sight at present around San Luis Potosí are the large circular stones from the *molinos* (called Chilean mills in the English literature), Figure 2-2, used to crush the raw ore placed in the path of the stone within the circular trough.[192] In this example the stone was powered by a mule tethered to the arm leading to the axle of the wheel.[193] Smelting does not require the flour-like consistency demanded by amalgamation (see next chapter), so breaking down the ore by hand was a viable option, especially so for small refining *haciendas* set up during the early years of refining.[194] It is not clear when and to what

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eds., *Mina y metalurgia en los Andes del sur: desde la época prehispánica hasta el siglo XVII* (La Paz: Institut de Recherche pour le Development / Instituto Francés de Estudios Andinos, 2008).; Warwick Bray, "Ancient American Metal-Smiths," *Proceedings of the Royal Anthropological Institute of Great Britain and Ireland*, no. 1971 (1971): 29-32.; Heather Lechtman, "A Metallurgical Site Survey in the Peruvian Andes," *Journal of Field Archaeology* 3, no. 1 (1976): 36-38.; Heather Lechtman et al., "Procesamiento de metales durante el Horizonte Medio en el Altiplano Surandino (Escaramayu, Pulacayo, Potosi, Bolivia)." *Boletín del Museo Chileno de Arte Precolombino* 15 (2010): 9-27. For a questioning whether cupellation was practised before the arrival of the Spaniards see Mary Van Buren and Claire R Cohen, "Technological Changes in Silver Production after the Spanich Conquest in Porco, Bolivia.," ibid.15: 33.

191 For sixteenth century practices in Spain and the New World, Barba, *Arte de los metales*, 130-170.; González, *Noticia histórica minas de Guadalcanal*, II 410-411.; Carlos Sempat Assadourian, *Zacatecas, conquista y transformacion de la frontera en el siglo XVI : minas de plata, guerra y evangelización* (México, D.F.: Colegio de México, Centro de Estudios Históricos, 2008), 151-152. For later smelting practices see Francisco de Paula Hermosa, *Manual de Laboreo de Minas* (Besanzon: Libreria de Rosa Bouret y Cia, 1857), 250-260. In English the nineteenth century texts are the most useful, for example Phillips, *Metallurgy Silver*, 497.; Henry F. Collins, *The Metallurgy of Lead & Silver* (London: Griffin & Co., 1899), 273-352.

192 Manuel Amador, *Tratado práctico y completo de trabajos de minas y haciendas de beneficio* (México: E. Sánchez, Editor, 1901), 66-68, Lamina 5a Figura 1.

193 For a general description see Egleston, *The Metallurgy of Silver*, 269-270.

194 The final size should range between a grain of rice and that of a '*Grueso de garvanzo'*, the thickness of a chick pea, and the more docile the ore, the bigger the particle, according to Garcés y Eguía, *Nueva teórica del beneficio de plata*, 63-64. The bean size had already been pointed out in Biringuccio, *The Pirotechnia*, 153.

a)

b)

c)

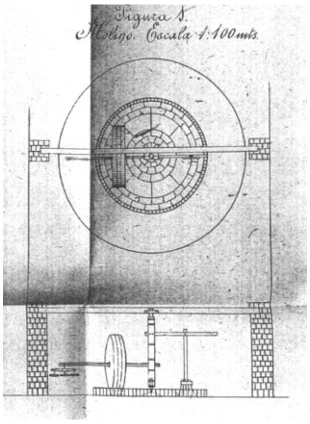

Figure 2-2. a) *Molino* mill stones, Monte Caldera, San Luis Potosí. The diameter can reach 2 m b) a modern reconstruction of a *molino* in Zacatecas, at the exit of the El Edén mine c) drawing of a *molino,* reproduced from footnote 192.

extent these *molinos* were used in the seventeenth century smelting *haciendas* of San Luis Potosí. The legal documents of the period are ambiguous, since they mention a wheel (*rueda*), but in such a way that it could also apply to the assembly required by a bellows and not only the *rueda* of a *molino*.[195] According to West, Chilean mills were not introduced in New Spain

[195] 'wheel, pinion, shafts, cross-beam and bellows' - '*la rueda y lanternilla peon exe y gualdra y fuelles*', as in the sales contract between Nicolas de Peralta and Cristobal Zapata, AHSLP, Fondo Alcaldía Mayor 1667.3, expediente 6, 18 July 1667. I have used the English translation for the Spanish terms as reported in Appendix I of Peter J. Bakewell, *Silver Mining and Society in Colonial Mexico: Zacatecas, 1546-1700* (Cambridge, U.K.: University Press, 1971), 267. A guide in Spanish appears in de Gamboa, *Comentarios Ordenanzas de Minas*, 399-401. Another example is the listing of '*gualdra, lanternilla, peon y rueda y tablon y canones*' which includes the *cañones* or nozzles of the bellows, in the sale contract dawn up by Juan Dominguez de Sequera, AHSLP, Fondo Alcaldía Mayor 1653.1, expediente 8, 14 March 1653. The drive wheel is a fundamental element that transforms the horizontal circular motion imparted by mule or water power via a crankshaft into the reciprocating movement that drives the bellows for the furnace.

until the nineteenth century.[196] For the largest of the smelting establishments Salazar Gonzalez identifies a *mortero* (stamp mill) by 1628, and a stamp-head for a *mortero* by 1703 as part of their infrastructure.[197]

b) The role of dressing ores: the importance given to the requirement of water for the smelting *haciendas* at first sight is surprising, since water seems a more critical issue for amalgamation than for smelting:

"Antonio de Espinoza … townsman and miner of the mines of San Luis Potosi states that as is notorious and public [knowledge] the ores that are extracted from this hill [Cerro San Pedro] cannot be processed or smelted without washing. And due to the great lack of water that has been and still is … some *haciendas* have ceased to process [these ores].'[198]

The need to have water for the workers and animals is evident.[199] What is interesting is the use of water for the washing of the ores. This meant that silver ores in San Luis Potosí were dressed, concentrated for silver and lead content prior to smelting based on a differential sedimentation rate in water depending on the density of the mineral particles, in the process explained by Agricola as of the sixteenth century.[200] According to Barba, washing ores prior to smelting was not normal practice in the New World.[201] The dressing of ores that was an important part of the initial strategy of the English investors of the nineteenth century in Pachuca was in fact never implemented (Chapter 4). It is important therefore that the

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[196] West, *The Parral Mining District*, 113. In Chapter 3 I cite evidence that places them in Zacatecas earlier.
[197] Guadalupe Salazar González, *Las haciendas en el siglo XVII en la región minera de San Luis Potosí: Su espacio, forma, función, material, significado y la estructuración regional San Luis Potosí* (Universidad Autonoma de San Luis de Potosí, 2000), 84, 90.
[198] '*Antonio de Espinoza ... vezino y minero de las minas de San Luis de Potosi digo que como es notorio y publico los metales que deste serro se sacan no se pueden beneficiar ni fundir sin labar. Y por la gran falta que a avido y ay de agua ... a sesado el beneficio en algunas haciendas*' AHSLP, Fondo Alcaldía Mayor 1635.1, expediente 6, 16 January 1635.
[199] Where water power was deficient, animal power was required to drive mills and bellows, as well as to haul ore from the mines to the haciendas. As late as 1778 a new invention was being touted in San Luis Potosí that would not require 'abundant water for the beasts' – '*ni abundancia de Agua para Bestias'*. Claim by Don Juan Martin de Irrazu, AHSLP, Fondo Alcaldía Mayor 1778.2, 30 October 1778.
[200] Agricola, *De re metallica*, 300-310.
[201] 'at great length Agricola teaches how to wash ores prior to smelting; it is not much used in these Kingdoms'- '*muy dilatadamente ensena el Agricola a lavar los metales antes de fundirlos; poco se usa en estos Reynos*' in Barba, *Arte de los metales*, 148.

documents show that for San Luis Potosí dressing was part of the common practice in smelting *haciendas*. *Lavadores*, workers who carried out the washing of ores, are mentioned amongst the labour force of a smelting refining *hacienda* in this area as late as 1773.[202]

c) The chimneys of the smelting furnaces: smelting was carried out in an *horno castellano*.[203] Barba defines them as simply the same type of furnace as currently in use in most of his known world to smelt all sorts of ores, as described by Agricola.[204] They were initially very simple structures built from stone and lime mortar ('*piedra y cal*') in the form of a square pillar up to 2 metres tall and with an internal square cross section of under one square metre, or built in the shape of an inverted sectioned cone.[205] It was an inexpensive construction made from local materials that could be easily rebuilt as required by the wear and tear of smelting. An inventory of a rented smelting *hacienda* in Zacatecas, dated 1608, describes well the precarious nature of the early structures: 'two chimneys of stone and lime one good and the other with openings in three or four places … four furnaces of stone and lime with chimneys made from adobe, all open in many places and propped up'.[206] Their presence in the ruins of these *haciendas* is inferred by the more evident remains of a tuyere, an *alcribis* in Spanish texts,

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[202] Weekly accounts of the Hacienda de Nuestra Señora de los Dolores, signed by Lorenzo de Mata for the year 1773, AHSLP, Fondo Alcaldía Mayor 1773.2.

[203] This is translated to English as a castillian furnace, though the term 'Spanish furnace' might be more appropriate.

[204] '*Llaman en este Reyno Hornos Castellanos a los que en las otras tres primeras partes del mundo, han sido usados, y comunes para la fundición de toda suerte de metales. De ellos solos trata el Agricola para este efecto'*. Barba, Arte de los metales, 139.

[205] 'erect these furnaces plumb to the ground, in the shape of a square pillar somewhat taller than wider at the cavity. Their height is one *vara* [approx.. 80 cm], some nearly two and some less … at the back they have a small aperture … the [*alcribis*] where the nozzles of the bellows are placed … others make these furnaces round, wider at the top than at the bottom' … '*Levantase estos hornos a perpendículo, en forma de un pilar cuadrado algo mas largos, que anchos por lo hueco. Tienen de alto algunas una vara, otros casi dos, y otros menos … por la parte de atrás en una ventanilla … el alchrebiz en que han de estar los cañones del fuelle … otros hacen estos hornos redondos, mas anchos de arriba que de abaxo*' ibid.

[206] '*dos chimeneas de piedra y cal la una buena y la otra abierta por tres o quatro partes … quatro hornos de piedra y cal con las chimeneas de adobe todas abiertas por muchas partes y apuntaladas*' in the inventory drawn up by Pedro de Medina and Andres Pereira for an hacienda 'de refinar y afinar' (to smelt and refine) rented from Doña Margarita de Cobarrubia in Fresnillo, 20 March 1608, AHEZ, Notaria-Colonia, Numero 01 (Pedro Venegas pendiente), expediente 1, 4r.

the element of the furnace wall fitted with an orifice that allowed the bellows to pump air through a nozzle (*cañon*) into these furnaces.[207]

Low chimney heights would leave the workers and immediate surroundings exposed to the lead fumes issued from the furnace.[208] The surviving pyramidal chimney that characterizes the ruins of the smelting *haciendas* around San Luis Potosí (Figure 2-3) is not the original from the early period but acquired its present shape and height following the mining laws of the eighteenth century.[209] By the nineteenth century 'ordinarily two of these furnaces are placed one beside the other, under the same pyramidal chimney without a roof on its top'.[210] The only example I found of two standing chimneys (Figure 2-4) was in the ruins of the *Hacienda* de Aranzazu situated in Guadalcazar, a historical mining and refining district some 100 km north-east from the town of San Luis Potosí.[211] The ruins of this *hacienda* have not yet been analysed or reconstructed from an architectural standpoint. The castillian furnaces

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[207] This would have been the most critical part of the furnace, judging from the manner in which the weight of the *alcribis* is singled out in the rental agreement between Fraga Gorbaran and Rodrigo de Aldana, in which it is stated that the new *alcribis* that weighs 37 lbs must be returned at the end of the rental period. AHSLP, Fondo Alcaldía Mayor,1631.3, expediente 38, 27 December 1631. In a similar vein the cost of three sets of bellows (at 70 pesos each) and the set of an alcribis said to weigh 48 lbs and a nozzle of 13 lbs costing together 60 pesos are among the few fixed costs listed by Juan Lopez de la Madriz in his book of accounts, AHSLP, Fondo Alcaldía Mayor 1650.3, expediente 8. The importance given to the weight of the *alcribis* in both documents is noteworthy.

[208] The chimneys of these early furnaces were sometimes raised in height not because of the fumes but to capture any silver entrained in the flue gas. Barba, *Arte de los metales*, 167. Barba's dimensions and the height of the extant pyramidal chimneys measured in Monte Caldera and Guadalcazar are significantly lower than Bakewell's account of a mining edict implemented by Vice-Roy Toledo in 1574 in Peru whereby lead smelting had to be carried out an enclosed building with chimneys some 7 meters tall (4 estados). Bakewell, *Miners of the Red Mountain*, 150.

[209] Prof. Gonzalez Salazar, private communication. Hermosa describes a 'German furnace' in the nineteenth century with a height of 6 *varas*, under 5 m, which is more in line with extant chimney heights. Hermosa, *Manual de Laboreo de Minas*, 254-255.

[210] '*ordinairement deux de ces fourneaux sont places a cote l'un de l'autre , sous une même pyramide sans toiture dans le haut*' in Duport, *Métaux précieux au Mexique*, 70. There is an illustration of the side by side arrangement of furnaces under a common chimney in the paper on silver smelting by Václav Vaněk and Dalibor Velebil, "Staré hutnictví stříbra," in *Stříbrná Jihlava 2007. Studie k dějinám hornictví a důlních prací* (Jihlava: Archaia Brno / Muzeum Vysočiny Jihlava, 2007). The illustration can be accessed via http://www.velebil.net/clanky/hutnictvi-stribra/stribrna-hut-4.

[211] I visited Guadalcazar at the urging from the Director of the Archivo Histórico San Luis Potosí, Dr. Rafael Morales Bocardo. In Guadalcazar I was led to the ruins of the Hacienda de Aranzazu by Doña Maria Esther, who is also in charge of the colonial museum of the church. For further general information on the area see Alejandro Galvan Arellano, *Arquitectura y urbanismo de la ciudad de San Luis Potosí en el siglo XVII* (San Luis Potosí: Editorial Universitaria Potosina, 1999), 70.

described in eighteenth and nineteenth-century texts correspond to more elaborate affairs than Barba's '*horno Castellano*'.[212] By the nineteenth century, blast furnaces were installed in Mexican smelting *haciendas*, with the blast of air driven either by water or steam engines. These furnaces required top-loading of the smelting charge, via an opening to the furnace situated at an upper floor to the level of the furnace hearth, as indicated in Figure 2-5.[213]

Figure 2-3. Exterior of smelting furnace at the ruins of the *Hacienda* Santa María in Monte Caldera. The arched port would have been used to feed ore or fuel to the furnace.

[212] For example, in de Sarria, *Ensayo de metalurgia*, 109-110.; Garcés y Eguía, *Nueva teórica del beneficio de plata*, 67-68.; Duport, *Métaux précieux au Mexique*, 69.; Pique, *A Practical Treatise on Silver*, 67-69.; Phillips, *Metallurgy Silver*, 477.
[213] Robert H. Lamborn, *The Metallurgy of Silver and Lead : A Description of the Ores; their Assay and Treatment, and Valuable Constituents* (London: C. Lockwood, 1878), 125.

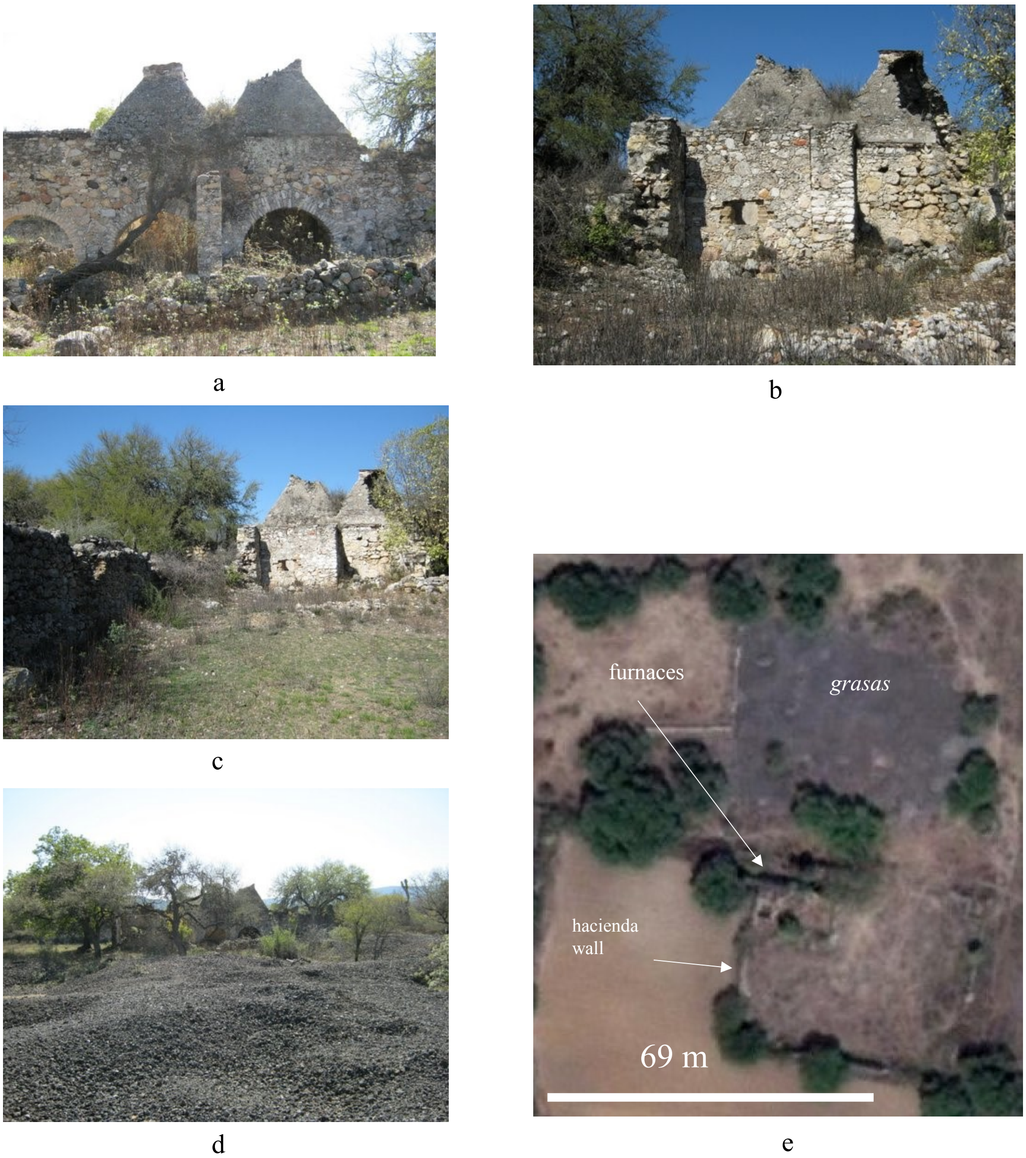

Figure 2-4. Ruins of the *Hacienda* de Aranzazu in Guadalcazar. a) front view showing archways under two smelting furnace chimneys, height around 7 m b) back view of chimneys, showing possible aperture for drive shaft of bellows c) section of *hacienda* wall d) fields of *grasas* e) image from Google Earth © 2014 DigitalGlobe, 22°37'21" N 100°24'9" W.

Photographs of these furnaces as installed at the *Hacienda* de Regla, near Pachuca, are provided in Chapter 4.

Because a smelting furnace required a set of adjacent bellows, its architectural footprint required an additional area contiguous to the furnace to fit both the bellows, the mules turning round in a circle, or a waterwheel fed by hydraulic power. Thus for example: 'there are two joined mules that move the wheel of said *ingenio* [machinery] that makes the blast provided by

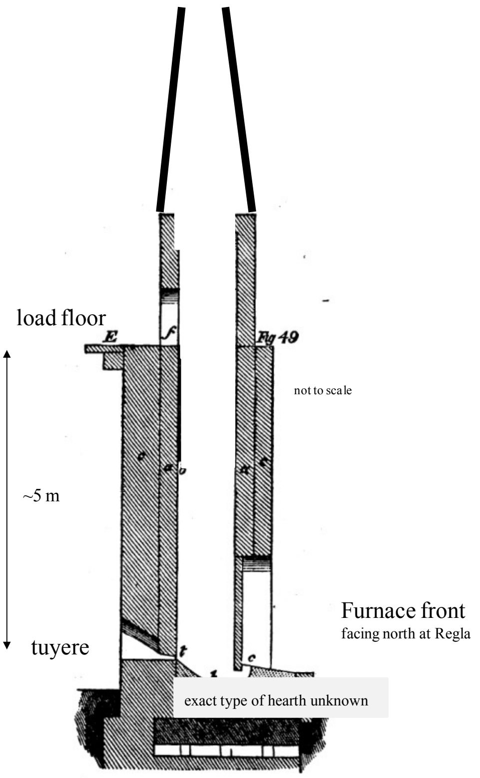

Figure 2-5. Section of a blast furnace as found at Regla. Adapted from footnote 213.

a set of bellows that are placed on the side of one of two furnaces that are found in this *hacienda*'.[214] In the nineteenth century the description had hardly changed : 'the blast of air is given by two bellows … one mule for each furnace'.[215] The space required by this additional area shared by up to a pair of furnaces, where the effective power to drive the bellows was generated, is not always possible to identify in the reconstruction of smelting *haciendas*.

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[214] '*estan dos bestias mulares uncidas que mueven la rueda de dicho ingenio y hacen dar soplo a una parada de fuelles que están puestos hacia la parte de un horno de dos que hay en esta hacienda*' from the report of 1593 written by Juan Lopez de Riego on the smelting hacienda of Captain Miguel Caldera, as cited in Galvan Arellano, Arquitectura de San Luis Potosí, 60-61.

[215] '*le vent est donne par deux soufflets ... une mule pour chaque fourneau*' in Duport, *Métaux précieux au Mexique*, 70.

Cupellation of the silver-enriched lead bars (*barras* in Spanish texts, or 'pigs' in the English literature) usually took place in a separate reverberatory oven, where heating is by indirect reflection from a curved roof and the ore is not in direct contact with the carbon fuel.[216] The whole set, furnace and prepared bed, is named a *vazo, baso* or *vaso* (literally a vessel, a tumbler) in the legal documents of San Luis Potosí and Zacatecas.[217] A single *vaso* could serve to refine the enriched lead bars from up to four smelting furnaces.[218]

Because of the attrition of the processes on these structures it is not usual to find whole *vasos* from the first two centuries of refining activity. In the ruins of *Hacienda* Number 2 (HMC 2) in Monte Caldera are two caved-in depressions in the shape of bowls connected via a tubular structure (Figure 2-6). A complete archeological study would be required to establish if these are the remains of a *vaso* from the original smelting *hacienda*.

d) The fields of *grasas*: the smelting furnaces produced a solid waste that was dumped close to the refining *hacienda*. Historically, smelting refineries have had no compunction about soiling their own nests, and major slag heaps still abound around the husks of smelting *haciendas* in San Luis Potosí, giving the landscape the desolate look and crunchy step of an old lava field (Figure 2-7).[219]

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[216] The low domed roof of these ovens reflects the heat from the wood fire onto a separate chamber where the material to be heated is placed. For details of early sixteenth century reverberatory ovens used in the New World see Barba, *Arte de los metales*, 136-38.; for later periods there are more sources, for example Phillips, *Metallurgy Silver*, 449.

[217] By the nineteenth century they are still called *vasos*: '*le vaso ou fourneau du coupelle*', the biggest with of 1.2 and 1.4 m, and a depth of 15 cm; these ovens do not have an enclosed vent to the roof. Duport, *Métaux précieux au Mexique*, 70-72.

[218] The concentration of silver in the lead bars refined in the *vaso* is said to be between 8 and 10%. Pique, *A Practical Treatise on Silver*, 59.; Phillips, *Metallurgy Silver*, 488. This explains why these enriched bars were stolen from haciendas, as in the claim by Rodrigo de Noriega against Juan Rodríguez for allowing two indigenous workers to refine three stolen bars of lead using his set of bellows. AHSLP, Fondo Alcaldía Mayor 1650.3, expediente 1, 13 June 1650.

[219] The heaps of slag at Laurion in Greece were of the order of several million tons, of which 1.5 million inland and the same dumped into the sea. Hans-Gert Bachmann, "Archäometallurgische Untersuchungen zur antiken Silbergewinnung in Laurion. II. Charakterisierung von Bleiverhüttungsschlacken aus Laurion=

a

b

c

d

Figure 2-6. a) Ruins of smelting *hacienda* HMC2, with chimney b) *alquibris* (tuyere) c) one of two bowl-shaped depressions with caved-in roof, connected via the tubular section observed in d).

The lead-rich slag from smelters are termed *grasas* (literally 'greases') in Spanish texts of the period.[220] Other solid waste products are called *granzas* and *mazamorras* (discarded broken-down ore with very low silver content) or *lamas* (fine waste from washing the ores during

Archaeometallurgical Investigation on Ancient Silver Smelting at Laurion. II. Characterisation of Lead Smelting Slags from Laurion," *Erzmetall* 35, no. 5 (1982): 246.

[220] I have not found an etymology for this use of the word '*grasas*'. A clue may lie in the description by Barba of molten slag from lead ores: 'when the slag is well melted, and liquid like oil'-'*quando la escoria esta muy derretida, y liquida como azeyte*'. The visual similarity to oil from grease may have led to the word '*grasas*'. Barba, *Arte de los metales*, 152.

dressing).[221] None of these solid wastes were considered truly final and worthless products, and the sale contracts for smelting *haciendas* carried a stock phrase along the lines of explicitly including '*grasas granzas lamas mazamorras y desechaderos*' among the tangible assets of the *hacienda* being sold.[222]. Furthermore, idle land that was suspected of containing waste from previous refining activity was sought after and dug up to recover these potential sources of recoverable traces of silver and lead.[223]

a)

b)

Figure 2-7. Mounds of *grasas* in Monte Caldera a) *Hacienda* Santa Maria, chimney of Figure 2-3 in the background b) *Hacienda* HMC2.

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[221] Ricardo N. Alonso, *Diccionario Minero. Glosario de voces utilizadas por los mineros de Iberoamérica* (Madrid: Consejo Superior de Investigaciones Científicas, 1995).
[222] Contract for sale of smelting hacienda by Juan Dominguez de Sequera to Cristobal del Castillo in Monte Caldera, AHSLP, Fondo Alcaldía Mayor 1653.1, expediente 8, 14 March 1653; by Nicolas de Peralta Pimentel to Cristobal Zapata, AHSLP, Fondo Alcaldía Mayor 1667.3, expediente 6, 18 July 1667; by Pedro de la Perna to Captain Juan Manuel Rendon, AHSLP, Fondo Alcaldía Mayor, 1696.3, 6 November 1696.
[223] Request by Juan Lopez de Meza to dig up a site previously occupied by a smelting hacienda near the Convent of San Agustin in San Luis Potosí in order to process its content of *grasas* and other solid waste. AHSLP, Fondo Alcaldía Mayor 1672.1, 10 February 1672.

2.5 The architecture of smelting in New Spain

The region around the town of San Luis Potosí epitomizes the use of smelting to refine silver ores in New Spain, so its *haciendas* are a prime example of the physical structure of this genre. In the historical legal documents, these *haciendas* are not characterized by their nameplate production capacity, expressed as their capacity to handle a certain throughput of ore per month or year. Rather they are described by the number of smelting furnaces (*ornos* or *hornos*) and cupelling furnaces (*vasos*) they possessed, which would indicate that furnace size was uniform and their capacity so well known it did not merit a special mention in the legal documents pertaining to the sale or rent of these *haciendas*. A non-exhaustive survey of textual sources points to a range of smelting furnaces per *hacienda* between one and sixteen, while the number of cupelling furnaces is in general just the one, very rarely two.[224] The only textual clue as to the capacity of these smelting furnaces is found in a document dated 1620 which states that a total of 22 smelting *haciendas* produced in a year 150,000 marks of silver from 100 furnaces.[225] If the size of these furnaces is as standard as I have assumed, on average one smelting furnace could produce at least 1,500 marks of silver (345 kg) per year. The data can also be interpreted to mean that an average smelting *hacienda* had between 4 to 5 furnaces, and produced in that period approximately 1.5 tons of silver per year.

There is an account book of smelting operations in the Valle de Pozos (see Figure 2-14 below) that gives credence to this average. It dates from a later period, 1660 to 1661, and was

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[224] Sale by Juan Dominguez de Sequera to Cristobal del Castillo of an hacienda in Monte Caldera with one smelting furnace, AHSLP, Fondo Alcaldía Mayor 1653.1, expediente 8, 14 March 1653; sale by Nicolas Peralta de Pimentel to Cristobal Zapata of an hacienda within the town of San Luis Potosí with two smelting furnaces, AHSLP, Fondo Alcaldía Mayor 1667.3, expediente 6, 18 July 1667; rental by Mathias Pardo to Sanchez and Rodriguez of an hacienda with four smelting furnaces in the valley of Pozos, AHSLP, Fondo Alcaldía Mayor 1629.3, expediente 24, 31 March 1629; the Hacienda de Briones in Monte Caldera is reported as having eight smelting furnaces in 1628, and up to sixteen furnaces have been reported according to Salazar González, *Las haciendas de San Luis Potosí*, 90, 97.

[225] Ibid., 24, 80.

presented as evidence for the state of business dealings ('*trato*') between Juan Lopez de la Madriz and the deceased Miguel de Santibañez. As such it is not an account book based on operational data, but a set of prepared accounts of expenditures and revenues from sales of silver and gold produced between May 1660 and December 1661 that are presented in defence of its author, de la Madriz. The entries cannot be used to establish an operational cost of production, since they deal mainly with payments made to individuals over this time period. The account book however includes a series of entries at the end that detail the amount of silver and gold produced. The pages are still stitched together within their original leather bindings, and the folio numbers are consecutive, but there is no guarantee that it reproduces all the production data for the period covered. The aggregate amount of silver reported from May to November 1660 was approximately 500 kg, which prorated to the whole year corresponds to approximately 860 kg, ignoring production fluctuations according to the season. A similar aggregate amount (approximately 880 kg) is reported for the whole year of 1661. If these records correspond to the production of a single *hacienda*, a fact that cannot be established from the documents, then in both years the maximum monthly production was approximately 150 kg of silver, within the range (20% above) of the yearly average of 1.5 tons calculated for 1620. The other finding of note to come out of this account book is the role played by the revenues from gold refined from these silver ores. In 1660 and 1661 gold contributed around 25 to 30% of the total revenues reported by its author, Lopez de la Madriz.[226] Thus the presence of gold would have played a major role in meeting the production costs of smelting.

The whole state of San Luis Potosí has at present 36 ruins of refining *haciendas* that correspond to the sixteenth and seventeenth centuries, all either in an advanced state of decay

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[226] AHSLP, Fondo Alcaldía Mayor 1650.3, expediente 8, selected accounts of the years 1660 and 1661. For the detailed calculation see Appendix A.

or with substantial changes to their original architecture. Galvan Arellano commenced and Salazar Gonzalez has continued in greater detail and scope the architectural study and reconstruction of some of these *haciendas*.[227] Without a detailed knowledge of the spatial size and distribution of the production elements within a smelting *hacienda* it is impossible to determine the spread of the environmental impact around each smelting location. An estimate of the architectural footprint, and of the area outside the boundaries of the *hacienda* proper that can be deemed industrial and thus off-limits to agricultural activities or to dwellings is also required. Finally, the local wind patterns and proximity to waterways that can extend the geographical area impacted by the production process also has to be established for each refining unit. This is a very detailed agenda for every refining district and in this section I will only carry out an approximate exercise for a few examples in the area of Monte Caldera.

The area occupied by a smelting *hacienda* is an important factor, since a large area would tend to contain within its boundaries a larger share of the wind-borne lead from low furnace chimneys, thus attenuating its impact on neighbouring habitations. A document from 1772 details the sale of a smelting *hacienda* in Monte Caldera between Cristobal Pardo and Juan Nieto for 640 *pesos*, with a dimension of '*140 varas de oriente a poniente, 85 varas de norte a sur'*, approximately 110 m east to west by 70 m north to south, for an area of 7,700 m2. It included a small reservoir ('*tanquesito*') to collect water in the rainy season.[228] An idea of the balance between functional areas and waste areas can be gained from modern satellite images. Figure 2-8 shows satellite images of the area around the village of Monte Caldera, and the location of ruins of smelting *haciendas*. The approximate area for the Hacienda HMC1 is

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[227] Galvan Arellano, *Arquitectura de San Luis Potosí*, 211-13, 271-72.; Salazar González, *Las haciendas de San Luis Potosí*, 83-119, 428-34. Due to the generous arrangements provided by Prof. Salazar I was able to visit four of the eight haciendas that according to Galvan existed in Monte Caldera. Galvan Arellano, *Arquitectura de San Luis Potosí*, 56.

[228] AHSLP, Fondo Alcaldía Mayor 1772.2 expediente 18, 7 November 1772.

3,000 $m^{2,}$ of which approximately 2,000 m^2 are taken up by the waste *grasas*. In the case of the *Hacienda* Santa María, approximately 3,500 m2 correspond to operational areas including the water reservoir, and approximately the same area for the *grasas.* In each of these satellite images the area occupied by the waste *grasas* either matches or surpasses the extant footprint of the historical *hacienda*, thus doubling the size of the industrial plot required overall for silver production.[229] The environmental implications are important, since these wastelands of *grasas* inadvertently helped to isolate the *hacienda* from agricultural or cattle grazing activities and from human dwellings, and by desolating their stretch of land they acted as a sink of further chemical depositions issued from the smelting chimneys.[230]

Some of the smelting *haciendas* of the state of San Luis Potosí were set up within town limits.[231] It would not have been possible for each smelting *hacienda* within the town to have occupied a space or to have spread its mineral waste in the same manner as in the countryside, but I have no information on sizes, areas or how *grasas* were legislated by the town authorities. Mounds of *grasas* from previous or existing smelting *haciendas* inside the city were considered to be sufficiently part of the urban landscape that they merited being included in a map of San Luis Potosí from as late as 1789 (Figure 2-9). When the streets of present day San Luis Potosí are dug up for major road works or to lay pipes, workers come across an underground layer of *grasas*, as if a historic volcano had at one time covered the area in ash.[232]

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[229] Satellite images do not necessarily show the whole extent of the hacienda or the *grasas*, the former due to a blurring of physical perimeter walls with time, the latter due to cover from trees or displacement with time by agricultural land, disposal as gravel to line tracks in the countryside around Monte Caldera, or even by the stream when in flow. Even with these limitations the images are a useful tool to appreciate the relative dimensions of each area.

[230] The large area taken up by *grasas* and other solid wastes is another reason to include them in sale contracts that involved the ownership of land.

[231] For the location of haciendas in the region close to the city see Salazar González, *Las haciendas de San Luis Potosí*, 396.

[232] Personal communication from Dr. Rafael Morales Bocardo.

Figure 2-8. The solid white lines encapsulate the minimum area that can be clearly identified with each smelting *hacienda*, the dotted line the minimum area of the extant dumps of *grasas*. All satellite images from Google Earth © 2014 DigitalGlobe. The *Hacienda* Santa María lies at 22°12’10” N 100°44’27” W, and the *Hacienda* HMC1 at 22°12’31” N 100°44’47”W.

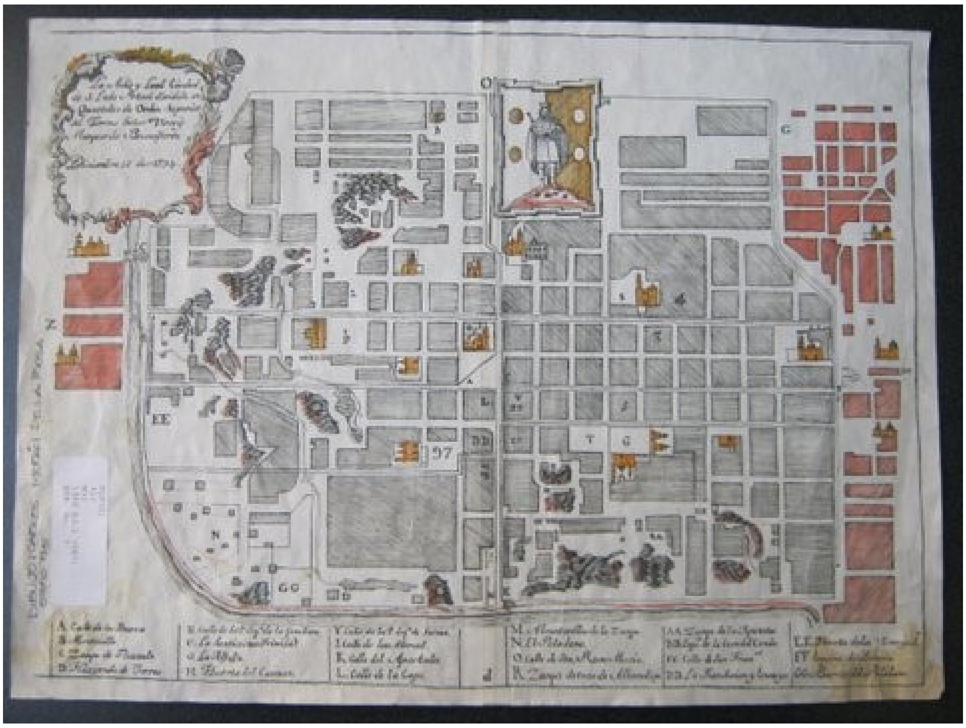

Figure 2-9. Copy (1986) drawn by Carlos Morán de la Rosa of the original map by Captain Manuel Pascal de Burgoa, 1794, showing the division of the city of San Luis Potosí into *barrios* (quarters) by the Viceroy Marques de Branciforte. Digital copy courtesy of AHSLP, Colección Mapas y Planos.

It would be useful if either the historical sale price or the rent of these *haciendas* were a guide to their refining capacity, and thus their size. However the data are not conclusive, since the assets sold or rented do not only comprise furnaces but at times mines, charcoal making facilities (*carboneras)*, slaves, indigenous work squads, livestock and mounds of solids of varying magnitude. The limited evidence for now points to the year of the sale, rather than the number of furnaces or other assets, that determines the market value of the *hacienda*. This would be consistent with a valuation based on expected future cash-flows rather than on the cost of construction. Thus an *hacienda* with four smelting furnaces is to be sold for 20,000 pesos in 1628, while another with just one smelting furnace is sold for 1,700 pesos in 1653, and another *hacienda* with just one furnace is sold for 700 pesos in 1667. The near halving in price per furnace as the century advanced correlates well with a decrease in the silver refining activity in the area.[233] I only have one reference to the actual cost of building a smelter within an *hacienda* in the Valle de Bledos being rented by Juan de Sandoval in 1607. It cost 525 pesos to build, but the cost excluded both wood and certain basic equipment (bellows and other accessories) furnished by Sandoval. The contract calls for construction to be completed within budget in 40 days, which reflects a simple structure. It does not state how many furnaces are covered by the contract.[234]

Some, but not all, rental contracts of smelting *haciendas* also specify the number of furnaces being rented, as well as a wide menu of additional services, such as workers, or access to mines or mounds of *grasas*, which in turn determine a range in rents between 250 and 1,000 pesos per year.[235] In the case of rents the correlation with the year is less evident. The most intriguing contract is for the use of a smelting furnace at 5 pesos per day, and for mines and two indigenous workers 'that belong to me' at 50 pesos/y, since it shows a significant degree of uninhibited entrepreneurship within the private silver refining business in this region.[236]

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[233] Proposed sale of the hacienda of the deceased Juan Perez Basurto by Antonio de Arismendi Gogorron for the proposed sum of twenty thousand pesos, photocopy of original document dated 30 May 1628, folio 52 r, AHSLP, Colección Miguel Iwadare; sale by Juan Dominguez de Sequera to Cristobal del Castillo of an hacienda with one smelting and one refining furnace in Monte Caldera for 1,700 pesos, AHSLP, Fondo Alcaldía Mayor 1653.1, expediente 8, 14 March 1653; sale by Nicolas de Peralta Pimentel to Cristobal Zapata of an hacienda behind the convent of St. Francis in the town of San Luis Potosí with one smelting and one refining furnace for 700 pesos, AHSLP, Fondo Alcaldía Mayor 1667.3, expediente 6, 18 July 1667.

[234] The builder, Juan de Vargas, is asking for the pending amount of 232 '*pesos de oro común*' that have not yet been paid since Sandoval is not satisfied with the work carried out. AHSLP, Fondo Alcaldía Mayor, 1607, expediente 1, 9 October 1604 and 24 April 1608.

[235] Two refining haciendas, furnaces not given, and their mounds of *grasas*, at 500 pesos/y each, between Geronimo de León and Palomo y María de Mendoza. AHSLP, Fondo Alcaldía Mayor 1627.5, expediente 27, 24 December 1627; one hacienda with four smelting furnaces at 500 pesos/y between Mathias Pardo and Sanchez and Rodriguez (document damaged). AHSLP, Fondo Alcaldía Mayor 1629.3, expediente 24, 31 March 1629; one of four furnaces within a smelting hacienda, plus use of refining furnace once a month, and partial use of existing workforce, plus supply from existing mounds of *grasas*, at 1,000 pesos/y between de Fraga and Rodrigo de Aldana Chavez. AHSLP, Fondo Alcaldía Mayor 1631.3, expediente 38, 27 December 1631; one smelting and one refining furnace but without fuel at 250 pesos/y between Gaspar de Villanueva and Fernando de Mesa Godines. AHSLP, Fondo Alcaldía Mayor 1641.1, expediente 9, 25 June 1641; an hacienda with two smelting and one refining furnace for 400 pesos/y between Geronimo Dias and Alonso de Borja. AHSLP, Fondo Alcaldía Mayor 1658.1 expediente 4, 7 January 1658; an hacienda with three smelting furnaces for 750 pesos/y between Francisco Dias del Campo y Diego Sanchez. AHSLP, Fondo Alcaldía Mayor 1658.1, expediente 18, 18 March 1658.

[236] Rental agreement between Francisco Dias del Campo and Hernan Vasquez, AHSLP Fondo Alcaldía Mayor 1635.5, expediente 28.

Overall these contracts show a cross-section of an active market for the outsourcing of refining services. The level of rent in this market was the equivalent of approximately 30 to 120 marks of silver per year, at the most some 1% of the average silver production per *hacienda* registered in 1620. It is interesting that the rental contract was not tied in some manner to the total silver produced by the renter. One strong incentive to rent must have been the provision of ores and skilled workers more than the relatively simple infrastructure that could be built in five weeks.

Towards the end of the eighteenth century, smelting would be overshadowed by *cazo* amalgamation in the refining of silver presented to the *Caja* (Treasury) of San Luis Potosí. The boom in silver production shifted to the mines of Catorce in the northern part of the state, where the nature of ore (mainly silver halides, poor in lead) made the *cazo* process the best refining option.[237] The difficulties faced by some smelting *haciendas* during this period is reflected in the nineteen surviving weekly accounts from the *Hacienda* de Nuestra Señora de los Dolores, corresponding to the year 1773. An analysis of the records that tracked the silver refined per week indicate that on average 2.4 kg of silver were produced on a weekly basis, approximately 0.12 tons per year. This is one third of the value reported for just one furnace in 1620. If the number of *cargas* of ore set down in these weekly accounts were the source of the silver refined, the values indicate a silver content for the ore being smelted around 0.6%. The data show a persistent operational loss in the accounts being rendered, based only on silver revenues.[238]

2.6 The environmental impact vectors from smelting

The smelting process presents two environmental impact vectors of special importance: the emission of lead products and the consumption of wood for charcoal. I treat these

[237] See Chapter 6.
[238] Weekly accounts signed by Lorenzo Mata that cover, with major gaps, the period from 27 December 1772 to 28 November 1773, AHSLP, Fondo Alcaldía Mayor 1773.2. The details of the calculation based on the primary data are given in Appendix A.

production variables as vectors, since they not only have a magnitude but also a directionality that is relevant to any environmental analysis. In modern environmental impact studies the level of emissions is determined by *in situ* field measurements of the chemicals being studied. For historical estimates of chemical emissions I will use the principle of the conservation of matter in this and the following chapters. The mass of all the chemical reagents and ore that entered an *hacienda* has to equal the silver produced, any by-products sold, and the total emission of chemicals and inert mineral matter to the environment.[239] The method will provide the quantitative ratio of each emission or amount of energy consumed per kg of silver refined. This ratio in turn will allow me to project over a whole region the quantitative environmental impact of each major emission or energy source simply by knowing the amount of silver produced either by smelting or amalgamation. While the macro-impact lends itself to this method, the local impact is location specific, and thus can only be established on a case by case basis.

2.6.1 Lead: its nature and magnitude

In the case of lead the only sources that supply it to the smelting process are the ore itself and / or any fresh lead compound (poor lead, *greta* or *cendrada*) that is added to compensate for the dryness of the ore or for losses of lead during the smelting process. Recycling of lead, *greta, cendrada* or the recovered accretions from the furnace walls does not enter the gross mass balance equation. The amounts of lead that must be replenished during the smelting process are due to four causes (Figure 2-10):

[239] I have not come across any similar application to estimate historical environmental impacts, but cannot affirm the method is original across all disciplines. I would argue it provides better order of magnitude estimates than to measure modern soil concentrations of the offending chemical and then projecting back in time a quantitative emission factor for said chemical.

1. Loss to the atmosphere of lead and its compounds, spread via the chimney flue gas or within the area around the smelting and refining furnaces. The heating of lead or lead ores creates was is known as a lead fume, an aerosol of particles composed mainly of lead sulphide, lead sulphate, lead oxide, lead carbonate and metallic lead.[240] The exact chemical composition and the size distribution of the particles varies according to the temperature in the furnace, the presence of oxygen, and the other compounds present in the furnace. This fume is so rich in lead and lead products that in Europe it was recovered in horizontal flue traps to extract its lead products as of the end of the eighteenth century.[241]

The toxicity to humans of these lead compounds varies substantially, both with chemical nature, particle size and type of exposure (inhalation, ingestion, contact with the skin). Because of the many combinations of factors possible, a very approximate scale of high to low toxicity spans lead oxide, lead carbonate, small particles of lead inhaled, to the least toxic lead sulphide.[242] The toxic effects of the lead fume that constituted the accretions to the smelting furnace walls on the workers who were assigned to dislodge them at the end of a smelting run

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[240] Pure lead melts at 328° C and its boiling point is 1750° C. Modern studies on the composition of lead aerosols from smelting lead indicate the presence of Pb, PbS, PbSO4, PbO, PbCO3 and others. USEPA, *Air Quality Criteria for Lead EPA/600/R-5/144aF*, vol. I (2006), 2_4, 2_8. Lead fumes analysed in the nineteenth century, when furnace conditions corresponded more closely to the period of this study, conform to this profile, but the source of the fume (ie furnace conditions and presence of other compounds) determine which specific lead compound predominates. See examples in John Percy, *The Metallurgy of Lead Including Desilverization and Cupellation* (London: J. Murray, 1870), 451-58. Why metallic lead should be present in the aerosol is not evident due to the high boiling point of lead. Measurable volatile lead is reported from 1,200 °C, in Katsunori Homma, "Experimental Study for Preparating Metal Fumes," *Industrial Health* 4, no. 3 (1966): 132. Volatile lead is reported from approximately 1,100 °C and volatile lead oxide from 550 °C, but the presence of sulphur and chloride will shift the lead compounds to lead sulphate and very volatile lead chlorides, in Anders Ljung and Anders Nordin, "Theoretical Feasibility for Ecological Biomass Ash Recirculation: Chemical Equilibrium Behavior of Nutrient Elements and Heavy Metals During Combustion," *Environmental Science & Technology* 31, no. 9 (1997): 2502. This is a range of temperature that could be attained in the furnaces of the period in question. In the discussions that follow I will refer to 'lead and its compounds' to encompass all the lead speciation present in lead fumes that are produced during smelting.

[241] Percy, Metallurgy of Lead, 434-51.

[242] The estate of research on the toxicity of lead and its compounds is extensively covered in USEPA, *Air Quality Criteria for Lead EPA/600/R-5/144aF*, vol. I,II (2006). A more accessible guide as to the approximate order of toxicity is the early article by Lawrence T. Fairhall, "Inorganic Industrial Hazards," *Physiological Reviews* 25, no. 1 (1945): 184-85.

is well documented by de Gamboa in his description of the smelting of silver ores at the end of the nineteenth century in New Spain.[243] The phrase 'lead poisoning' or 'lead toxicity' has to be taken to refer not only to the metal itself but to its many toxic compounds.

2. Loss via solid particles spread by the wind from stockpiles of ore, *greta* or *cendrada* within the *hacienda* compound (fugitive lead). Again the size, chemical nature and type of exposure of the particles would determine their toxicity. Ingested *greta* or *cendrada* (containing lead oxide) would be the most toxic, gross particles of the ore (lead sulphide) the least. Oral ingestion by children of the workers of this fugitive lead would be a major problem.[244]

3. Loss of lead contained in the solid *grasas* dumped alongside the *haciendas*. This lead (metallic lead, lead sulphide, other lead compounds) is encased in a solid matrix, either porous like a lava stone or glassy. Leaching of the lead into the soil would be expected under mostly acidic conditions.[245]

4. Sales of poor lead and/or *greta* as a by-product of the process. The last group is contingent on the manner in which each individual smelting *hacienda* managed its business. Lead-poor ores would require a total recycling of any *greta* or poor lead to minimize the purchase of fresh additions of lead to reach the required lead to silver ratios in the smelting recipe. Lead-rich ores would create a surplus of *greta* that would be thrown away as waste or else offered to other mining localities that were deficient in lead. In San Luis Potosí legislation

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[243] de Gamboa, *Comentarios Ordenanzas de Minas*, 286.

[244] The topic is addressed for modern cases of workers acting as transport vectors for lead compounds from the workplace to the home, or of children poisoned by ingestion of lead contaminated soil or dust, in USEPA, *Air Quality Lead*, I 3_17, 3_27, 3_28.

[245] One study of the portioning of lead in the soil of historical lead smelting sites and the mobility of lead with decreasing pH is J. E. Maskall and I. Thornton, "Chemical Partitioning of Heavy Metals in Soils, Clays and Rocks at Historical Lead Smelting Sites," *Water, Air, and Soil Pollution* 108, no. 3-4 (1998). During the visit to the ruins of the Hacienda Santa María in Monte Caldera, one of the family members who uses the remains of the hacienda as an animal pen remarked that when they last held a barbeque and used *grasas* to line the fire pit, these exploded with the heat and some of the family fell ill afterwards. It is only one anecdotal instance, but the heating of the slag will liberate the lead content, among other toxic substances.

was in place that regulated this export of *greta*, forcing potential sellers to offer it locally during nine consecutive public offerings (*pregones*) at a set price before it could be sold out of the jurisdiction.[246] Penalties for contraband export set in 1678 were high: confiscation of the *greta*, the cart, fines, jail for the Spaniards, and 200 lashes for any indigenous workers or African slaves caught participating in the act.[247] Overall, the fact that it is documented that *greta* was offered with no takers locally, or that contraband was attempted, would confirm indirectly that lead was not an issue for the *haciendas* of San Luis Potosí. As for poor lead, it will figure in my mass balance of Chapter 4 for the case study in Pachuca, but I did not find any evidence for a market of poor lead in San Luis Potosí. My mass balance analysis will therefore focus on the first three groups.

To calculate the emissions of lead and its compounds into the environment per kg of silver refined by smelting I will base my mass balance calculation on the weight of lead coming in and out of a smelting operation, regardless of the nature of the chemical compound of lead involved. This allows me to arrive at a mass ratio without having to know exactly the profile of lead compounds involved for each specific furnace condition. A more detailed study on the toxic effects of this loss of lead will require a more detailed knowledge of the speciation of lead products issued during smelting.

[246] Request by Antonio Maldonado Zapata to sell in Sombrerete and Guanajuato 200 *quintales* of *greta*, AHSLP, Fondo Alcaldía Mayor 1674.3, expediente 11, 31 August 1674; request by Dionissio de Rojas y Valdez to export 30 *quintales* of *greta,* AHSLP, Fondo Alcaldía Mayor 1674.4, expediente s/n, 18 September 1674; request by Fernando de Vaca y Castro to offer locally or export 600 *quintales* of *greta* or of lead obtained therefrom, Fondo Alcaldía Mayor 1680.2, expediente 10, 5 October 1680.
[247] Capture of contraband of 27 *cargas* of *greta* destined for Guanajuato by Antonio Veles de la Torre, *Alcalde Ordinario* of San Luis Potosí. An added incentive was the share of the proceeds from the sale of the impounded contraband *greta* between the judge and the person who informs / captures the contraband. AHSLP, Fondo Alcaldía Mayor 1686.1, expediente 11, 14 March 1686.

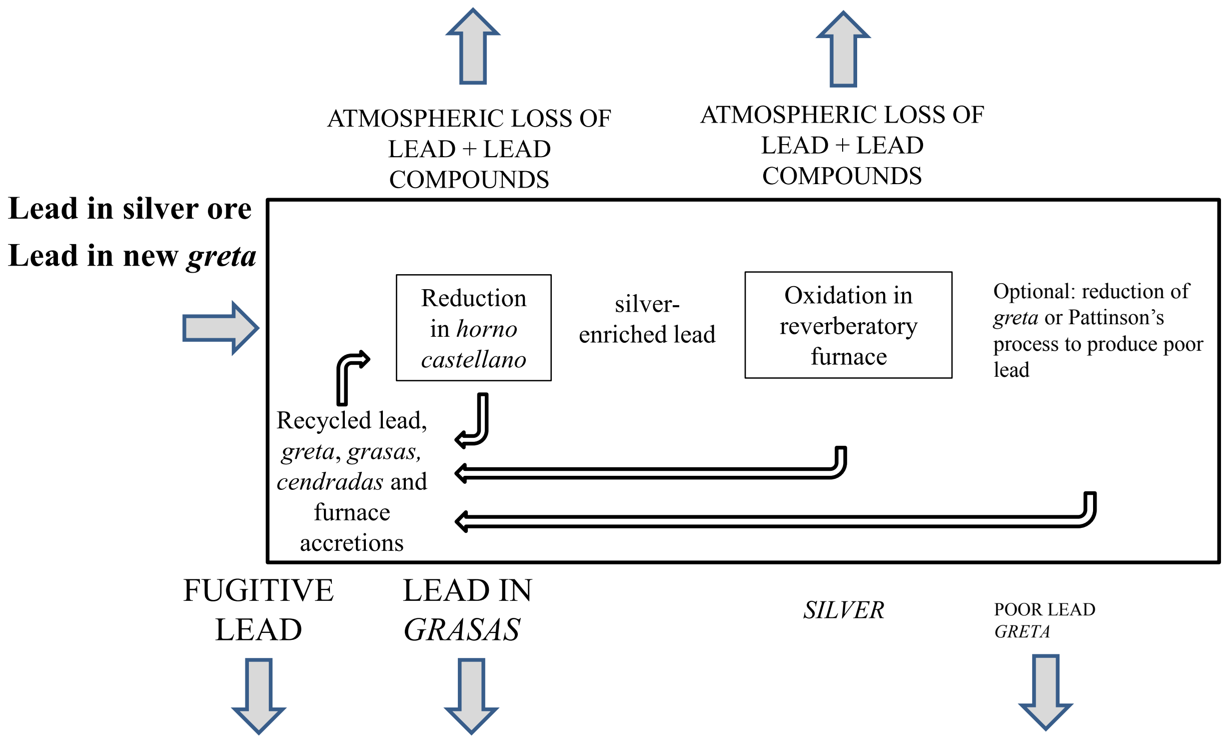

Figure 2-10. Scheme of the mass balance for lead during the smelting of silver ores. Letters in bold indicate mass input, letters in capitals indicate mass output.

Since both lead rich and lead poor silver ores were smelted, using added *greta* or recycled lead to make up any deficiency in lead, the key is to know what is the average total lead to silver ratio in the smelting recipe. The smelting recipes that appear in the historiography do not provide sufficient information on the lead content of the ores or the quality of the *greta* to allow a calculation of this ratio. There are however direct and indirect indications of this ratio, as set out in Table 2-I.[248] The indirect values are given as proportions of lead and lead

[248] a) Barba proposes a ratio between 2:1 and 5:2 for ores rich in silver, and for smelting silver sulphides he recommends a ratio approaching 4:1. Barba, Arte de los metales. b) A ratio of 1.5:1, subject to the lead and silver content of the ores. Gómez de Cervantes, *Nueva España siglo XVI*. c) West quotes from a 1539 document that in Taxco (New Spain), 25 hundredweight of litharge were required to refine 75 to 126 ounces of silver. Robert West, "Aboriginal metallurgy and metalworking in Spanish America: a brief overview," in *In Quest of Mineral Wealth. Aboriginal and Colonial Mining and Metallurgy in Spanish America.* , ed. Alan Craig and Robert West, *Geoscience and Man* (Baton Rouge: Geoscience Publications, 1994). d) The ratios could range from just over 1:1 to 4:1 according to J. de Oñate, *Nuevas leyes de las minas de España: 1625 edición de Juan de Oñate: con tratado de re Metalica de Juan de Oñate* (Santa Fe, New Mexico: Sunstone Press, 1998). e) de Sarria, *Ensayo de metalurgia*. f) Hermosa, *Manual de Laboreo de Minas*. g) Bruno Kerl, William Crookes, and Ernst Otto Röhrig,

containing fluxes (*greta*, *cendrada*) to the amount of ore, without providing the total lead content of the flux or the silver content of the ore. Thus the values in italic in the table have been calculated based on a 100% content of lead in the flux and a 2% content of silver in the ore. The former is an approximation,

weight lead per unit weight silver	location	source
100 to 200	New Spain, 16c	a, 152-161
> *75*	New Spain, 16c	b, 158-159
250-450	New Spain, 16c	c, 127
50 to 200	New Spain, 17c	d, 81-85
200	New Spain, 18c	e, 105
100	New Spain, 19c	f, 254
200 to 300	Halsbrucke, 19c	g, 219
100 to 1	Utah, 19c	h, 355

Table 2-I. Published weight ratios of lead to silver used in the smelting of silver ores. Sources are given in footnote 248.

based on the fact that *greta* with an 82% content of lead would have been the main substitute to pure lead in the recipe. The latter assumption is based on data presented in Chapter 4. They fall within the same order of magnitude, 100 to 300, and apply on both sides of the Atlantic.

A Practical Treatise on Metallurgy Adapted from the Last German Edition of Prof. Kerl's Metallurgy (London: Longmans, Green, and Co., 1868). h) smelted ore had a silver content of 0.16% and a lead content of 16%, in Eissler, *The Metallurgy of Argentiferous Lead*. Garcés y Eguía states that he uses one quintal of *greta* for every six marks of silver in an ore, but he does not provide the lead content of the ore. Garcés y Eguía, *Nueva teórica del beneficio de plata*. There are other higher published ratios but they correspond to recipes for assaying small quantities of ore by smelting.

There is an operational record dated 1718 that provides confirmation of the ranges reported in Table 2-I. It forms part of a bundle of accounts rendered by Andres de Soliz related to his management of a 'fuelle' (a bellows) in Veta Grande (Zacatecas), '*en que me ocupó de mayordomo en un fuelle que tenía en Beta Grande*', belonging to Captain Don Salvador de Inostrosa.[249] 'Fuelle' in this context is a smelting furnace situated close to the minehead. The specific account that is of interest is signed by Marcos Alcay and begins with an invocation to 'Jesus, María y Joseph', followed by the title: 'Book of charges and discharges of lead and ore that were received in this smelter of captain Don Salvador de Inostrosa … August 16 1718 year'. It contains a record of individual smelting runs carried out from August 16 to September 15 in the year 1718, registering the amount of lead added to a specified quantity of silver ore, and the total amount of silver obtained from the operation.[250] I have included in Table 2-II the information provided in the document, except for two runs where the data are not clear, and my calculations of the minimum silver content of the ore being smelted, and the resulting lead to silver weight ratio for each run. The results show that the richer silver ores required less lead for smelting, and that a ratio of 100 to 1 can represent the operational range of the lead to silver weight ratio used to smelt silver ores with approximately 2% silver content.

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[249] AHEZ, Serie Civil C15-E08.

[250] 'Libro de cargo y descargo del plomo y metal que resivo en este fuelle del capitán Don Salbador de Inostrosa, Agosto 16 de 1718 años', AHEZ, Serie Civil C15-E08, 13r, 17 r,v.

year 1718	lead added		ore		silver smelted		silver in ore	lead to silver
	quintales	*arrobas*	*quintales*	*arrobas*	marks	oz	% minimum	ratio
16 August	8	2	4	2	9	2	1.03%	184
	2	3		5	4	3	1.75%	126
21 August	5	1	3		8		1.33%	131
26 August	2	3	0	6	10		3.33%	55
	2	2		6	7	3	2.46%	68
	3	3		9	4		0.89%	188
	2	1		5	3		1.20%	150
01 September	5	2	3	1	10	2	1.58%	107
05 September	7	1	4		19		2.38%	76
	5			9	19		4.22%	53
15 September	8		4	1	14	2	1.68%	112
19 September	4		2	1	3	4	0.78%	229

Table 2-II. Range of lead to silver weight ratios from individual smelting runs carried out in the region of Veta Grande, Zacatecas, in 1718. The source data are from footnote 250.

With respect to the losses of lead, they have been reported either as total losses, losses in slags or losses as lead and lead compounds to the atmosphere. Table 2-III sets out the range of published values.[251] According to Biringuccio it was preferable to lose a certain amount of lead through losses to the atmosphere as lead fume in the last step of cupellation rather than to lose silver entrained during the removal of the last traces of litharge.[252] The sources derive their values from European lead smelters where there was an economic incentive to avoid as much as possible losses of lead. Thus these values are minimum values, since this incentive did not

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[251] a) Ian Blanchard, "Technical Implications of the Transition from Silver to Lead Smelting in Twelfth Century Britain," in *Boles and Smeltmills Seminar*, ed. Lynn Willies and David Cranstone (Reeth, Yorkshire: Historical Society, Ltd., 1992). b) Michael C. Gill, "Analysis of Lead Slags,"ibid. c) Jerome O. Nriagu, "Tales Told in Lead," *Science* 281, no. 5383 (1998). d) Eissler, *The Metallurgy of Argentiferous Lead*. e) Lynn Willies, "Derbyshire Lead Smelting in the Eighteenth and Nineteenth Centuries," *Bulletin of the Peak District Mines Historical Society* 11(1990). f) Pique, *A Practical Treatise on Silver*. g) Phillips, *Metallurgy Silver*. h) Rivot, *Description des gites métallifères*. i) Danuta Molenda, "La metallurgie du plomb en Pologne au moyen age et aux XVIe - XVIIIe siecles. ," in *Mines et métallurgie* ed. Paul Benoit, *Les chemins de la recherche* (Villeurbanne: Programme Rhône-Alpes recherches en sciences humaines, 1994).

[252] Biringuccio, *The Pirotechnia*, 165.

total	as slag	in lead fume	process	source
12			lead smelting 14c	a, 10
6		5.4	lead smelting 19c	b, 53
	one to four, ratio of loss as slag to volatile lead		slag in castillian furnace 19c	
		10 to 25	cuppellation, early	c, 1623
		2 to 5	cuppellation, 19c	
up to 40			Nevada mid 19c silver smelting	d, vii
		5 to 20	other smelting furnaces	e, 13
		75	Spanish slag hearth	
over 10			other smelting furnaces	
7			silver ores with one step smelting	f, 59
14			cupellation 19c	g, 488
17	5	12	blast furnace19c	g, 480
10		6 to 10	cupellation, 19c	h, 187
30			cupellation Poland, 13 - 18c	i, 53

Table 2-III. Range of percentage values for lead losses during smelting of lead ores. Sources in footnote 251.

necessarily apply to silver refiners in New Spain, where in some localities the lead content in the ore would have sufficed to smelt without added *greta*, and thus any *greta* produced would have had to be disposed of or sold. At the limit, even a total loss of lead during refining could have been accommodated without impacting the silver refining profit.[253] I will therefore assume as a conservative scenario that 5 to 10 % of the total lead mass input was lost as lead and lead compounds to the atmosphere in both heating stages of the smelting process.[254]

This implies as a minimum a range of 5 to 10 kg of lead and lead compounds issued to the atmosphere per kg of silver refined. With respect to the lead content that remained trapped by the mounds of *grasas* around each smelting *hacienda*, Table 2-IV summarizes what has been measured at silver smelting sites from various historical periods.[255] The lead content of two samples taken from the surface of the mounds of *grasas* that line the southwest side of the *Hacienda* Santa María in Monte Caldera was measured, and gave the results shown in Table 2-V.[256] The values for lead fall within the expected average range for an efficient smelting

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[253] A similar assumption has been applied to other historical silver smelting sites: 'the principal objective of most ancient smelting operations seems to have been the recovery of silver from argentiferous lead minerals and not the production of lead metal. Under such circumstances significant lead losses are unlikely to have been considered disadvantageous'. Paul Budd et al., "The Possible Fractionation of Lead Isotopes in Ancient Metallurgical Processes," *Archaeometry* 37, no. 1 (1995): 148.

[254] This analysis concurs with the conclusions reached by Collins in his textbook that : 'there are very few figures obtainable on this point [loss of lead fume during smelting of silver rich ores]. The average loss of lead … on the whole refining process is supposed to vary between 3 and 8 per cent, by far the largest part of which is in the cupellation'. Collins, *Metallurgy of Lead & Silver*, Vol. I, 347. In the early centuries I would expect the loss in New Spain to have been substantially higher. For example, in the nineteenth century a "Spanish slag hearth' was introduced in England to smelt lead ores. The diagram of this furnace and dimensions are similar to that of an *horno castellano*. Up to 75% of lead was lost when using this furnace, according to Willies, "Derbyshire Lead Smelting," 13. A report dated 1802 on smelting tests carried out at Catorce (reproduced in full in Appendix C) lists a total loss of 18 *arrobas* (207 kg) of '*perdida de liga*', loss of added lead flux, incurred in refining 7.5 marks (1.7 kg) of silver. This is a ratio of over 100 to 1, of which according to the working assumption of this section 5 to 10% was lost as lead and lead compounds to the atmosphere and over 90% was lost mainly as slag.

[255] a) Gill, "Analysis of Lead Slags." b) John Percy, *Metallurgy. The Art of Extracting Metals from their Ores. Silver and Gold*, vol. I (London: J. Murray, 1880). c) Willies, "Derbyshire Lead Smelting." d) Phillips, *Metallurgy Silver*. e) I C Freestone et al., "Role of Materials Analysis in the Reconstruction of Early Metal Extraction Technology: Zinc and Silver-Lead Smelting at Zawar, Rajasthan," *Materials Research Society Symposia Proceedings* 185(1990). f) Bachmann, "Archäometallurgische Untersuchungen zur antiken Silbergewinnung in Laurion. II. Charakterisierung von Bleiverhüttungsschlacken aus Laurion= Archaeometallurgical Investigation on Ancient Silver Smelting at Laurion. II. Characterisation of Lead Smelting Slags from Laurion."

[256] The analysis was carried out by a commercial laboratory (Actlabs, Ontario, Canada). Samples were first prepared by milling and then digested with sodium peroxide. Sulphur was measured by Infrared (IR) analysis and lead and sulphur by Instrumental Neutron Activation Analysis (INAA). No procedural blanks were run. A certified sample was run by Actlabs for every analytical procedure used. The results of the certified samples indicate that lead values are within 5.5%, sulphur within 2.5% and arsenic within 1%. A third sample was measured by Prof. Salazar González and gave 3.35% lead (personal communication), method unknown. Electron microscopy of sections of these samples show the presence of galena particles within the matrix of the fused slag (courtesy of Prof. Raynald Gauvin and Mr. Nicholas Brodusch of the Department of Materials Engineering of McGill University).

operation, if no leaching has taken place over the centuries. Arsenic levels are high, just approximately 30 to 40 times less on average than the lead content.[257] Two samples taken from the surface of the mounds, thus from the most recent historical period, are not statistically significant, and the analysis was undertaken solely as an initial probe into the probable chemical make-up of the slags. Even with these limitations in mind, the limited results definitely point to the need to carry out a formal study with historically relevant sampling areas and sample sizes, together with the required chemical analysis and leaching measurements to determine their long-term effect on the groundwater. During smelting arsenic would have been

average lead in slag (%)	range (%)	location	source
3	0.15 to 11	England, 19c	a, 53
	8 to 25	general	b, 280
	10 to 12.5	England, 19c	c, 10
	2 to 8		c, 12
2		most favourable conditions silver smelting 19c	d, 478
	4 to 13	India, first millenium	e, 619
15	9 to 25	Laurion, antiquity	f, 248

Table 2-IV. Lead content in slags from different smelting sites and periods. Sources in footnote 255.

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257 1% is equivalent to 10,000 ppm.

another toxic element present in the lead fume, though primary sources even up to the nineteenth century do not provide much guidance in this regard. The limited measurements of Table 2-V indicate that lead is not the only toxic element present in these mounds of waste.[258] Though arsenic will not figure in the subsequent discussion in this work on the environmental impact of historical silver refining, it has already received attention in current research in Mexico.[259]

sample	Lead (%)	Arsenic (ppm)	Sulphur (%)
1	2.67	832	0.8
2	4.27	964	0.55

Table 2-V. Lead, arsenic and sulphur content of two samples of *grasas* from Monte Caldera.

Sulphur levels are inconclusive, since in sample 1 they would be consistent with high levels of galena, which was identified via electron microscopy, while in sample 2 they are much lower than expected if all the lead was in the form of galena.[260]

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[258] I would like to thank Prof. Pamela Welbourne for arranging a presentation on my on-going research at Queen's University, Ontario, where the presence of arsenic in silver ores was brought to my attention by Dr. Geme Olivo.
[259] See for example Yolanda Jasso-Pineda et al., "An Integrated Health Risk Assessment Approach to the Study of Mining Sites Contaminated With Arsenic and Lead," *Integrated Environmental Assessment and Management* 3, no. 3 (2007).
[260] Electron microscopy of sections of these samples show the presence of galena particles within the matrix of the fused slag. Particles of fused lead sulphide are said to indicate lower furnace temperatures, but the results obtained for these samples is too limited in scope at present to attempt to recreate the smelting conditions that gave rise to them. See Gill, "Analysis of Lead Slags," 51.

Table 2-VI is an estimate of the magnitude of lead losses from an average smelting *hacienda* fitted with four smelting furnaces (*hornos castellanos*) and refining an ore with an average of 2% silver. The ratios are those derived in the previous sections, and I further assume

smelting furnaces	4	
silver per furnace	345	
total	1,380	
incoming ore at 2%	69,000	
solid waste generated	67,600	
lead + compounds to atmosphere	6,900 to 13,800	kg/y
weight of slag	67,600	
3% lead in slag	2,000	
fugitive lead	unknown	

Table 2-VI. Assumptions applied to the mineral and lead mass balance for the *Hacienda* Santa Maria, Monte Caldera. For details and sources see text.

that all the non-silver solids in the incoming ore is incorporated into the waste slag.[261] Losses via fugitive lead are impossible to estimate, so I acknowledge them in the table but cannot quantify them. Fugitive losses would be located all around the soil and walls of the *hacienda* compound, and would also include lead taken out of the compound entrained on the skin and clothes of workers and their families, or on pack animals.[262] The outstanding figure is that for

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[261] 'slag consisted of … unburnt ore, partially oxidized or reduced ore, gangue (non-metallic materials), and metallic lead' in Willies, "Derbyshire Lead Smelting," 2.

[262] Modern environmental impact assessments around lead smelting facilities have concluded that 'fugitive emissions, or those from non-point sources, such as transportation routes and smelter floors, are major sources of particulate matter, even exceeding stack emissions, but only within the smelter confines'. Measurements at a modern smelter site in Trail, British Columbia, Canada, show that from 41% to 87% of total lead losses are attributable to secondary sources. Fariborz Goodarzi et al., "Sources of Lead and Zinc Associated with Metal

losses of lead and lead compounds to the atmosphere, with a minimum range from approximately 7 to 14 tons of lead per year from an average sized smelting *hacienda*.

2.6.2 Lead: its directionality

In 1761 a refiner by the name of Manuel Correa started digging the foundations for a new smelting *hacienda* in the Real de Pánuco, Zacatecas. In what might be one of the shortest colonial civil suits on record in New Spain (it was initiated on the 28th March and an agreement reached between the parties on the 8th of April 1761) a group of townspeople objected to the new *hacienda* on the grounds of the toxicity of its smoke and its effect on the neighbours and nearby church.[263] The wording of the complaint and of the defence made by Correa are worth quoting extensively since they make very clear that for the communities the most evident environmental impact of a smelting *hacienda* was through the smoke of its smelting operation:

'Juan Estevan y Francisco Messa and all the other residents of the Real de Panuco … that were named in the previous writ … [on] the opposition to the construction of an *Hacienda* for extracting silver by fire in the proximity of said Real by Manuel Correa … since with its smoke … it will add to the imminent damage to all the neighborhood, since not a single expert in Medicine exists that does not disapprove of the noxious, diffuse and extended turbulence of the air over the Real of the pestiferous smoke from diverse ores, and ingredients, that will be poison to the health of the inhabitants … no smelting *haciendas* are found in centres of population knowing that … it [the smoke] harms so that it kills all the animals it comes across'[264]

Smelting Activities in the Trail Area, British Columbia, Canada " *Journal of Environmental Monitoring* 4, no. 3 (2002): 403. However, I have no way of quantifying historical fugitive losses, since the modern percentage figures from Trail cannot be extrapolated to colonial smelting haciendas. The modern smelter at Trail fitted with a 100 m chimney stack and filters to maintain a low level of lead in the flue gas increases the relative importance of fugitive emissions as a percentage of the total losses of lead. In historical smelting haciendas, with a much higher expected amount of lead in the flue gas since no attempt was made to recover or contain the flume, the relative percentage of the fugitive emission to total emissions would be substantially lower.

263 An earlier but similar case of complaint against the construction of a smelting hacienda has been documented in Bernd Hausberger, "Una iniciativa ecológica contra la industria minera en Chihuahua (1732)," *Estudios de Historia Novohispana* 13, no. 13 (1992). It is interesting that in both cases the parish priest took the side of the smelter being questioned.

264 '*Juan Estevan y Francisco Messa, y todos los demás vecinos del Real de Panuco ... que se nombraron en el anterior escrito ... [de] la oposición a que se construya Hazienda de sacar plata por fuego próxima a dicho Real por Manuel Correa ... pues con sus humos ... se agregara el daño inminente a todo el vecindario, pues no abra perito en Medicina que no desapruebe la nosiva turbulencia difusa, y estendida por los aires sobre el Real de los humos pestíferos de diversos metales, e ingredientes, que serán veneno de la salud de los moradores ... no se*

Even the irony in the argument put forward by Correa to defend his decision to build the smelting *hacienda* is built on the toxic nature of the smoke:

'Unhappy would be the city of Zacatecas if it consented that in its centre be built similar *haciendas*, that all would live either sick, or bothered by their smoke: but what am I saying? Can my adversaries deny, that they have right in the middle of the city four *haciendas* surrounded by many houses?[265]

In the concluding writ, where Correa desists from his intentions to build the *hacienda* after agreeing that both parties should share the costs of the litigation, the negative view on the nature of the smoke is repeated: ' because of the harm to the neighborhood of said Real from the sulphurous particles in the smoke from said ores'.[266]

The problem with the smoke was not so much sulphur as lead, as evidenced in the levels of lead and lead compounds issued to the air as a result of smelting silver ores presented in the previous section. In Figure 2-11 I use the reconstruction of the *Hacienda* Santa María (Monte Caldera) proposed by Salazar Gonzalez to illustrate the directionality of these loss vectors of lead and lead compounds issued to the atmosphere.[267] The first area within the compound of high concentrations of lead in the air is the working space around and in front of the smelting furnaces. The lead *barras*, or pigs, were handled in the open area in front of the furnace where the molten lead flowed into its moulds, so there is no doubt ambient lead levels were much

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descubre introducir haciendas de fuego en las poblasones sabiéndose que … perjudica de modo que es homicida de quantos animales encuentra' AHEZ, Serie Civil C37-005, 28 March 1761

[265] '*Infeliz fuera la ciudad de Zacatecas si consintiera que en su centro se fabricasen semejantes haziendas que todos vibirian , o enfermos, o fastidiados de los humos de ellas: mas que dije? Podran negarme los adversarios , que en su puro medio tiene esta ciudad quatro haziendas rodeadas de muchas casas?*' arguments by Manuel Correa, 31 March 1761, AHEZ, Serie Civil C37-005.

[266] '*por lo perjudicial que pueden ser al besindario de dicho Real las partículas asufrozas que enbuelben en si los humos de dichos metales', agreement to suspend litigation between the parties*, 8 April 1761, AHEZ, Serie Civil C37-005.

[267] Salazar González, *Las haciendas de San Luis Potosí*, 432.

higher than any modern industrial and occupational guideline.[268] The second area of high risk to the *hacienda* workers was the refining furnace, graphically described in the nineteenth century in terms that leave no doubt as to the toxicity of this space for the workforce:

‘these ovens do not have chimneys, and the smoke exits the furnace at the place where the circumference of the cupel ends … the smoke and the lead vapours that coat the walls in lead oxide rise in a thick column under a pyramid similar to those of a castillian furnace’[269]

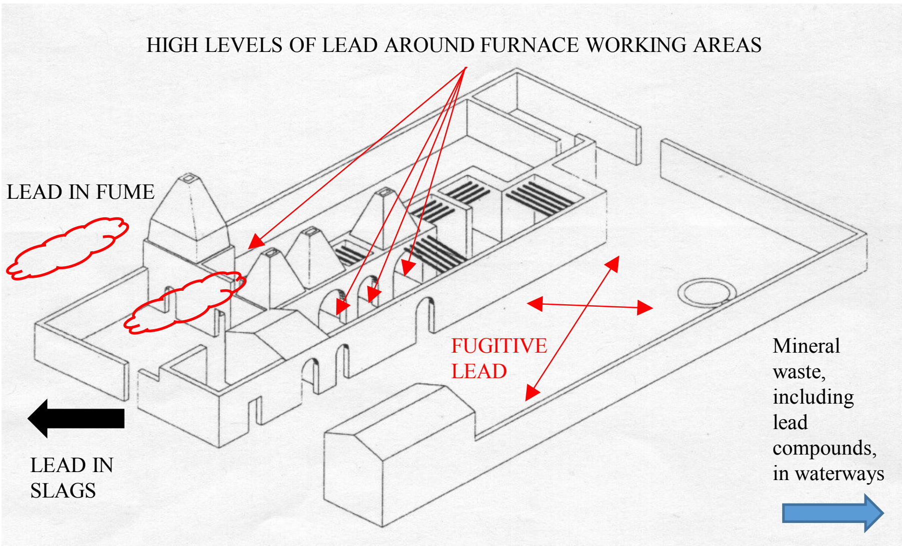

Figure 2-11. Main areas of lead deposition within and around the reconstruction of the *Hacienda* Santa Maria in Monte Caldera, adapted from original drawing with permission of Prof. Guadalupe Salazar González, footnote 267.

Whatever fraction of lead fume escaped through each chimney from the *hornos* and *vasos* was then deposited around the surroundings of the *hacienda* leaving a footprint that

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268 There is a very illustrative drawing of a blast furnace at work, showing pigs being formed in the area in front of the furnace hearth. While part of the hearth may have been under a hood, the ambient levels of lead fumes would have been substantial in all this work area. Mark Bowden, *Furness Iron : the Physical Remains of the Iron Industry and Related Woodland Industries of Furness and Southern Lakeland* (Swindon: English Heritage, 2000), 4, 52.

269 ‘*ces fours n'ont pas de cheminées, et la fumée sort du fourneau à l'endroit où se termine la circonférence de la coupelle, … la fumée et les vapeurs plombeuses qui tapissent les paroirs en oxyde de plomb s'élève en colonne épaisse sous une pyramide semblable à celle des fours castillans'* in Duport, Métaux précieux au Mexique, 71-72.

mirrors the shape of the wind rose at each locality. The thick column of smoke described by Duport is well evident in the photograph in Figure 2-12 of a nineteenth century smelting *hacienda*. Two smelting furnaces and possibly one refining furnace are at work, and the thick smoke has to be pictured issuing from an *horno castellano* at just above the eye-level of the workers in the early centuries of smelting in New Spain, not at over 10 m as in the photograph. Contrary to Correa's argument that 'as every idiot knows, the centre of smoke are the aerial regions', in the period under study much of this lead rich smoke would have been closer to the ground on which lead would ultimately deposit.[270] The exact distribution of the lead deposited between *hacienda* compound, immediate vicinity (i.e. over fields of *grasas*) and long-distance spatial spread remains to be established. For the workers involved in scraping the inside of furnaces and chimneys between smelting runs, the dust would represent an additional source of ingested lead and lead compounds.[271]

What is reported is that the concentration of lead deposited in the areas surrounding a smelter could be so high as to cause the deaths of livestock and other animals, a fact acknowledged in the extracts quoted above from the legal writ against Correa. This phenomenon was well known in England in the eighteenth and nineteenth century: 'fumes emitted from Cupolas or low arched reverberatory furnaces … poisoned herbage for ¼ mile or more around the Cupolas, and owners were obliged to pay a rent to the farmers for the damage caused to their land'. The poisoning of cattle and humans in Derbyshire went by the local term of Belland or bellanding, and hens, sheep and even dogs were also poisoned by the lead deposited from the smoke of the smelters. No statistics were recorded for any of these

[270] '*Siendo sabido a el mas idiota, que el centro del humo son las regiones aereas*' writ by Manuel Correa, 31 March 1761, AHEZ, Serie Civil C37-005.
[271] de Gamboa, *Comentarios Ordenanzas de Minas*, 286.

incidents.[272] In England lead smelters started to recover fume as of 1792, and especially as of mid-nineteenth century, by installing long flues attached to the exit of the chimneys.[273] No such measures of control have been detected in the *Hacienda* de Regla run by English management and investment in the first half of the nineteenth century (see Chapter 4).

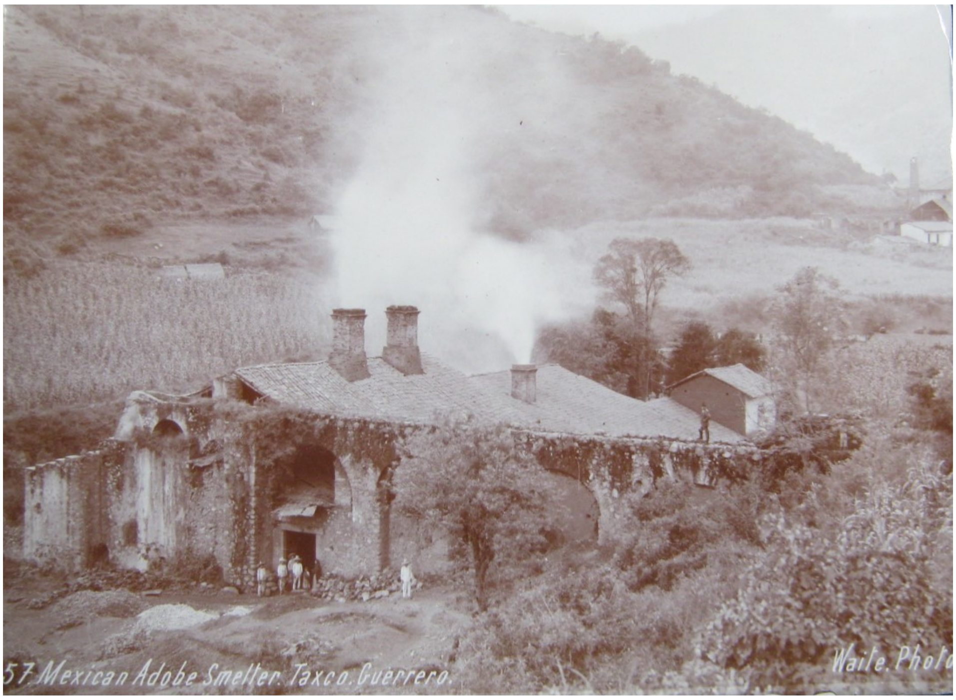

Figure 2-12. Digital copy of photograph by Charles Waite titled ‘Mexican Adobe Smelter Taxco Guerrero’, 1905, number 13 in the series *Tema y Tecnología* (CIG-AGN).

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[272] I. Thornton and P. Abrahams, "Historical Records of Metal Pollution in the Environment," in *Changing Metal Cycles and Human Health*, ed. J. O. Nriagu (Heidelberg, New York, Tokyo: Springer-Verlag, 1984), 12. For studies on the lead concentration around historical lead smelting sites in England and the incidence of bellanding even in recent times from historical lead deposits is discussed in Mike Wild and Ian Eastwood, "Soil Contamination and Smelting Sites," in *Boles and Smeltmills Seminar*, ed. Lynn Willies and David Cranstone (Reeth, Yorkshire: Historical Society, Ltd., 1992). See also Willies, "Derbyshire Lead Smelting," 3, 13. Similar cases of compensation are not reported in the historiography in New Spain nor have I found any in my non-exhaustive search of the records from San Luis Potosí, Zacatecas, Guanajuato and Pachuca. One reason may be the common ownership of refining haciendas and cattle/agricultural haciendas as documented by Salazar González, *Las haciendas de San Luis Potosí*, 153-210. and Eugenio Martín Torres, *El beneficio de la plata en Guanajuato, 1686-1740* (Guanajuato: Presidencia Municipal de Guanajuato, 2001), 162-166.

[273] ‘fume is the general name given to the usually greyish white, feathery , partially crystalline , partially dusty deposit [lead sulphate and oxides, arsenic, silver] which sublimates or adheres onto the sides of chimneys and other flueways along which gaseous material from the furnaces pass’ in Willies, "Derbyshire Lead Smelting," 13. For the installation of flues see Gill, "Analysis of Lead Slags," 53.; Willies, "Derbyshire Lead Smelting," 3, 14. The use of chambers to condense and extract metal fumes from the furnace appears as early as Agricola, *De re metallica*, 394. See also Pique, *A Practical Treatise on Silver*, 72.

Owners and builders of the smelting *haciendas* were conscious of the need to site these facilities taking into account the prevailing winds of the region. Again the civil suit against Correa provides interesting insights:

'there being more than two hundred paces between my church and home and the place Manuel Correa intends to build his *hacienda*, and being this location at a greater height than the church, and my home, without the winds from the South and West (as it seems to me) being able to push the smoke so that it can harm the church or me … since it seems to me only the winds from the Southwest could cause harm according to what was established by the Architects for the construction of this *Hacienda*'[274]

Indirect evidence of the care taken to integrate the wind direction with the orientation of the smelting furnaces within the *haciendas* comes from the reconstruction of the smelting *haciendas* in the area of Monte Caldera, San Luis Potosí. Figure 2-13 aligns the architectural footprint of three *haciendas* published by Salazar González with the direction of due North.[275] The three arrays of smelting furnaces appear remarkably parallel to each other, and the only common factor to all would be the predominant wind direction in the area of Monte Caldera. Even without specific knowledge on the wind rose of the area during the colonial period, the parallelism observed in Figure 2-13 indicates that local builders took it into account when locating the smelting furnaces within the *hacienda* compound, so as to minimize the impact of the plume on the compound itself.

In addition to the main loss via lead fume, three other directions for the loss of lead need to be considered. One is within the compound, in the form of fugitive lead loss, from the

[274] *'haviendo de la iglesia y de mi casa mas de doscientos pasos a el lugar adonde intenta Manuel Correa poner su hazienda, y hayarse este sitio en gran altura respecto de la Iglesia, y de mi casa, sin que los Aires de Sur y Poniente (según me pareze) puedan aviolentar a el humo para que perjudique o a la Iglesia o a mi … por parecerme ser solo el aire Suroeste el que hubiese de dar algún perjuicio según lo determinado por los Arquitectos para la favrica de dicha Hazienda*', sworn statement by the parish priest, Don Joseph de Siloa, in support of Manuel Correa, 28 March 1761, AHEZ, Serie Civil C37-005.

[275] Salazar González, *Las haciendas de San Luis Potosí*, 428, 431, 436.

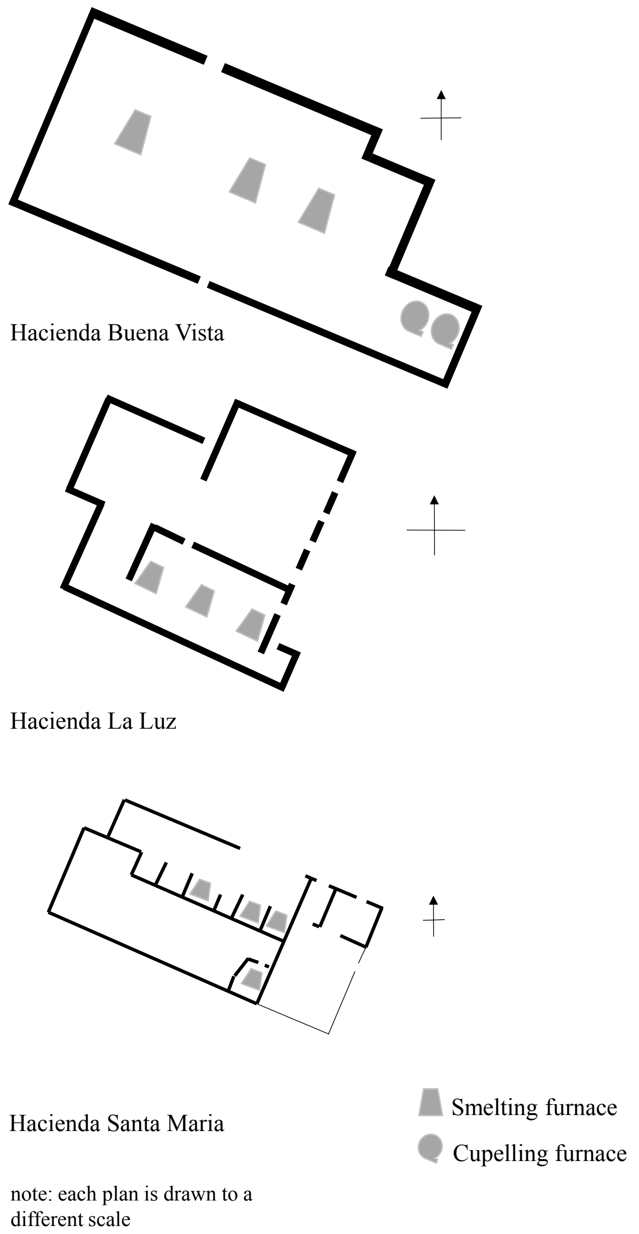

Figure 2-13. Relative alignment of arrays of furnaces from three different smelting *haciendas* in the area of Monte Caldera, adapted from the architectural reconstructions in footnote 275.

physical loss of lead or litharge as dust. The second direction is through leaching of lead and lead compounds from the slag heaps into the soil and water table. It is important to know the nature of the lead compound in the *grasas* since it will determine in part its extraction rate to the environment under long- term atmospheric exposure. A more systematic study of the environmental impact of these *grasas* is required, that includes establishing the leaching behaviour of the *grasas* and its potential consequences to the local population, livestock, crops and the water sources of each area.

The remaining vector of lead emissions from each *hacienda* was the waste water from the washing of the ores. 'The process of Buddling – separating lead ore from gangue materials using water- used to poison the streams', made rivers suddenly turn yellow with the amount of mineral sediment voided into them, and fish died and cattle were poisoned from drinking this industrial waste in the water.[276] The magnitude of this vector can only be established comparing the amount of lead in the mined ore with the amount of lead in the dressed ore, but these data are not yet available for the period in question.

2.6.3 Lead: its source

The absence of lead in silver ores was never an obstacle to smelting them. In Europe since at least the mid-fourteenth century there had been a traffic of lead to supplement the so-called 'dry' ores: 'by the 1330s Polish lead was utilised for smelting and refining the "dry" gold and silver ores processed in the metallurgical enterprises of the Hungarian-Transylvanian Carpathians and the Bohemian-Moravian and Saxon Erzegirbe.'[277] In fact, the lead industry of Europe was forced to respond to the increase in demand once the copper liquation process was applied to argentiferous copper ores. By the 1540s England was already an important supplier of lead to the silver/copper refining centres of Europe, which required around 4,800 tons of lead per year and absorbed 60-85% of an English lead production of 3,200 tons.[278] Then, from 1543 to 1549, the traditional European market chain for lead destined to silver-copper refining

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276 Thornton and Abrahams, "Metal Pollution in the Environment," 12.
277 Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 1468.
278 Kellenbenz, "Final Remarks Silver Production," 332.

was disrupted by the appearance of English lead stripped from Church holdings that halved the prices as of 1538-1539.[279]

Local sources of galena at Taxco and Sultepec had been sufficient initially to provide the required quantities of lead for smelting, but soon the whole dynamic changed and imports of lead to New Spain were initiated.

‘From 1536 the trade, based now almost entirely on monastic lead, passed directly to Seville [and] shipped to the New World ... *abundant and cheap* supplies of lead benefited the bullion producers of central America ... via Seville English lead, carried as ballast by the Indies fleets, passed to Veracruz and thence northwards to satisfy the demands of the producers in the booming centre of Zacatecas, where the deposits, though rich in silver, were poor in lead ... [this would create] a dependence which left the central and south American smelter dangerously exposed ... by 1554 prices rose again on the Seville market and [New World] producers were drawn into the general bullion crisis’ [emphasis added].[280]

As demand rose from a European industry requiring more lead per unit of silver refined and a New World providing further new silver deposits to Spain refined on the basis of smelting with lead, a brake on English lead exports brought about strong pricing fluctuations that saw a threefold rise in prices in the early 1560s (compared to prices in the 1540s) until they dropped to a third above 1540s level. Between the 1560s and late 1570s lead supply would be re-established from various European sources, but by that time mercury was displacing lead as the main refining agent of choice by Spain to the point that by 1572 an English visitor in Central America could say

‘as for this charge of quicksilver it is a new invention, which they find more profitable then to find their use with lead ... wherefore they shall not need any of our lead, as they have neede thereof in times past.’[281]

[279] Blanchard, "England and the International Bullion Crisis of the 1550s," 87.
[280] Ibid., 89, 90, 107.
[281] Ibid., 95-108., citing R. Hakluyt, The Principall Navigations Voiages and Discoveries of the English Nation (1589), II, p. 549

According to Blanchard English lead would continue to be exported to New Spain from 1580 to 1590, from 1610 to 1614 and from 1625 to its final phase in the 1640s, after which point it was displaced by local lead sources in New Spain.[282] From the mid-seventeenth century onwards the movement of lead, litharge and silver-rich ores between mines and refining haciendas in the same or different *Caja* districts is not documented in the historiography. This intra- and inter- regional transit of silver-rich lead ores and lead fluxes required for smelting would determine the balance between amalgamation and smelting, as will be seen in Chapter 6.

2.6.4 Charcoal and wood: its magnitude

Charcoal was the main fuel requirement for smelting in New Spain, while wood was the minor fuel for cupelling in the reverberatory ovens.[283] Charcoal was necessary not only to provide the heat required to reach the necessary furnace temperatures, but also to act as reducing agent during smelting. Charcoal was used to smelt all metal ores, but the quantities required varied according to the metal. To smelt copper during this period the weight ratio of charcoal to copper was in the range of 20:1 to 50:1.[284] In the case of iron, the ratio was 30:1 approximately.[285] Lead required less charcoal, with values as low as 3:1 or 6:1 being reported for ores containing 45% lead.[286] In sharp contrast, for the smelting of silver ores the metal to charcoal weight ratios reported in the historiography are considerably higher. Between 975 and 1,145 kg of charcoal are reported as being required by the smelting operations at Wissenbach

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[282] *Russia's "Age of Silver". Precious-metal Production and Economic Growth in the Eighteenth Century* 19. In Chapter Six I will come back to the important question as to whether there were sufficient endogenous lead deposits in New Spain to have met the requirements for smelting, and the attitude of the Spanish Crown with respect to prospecting for lead.

[283] Duport, *Métaux précieux au Mexique*, 81. In Chapter 4 the large difference in fuel requirements for charcoal and wood in smelting will be fully documented, so for the rest of this chapter I will only focus on charcoal.

[284] Craddock, *Early Metal Production*, 193.; Salkield, "Ancient Slags in the South West of the Iberian Peninsula," 93.

[285] Nef, *Conquest of the Material World*, 174.

[286] Craddock, *Early Metal Production*, 209.

(Europe, Vosges, late sixteenth century) to produce 1 kg of silver from ores containing between 0.07 and 0.13% silver. Rech also cites data from smelting of silver ores in the eighteenth century (nature of ore and silver content not given), that required between 800 and 960 kg of charcoal to produce 1 kg silver.[287] Studnicki-Gizbert and Schecter have used the information in the accounting books of two smelting *haciendas* in New Spain to calculate a ratio of 1,185 kg of charcoal per kg of silver in San Luis Potosi (1611-1612) and 1,168 kg of charcoal per kg of silver in Pachuca (1782-1783), though the silver content of these ores is not given.[288] I will thus use as a working figure an average weight ratio for charcoal of 1,000:1 up to the nineteenth century, when the use of more efficient blast furnaces will decrease substantially this ratio (Chapter 4).

2.6.5 Charcoal and wood: its directionality and source

The directionality of this vector is determined by the location of the woodlands that ultimately provided the charcoal to the smelting furnaces. These vectors were not distributed radially around each refining nucleus, but could extend like tendrils for many kilometres in a single direction. In the case of the region around San Luis Potosí, charcoal was sourced as far away as Peotillos (Figure 2-14). In order to estimate the amount of natural resources required to meet this high consumption of charcoal it is necessary to proceed in stages. Charcoal is obtained from wood, wood is obtained from forests, and forests are organic systems that can be regenerated given sufficient time. To estimate the amount of charcoal generated from a hectare (ha) of woodland, the following factors have to be taken into account: a) individual tree species can produce quite distinct amounts of charcoal per cubic metre of wood b) the moisture

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[287] Georges Rech, "La fonderie de Wisenbach (Vosges)," in *Mines et métallurgie* ed. Paul Benoit, *Les chemins de la recherche* (Villeurbanne: Programme Rhône-Alpes recherches en sciences humaines, 1994), 178-81.
[288] Studnicki-Gizbert and Schecter, "Colonial Fuel-Rush," 112.

content also varies according to the state of the wood and c) the type of charcoal making process will also determine the efficiency of the operation. The average amount (expressed as volume in cubic metres) of growing stock (trees above a certain height and diameter) per ha of forest 'is an estimation of how well or how poorly stocked the forests are'. For the year 2010 the Food and Agricultural Organisation of the United Nations (FAO) has calculated an average of 44 m^3/ha for Mexico.[289]

As to the efficiency of the transformation from wood to charcoal, the FAO establishes a range for developing countries of 10 to 27 m^3 of wood required to produce 1 ton of charcoal.[290] Using the average density of wood reported by FAO (650 to 750 kg per m^3), this range of conversion of 5 to 15% of the weight of wood to weight of charcoal overlaps fairly well with the estimation in the historiography that in general the amount of charcoal corresponds to 10 to 20% of the weight of wood.[291] Thus using an average of 18.5 m3 of wood per ton of charcoal (approximately 10% conversion), and a charcoal to silver weight ratio of 1,000 to 1, the amount of forest area required to produce enough charcoal for the refining of 1 kg of silver in New Spain (Mexico) would have been 0.4 hectares in New Spain (Mexico).[292] Studnicki-Gizbert and Schecter estimate that one kilogram of silver consumes 6,332.8 m^2 (0.63 ha) of woodland, based on reported data by other authors from *mesquite* growth and charcoal production in the arid regions of Arizona.[293] Their projection is within the order of magnitude predicted using FAO data.

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[289] *Global Forest Resources Assessment 2010*, (Rome: Food and Agriculture Organization of the United Nations, 2010), 270-271. http://www.fao.org/docrep/013/i1757e/i1757e.pdf , accessed 15 July 2012. For the other silver producing regions the values are 74 m^3/ha for Bolivia and 120 m^3/ha for Peru

[290] http://www.fao.org/docrep/Q1085E/q1085e0c.htm.

[291] Table 11 in http://www.fao.org/docrep/007/j4504E/j4504e08.htm; Craddock, *Early Metal Production*, 193.

[292] 0.2 hectares in colonial Peru (average of modern day Bolivia and Peru).

[293] Studnicki-Gizbert and Schecter, "Colonial Fuel-Rush," 112. In my limited discussions with local historians and residents it seems *encino* (evergreen oak) and not *mesquite* was the tree of choice for mining and charcoal manufacture around San Luis Potosí, Zacatecas, Guanajuato and Pachuca.

A projection can also take into account the capacity of forests to regenerate themselves in the space of decades, even without the assistance of modern forestry methods. Values vary in the published literature, but for forests in the tropical zone the above ground biomass has been reported to be recoverable in a span of 20 to 30 years, though this type of estimate is again very site-specific.[294] Jones and Salkield in their studies of the slag heaps from Roman mining of silver at Rio Tinto in Spain use a 40 year cycle of forest generation in South-West Spain to estimate the amount of forest required to supply 40,000 tons of charcoal per year.[295] On the other hand, Studnicki-Gizbert and Schecter do not take into account any natural reforestation and multiply the forest depletion per unit of charcoal by the total charcoal required by the aggregate of historical production of silver in New Spain.[296] Since during the period covered in the present study there were no strong demographic pressures acting on the forests, a 30 year cycle of regeneration to estimate total deforestation requirements would take into account the natural resiliency of this resource. This would reduce substantially any long-term projection on forest depletion due to mining activities.

A supporting infrastructure was set up to supply with charcoal the smelting operations of ores from some of the largest silver deposits in New Spain, as can be read in an extract from a report on the *hacienda* of Gonzalez de Mera in 1584:

‘a large quantity of silver has been and is being produced ... and to improve this production, he founded and peopled a settlement of charcoal makers in the *Serrania* of Santa Catalina, where

[294] M.V.N. d'Oliveira et al., "Forest Natural Regeneration and Biomass Production after Slash and Burn in a Seasonally Dry Forest in the Southern Brazilian Amazon," *Forest Ecology and Management* (2011): 1496.
[295] Salkield, "Ancient Slags in the South West of the Iberian Peninsula," 94.; G. D. B. Jones, "The Roman Mines at Riotinto," *The Journal of Roman Studies* 70 (1980): 161.
[296] Studnicki-Gizbert and Schecter, "Colonial Fuel-Rush," 99. As I will explain in greater detail in Chapter 6, their method overestimates the depletion of forest cover by a factor of at least 4, or greater if natural cycles of forest renovation are taken into account. Smelting consumed much more charcoal than amalgamation, thus the calculation must be adjusted to take into account the consumption ratio for each refining process, and the split between silver produced by smelting and by amalgamation. In addition the specific fuel requirements of the *cazo* amalgamation process as practised in the area of Catorce must be determined, since it accounted for the majority of silver production in the last quarter of the eighteenth century.

they produce a large quantity of charcoal for the smelting of said ores and those of the mines of Mazapil, Nieves, Sombrerete and Fresnillo, which became of great importance'[297]

These *carboneras* could be owned by smelting *haciendas* or the charcoal could be produced by third parties, at times indigenous groups, who then supplied the *haciendas*. In the latter case the conflict of interests is shown in a document whereby the suppliers of charcoal complain to the authorities that the *hacienda* owners try to cheat them by hitting too many times the bags of charcoal on delivery, thus decreasing artificially the volume occupied by the solid fuel. The purchase price corresponded to the volume of charcoal occupied within a bag that could be hit up to three times on delivery to insure its contents were well packed.[298]

2.6.6 Regional and local environmental impact of smelting

The pollution of air and waters due to smelting of ores is as old as metallurgy, as Agricola was well aware: 'the miners violate Nature: they make the air pestilential with their smoke and the waters with their waste: they destroy their health'.[299] Once the nature of these pestilences has been established, the next step is to quantify an order of magnitude of their historical amounts. The method employed in the previous sections has been based on a review of numerical data from the historiography and primary sources. In Chapter 4 a more specific mass balance for all chemicals and fuel consumed in the smelting process will be calculated

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[297] '*se ha sacado y se saca gran cantidad de plata ... y para que esto se pudiese mejor hacer , fundo y pobló un asiento de carboneras en la Serrania de santa Catalina.. donde se hace mucha cantidad de carbón para la fundición de dichos metales y de los de las minas de Mazapil, y de las Nieves, Sombrerete y Fresnillo, que fue de mucha importancia*' Lacueva Muñoz, "Nueva Vizacaya y sus yacimientos minerales hasta el descubrimiento de San José del Parral," 99.

[298] Complaint by a group of charcoal makers to the authorities, AHSLP, Fondo Alcaldía Mayor 1767.2, expediente 3. The original document is so damaged it is not available to researchers, so I have taken the description of its content from the summary in the file by Mrs. Carmen Cordero; in 1616 a *caxon* (box) of charcoal had to contain at least 30 *sacas* (bags) of charcoal which have been hit twice. AHSLP. Fondo Alcaldía Mayor 1616.5, expediente 33, 20 December 1616.

[299] '*les mineurs violent la nature ... ils empestent l'air de fumées et l'eau de déchets ; ils se détruisent la sante*' Agricola, *Bermannus*. p. xviii.

based on operational data from the Hacienda de Regla. This will allow a crosscheck to be effected between the factors estimated in this chapter and the reality of industrial operations.

The aim of establishing a self-consistent set of weight ratios of environmental impact vectors (lead, charcoal) per kg of silver refined by smelting is to configure a macro-scenario of its environmental impact by mining region. This calculation will be carried out in Chapter 6 based on the registers of smelted silver reported or estimated for each regional *Caja* (Treasury). On the micro-level the exercise is much more complex, but would be required in order to better estimate the consequences of lead emissions or deforestation on the local population and ecology. Each hacienda is an environmental world on its own, location and period specific: the architecture (height of walls and chimneys, type of furnace efficiency, size of courtyards, internal disposition of spaces), extent and location of the deposits of *grasas* around the *hacienda*, the wind rose, rainfall and temperature, the water basin corresponding to nearby streams, rivers or wells. In addition, the location of each *hacienda* with respect to population and agricultural centres will play a critical role in the consequences of the chemical emissions to the environment. I will briefly discuss the case of the smelting activity around San Luis Potosí in the seventeenth century to illustrate the scale of the challenge facing a detailed environmental impact assessment from historical silver refining.

First of all the main historical centres of human and economic activity in the refining region have to be identified, as well as all the mines and refining *haciendas* for each period. An example is the research carried out by Salazar Gonzalez for the area around San Luis Potosí, which I reproduce in a simplified way in Figure 2-14.[300] The next step requires identifying the refining capacity of each *hacienda* and determining the area of deposition of lead from its

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[300] Salazar González, *Las haciendas de San Luis Potosí*, 396.

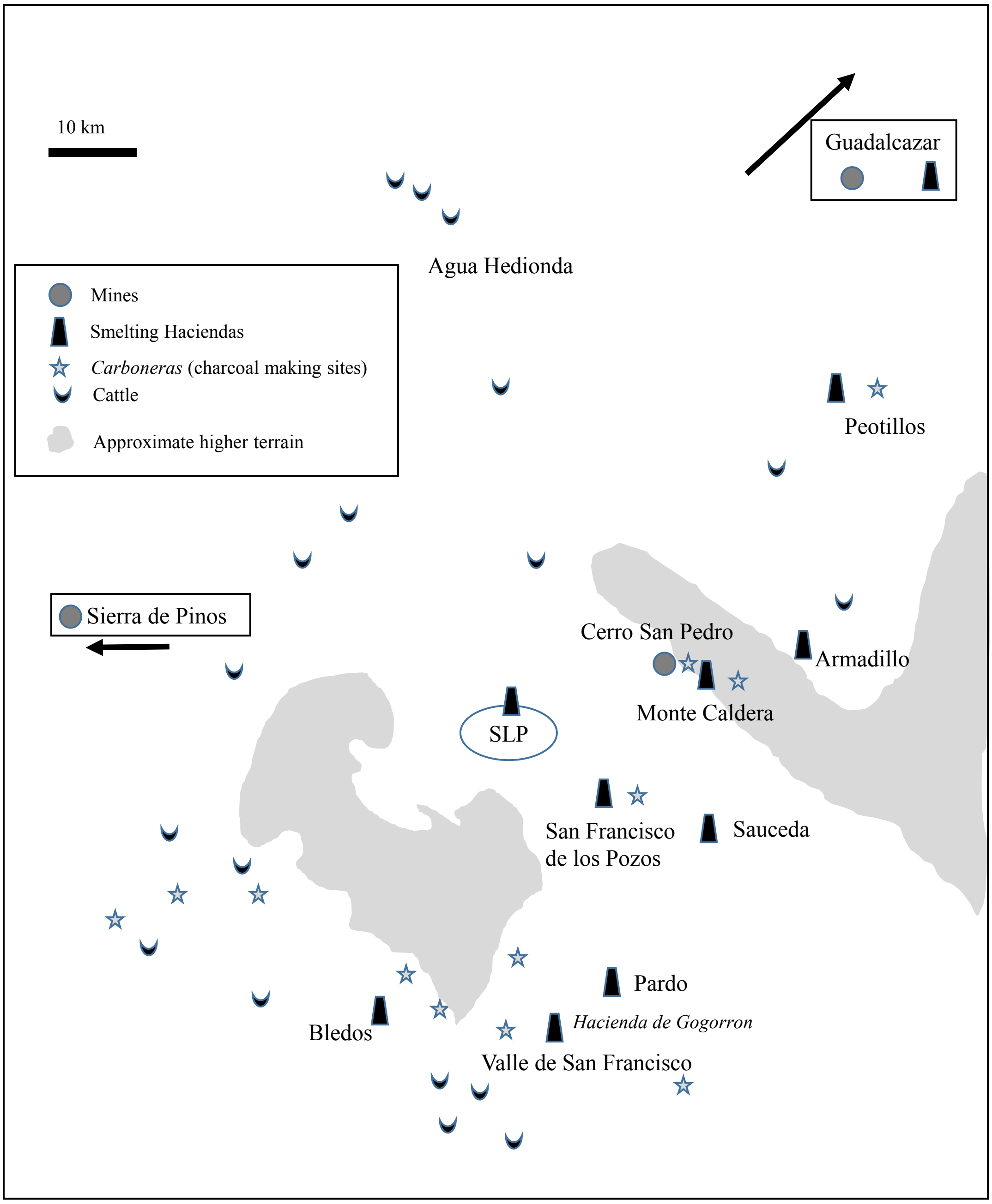

Figure 2-14. Location of the main mines, smelting *haciendas*, charcoal production, agricultural and cattle rearing areas around the town of San Luis Potosí, adapted from the original map in footnote 300.

furnaces according to the wind rose at each location, subject to the architectural reconstruction of each *hacienda* or by using an average size *hacienda* as a generic point source. At first sight it seems that refining centres in the area of San Luis Potosí were sufficiently apart from cattle rearing and agricultural centres to lower substantially the risk of bellanding (see above, Section

2.6.2), but the air dispersion of lead should be mapped, as well as the diffusion channels along the water basins in the area.

The direct risk to human population centres seems more pronounced than the risk to agriculture, though again the exercise requires a quantitative accounting of smelting carried out within city limits in San Luis Potosí and Guadalcazar, to name two population centres with known refining activity. Major refining *haciendas* are reported by Salazar Gonzalez well outside the city limits. Thus the *Hacienda* de Gogorron, with its sixteen furnaces could have produced on average around 50 tons of lead and lead compounds issued to the atmosphere per year, yet its relative isolation (Figure 2-14) would have restricted its impact to the local population, its workers and their families within its compound. A smaller *hacienda* behind the convent of St. Francis within the town of San Luis Potosí would have caused much greater problems on a per capita basis to the general population around it.

In all cases the brunt of the environmental impact of lead smelting would have been borne by the workers labouring close to the furnaces, handling the bars of molten lead and transporting *greta* within the compound.[301] The families of the workers would be the second most exposed segment of the population to lead. Wives working as ore crushers and /or washing contaminated clothes would have been subject to higher lead levels than normal. Children playing in the dirt of these compounds would have shown at a minimum the same high level of lead in their blood as has been measured in modern times for children living in houses built upon old slag heaps near to Zacatecas.[302]

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[301] For details on the social role of living spaces for the indigenous workers of a smelting hacienda in the area of San Luis Potosí see the Ph. D. thesis by Laurent Corbeil, "Identities in Motion. The Formation of a Plural Indio Society in Early San Luis Potosi, New Spain, 1591-1630 " (McGill, 2014), 171.

[302] The impact of lead from old slag heaps has been researched in Zacatecas, where dwellings have been constructed on top of the *jales*. Abnormally high levels of lead have been detected in children who live in these areas. Blood samples of children living over old mining dumps and in the vicinity of current mining operations in

To be studied in detail each refining region requires a mapping of activities such as shown in Figure 2-14 as a function of time, each temporal snapshot as specific as a fingerprint, with its ridges of hills and climates, and its whorls of different human activities and architectural variations. The sequence of snapshots would see pollution loci appear and vanish as mines became depleted or new ones sprung up, total shifts in pollution patterns as refining shifted from smelting to amalgamation and back again, variation in pollution levels as chimney heights increased and/or furnace efficiency improved, population density and agriculture pulsing closer or retreating from refining centres as a function of local mining activity, woodlands receding or advancing as a function of refining and mining intensity. No gross extrapolations can be applied from one mining region to the other, or within a mining region across the centuries. Each matrix of smelting *haciendas*, main urban centres, wood sources for charcoal, agricultural and cattle rearing areas requires a degree of quantitative information that may be available but awaits to be deciphered.

2.7 Concluding remarks

Little is known of the day-to-day working environment in a smelting *hacienda* of New Spain, as of the sixteenth to the seventeenth century. No texts written by practising metallurgists or working owners of smelting *haciendas* have as yet come to light, in contrast to what I will review in the following chapter for the Peruvian Andes of the same period. It is fortunate therefore that smelting of ores to extract metals from their mineral matrix is one of

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Vetagrande, Zacatecas, have shown very high levels of lead in the blood, with levels of 15 to 24 µg/dL in one third of the children. Children under the age of 11 are the most affected by lead as a result of playing closest to the soil. Both the floors of the houses and the streets where the children live are just compacted earth, so conditions would be similar to those of the historical period of interest in this chapter. Eduardo Manzanares Acuña et al., "Evaluación de riesgos ambientales por plomo en la población de Vetagrande, Zacatecas,"(Zacatecas: Universidad Autónoma de Zacatecas, Unidad de Estudios Nucleares, 2005).; Eduardo González Valdez et al., "Niveles de plomo en sangre y factores de riesgo por envenenamiento de plomo en niños mexicanos " *Revista de la Facultad de Ingeniería de la Universidad de Antioquia*, no. 43 (2008): 116-18. Hausberger's study on the complaints by the community of Chihuahua against lead smelters singles out the greatest toxic effect of smoke on young children. Hausberger, "Una iniciativa ecológica contra la industria minera en Chihuahua (1732)," 120.

the oldest technical processes applied by mankind to convert nature into mass man-made objects. The data from historical smelting practices together with Barba's testimony from the Andes can be used to flesh out the sparse information from documentary sources in the historical record for New Spain. Inventories of assets sold or rented, requests to the local authorities on issues related to smelting, criminal cases for contraband, accounts after the fact rendered as a result of legal wrangles between owners, their inheritors, and the administrators that run the smelting *haciendas*, all have provided pieces of the puzzle. The major missing link remains to this day a detailed operational account book that can provide a day to day diagnostic of the inner workings of a smelting *hacienda*, but as I will further explore in Chapter 5, this is a failing that applies both to smelting and amalgamation in New Spain up to the nineteenth century.

Thanks to the work carried out by Prof. Guadalupe Salazar González it is possible to drape the information derived from the texts around the three dimensions of the infrastructure of smelting. The deterioration of the surviving ruins of smelting *haciendas* around San Luis Potosí adds a level of urgency to her research. The historical mines within the Cerro San Pedro have already vanished under the grinding machinery of modern open-pit mining, but it was their deposits of lead-rich silver ores that made this region a showcase for smelting in New Spain for nearly two centuries, as of 1592. San Luis Potosí and its mines do not seem to have suffered the ignorance and wasteful predatory efforts of the first cohorts of dilettante refiners in New Spain. Its silver deposits did not offer the easy-to-refine silver chlorides that spoilt, and were spoilt by, the initial primitive Spanish refiners. The Cerro San Pedro offered the traditional European silver ores, rich in lead, which required the standard European approach based on a smelting process. A picture emerges of a community around San Luis Potosí geared to provide the necessary context within which the smelting process could function, sufficiently pragmatic as to comprise women with leading roles on both sides of the refining business.

The mines were fixed by the geology of the region, while the smelting *haciendas* sprouted close to water, to pastures and at times close to the safety of numbers provided by the towns. Ores were dressed by washing away the lighter non-productive fraction in water. The same gold that at present has caused the annihilation of the Cerro San Pedro, contributed to the revenues of these *haciendas*. The presence of lead was the sine qua non condition to implement smelting in the first place, but gold and lead combined to guarantee its permanence and success. In New Spain neither the sale of copper nor lead served to meet the cost of smelting of silver ores, as in Europe (see Chapter 5), but additional revenues from gold did. How much lead was present in these ores is not evident, though at least some of them were dry ores, in the parlance of the period. Enough lead flux was generated in some districts to permit its export to other silver smelting regions in New Spain, either officially or by contraband. Charcoal, the other prime necessity of the smelting process, was made wherever wood was available, sometimes by owners of *haciendas* who diversified upstream. Distance in procuring fuel does not seem to have been an obstacle. An energetic private enterprise sector manifested itself through rental contracts that offered a varied menu of services for hire to those who wished to pursue the illusion of become refining magnates.

Casting its pall over this hive of entrepreneurial activity were the emissions of lead and lead compounds from the smelting and refining furnaces. There can be no doubt that lead emission levels within the workspaces of the *haciendas* exceeded by far any modern standard set by legislation on occupational safety and health standards. When Medina predicated the merits of amalgamation with mercury he was correct in highlighting the dangers that smelting posed to the welfare of the indigenous and slave labour, ironic as this may seem in the light of modern knowledge on mercury. For every kg of silver smelted, five to ten kg of lead or lead compounds was disseminated from the furnace area into the surrounding air, to be deposited around each working area close to the furnaces or entrained by the flue gas out of the chimney stacks to ultimately settle on the soil, streams and surfaces within and without the hacienda. It remains to be determined how much of this lead ended up by chance within the desolate no-man's land of the mounds of *grasas* that established a non-sanitary cordon around each smelting *hacienda*. It is an intriguing question whether the extensive fields of *grasas* were ever expressly located downwind of the arrays of smelting furnaces, to act as lead sinks on a ground already condemned to a barren future.

Additional lead would be trapped within the fused shards of slag, or as the insidious dust of fugitive emissions within each compound, which at times harboured the indigenous workers, slaves and their families, and a Spaniard or two who could not yet afford his own independence. The location of the fields of slags, their extension, the architecture and wind patterns around each *hacienda* convert every refining unit into a unique footprint of lead depositions that can only be studied on a case by case basis. The mass balance of lead smelting determined in this chapter will serve to guide the regional calculations in Chapter 6. Without the geographical fingerprint of the centres of human activity within each mining region, as set out by Salazar Gonzalez in her integrated study of San Luis Potosí, together with a detailed breakdown of the size, architecture and wind rose at each locality, it is not yet possible to establish in detail the environmental impact of the individual lead emission footprints from the scattered clusters of smelting *haciendas*.

The Spaniards and Germans of the sixteenth and seventeenth centuries who smelted silver ores with lead knew of the environmental impact of the operation. Even Agricola decorated his textbook with bare hillsides dotted with stumps of trees, while heavy smoke billows out of furnaces, to be captured at times in chambers that have not appeared as yet in the infrastructure of smelting *haciendas* in New Spain or Mexico. Up to the sixteenth century they did not even have a choice, since heat and the reducing power of carbon were the only means available to extract metals from their ores. In the second half of the sixteenth century an alternative to smelting would be implemented in the New World, a reduction of silver compounds to silver metal without the need to heat to high temperatures with charcoal. It was first applied simply as an extension of deceptively similar practices used for gold, but mercury amalgamation of silver ores was a chemical reaction in disguise that would not be fully deciphered until late in the nineteenth century. With no theory to guide them, its self-taught practitioners would stumble through a unique process of trial and error in the scientific wasteland of the sixteenth century Andean highlands until they configured in just under sixty years a mature industrial-scale process capable of refining even the silver sulphide ores.

3 The wet process, amalgamation of silver ores

'I am a spagyric philosopher, alchemist … I make gold from herbs, from egg-shells, from hair, from blood, from urine … if the princes knew of this they would stuff me in a jail so as to save on the trips to the Indies'. Francisco de Quevedo, *La Fortuna y el Seso y la hora de todos* (1635).[303]

'I was then and there convinced that metallurgy in settled and civilized countries was one thing, and metallurgy in the wilderness another … in the latter he has to adapt himself as best he can to circumstances'. Eisler, *The Metallurgy of Argentiferous Lead* (1891)

3.1 Introduction

Seville had become the conduit that was feeding new supplies of bullion from another continent to Europe. The application of a new technology based on amalgamation with mercury had increased substantially the production of bullion to meet the ever increasing demands from a Europe that had little else to offer the merchants of Asia. The new process was based on mixing the mineral ore with an excess of mercury until an amalgam was formed, placing the liquid amalgam in a cloth and squeezing out the excess mercury. The solid amalgam was then carefully heated to separate the mercury, while the solid precious metal left behind could be further purified by smelting. For Spain this new outlet for mercury from its mine at Almadén represented therefore a novel marketing opportunity, and foreign bankers and merchants were involved at many stages of this new activity. A description on how to refine the precious metal using mercury amalgamation had already been long in print. Europe did not know a New World full of silver even existed.

The period in question was 1460 to 1485, and according to Blanchard the bullion was African gold, eight tons of which had been produced via amalgamation in Egypt and North

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[303] '*soy filosofo espagírico, alquimista ... hago oro de yerbas, de las cascaras de huevo, de cabellos, de sangre humana, de la orina ... si lo supiesen los príncipes me engullirían en una cárcel para ahorrarse los viajes de la Indias*'

Africa, with an additional three tons produced in Europe. A total of forty five tons of mercury from the Almadén mine in Spain was consumed in the process.[304] The description of amalgamating gold is from Theophilus, ca. twelfth century, as quoted by Dorothy Wyckoff in a footnote to her translation of Albertus Magnus' Book of Minerals.[305] Bartolomé de Medina, the cloth salesman of Seville, had not yet been born. As the French historian Jacques Heers has explained:

'From mid fifteenth century, before the discovery of gold from America, Castille was already the major redistribution centre of precious metals: it is there that came the Genoese and Florentines ... Cadiz, Seville are for certain, towards 1460, the <capitals> of gold and of the white metal … before America the pattern was already established'.[306]

The history of amalgamation of silver in the New World is one of continuity, rather than of a magnificent Ibero-American singularity devoid of a relevant past and with no negative repercussions as to the future. Amalgamation as a large-scale method to refine silver ores did not suddenly erupt on the world scene in Pachuca during the 1550s. The sequence of events that led to the industrial use of mercury in the New World is a much more interesting history of blind alleys and pragmatic refiners that is best deciphered through the chemistry of the process. Silver and quicksilver (mercury) had been firmly wedded in the chymical mind-set of the age much earlier than the discovery of silver by Spain in the New World.[307] These are the roots of the *mentalité* of a period that would lead to the longest continuous anthropogenic disposal of mercury products to the environment in the history of mankind, from the adoption

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[304] Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 1034.
[305] Albertus Magnus, *Book of minerals*, trans. Dorothy Wyckoff (Oxford: Clarendon Press, 1967), 180.
[306] '*Dès le milieu du XVe siècle, avant la découverte de l'or d'Amérique, la Castille est déjà le grand centre de redistribution du métal précieux ; c'est là que viennent Génois et Florentins ... Cadix, Séville sont bien, vers 1460, les <capitales> de l'or et du métal blanc ... avant l'Amérique les habitudes sont déjà prises*' Jacques Heers, Gênes au XVe siècle, activité économique et problèmes sociaux (Paris: S.E.V.P.E.N., 1961), 71.
[307] '"Chymystry" [is the] archaic word [that refers] to early modern alchemy-chemistry, a discipline that still viewed the transmutation of base metals into gold (chrysopoeia) as viable and yet contained much in addition that is identifiable to us moderns as chemistry'. Newman, *Atoms and Alchemy : Chymistry and the Experimental Origins of the Scientific Revolution* xi.

of amalgamation in the mid-sixteenth century until its displacement by the cyanide process at the end of the nineteenth century.[308] In contrast to smelting, it was a wet process, due not only to the use of liquid mercury, but because water was such a critical part of the process that as Thierry Saignes, the French historian of Bolivia, quoted: 'when it rained they say it rains silver'.[309]

3.2 The alchemy of Mercury

For many centuries the only substance known to physically interact without altering the two most precious of metals, gold and silver, was mercury, the semen of Shiva.[310] This alone would have been enough to anoint it as a special substance of the material world. Together with the visual allure and the mystery of a metal that was liquid at room temperature, it became an ontological force within the Arab and European theories on matter and metals, summed up in the phrase '*Mercurie* without which nothing being is'.[311] The line of intellectual stepping stones that led to this sweeping judgement can be traced back to Plato, for whom matter was a passive recipient on which properties can be imposed. The one and only primordial matter would be the *prima materiae.* Aristotle then postulated all metals had a common origin and were produced from two vapours which rise through the earth; so subtle they pass through stones but are capable of condensing into forms of metals. Under this concept transmutation is simply the readjustment of the quantities of these two vapours.[312]

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[308] In 1891 MacArthur and Forrest would request formal permission to the Mexican government to apply their new cyanide process to refine first gold then silver ores. Mendizábal, *La mineria mexicana*, 107.

[309] Thierry Saignes, "Las técnicas mineras de Potosí según una relación inédita de 1600," *Arte y arqueología* 8, no. 9 (1982/1983): 171.

[310] John Read and F. H. Sawyer, *Prelude to Chemistry; An Outline of Alchemy, Its Literature and Relationships* (London: G. Bell and Sons, ltd., 1936), 19.

[311] George Ripley, *The compound of Alchemy* (London: Thomas Orwin, 1591), following B3.

[312] For a more in-depth discussion on the sequence of ideas from Plato to Aristotle see Aitchison, *History of Metals*, 260-302.

Arab thinkers then associated mercury with Aristotle's moist vapour and sulphur with the dry or smoky vapour.[313] 'The view that sulphur and mercury were the basic components of all metals first entered Europe textually in the work of Jabir Ibn Hayyan ... and continued to be the cornerstone of alchemical theory up through the seventeenth century'.[314] Mercury evolved into 'the *prima materia* of which all metals were made', and only the relative quantities of sulphur and mercury defined each type of metal.[315] Raymond Lull, one of the most famous alchemists from Spain in the thirteenth century, held that mercury was the first matter of Genesis and that it was found in everything that had been created by God, and that mercury served as the channel whereby the heavenly bodies could induce changes in the sublunary world.[316] Arnaldo de Vilanova would call it the 'sperm of metals'.[317] In some alchemical texts the Sophic Mercury (the essence of mercury, not to be confused with the mercury of the laboratory) was referred to as Azoth, showing the same Arabic roots to the word used in Spanish texts for mercury, *azogue*.[318]

The alchemical symbol of mercury was the only one to fuse the symbols of the moon (silver) with that of the sun (gold).[319] 'Beyond a doubt [mercury was] the metal most commonly used as a reagent [in alchemy]... it is ... so nearly a precious metal that one recipe tells how to

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313 Ibid., 268.
314 Pamela H. Smith, "Vermilion, Mercury, Blood, and Lizards: Matter and Meaning in Metallurgy," in *Materials and Expertise in Early Modern Europe : Between Market and Laboratory*, ed. Ursula Klein and E. C. Spary(Chicago: University of Chicago Press, 2010), 39.
315 L. Fabbrizzi, "Communicating about Matter with Symbols: Evolving from Alchemy to Chemistry," *Journal of Chemical Education* 85, no. 11 (2008): 1506.
316 Bruce T. Moran, *Distilling Knowledge : Alchemy, Chemistry, and the Scientific Revolution* (Cambridge, Mass.: Harvard University Press, 2005), 20.
317 Juan Eslava Galán, *Cinco tratados españoles de alquimia* (Madrid: Tecnos, 1987), 31.
318 Bruce T. Moran, *Andreas Libavius and the Transformation of Alchemy : Separating Chemical Cultures with Polemical Fire* (Sagamore Beach, MA: Science History Publications/Watson Pub. International, 2007), 63.
319 Smith, "Vermilion, Mercury, Blood, and Lizards: Matter and Meaning in Metallurgy," 40-41. Eslava Galán, *Cinco tratados españoles de alquimia*, 30, 43, 44, 46. Also Read and Sawyer, *Prelude to Chemistry; An Outline of Alchemy, Its Literature and Relationships* 20.; John Read, *Through Alchemy to Chemistry; A Procession of Ideas & Personalities* (London: G. Bell, 1957), 44.

make mercury alchemically out of lead'.[320] It was used either as an aid to achieve transmutation of base metals into silver or gold, or as the object of transmutation itself. According to Flamel 'the first time that I made proiection ... was upon Mercurie, whereof I turned halfe a pound ... into pure Silver, better than that of the Mine ... this was upon a Munday, the 17. of January ... in the yeere ... 1382.'[321] According to William Newman, one of the historians of alchemy, in the fourteenth and fifteenth centuries 'it was to be a favourite and prevailing theory of transmutation ... that gold and silver could be made artificially from mercury alone, using perhaps a little gold or silver to initiate the process'.[322]

Mercury generated a very rich alchemical symbolism, and became one of the popular images of the art to the laymen of the time. The following extract is from a masque performed for King James II of England in early 1616 titled 'Mercury vindicated from the alchemists at court,' by Ben Jonson, the dramatist contemporary with William Shakespeare:

'I am ... their Hermaphrodite ... I am corroded, and exalted, and sublim'd and reduc'd and fetch'd over, and filtred and wash'd and wip'd ... now a sous'd *Mercury*, now a salted *Mercury*, now a smoak'd and dri'd *Mercury* ... now a pickl'd *Mercury* ... my whole life with them hath bene an exercise of torture ... they eat nor smell no rost-meate but in my name ... [the alchemists promise] mountains for their meat, and all upon Mercuries securities.'[323]

In this same vein Quevedo in Spain would mock alchemy as presenting a better alternative to the trips to the New World in search of precious metals.[324] Framed by the lore of

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[320] W. J. Wilson, "An Alchemical Manuscript by Arnaldus de Bruxella," *Osiris* 2 (1936): 251.
[321] Read, *Through Alchemy to Chemistry; A Procession of Ideas & Personalities* 52. Though my examples on mercury are all taken from the European experience, from the second to the fifth century CE, Buddhist texts are said to report the attempted transmutation of metals into gold using mercury together with other substances, and this craft was called *raseśvaradarśana* (the science of mercury). Arab and Hindu texts recognize the capacity of mercury to feed (amalgamate) on certain metals. Wilson, "An Alchemical Manuscript by Arnaldus de Bruxella," 326.
[322] William .R. Newman, *The 'Summa perfectionis' of Pseudo-Geber: A Critical Edition, Translation and Study*, vol. 35 (Leiden: Brill, 1991), 205.
[323] S.J. Linden, "Jonson and Sendivogius: Some New Light on Mercury Vindicated from the Alchemists at Court," *Ambix* 24, no. 1 (1977): 39, 46, 49.
[324] The quote from Quevedo in the epigraph to this chapter is taken from 'La Fortuna y el Seso y la hora de todos' in Eslava Galán, *Cinco tratados españoles de alquimia*, 112-13.

alchemy, the practical knowledge on the amalgamation of mercury with various metals began to appear in texts. Gerber in the early thirteenth century classified the perfection of bodies according to how well they amalgamated with mercury, citing the 'easy amalgamation of quicksilver by a body of solar [gold] or lunar [silver] perfection'.[325] From trials of amalgamation to its application in refining silver ores was a small step. Biringuccio (1540) is the most widely cited source on the use of mercury on silver ores, but there is another contemporary text among the works of Paracelsus that is not widely quoted:

'volatile and fugitive metals, such as gold and silver, if they are to be separated from their minerals, since they can neither be treated by fire nor with strong waters, should be amalgamated, separated and extracted by means of *Mercurius vivus*. Afterwards the *Mercurius vivus* must be abstracted and separated from the calx of the gold, or silver by the grade of distillation ... for this is the nature of *Mercurius vivus* that it is amalgamated with metals and wholly united with them, but more quickly or more slowly with one than another, according as the metal is more or less akin to its nature'.[326]

In this period there is an overlap between alchemical practice and the pragmatic world of mining and refining. For example, silver is reported as having been obtained by transmutation not less than fourteen times in London in 1578, in which copper was converted into silver.[327] There is an obvious link between these exercises in transmutation and the fact already established at the time that lead and copper ores contained silver that could be extracted without the need to recur to additional effects of legerdemain. As mining became more important in Europe starting from the eleventh century, it also relied for the refining of ores on the practical knowledge generated in the alchemical workshops, and vice-versa, so that as Tara Nummedal states :

[325] Newman, *'Summa perfectionis' of Pseudo-Geber*, 35 783.
[326]Biringuccio, *The Pirotechnia*, 47-48.; Paracelsus, *The Hermetic and Alchemical Writings of Aureolus Philippus Theophrastus Bombast, of Hohenheim, Called Paracelsus the Great : Now for the First Time Faithfully Translated into English* trans. Arthur Waite (1976), 164.
[327] Eslava Galán, *Cinco tratados españoles de alquimia*, 132, 141.

'distinguishing alchemy from metallurgy ... in the early modern period is quite difficult …Princes and wealthy investors ... thought about alchemy as an extension of their long-standing interest in mining technology. Patrons hired alchemists and mine experts to address the same kinds of technical problems ... patrons frequently responded to alchemical proposals with the same kind of investor mentality that framed their responses to mining proposals ... alchemists were expected to produce not merely ideas but also increased profits'.[328]

Mercury, silver and alchemy were therefore already very much present in the *mentalité* of the Spanish Crown by the time the first silver mines were being exploited in the New World. When King Philip II of Spain turned to alchemy and the transmutation of mercury to silver in order to pay off the numerous debts of the Crown he was acting in perfect consonance with the context of the age. He is known to have sought the services of alchemists in 1557, 1559 and 1567, dates that overlap the introduction of amalgamation in the New World. The first attempt took place in Flanders just one year into his reign, when he declared his first default on payments by the Crown.[329] From a report filed by the Venetian Ambassadors to the Spanish Court it is stated that a German called Pedro Sternberg successfully transmuted for the King six parts of mercury into six parts of silver, a one to one equivalence of mercury to silver produced, with the aid of one ounce of unidentified 'powders'.[330] This type of transmuted silver was considered an option to pay the troops in Flanders.[331] By 1567 Philip II was still pursuing transmutation of mercury so as to be able to pay his creditors.[332]

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[328] Tara E. Nummedal, *Alchemy and Authority in the Holy Roman Empire* (Chicago: University of Chicago Press, 2007), 33,86. For an example of the historiography on the evolution of ideas of alchemy and metallogeny through the early Modern Era, and its relation to the development of science and mining in general, and also to mining practice in the New World see Newman, *Atoms and Alchemy : Chymistry and the Experimental Origins of the Scientific Revolution* and J. Norris, "The Mineral Exhalation Theory of Metallogenesis in Pre-Modern Mineral Science," *Ambix* 53, no. 1 (2006).
[329] Francisco Javier Puerto Sarmiento, "La panacea aúrea. Alquimia y destilación en la corte de Felipe II (1527-1598)," *Dynamis (Granada, Spain)* 17(1997): 114.
[330] Francisco Rodriguez Marin, *Felipe y la Alquimia* (Madrid1927), 16-17.
[331] Ibid.
[332] Ibid., 18-26. Philip II's attitude in this episode, a mixture of pragmatic scepticism and blind faith, is well summarized in the Spanish saying '*no creo en brujas, pero de que vuelan, vuelan'* – 'I don't believe in witches, but that they can fly, they can fly'.

Philip II's interest in alchemy went beyond the practicalities of transmutation, as his design of El Escorial has shown.[333] For the Spanish historian Puerto Sarmiento the King's interest in the transmutation of mercury into silver was triggered by the success of Medina's amalgamation process in New Spain. This however does not match well with the dates or the general alchemical context of the period. I would argue quite the contrary, that one major reason why mercury would always receive such prompt backing from the Spanish Crown and its officials was the aura of its alchemical and ontological role in the transmutation to silver. Philip II would keep to his death a gift of a silver tray claimed to have been made in Brussels from transmuted silver.[334]

Did the *mineros* in the field think that mercury was transformed into silver during the treatment of the ores by amalgamation? At least one contemporary voice certainly thought they did. Juan de Cardenas, a medical doctor who published in 1591 the earliest extant technical description of the amalgamation process as practised in New Spain, states that 'some say that since mercury is so similar to silver ... those ... pounds ... that are missing of mercury were converted into silver'.[335] As Barba tells the story, the discovery of his *cazo* process started as an attempt to 'coagulate' (*cuajar*) mercury in an iron vessel; since he did not have much iron to build the vessel, he tried out a copper one, and added some silver ore powder to assist in the coagulation.[336] Coagulation of mercury into Luna, set on its way by the addition of some silver, was a common alchemical attempt at transmutation. A later historian concurs, stating that in

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[333] Eslava Galán, *Cinco tratados españoles de alquimia*, 110-11. His nephew, the Emperor Rudolph II, would also become a patron of alchemy in Prague. David Goodman, "Philip II's Patronage of Science and Engineering," *The British Journal for the History of Science* 16, no. 1 (1983): 55. The role of alchemy and royal patronage in Europe has been studied by Nummedal, *Alchemy in the Holy Roman Empire*.

[334] Puerto Sarmiento, "La panacea aúrea. Alquimia y destilación en la corte de Felipe II (1527-1598)," 115.

[335] '*algunos dicen que como el azogue es tan semejante a la plata ... aquellas ... libras ... que faltan de azogue se convirtieron en plata*' in Juan de Cárdenas, Primera parte de los problemas y secretos maravillosos de las Indias (México: Academia Nacional de Medicina, 1980), 161.

[336] Barba, *Arte de los metales*, 105.

the sixteenth century amalgamation was confused with transmutation.[337] I would posit it was deeper than a simple confusion, that there had never been a strong conceptual divide between the two. As I follow the path of amalgamation to its industrial apotheosis in the New World, I will point out the many traces of its alchemical past that crop up in the recipes, the words and the lore of the amalgamation refiners.

3.3 The gold connection

According to Brading and Cross, 'at first the industry [New World silver mining] formed little more than an overseas extension of the great central European mining boom of the years 1451 -1540'.[338] On mining techniques this statement may apply up to a point, but on refining methods it merits a more critical assessment. The European boom to which it refers was based mainly on the *Saigerprocess* or copper liquation, a more complex smelting technique than cupellation, but still based on using lead as the primary refining agent. It is thus difficult to understand how European silver refiners, who had nurtured all their technical skill from the smelting of argentiferous copper or lead, would have any expertise outside of smelting with lead to offer the New World. Amalgamation was never applied to argentiferous copper or galena in Europe because it did not work on this type of silver ore, as will be made clear in the following sections of this chapter.

The picture changes if we focus on the introduction of a different technology that appears on a large scale in Europe around the middle of the fifteenth century. Blanchard speculates on the role played in its transmission either via Alpine gold workings of the twelfth

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[337] '*en el siglo XVI se confunde la amalgama con la transmutación*' Rodriguez Marin, *Felipe y la Alquimia* 62-69. Other historians have remarked upon the alchemical context of the sixteenth century, for example Bargalló, *La química inorgánica* 101-104.; Castillo Martos, "Plata y revolución tecnológica," 91.;"Alquimia en la metalurgia de plata y oro en Europa y America ".; *Bartolomé de Medina*, 54-55, 59-79. I have not come across a detailed tracing of the roots of mercury and amalgamation as presented in this section.
[338] Brading and Cross, "Colonial Silver Mining: Mexico and Peru," 545.

and thirteenth centuries or by Genoese spies in the Maghreb in the 1430s. Whichever the channel:

‘in the 1440s Genoese merchantmen may be seen transporting mercury from Almadén to Bruges for transhipment to the Rhineland where knowledge of the intricacies of mercury amalgamation, previously confined in the main to the gold refineries of Asia and Africa [Sudan], was now current’.[339]

The skills developed during the amalgamation of tons of gold ore in Europe are very relevant to the development of silver amalgamation in the New World. Between 1460 and 1485 Blanchard states that approximately eight tons of gold were produced via amalgamation in Egypt and North Africa with an additional three tons produced in Europe, requiring a total use of forty five tons of mercury from the Almadén mine in Spain.[340] Blanchard’s data challenge the notion that amalgamation before the New World was only practised using minor quantities of material. An industrial scaling-up of gold amalgamation had already taken place in Europe half a century before Columbus sailed to the New World.

As soon as Columbus found samples of placer gold on Hispaniola he returned on his second expedition with a contingent of experienced miners from Almadén for mining and from other sites for the extraction of placer gold from washings. The finding of one kg of mercury at the site of La Isabela, the first colony to be founded on Hispaniola in 1494, together with

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[339] The exact roots of amalgamation applied to ores is unknown but according to Blanchard were Afro-Asiatic in origin. Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 1029. A thriving market for mercury exports from Spain existed well before the fifteenth century: ‘Geniza [Old Cairo, Egypt] records show ... mercury ... carried eastward ...after copper, mercury and its derivative, mercuric sulphide (cinnabar) were the most noted Andalusi metallic exports. Amongst other uses, mercury was important in the refining of gold [this is a statement applying to a period before 1212] ... mercury was traded through Seville to markets in the Mediterranean, England and Flanders during the thirteenth and fourteenth centuries ... references to the export of Andalusi mercury are earlier than those for copper, with Mas’udi describing Andalusi mercury “exported to the entire Islamic and non-Islamic world” by the middle of the twelfth century’, in Olivia Remie Constable, *Trade and Traders in Muslim Spain : the Commercial Realignment of the Iberian Peninsula, 900-1500* (Cambridge; New York: Cambridge University Press, 1994), 20, 165, 186-87, 217.

[340] Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 1030, 1034.

galena and implements required for the assaying by smelting of ore samples, is strong evidence for a technical approach to gold refining from the start.[341] As Born recognized in his 1791 text, 'quicksilver … after the arrival of the Spaniards … may have been used even in America for the extraction of gold-dust from the sands'.[342] Mercury would have been used to assay or refine by amalgamation placer gold, using methods similar to those that Biringuccio and Agricola would include in their works published some 50 years later.[343]

The production and export of gold by the Spaniards in the Caribbean islands have been interpreted as being somehow deficient in the historiography:

'The searches for sources of both metals [gold and silver] carried the Spaniards far and wide across the Americas ... on the promise of gold they first settled the Caribbean; finding little in the islands they were lured on by golden visions to the Isthmus'.[344]

However the hard data indicate otherwise. Gold exports just from Hispaniola between 1492 and 1555 reached a total of 23.4 t, and in the peak decade of 1501 to 1510 they averaged over 1.3 t per year.[345] This represents roughly half the total annual gold produced by amalgamation from Rhineland gold workings in Europe from 1460 to 1485.[346] Columbus had not exaggerated on the wealth of gold he found on Hispaniola, equivalent to any European source of gold known up to that time.[347] This major amount of new gold production attracted

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[341] A. M. Thibodeau et al., "The Strange Case of the Earliest Silver Extraction by European Colonists in the New World," *Proceedings of the National Academy of Sciences of the United States of America* 104, no. 9 (2007). Sanchez Gomez refers to a decree dated 1495 in which 15 *quintales* (approx.. 700 kg) of mercury are requested from Almadén to send to the Indies. It is further evidence of the technical approach adopted by Spain in its search for bullion in the New World. The mercury would have been used for assaying gold and also for production by amalgamation. Sánchez Gómez, *Minería no férrica en el Reino de Castilla*, 277.

[342] Inigo Born, *Baron Inigo Born's New Process of Amalgamation of Gold and Silver Ores, and Other Metallic Mixtures: As by His Late Imperial Majesty's Commands Introduced in Hungary and Bohemia*, trans. R.E. Raspe (T. Cadell, 1791), 8.

[343] Biringuccio, *The Pirotechnia*, 30.; Agricola, *De re metallica*, 243. A modern description of field assaying of gold ores with mercury is given in Young, "The Spanish Tradition in Gold and Silver Mining," 300-301.

[344] Bakewell, "Colonial Mining," 108.; 'Columbus first established bases on the islands ... though they yielded ... but little gold' in Aitchison, *History of Metals*, 360.

[345] TePaske and Brown, *Gold and Silver*, 33, 56.

[346] Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 1160.

[347] The same geological deposits of gold found by Columbus in Hispaniola have placed modern day Dominican Republic seventh among the top ten gold sources of the world, with over 33 million ounces of gold reserves at the

the attention of European miners and artisans with experience in gold amalgamation as already practised on an industrial scale in the Rhineland and Austrian mines. Did some of these miners have knowledge of the advances already made in Europe on the amalgamation of silver ores?

The Republic of Venice had also been working its silver mines on the mainland. Its geographical location (see Figure 1.7) made it an obvious choice for the export of silver and gold to Asia. According to Day it exported the equivalent of up to one metric ton of gold per year to Asia during the first half of the fourteenth century, equal in value to around 25% of all new silver mined in Europe in that period.[348]

'Italian prospectors searching for ores in Bohemian or German mountains ... known as "Vlach" in Czech ... were often sent out by glassworks in Venice to collect ores for the dyeing of glass. At the same time they gained recognition as able metallurgists and ... employed as such by the nobility and ... King ... [thus] the Royal Mint in Kutná Hora [is the] "Vlachian court" ... there is a Vlachian Street in Prague. Later these Italian prospectors reached the Harz Mountains in Germany ... they also experimented in ... transmutations'.[349]

It is more than probable that Venetian and German miners exchanged their know-how on gold amalgamation and silver refining during this very active production period. What was good for gold was good for silver as well, and the illustration on gold amalgamation in Ercker could well represent the later process on silver ores, down to the detail of mercury being squeezed from a leather pouch onto the ore being amalgamated.[350]

Vergani has described the Venetian silver mines at Schio in the Haut Vicentin area, which saw their highest level of activity in the period 1490 to 1530. He argues that though amalgamation of silver had been used for a long time in the gilding of metals and glass, it had not been used to refine silver ores prior to the sixteenth century. He presents strong evidence

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Pueblo Viejo deposit. Data from Global Gold Mines & Deposits 2012 Ranking, published by Natural Resource Holdings, http://www.nrh.co.il/i/pdf/NRH_Research_2012%20World_Gold_Deposits.pdf.

[348] John Day, "The Great Bullion Famine of the Fifteenth Century," *Past & Present*, no. 79 (1978): 11, 38-39.

[349] V.Í. Karpenko, "The Oldest Alchemical Manuscript in the Czech Language," *Ambix* 37, no. 2 (1990): 64.

[350] Ercker, *Treatise on Ores and Assaying*, 113.

that the first attempt took place in Venice in 1506, since the following year two ex-prospectors of gold, Tommaso Cusano and Giovanni Antonio Mauro of Verona applied for a patent from the Republic of Venice to '*extrahere argentums sine igne*', to extract silver without fire. According to the filing they were owners of a foundry and of mines of silver and lead in the Schio. Subsequent paperwork indicates 'without the shadow of a doubt that the invention consisted in treating the silver ore without fire and with water and quicksilver'. Wars intervened and it was only in 1526 that Mauro applied himself again to the process, and to defend the patent against unauthorized use by other refiners.

'all the information concerning these patents emphasize on the one hand the dearth of wood … and on the other on the fact that the new process can be carried out "without costs of charcoal and of wood" … according to an estimation made by Mauro in 1530 … the refining of one mark of silver from local ores cost 16 L. using traditional methods, against a cost of 5 L. using the new process, which in addition was four times faster'.[351]

Berenguccio stayed in Venice from 1507 to 1509. He mentions that he paid with a diamond ring worth 25 ducats to 'one who taught it to me', but does not provide either name or nationality.[352] The circumstantial evidence is strong that the origin of his amalgamation recipe came from refining practice in the Venetian mines of the Schio region.[353] Other reports in the historiography correlate well with Vergani's scenario. Mercury is being exported from Spain to the Schio area by mid fifteenth century.[354] According to Blanchard amalgamation of gold and silver ores was being practised in the mining regions of Bohemia and Austria as of the fourteenth century, and the Venetian mines were in the mainland territory contested

[351] *'toute la documentation relative a ces brevets met l'accent d'une part sur la penurie des bois ... et d'autre part sur le fait que le nouveau procede s'effectue "sans frais de charbon et de bois" ... selon une estimation de Mauro ... de 1530 ... l'extraction d'une marque d'argent des minerais locaux coutait alors 16 L. par les methodes traditionelles contre 5 L. par le nouveau procede, lequel était de surcroit quatre fois plus rapide'.* Raffaello Vergani, "La métallurgie des non-ferreux dans la république du Venise (XVe-XVIIIe siècles)," in Mines et métallurgie ed. Paul Benoit, Les chemins de la recherche (Villeurbanne: Programme Rhône-Alpes recherches en sciences humaines, 1994), 210.

[352] Biringuccio, *The Pirotechnia*, 384.

[353] P. Braunstein, "Les entreprises minières en Vénétie au XVe siècle," *Melanges d'archéologie et d'histoire* 77, no. 2 (1965): 529-607.

[354]Heers, *Gênes au XVe siècle, activité économique et problèmes sociaux* 490.

between the Republic of Venice and Austria.[355] The most telling corroboration is the fact that in 1557 Philip II is advised to seek the help of amalgamation experts from Venice:

'the refining of [silver] ores is held to be the right choice in New Spain … in Spain we believe it will also be so [referring to the new mines at Guadalcanal] ... it is in the interests of Your Majesty that we look in Venice for a good official that knows about this mercury [process]. It will be of benefit to all the mines and to your Majesty'.[356]

The good official may have been a Garci Hernandez, who received in 1565 the following letter:

'His Majesty understands that in that city [Venice] there are some masters who know the art to extract silver without fire … I have been entrusted to write to Your Excellency … [so that] you may send a true and correct report to His Majesty ... being satisfied that these are not fictions nor mockery as sometimes happens, because if this is true His Majesty will wish to bring them to Spain so as to gain from their art'.[357]

The contents of these letters show that even by 1565 there was still some hesitation at the highest levels in Madrid about the amalgamation process being tested in the New World, so that the more technical support at hand, the better.

Was the Venetian know-how of amalgamation the recipe that was originally transmitted to New Spain in the mid-1550s? Vergani argues that it is, and proposed a route originating in Haut Vicentin, then Germany, Spain and finally New Spain. He argues that the transmission agent was not Biringuccio's book, since in this period techniques were made known not so

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[355] Blanchard, *Russia's "Age of Silver". Precious-metal Production and Economic Growth in the Eighteenth Century* Footnote 5, 356.
[356] '*el sacar el metal con açogue se tiene en la Nueva España por muy açertado ... en Espana creo que será lo mismo ... conviene al seruicio de V.M. que se enuie a Veneçia por algún buen ofiçial desto del açogue. Aprouechara para todas las minas y redundara en prouecho de V.M.' Sánchez Gómez, Minería no férrica en el Reino de Castilla, 326.*
[357] *'Su Magd. a entendido que en esa cibdad ay alguns maestros que tienen arte para sacar plata sin fuego ... ame mandado que yo escriba a V.M. ... [para que] pueda embiar muy verdadera y çierta relación a Su Magd. ... estando satisfecho que no son fiçiones ni burlas de las que suele auer, porque siendo verdad querria su Magd. lleuarlos a España y fauoreçer su buen arte'.* Ibid., 315.

much through texts but by the migration of skilled artisans.[358] However the chemical signature of the Schio process, the addition of a water soluble copper compound to the amalgamation recipe, is not observed in the New World until the 1590s (see the following section). This is the only reason to doubt this interpretation, but it is a strong one. Had the experience from Schio been transmitted verbatim to the New World, it would have cut some 50 years from the learning curve of the Spanish amalgamators.

Independently of events at Schio, European and German artisans would have transmitted know-how on large-scale gold amalgamation to Hispaniola, from where it would arrive to New Spain. There are two examples of this technical migration attracted by the gold of the New World. In 1525 the Italian mining specialist Paolo Belvio was sent to Hispaniola with a batch of mercury to reactivate the placer gold workings.[359] A more intriguing trail is the mention by the German historian Schafer of a Fleming named Gaspar Loman, sent initially by the Welsers to extract gold in Venezuela, who then moves to Cuba in 1540 to revive copper mines in the Sierra Madre.[360] In 1550 a Gaspar Lohman is awarded a *merced* (a royal grant) for proposing a method to dress ores prior to smelting, and together with Bartolome de Medina another *merced* in 1556, in recognition for his proposal of an amalgamation process of silver ores, based on drawings he had brought from Germany of machinery used for the refining of gold and silver ores with mercury.[361] For the refiners of the day, if smelting was running into trouble, the use of mercury would have been a natural option to try next. Whether Loman and Lohman are one and the same remains to be established, but their lives illustrate well how

[358] Vergani, "La métallurgie des non-ferreux dans la république du Venise (XVe-XVIIIe siècles)," 207-211.; Biringuccio, *The Pirotechnia*, 384.
[359] Sánchez Gómez, *Minería no férrica en el Reino de Castilla*, 277.
[360] as quoted by West, *The Parral Mining District*, 106.
[361] '*recibe orden del virrey, como persona experta … había mostrado al virrey ciertos dibujos y trazas que el se trajo de Germania a Nueva España de unos ingenios en que se beneficiaban los metales de oro y plata con azogue'*. S. Zavala, "La amalgama en la minería de Nueva España," Historia Mexicana XI, no. 3 (1962): 418-19.

mining and refining in this period was a continuum of experience applied in the field, not restricted to any particular metal. When New Spain was found to be richer in silver than in gold, the Lomans of the time would have responded without a break in their stride.[362]

The large-scale mercury amalgamation of gold in Africa and then the Rhineland of Europe set the stage for the application of amalgamation in the New World. It is precisely because the initial recipe came from a much simpler process for amalgamating gold that its implementation in the New World for silver ores would require a learning curve spanning some fifty years. As the nature of the main silver ore being amalgamated changed from native silver and silver chlorides to the deeper silver sulphides, so too would the amalgamation recipe have to be adapted to each new challenge.

Peru would lag some fifteen years behind New Spain in applying a silver amalgamation process, but in less than 30 years would produce fundamental changes to the simple gold amalgamation recipe that would transform it into an efficient industrial refining process specifically tailored to silver ores. To follow these historical events it is first necessary to review the seven basic chemical principles that defined the history of amalgamation of silver ores in the New World.

3.4 The chemistry of amalgamation

1. <u>Mercury only amalgamates elemental silver. It does not amalgamate silver compounds</u>

This is the fundamental but often overlooked tenet of amalgamation with mercury. In the strict use of the term, amalgamation does not involve a chemical transformation of either

[362] The report to the Crown that silver was proving to be more important than gold in New Spain took place in 1533, according to Mendizábal, *La mineria mexicana*, 19-20.

mercury or of elemental silver. An amalgam does not have a fixed amount of mercury. It is a physical mixture that does not change the original chemical nature of its constituents. It can be either a liquid or a solid depending on the amount of excess mercury that it can retain like a sponge retains water.

The confusion arises when amalgamation is the term applied to the whole refining process using mercury, during which chemical reactions involving mercury takes place.

2. Mercury reduces silver chloride to silver, and in turn oxidizes to form calomel, mercurous chloride (Hg_2Cl_2)

This is the chemical reaction that allowed the first miners of weathered silver deposits in the New World to extract silver using the simple amalgamation recipe derived from the refining of gold. Mercury plays a double role in the amalgamation of silver ores: it is an amalgamating agent, and it is also an active chemical reagent that reduces any silver chloride it comes into contact with according to the following equation:[363]

$2Hg(l) + 2AgCl(s) \rightarrow 2Ag(s) + Hg_2Cl_2(s)$ **Reaction 1**

3. Iron and copper can also reduce silver chloride to silver

Iron and copper can also act as reducing agents to silver chloride, as for example: [364]

$AgCl\ (s) + Fe\ (s) \rightarrow Ag\ (s) + FeCl_2\ (aq)$ **Reaction 2**

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[363] In all the chemical reactions the letters in parenthesis indicate the physical state of the reactant, thus (s) solid, (l) liquid, (aq) in aqueous solution.

[364] Percy, *Metallurgy Silver*, 94. In the case of copper, this is the reason why the *cazo* process invented by Barba cuts down significantly the consumption of mercury during amalgamation. Iron would be part of the recipe in later versions of the *cazo* and barrel processes. Copper was added to amalgamation recipes to cut down loss of mercury at Guadalupe and Calvo according to Bakewell, *Silver Mining in Zacatecas*, 314.

4. Mercury does not reduce silver sulphide to silver

Laboratory runs carried out with mercury, salt and silver sulphide have failed to yield an amalgam of silver and mercury under conditions that replicate the amalgamation process of silver ores.[365]

5. Silver sulphide reacts with copper salts and sodium chloride in the presence of oxygen to form silver chloride

Silver sulphide reacts with cupric ions in saline solution to produce silver chloride:[366]

$$Ag_2S(s) + 2Cu^{2+}(aq) + 8Cl^{-}(aq) \rightarrow 2AgCl(s) + 2[CuCl_3]^{2-}(aq) + S(s)$$ **Reaction 3**

6. Heating a silver sulphide ore with salt will transform the silver sulphide into silver chloride

This is an alternative route to convert silver sulphides into silver chlorides prior to amalgamation with mercury. It is known by the term 'roasting' and was used intermittently in the New World.[367]

7. Lead renders a silver ore unfit for amalgamation

Lead amalgamates with mercury, and would be present in much larger quantities than silver in the galena ore. This competition between a much larger content of lead than silver for the same amount of mercury being added would lead to a serious depletion in the amount of

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[365] Dr. David Johnson, private communication.

[366] According to the laboratory experiments it is oxygen that acts as oxidizing agent and the copper in magistral ultimately does not change its oxidation state, thus acting only as a catalyst. D.A. Johnson and K. Whittle, "The Chemistry of the Hispanic-American Amalgamation Process," *J. Chem. Soc., Dalton Trans.*, no. 23 (1999): 4242. The amalgamation cakes were subjected to periodic turnovers and treading, all of which would have incorporated fresh oxygen into the slurry mix. Thus it is reported that continuous treading by mules over twenty four hours accelerated the amalgamation process, but costs were deemed too high to implement this on a regular basis, in Duport, *Métaux précieux au Mexique*, 266.

[367] Biringuccio, *The Pirotechnia*, 137,142.; Agricola, *De re metallica*, 273-276. A discussion on roasting as practised in the nineteenth century can be found in Egleston, *The Metallurgy of Silver*, 226.; C.H. Aaron, *Leaching Gold and Silver Ores: The Plattner and Kiss Processes* (Barry & Baird, Printers, 1881), 15-20.

mercury available to either amalgamate any silver or to reduce the silver chloride, leading to a very low extraction rate and efficiency of the process. Other metals such as copper and bismuth can also interfere with this process.[368]

In summary, silver ores without lead respond to amalgamation by three parallel routes: i) by the direct amalgamation of any native silver with mercury ii) by the reduction of silver chlorides with mercury, iron and/or copper to elemental silver, which then amalgamates with mercury iii) by the formation of silver chloride from silver sulphide in the presence of copper and chlorine ions in aqueous solution, which then reacts as in ii). Silver chloride can also be generated from the sulphide by roasting the ore with salt prior to amalgamation. The only scenarios where calomel is not formed is when native silver is being amalgamated, in which case consumption of mercury could drop to zero. If silver chloride is also reduced to silver by copper or iron, then the consumption of mercury during amalgamation will also be lower.

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[368] The historiography up to the end of the nineteenth century is very clear that lead was a major impediment to the use of amalgamation. Though I will cite only the main authors, there are many other documents of the whole period that underline that this was common knowledge in the field. For example: 'the lead content of an ore is a formal impediment to refining by amalgamation'-'*por quanto es impedimento formal lo plomoso de las piedras para el beneficio de azogue*' in José Antonio de Villaseñor y Sánchez, Theatro americano : descripcion general de los reynos y provincias de la Nueva España y sus jurisdiccions (Mexico: Imprenta de la Viuda de D. Joseph Bernardo de Hogal, 1746), 132. Sonneschmidt warns that amalgamation is not apt for ores that contain copper, lead or antimony. Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 55. 'moreover the ores of the Harz forest are very rich in lead, and cannot therefore be treated with quicksilver in so easy and cheap a manner as other ores' in Born, *Born's New Process of Amalgamation*, 239. Kerl, Crookes, and Röhrig, *Prof. Kerl's Metallurgy*, 319.; Eissler, *The Metallurgy of Argentiferous Lead*, 163-172.; G. Küstel, *Roasting of Gold and Silver Ores: and the Extraction of Their Respective Metals Without Quicksilver* (AJ Leary, stationer and printer, 1880), 14, 39. It is in the modern historiography that this knowledge becomes somewhat blurred. A case in point is the interpretation by historians of the failure of the amalgamation trials held at the newly discovered mines of Guadalcanal in Spain right after its implementation in New Spain. One of the few historians to have correctly interpreted the failure of the trials as caused by the lead content of their ores is Joaquín Fernández Pérez, "La amalgamación de los minerales de plata," in *El oro y la plata de las Indias en la época de los Austrias*, ed. Concepción Lopezosa Aparicio (Madrid: Fundacion ICO, 1999), 149. In contrast, Castillo Martos blames the failure on Boteller for attempting to pass as an expert on amalgamation, becoming unmasked by his inability to amalgamate the unamalgamateable, the argentiferous lead ores of Guadalcanal. Manuel Castillo Martos, "Primeros beneficios de la plata por amalgamación en la América colonial (1565-1600)," in *Minería y metalurgia. Intercambio tecnológico y cultural entre América y Europa durante el período colonial español*, ed. Manuel Castillo Martos (Sevilla, Bogota: Muñoz Montoya y Montraveta Editores, 1994), 383.

Towards the end of the eighteenth century German metallurgists were quite correct in pointing out that mercury only amalgamated with elemental silver. Born's original statement is unimpeachable: '[since] it is an axiom in chemistry … that quicksilver never unites with metallic calxes, it naturally followed that … silver cannot be extracted from … ores by quicksilver … but that the … silver calxes must be reduced into their metallic form'.[369] Thus the conclusion posited by the English historian Tristan Platt that 'German metallurgical discourse was based on a theory of matter that denied the possibility of refining most silver ores by amalgamation with mercury' or that there was a European 'monopoly of truth' or a 'system of ideas' that can be interpreted as opposing European science to American tradition, cannot be based on the assumption that the German scientists were mistaken in their concept of amalgamation.[370] It remained a fact of chemistry that amalgamation could not be applied to the majority of silver ores of Europe, which consisted either of silver-rich lead or copper ores.

In the early nineteenth century Humboldt was the first observer to attempt to understand the chemistry behind amalgamation by replicating its process under controlled laboratory conditions.[371] The lack of an established chemical theoretical framework hampered most efforts of the early nineteenth century to explain how mercury was able to extract silver from its ores.[372] The challenge was to recognize that mercury had two functions, one to create elemental silver from the fraction of silver chloride, the other to amalgamate all the metallic

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[369] To find a way around the fact that mercury only amalgamates silver metal, Born argued that silver particles, like larvae, were 'wrapt up in sulphur and arsenic … or other metals and semi-metals, so as to become wholly invisible to the naked eye … thus enveloped in ore and stony matter, should be freed of their external disguise … either mechanically or chemically … assisted by calcination, which expels and destroys these heterogeneous bodies'. Born, *Born's New Process of Amalgamation*, 5, 73-74. Born argues that metallic silver silver was always present, but hidden.

[370] T. Platt, "The Alchemy of Modernity. Alonso Barba's Copper Cauldrons and the Independence of Bolivian Metallurgy (1790-1890)," *Journal of Latin American Studies* (2000): 2, 3, 30.

[371] Humboldt, *Essai politique*, Tome IV, 76-80.

[372] Amalgamation of silver ores reached its industrial pre-eminence in the New World well before Mendeleyev published the first version of the periodic table of the chemical elements in 1869. Early theories on the mechanism of amalgamation can be found in Duport, *Métaux précieux au Mexique*, 120-44.; Laur, "De la metallurgie de l'argent au Mexique," 258-70.

silver present. It very soon became evident that a salt of mercury was being formed, which was variously described as ‘sweet mercury’ (which may reflect the sweet taste of calomel), chlorinated mercury, a subchloride or chloride of mercury, even if the exact formula was not yet known.[373] By 1868 a German textbook on metallurgy could state unequivocally that ‘the large loss [of mercury] is chiefly caused by the formation of chloride of mercury … the presence of mercury being necessary, not merely as a means of collecting the particles of silver … but also as a chemical reagent’. In addition it also recognized the fact that other metals could reduce silver chloride in place of mercury: ‘if iron is not present in sufficient quantity [in the amalgamation recipe]… mercury will be wasted by its conversion into calomel’.[374]

The work by Johnson and Whittle was a long-overdue modern laboratory study in which they put to the test the main amalgamation theories proposed in the historiography.[375] Their results confirm the transformation of mercury into calomel as an inherent part of the process, and yet the historiography in general has been slow to point out that mercury was not ‘lost’ during the process but consumed as a chemical reagent. The following example underlines the problem in not recognizing the chemical nature of the amalgamation process: ‘losses of mercury, an expensive substance, tended to be great when the amalgamation

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[373] ‘part of mercury is converted into a [chloride]’ -‘une partie du mercure se convertit en muriate’ in Humboldt, *Essai politique*, Tome IV, 77. ; *Mercurio dulce* in Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 125.; ‘du mercure chloriné’ in Duport, *Métaux précieux au Mexique*, 124.; ‘the chloride of silver … reacts on the metallic mercury, a portion of which is converted into subchloride, whilst the remainder combines with the silver thus liberated’ in Pique, *A Practical Treatise on Silver*, 115.
[374] Kerl, Crookes, and Röhrig, *Prof. Kerl's Metallurgy*, 325, 338-40. *Cloruro de azogue* (chloride of mercury) is identified in Hermosa, *Manual de Laboreo de Minas*, 239.
[375] Platt advocated that ‘future research, requiring chemical knowledge and laboratory resources, must attempt to repeat all the procedures experimentally … only then will be able to evaluate properly … American … practice’ of the amalgamation process. Platt, "The Alchemy of Modernity. Alonso Barba's Copper Cauldrons and the Independence of Bolivian Metallurgy (1790-1890)," 15-16. In the recent historiography the only attempt to correlate the laboratory with historical practice has been Johnson and Whittle, "The Chemistry of the Hispanic-American Amalgamation Process." Sets of chemical equations have been proposed that include the formation of calomel (for example Bargalló, *Minería y metalurgia colonial*, 194.; Castillo Martos, *Bartolomé de Medina*, 223. None have the correlation with experimental results presented by Johnson and Whittle.

processes of the day were applied to ores of very high silver content'.[376] The statement is misleading on two fundamental issues. First, mercury is mainly consumed via a chemical reaction, not lost. An industry that buys a reagent for its processes is not incurring a loss but a production cost. Ulloa makes reference to the disdain of European metallurgists on the amalgamation process as practised in the New World due to the great waste of mercury.[377] There was no such great waste, but simply the required consumption of mercury in a chemical reaction. Second, from a chemical point of view mercury is only consumed if there is silver chloride in the ore to react with, forming calomel. If the silver content is of native silver only, whether high or low, the consumption of mercury could in theory be nil, since it will not react chemically with native silver. This lingering misconception on the fundamental nature of the amalgamation process of silver ores affects the manner in which the environmental impact vector of mercury has been interpreted in most of the literature from the twentieth century to the present, so I will return to this critical issue in Sections 3.9 and 3.10.

3.5 The implementation by stages of the amalgamation process

Chronologies of the practice of amalgamation in the New World have been published in the historiography, but none follow the chemical *pas de deux* between the chemistry of the recipe ingredients and that of the silver ores being treated in the New World.[378] To follow the trail I will be switching from New Spain to the Andean experience around Potosí, since the historical records of the latter provide a wealth of technical detail not as yet found for the former, which correspond to the critical last quarter of the sixteenth century. It is a period of

[376] Bakewell, *Miners of the Red Mountain*, 18.
[377] Antonio de Ulloa, *Noticias americanas: Entretenimientos phisicos-historicos, sobre la America Meridional, y la Septentrional Oriental* (Madrid: Imprenta de Don Francisco Manuel de Mena, 1772), 267.
[378] Bargalló, *Minería y metalurgia colonial*, 112-133.**;** Carlos Sempat Assadourian, "Base técnica y relaciones de producción en la minería de Potosí," in *Ciencia colonial en América*, ed. Antonio Lafuente and José Sala Catalá (Madrid: Alianza, 1992).; Castillo Martos, "Primeros beneficios amalgamacion."

fifty years in which human ingenuity aided by the mineral riches of the subducted Andes guided the theoretically blind but very pragmatic Spanish refiners through the complexity of the concatenated chemical reactions needed to extract the most silver out of a suitable ore. The profile of the tongue-tied, uncouth yet skilled refiner that implemented the amalgamation process in the sixteenth century is well described by the Viceroy Toledo when he refers to the manner in which the amalgamation method was brought to Potosí, thanks to the arrival at Cuzco:

‘of a poor Spaniard from Mexico who calls himself Pero [sic] Hernández whose knowledge cannot be questioned even if it only covers what he does nor can he barely express himself were it not for a sharper companion who understood what lay within the simplicity of the other’.[379]

The end result was a process simple to operate at ambient temperature, requiring less skills than smelting, whose longevity and lack of change is not a sign of backwardness but rather of a chemical maturity achieved as early as the end of the sixteenth century.

In spite of the attention given to Bartolomé de Medina in the historiography as the man responsible for implementing amalgamation in the New World, there is at present not a single historical document that provides any detailed information of his refining activity carried out in Pachuca, New Spain, in the mid-1550s.[380] The first extant account with a minimum of

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[379] ‘*un español de Méjico pobre que se dice Pero Hernández y no lo es menos de entendimiento porque no le tiene para más de lo que hace ni aun apenas lo sabe declarar con otro compañero agudo que entendió lo que avía dentro de la simplicidad destotro*’ as quoted in Sempat Assadourian, "Base técnica y relaciones de producción," 128. The burst of empirical genius shown in the altiplano of the Andes in the sixteenth century has not received the same attention as Medina’s efforts in New Spain, even though the technical documents are much stronger for the Andes.

[380] The lack of due diligence on the claim that Medina invented amalgamation of silver ores, and the uncritical repetition of the claim in the historiography, raises the question whether a similar laxity would be shown by historians on a claim of similar importance in the history of technology in Europe. The Spanish historian who first brought to light of what little was left by Medina wrote: ’the documents [left by Medina] … do not deal with the discovery of Bartolome de Medina in its scientific aspect, but of its history … so, then, I will not deal with the technical part, only the historic one’ - ‘*los documentos ... no tratan del descubrimiento de Bartolome de Medina en su parte científica, sino en la historia ... asi, pues, no voy a tratar la parte técnica del descubrimiento, sino de la historica*’ in Francisco Fernandez del Castillo, "Algunos documentos nuevos sobre Bartolome de Medina,"

operational details of amalgamation in New Spain is from a report published in 1591 by Juan de Cardenas.[381] For the initial period that saw the introduction of amalgamation I therefore turn first to the description by Montesinos of Fernando de Velasco's pioneering attempts to use amalgamation in Peru:

'sometimes he added the rocks with metal to the mercury, sometimes he broke them down in pieces, and still in neither manner would the metal take the mercury, until tired of these trials he broke the rocks into smaller pieces and leaving them in mercury forgot about them for many days and went back to his smelting operations ... [after a few days he] separated the mercury ... squeezed it through a cloth and saw a bit of pella ... if the metal were to be more finely ground, the mercury would act more quickly'.[382]

The simplicity of the method mirrors the amalgamation of gold as practised in the Western Sudan in the twelfth century: 'garnering their fragments of gold (quartz), mixing them with mercury and mixing the whole over a charcoal fire so that the mercury evaporated leaving a mass of founded pure gold'.[383]

In 1585 Luis Capoche published his first-hand account of how amalgamation was carried out in Potosí during the period that had seen a nine-fold increase in silver refined, over eighty amalgamation units built, and seven of the system of lakes that would guarantee a

Memorias de la Sociedad Alzate 47(1927): 231-251. In the absence of any technical document, the claim in favour of Medina rests on two facts: that he was awarded a *merced* (a royal grant) that allowed him to receive payments from any refiner applying his amalgamation process, and that refiners using his method were failing to pay him. A *merced* by itself is not proof of a technical innovation that truly works, and during the same period a *merced* was also awarded to the use of *solimán*, mercuric chloride, a useless recipe that was soon dropped. A joint *merced* for amalgamation of silver ores was awarded both to Medina and Lohman, in 1557 leaving open the equally valid interpretation that both of them were adapting a known process to the silver ores of New Spain, not inventing one. For an example of a recent hagiography on Medina that includes all these facts, including the use of mercury amalgamation of silver ores in Venice prior to Medina, yet manages to exclude them from its overall conclusions, see Castillo Martos, *Bartolomé de Medina*. For a fictionalized reconstructions of events in Pachuca see Probert, "Bartolome de Medina: the Patio Process and the Sixteenth Century Silver Crisis."

[381] Cárdenas, *Primera parte de los problemas y secretos maravillosos de las Indias* 156-65.

[382] As quoted in Bargalló, *Minería y metalurgia colonial*, 136.

[383] As quoted from al-Idrisi in Blanchard, *Mining, Metallurgy and Minting in the Middle Ages*, 3 1157.

constant supply of water power to drive the stamp mills.[384] According to Capoche : 'having ground the ore … to a fine flour ... the Indians place it in …boxes … where they mortify it with brine ... and ... add mercury ... there is sufficient brine for the ore to make a slurry'.[385] This implies that up to 1585 the main ores being refined at Potosí were still mainly native silver and silver chloride, the only two sources of silver that would amalgamate under such a simple recipe that only required water, salt and mercury.[386] Silver sulphides would not have responded to the recipe described by Capoche, except under the spurious presence of soluble copper salts in certain batches of ore.

The huge amounts of weathered silver ore discarded by the initial wave of ignorant refiners were the source material for the simple amalgamation recipe initially tried out in New Spain. The chemical impotence of this primitive recipe derived from gold workings became evident once these weathered ores containing silver chloride and native silver run out, and refiners were faced with increasing amounts of silver sulphide ores (the *negrillos*). This in turn triggered in the following twenty years a burst of innovation that would not be repeated in the history of amalgamation in the New World. It would lead to the birth of an amalgamation process tailored specifically to silver ores, capable of refining not only native silver and silver halides but also the more abundant silver sulphides as well. It is very well documented thanks to the Spanish Viceroy of Peru, Don Fernando de Torres y Portugal, who in 1588 sent Juan Ortiz de Zárate to investigate the state of technical innovation in Potosí. He was not driven by

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[384] Capoche, "Villa Imperial de Potosi," 117. Arzans writing in the 1700s states that already by March 1577 a total of 10 million 'reales a ocho' had been invested in building some 100 'cabezas de Ingenio', mill heads, in Potosí. Arzáns de Orsúa y Vela, *Villa imperial de Potosí*, 169.

[385] '*molido el metal ... hacen la harina ... delgada ... la pasan los indios a los cajones ..., donde la mortifican con salmuera ... y ... echan el azogue ... echándole tanta salmuera que se hace el metal un barro* ' Capoche, "Villa Imperial de Potosi," 123-24.

[386] It is important to note that Henry Wagner, one of the few modern authors who had also been a miner in the field, made a similar point when he drew attention to the fact that mercury and salt only work on the weathered section of silver deposits. Wagner, "Early Silver Mining in New Spain," 64.

scientific interest but by the troubling rumours that more efficient recipes were being applied that would reduce the revenues from the sale of mercury by the Crown. Ortiz was instructed

> 'to find out with great care and diligence which new invention or inventions have been proposed or are being proposed to refine those ores and who began first and in which manner and who has continued them and wishes to continue in the future and which trials have been made on a small or large scale and which have been positive and which not'.[387]

The wide scope of the instructions resulted in a detailed technical snapshot of the state of amalgamation in Potosí precisely during the period when the refining community was empirically finding its own solution to the challenge of refining silver sulphide ores. Two innovations would persist until the end of amalgamation in the nineteenth century. First, finely ground iron was included in the recipe, which reduced the consumption of mercury.[388] The second innovation was the result of developments that are best seen as a weave of two synergistic and concurrent improvements rather than a planned sequence of events. The nature of the ores was changing: more and more silver sulphides (*negrillos*) were coming to the surface but were not responding to the simple amalgamation recipe. That the silver sulphides represented the major challenge to the amalgamation recipe being used at the end of the sixteenth century in Peru is confirmed by a letter from 1600 that requests the Spanish Crown

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[387] '*que con particular cuidado y diligencia sepa y averigue que invencion nueva o invenciones se han pretendido y pretenden hacer para el beneficio de los dichos metales y quien las comenzó primero y de que manera y quien las ha proseguido e quiere proseguir e que experiencias se han hecho por menor y por mayor e cuales han salido ciertas o inciertas*' as quoted in Jimenez de la Espada, *Relaciones Geograficas de Indias - Peru II*, 184, 121.

[388] For the trials that led to the use of iron, see ibid., 124-28. It was clear in the 1600s that iron only decreased the amount of mercury consumed, but did not increase the amount of silver extracted: 'even though iron helped to avoid loss of mercury, the silver extracted was so little that it was of little profit'- '*aunque el hierro ayudaba para que no se perdiese el azogue, era tan poca la plata que se sacaba que no era de ningun aprovechamiento*', in the anonymous document titled Descripción de la Villa y Minas de Potosí, Año 1603, as reproduced in Anonymous, "Descripción de la Villa y Minas de Potosí, año de 1603 " in *Relaciones Geográficas de Indias - Perú I* ed. José Urbano Martínez Carrera *Biblioteca de Autores Españoles* (Madrid: Atlas, 1965 (1588)), 375.

to send German silver refiners to Potosí to assist in finding the right refining method for the *negrillos*.[389]

Two new approaches were therefore adopted. The deeper and more abundant *negrillo* ores started to be roasted with salt prior to being mixed with the weathered surface ores (*pacos*) and then amalgamated.[390] This increased the pool of silver chlorides in the ore that would be reduced either by iron filings or mercury, leading to more silver extracted by amalgamation. At some point it was decided to use a mineral mix using copper rich mineral instead of the more expensive roasted *negrillos* to mix with the *pacos*, with even better results.[391] The idea may have come from the use of c*opapiri,* a blue stone from Lipes (a location in the surroundings of Potosí), that was added to the amalgamation recipe, as proposed by Juan Fernandez Montaño around 1588. *Copapiri* was a mineral rich in copper sulphates, the first step to the critical incorporation of copper ions to the recipe.[392] The use of roasted copper pyrites would displace the use of *copapiri*. The success achieved by employing all available materials at hand underscores Eissler's dictum that isolated refiners in primitive settings need to adapt to the circumstances of their surroundings.[393]

The last major innovation to the amalgamation recipe would be introduced by Alonso Barba in the early 1600s. By heating the amalgamation recipe in copper pots, the copper surface

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[389] Copy of a letter from the Audiencia of Charcas to the King of Spain, dated 6th march 1600, as quoted in Jimenez de la Espada, *Relaciones Geograficas de Indias - Peru II*, 184, 132.

[390] '*el pueblo esta contentísimo, porque es el beneficio que han menester, y de mayor importancia que beneficiar los metales negrillos de por si, que por ser pocos, se acabarían en buen tiempo, y ayudando a los pacos duraran*' excerpt from a letter written by Don Pedro de Cordoba Messia to the Viceroy of Peru, 1st novermber 1602, as quoted in ibid.

[391] The greater cost of roasted *negrillos* is claimed to be due to deeper and flooded mines, plus the treatment of the *negrillos*. See ibid., 375.

[392] Ibid., 122, 128.

[393] The quotation from Eissler at the beginning of the chapter, where he refers to metallurgists working in the wilderness, in fact referred to conditions in Nevada, U.S.A, in mid nineteenth century, which makes the innovations in the Andes of the late sixteenth century even more remarkable. Eissler, *The Metallurgy of Argentiferous Lead*, vi.

would serve (inadvertently) as a reducing agent to the silver chloride present, thus decreasing substantially the amount of mercury transformed into calomel.[394] Barba's process was never applied on a similar scale as the other amalgamation processes, since it suffered from the same problems that it passed on to its progeny, the barrel process promoted by Baron Born at the end of the eighteenth century. Namely, it only worked on ores rich in native silver and silver halides, such as those mined in Catorce (San Luis Potosi) towards the end of the eighteenth century.[395] For other types of silver ores it was necessary to roast them prior to amalgamation, in order to increase their content of silver chloride. Since the *cazos* and barrels were also heated, this led to very high consumption rates of fuel, as will be seen in Chapter 5.[396] The advantages of the *cazo* and barrel techniques was an important reduction in the reaction time to a matter of hours, not weeks, and a significant decrease in the consumption of mercury.

The *azogueros* of Potosí would remember in 1617 the despair and joy that led to each of the main recipe stages described in the previous paragraphs:

'it seems convenient to remember that the metals initially found in Potosí ... were so rich that they were refined by smelting and this lasted some twenty years until as they run out and became less rich ... in time it was necessary to introduce amalgamation ... however ... due to the great losses of mercury that occurred ... due to not having found the best way to amalgamate them ... when they [the refiners] were starting to weaken in their resolve, amalgamation adding iron appeared ... and some twelve years ago [1605] amalgamation with added copper, that was such that it caused a redemption of that city [Potosí]'.[397]

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[394] Barba, *Arte de los metales*, 105-29.
[395] For a nineteenth century description of the cazo process see Duport, *Métaux précieux au Mexique*, 144, 284.; on ores for the *cazo* process, Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 130.
[396] The best source for the barrel process is the work by its promoter, in Born, *Born's New Process of Amalgamation*.; on the presentation of the Born process to his refining peers in Europe see Teich, "Born's amalgamation process," 320-329.; Francisco Omar. Escamilla Gonzalez, "Ilustración alemana y ciencia novohispana: la biblioteca de Fausto de Elhuyar," in *Alemania y México: Percepciones mutuas en impresos, siglos XVI-XVIII*, ed. Horst Pietschmann, et al.(Ciudad de Mexico: Universidad Iberoamericana, 2005), 403-406.; on the historical timing of the Born proposal see Arthur P. Whitaker, "The Elhuyar Mining Missions and the Enlightenment," *The Hispanic American Historical Review* 31, no. 4 (1951): 578-579. Towards the end of the nineteenth century a pan amalgamation process was implemented in the silver refining mills of the United States of America, where it is claimed there was resistance to adopting the barrel process. Again the changes were in the physical infrastructure of the process, not in its fundamental chemistry. See Egleston, *The Metallurgy of Silver*, 348.; Eissler, *The Metallurgy of Argentiferous Lead*, 34-40.
[397] *'parece conveniente traer a la memoria, que los metales que dio el cerro de Potosí a los principios .. fueron tan ricos que se beneficiaron por fundición, y esto duro cerca de veinte años hasta que por irse acabando y*

The semblance of a chronological succession of three amalgamation recipes should not mislead the reader. The use of iron filings accomplished a completely different result from the effect of roasting or adding copper sulphate. Iron (or a copper surface) decreased the consumption of mercury, while roasting and the addition of copper sulphate converted the silver sulphides into silver chloride, which could then be reduced either with iron, copper or mercury.

The evolution that took place in the amalgamation process is a very good example of how to be right for all the wrong reasons. The use of salt in the recipe was justified at the time by the need to remove any physical impediment between the mercury and the silver metal particles believed to be embedded in the ores: 'to clean (castrate or peel away from) silver of the films or coverings within which it is found'.[398] Acosta states that the ore was 'mortified with a concentrated salt solution … and this is done so that the salt can degrease the ground metal, from the mud or inert content, so that mercury can receive better the silver'.[399] The use of the term 'mortified' is one of the signs of the alchemical context of the process: 'nothing can be Animated and born again, unless it first suffer Mortification … by which dissolution … a most secret and noble change is brought about'.[400] Mercury was thought to be consumed because it tended to split up into tiny drops (*lis*) when subject to mechanical agitation. *Lis* would then be lost in the interstices of the locations where amalgamation was carried out, or

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teniendo ya menos riqueza...obligo el tiempo a que se introdujese el beneficio de los azogues… sin embargo … por las grandes pérdidas que tuvieron de azogue … por no haber dado en el punto de su beneficio… cuando ya comenzaban a enflaquecer, se dio el beneficio del hierro… y habrá doce años que se dio en el beneficio del cobre, que fue tal que causo una redempcion de aquella villa' Juan de Ibarra, "Suma de lo que el licenciado J de Ybarra como procurador general de la villa de Potosi pide [14 Agosto 1617],"(Madrid, 1617), BL General Reference Collection C.62.i.18.(37).

398 '*aplicar la sal para que limpie (castre o desenzurrone) la plata de las telillas o capuzes con que se halla'*. Bargalló, *Minería y metalurgia colonial*, 180.

399 '*Mortifican el metal con salmuera … y esto se hace para que la sal desengrase la harina de metal, del barro o lama que tiene, con lo cual el azogue recibe mejor la plata*.' In the same alchemical-religious vein Acosta would claim that the torment and purges suffered by silver metal were akin to those suffered by souls in their path to God. Acosta, *Historia de las Indias*, 113-14.

400 S.J. Linden, "Alchemy and Eschatology in Seventeenth-Century Poetry," *Ambix* 31, no. 3 (1984): 119.

washed away with the water. Iron filings were claimed to help coalesce the *lis* into larger particles that were easier to recover.[401] Barba argued that his process avoided mercury losses because:

'the loss of mercury ... that is caused by its diminution and division into very small parts with each mixing, due to which it is entrained by water and in the *lamas* [fine silt]. This inconvenience does not happen in this [Barba's] refining process, because mercury lies as a whole on the bottom ... without any movement that will break it down, and so no *lis* is ever seen in this process'.[402]

Roasting an ore was seen to disaggregate the particles of an ore, to eliminate *malezas* (weeds, in the sense of an unproductive and interfering component) as well as unwanted sulphur, and thus paved the way for a more intimate mix with mercury. Adding roasted copper pyrites gave heat to mercury and so hastened its embrace of silver, while lime was added to cool down an overheated process.[403]

For lack of primary sources it is impossible at this time to reconstruct in a similar manner the evolution of the amalgamation recipe in New Spain. If the recipe applied by Medina, Lohman and others in New Spain from the start had been taken from Biringuccio's work, it would have included not only salt but also verdigris.[404] The Viceroy of New Spain mentions in a letter addressed to the King dated 20th November 1554 that Medina has added 'a certain' *magistral* as part of his amalgamation recipe.[405] The term m*agistral* in the context of

[401] Garcia de Llanos, *Diccionario*, 39.
[402] '*la perdida del Azogue ... que se causa por subtilizarse, y dividirse en pequeñísimas partes con los repasos, a cuya causa se sale con el agua, y con las lamas. Inconveniente, que en todo cesa en este modo de beneficiar; porque se esta en el fondo el Azogue unido ... sin movimiento que lo desmenuce, y assi nunca se ve lis en este beneficio'*. Barba, Arte de los metales, 117.
[403] Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 96. A good guide to how historical observations on the amalgamation process can be interpreted with modern chemical theory can be found in Johnson and Whittle, "The Chemistry of the Hispanic-American Amalgamation Process," 4242.
[404] Biringuccio, *The Pirotechnia*, 384. Verdigris is a complex mixture of copper salts, some of them soluble in water, and thus a potential source of copper (II) ions for the conversion of silver sulphide to silver chloride.
[405] Berthe, "Le mercure et l'industrie mexicaine au XVIéme siècle," 142.

New World silver has become synonymous in much of the historiography with a copper sulphate additive, but to interpret the Viceroy's letter it is necessary to place the word '*magistral*' in the alchemical context of the period. The alchemical art was known in Spanish as the *Magisterio*, and *magistral* referred to any powdered substance used to assist in transformations.[406] It is not possible to conclude therefore from one isolated reference whether Medina used copper sulphate as early as 1554. We do not even know if he actually made the comment to the Viceroy, since the term *magistral* does not appear in the few extant papers from Medina. It could well have been the Viceroy giving an alchemical turn to his report to a King known to be steeped in alchemical lore.

The sparse reports on amalgamation in New Spain prior to the seventeenth century do not mention the addition of a copper salt to the recipe. The reports on expenses incurred in materials required for amalgamation of ores from Taxco in New Spain in an amalgamation *hacienda* from 1562 to 1564 do not include any copper additive.[407] Neither Gomez de Cervantes nor Juan Cardenas mention copper *magistral* in their descriptions of amalgamation in New Spain dating from the last decade of the sixteenth century. The earliest mention of *magistral* in New Spain is from 1602, when the Bishop Alonso y Mota does refer specifically to the need to add it in order to be able to refine *negrillos*.[408] If the need for copper *magistral*

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[406] '"Magisterium" is a word which even in classical times had developed the meaning of "method", and the alchemists often use it of their processes ... from this sense the word slipped over rather easily into a designation of the effective agent ... i.e. "salt alemboch is the magistery of all magisteries ... of itself it congeals and holds mercury, and converts silver into purest gold" ... here magistery is a substance' in Wilson, "An Alchemical Manuscript by Arnaldus de Bruxella," 303-304. It is in this general context that for example the term *magistral* was applied to *solimán*, mercuric chloride, as stated in Castillo Martos, *Bartolomé de Medina*, 210.

[407] García Mendoza, "Minas de plata en Taxco," 54.

[408] Gómez de Cervantes, *Nueva España siglo XVI*, 143-153.; Bargalló, *Minería y metalurgia colonial*, 125-27.; Brading and Cross, "Colonial Silver Mining: Mexico and Peru," 553.

to complete the amalgamation recipe was not established by trial and error in Peru until the 1590s, it is most probable that it only became known in New Spain until after that date.[409]

To argue otherwise would open the door to a very intriguing scenario whereby the Vice-Royalty of New Spain held back for nearly 50 years critical information from the main producer of silver at the time, to the detriment of the Spanish Treasury. Since the authorities of New Spain had awarded at least two *mercedes* on amalgamation they could not have pled ignorance as to the technical details of the processes involved.[410] Taking into account the surprising level of technical interest shown from Madrid into developments taking place with mercury and silver in the Americas during this period, this is a scenario hard to justify.[411] If the refiners of Peru were the first to identify the usefulness of copper *magistral* it remains to be seen how this

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[409] Even in Spain the use of a copper salt *magistral* does not figure in the recipe for amalgamation 'as applied in New Spain' for the ores of Guadalcanal as of the 1560s. González, *Noticia histórica minas de Guadalcanal*, II 408-12. The majority report in the historiography is that a copper salt *magistral* was introduced in New Spain only towards the turn of the sixteenth century. See for example Bargalló, *La química inorgánica* 90.; Wagner, "Early Silver Mining in New Spain," 66.; Bakewell, *Silver Mining in Zacatecas*, 203.;Pérez Sáenz de Urturi, "La minería colonial americana bajo la dominación española," 67.

[410] Castillo Martos, *Bartolomé de Medina*, 115-19.

[411] The chronology of events shows a central bureaucracy moving at colonial light speed. We have seen how Viceroy Velasco kept Charles V informed on Medina's testing of amalgamation during 1554. The Viceroy states he urged Medina to send for the German (identified in the July letter as Lorenzo) in view of the importance of this process for the Spanish Treasury (Berthe, "Le mercure et l'industrie mexicaine au XVIéme siècle," 142-43.). The King had also received from another channel the report of the arrival of Medina and of his claims to be able to refine silver ores with mercury. The report suggests his German advisor be allowed to travel to New Spain and to bring major amounts of mercury with him (Castillo Martos, *Bartolomé de Medina*, 86.) In early September 1555 the Crown is already instructing Viceroy Luis de Velasco to start searching for mercury mines. On the 29 December 1555 Medina set down on paper in Xilotepec, New Spain, how he managed to refine silver ores with mercury, though managing to leave out all practical information on the process itself (Fernandez del Castillo, "Algunos documentos nuevos sobre Bartolome de Medina," 231.). On the 31 December 1555 the Princess Regent of Spain would request the administrator of the Guadalcanal mines to check with the German Johann Schürren, the delegate from the Fuggers in charge of mining affairs in Spain, to determine if they had used mercury to refine silver ores, in view of the news coming out from New Spain (Sánchez Gómez, *Minería no férrica en el Reino de Castilla*, 325.). The ores of Guadalcanal were mainly argentiferous galena, so I would expect the Germans to have shrugged their shoulders in genuine ignorance of this application of mercury to silver and not gold. It is the chemical nature of the silver ores in Guadalcanal that explains the lack of success of the amalgamation trials in 1557 by Rivas, then by Mosen Boteller in 1562, and not any technical ignorance on the part of the frustrated amalgamators as has been suggested in the historiography (Bargalló, *Minería y metalurgia colonial*, 121-24.; Manuel Castillo Martos, "Introduccion," in *Minería y metalurgia: intercambio tecnológico y cultural entre América y Europa durante el período colonial español*, ed. Manuel Castillo Martos (Sevilla, Bogota: Muñoz Montoya y Montraveta Editores, 1994), 383.). By 1559 Spain restricts the supply and sale of mercury to the monopoly of the Crown (*Bartolomé de Medina*, 141.)

information was transmitted back to New Spain. It also implies that as in Peru, New Spain would be refining mainly native silver and silver chlorides until the turn of the century.

A timeline of the main events in the implementation of amalgamation of silver ores in the New World is provided in Figure 3.1.

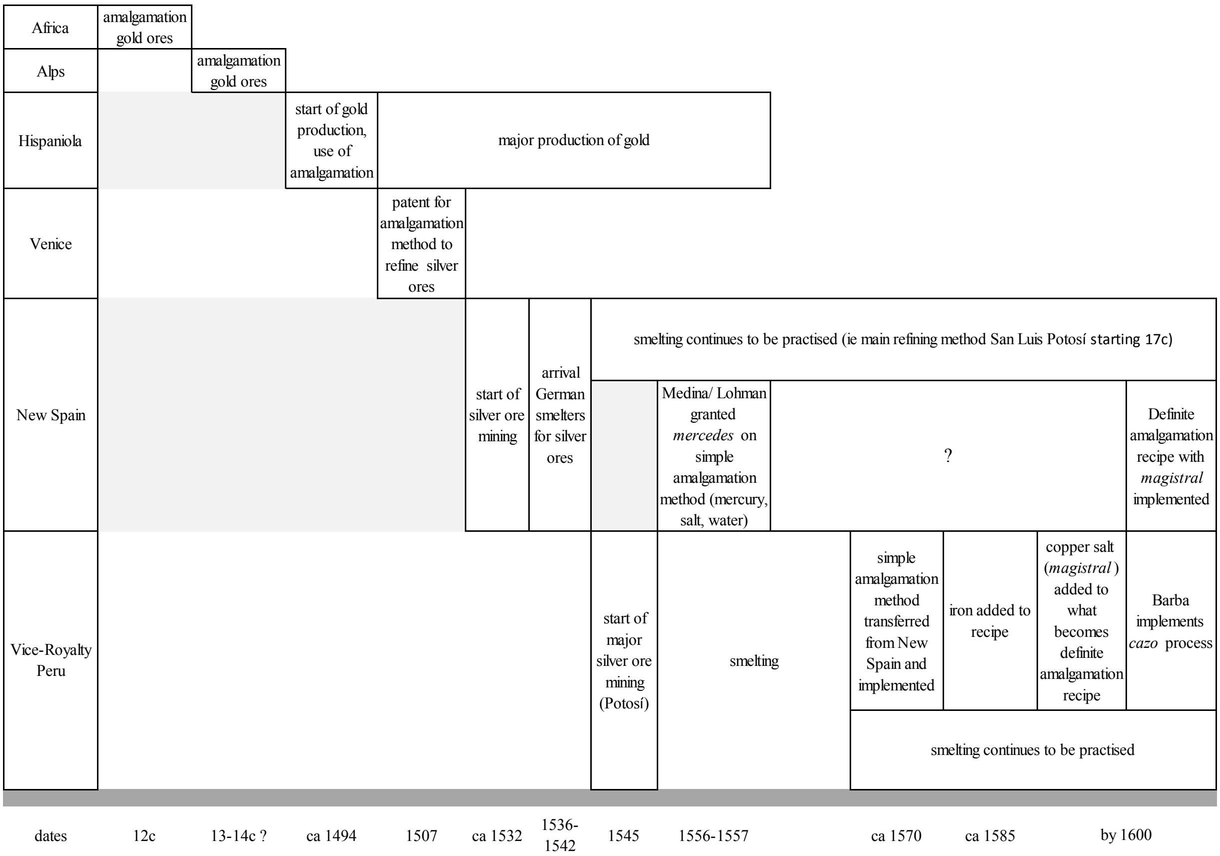

Figure 3-1. Timeline of main stages in the implementation of amalgamation in the New World.

3.6 The infrastructure of amalgamation in New Spain

Once the critical breakthrough was made on the amalgamation recipe to allow its use on silver sulphides, it would remain to all practical purposes unaltered in its chemical principles until its substitution at the end of the nineteenth century by another chemical process based on cyanide. Amalgamation has been described at length in the historiography, and in the case of

New Spain it is referred to in the later historiography as the *patio* process, since the amalgamation slurry was spread out in *tortas* (cakes) placed in a courtyard (*patio*).[412] The best sources to consult are those written by first-hand observers from the nineteenth century, who present a better picture of the tight mosaic of multiple concatenated operations that is sometimes lost in the more summarized versions in the modern historiography.[413] Figure 3-2 is the basic outline of the operation, once the silver ores have been sorted either for amalgamation or smelting. Its virtual immutability means that data from the nineteenth century, including a pool of technical drawings and even photographs, provide a much needed depth to the sequence set out in Figure 3-2, as detailed in the following sections.

3.6.1 Milling the ore

If the number of smelting furnaces was the defining feature in the legal description of smelting *haciendas* in San Luis Potosí, it is the number and nature of the milling equipment that is the heart of the description of '*haciendas de minas del beneficio de sacar plata por azogue*' in legal documents of two of the main mining districts of the period, Zacatecas and Guanajuato.[414] Detailed descriptions of the various components of *morteros* (stamp mills) and *molinos* (Chilean mills) figure prominently in seventeenth century documents for Zacatecas.[415]

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[412] It has been suggested that the term *patio* amalgamation was only applied in New Spain as of the eighteenth century. *Bartolomé de Medina*, 185-86.

[413] The following accounts are good guides to the historical process: Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 38-47.; Duport, *Métaux précieux au Mexique*, 86-120.; Laur, "De la metallurgie de l'argent au Mexique," 137-215.; Hermosa, *Manual de Laboreo de Minas*, 192-242.; Collins, *Metallurgy of Lead & Silver*, 34-62.; Amador, *Tratado práctico de haciendas de beneficio*, 65-91.

[414] For Zacatecas I have only found the term '*Hacienda de Patio*' in a document dating from the late eighteenth century, an incomplete valuation of inventory of an '*Haz. de Patio*', 2 July 1788, AHEZ, Poder Judicial Civil, C45-E18. It is also the only document of Zacatecas in which I found the term *taona*.

[415] For Zacatecas, seventeenth century: Rental agreement, inventory of Hacienda Santa Catalina Mártir, 7 June 1651, AHEZ, Notarías/Colonia, Number 4 (Manuel Rodriguez), 73r to 74r; inventory hacienda of Doña Isabel Saldivar Mendoza, 28 July 1659, AHEZ, Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 3, 142 r to 143 r; rental agreement by the Jesuits for an hacienda, 20 December 1664, AHEZ, Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 4, 141 r 141 v; sale agreement by Captain Joseph de Monrreal, 7 December 1671, AHEZ, Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 5, 199r to 200v; inventory of the Hacienda de La Sienaguilla, 9 May 1673, AHEZ

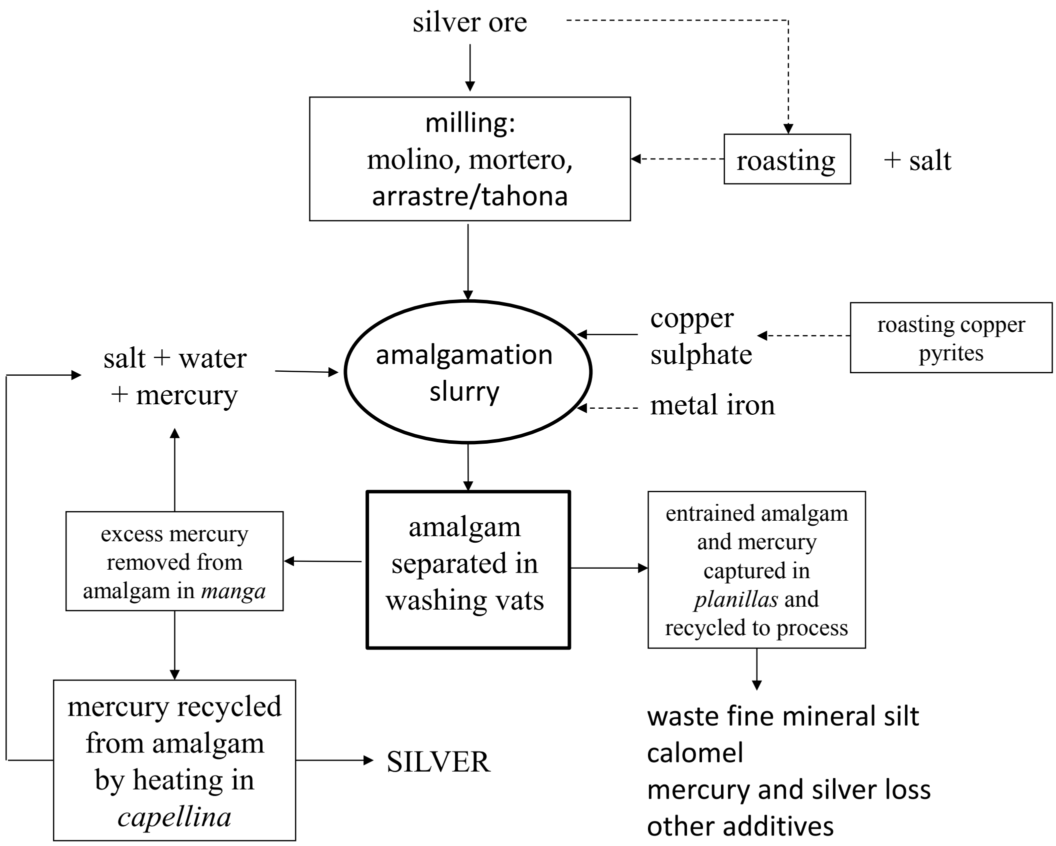

Figure 3-2. The main stages of the patio amalgamation process as practised in New Spain / Mexico. Dashed lines indicate optional stages.

Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 6, 46 v to 48v; rental agreement by Doña Cathelina, Doña Maria and Doña Agustina Hurtado (?), 9 October 1673, AHEZ Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 6, 125v to 127r; rental agreement by the Jesuits, 4 June 1674, AHEZ Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 7, 50r to 52r; rental agreement by Ramón Guerero, 27 June 1674, AHEZ Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 7, 59v to 61r; rental agreement by Don Fernando de Aranda , 9 July 1674, AHEZ Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 7, 72r, 72v; rental agreement by the Jesuits , 1678?, AHEZ Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 8, 3r to 4r; rental agreement by Doña Elvira Perez de Bocanegra , 30 June 1678, AHEZ Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 8, 93r to 94r; rental agreement by Doña Magdalena Guerrero, 8 April 1690, AHEZ Notarías/Colonia, Number 11 (Lucas Fernandez Pardo 1690-1700), expediente 2, 86v to 88v; lawsuit between Ramón de Mendoza y Juan Miguel de Bouzo (?), 21 September 1696, AHEZ Notarías/Colonia, Number 11 (Lucas Fernandez Pardo 1690-1700), expediente 2, 168r to 172r; rental agreement by Francisco de Aragón, 29 September 1694, AHEZ Notarías/Colonia, Number 11 (Lucas Fernandez Pardo 1690-1700), expediente 5, 201r to 203r. A very useful guide to colonial stamp-mills using the data from Potosí is Peter J. Bakewell, "The First Refining Mills in Potosi: Design and Construction.," in *In Quest of Mineral Wealth: Aboriginal and Colonial Mining and Metallurgy in Spanish America.*, ed. Alan K. Craig and Robert C. West (Baton Rouge: Geoscience Publishers, 1994).

According to Rankine the *molino* was first introduced in Zacatecas, and only later in Guanajuato, as a better option than the *morteros*, processing up to seven times more ore and milling it to a finer size.[416]

The importance of the mills to the success of the process is reflected in the Christian names given to each mill within the *hacienda*: Jesus, Santa Ana, San Pedro, San Pablo, San Jose, Santa Isabel, among others.[417] A photograph of a *molino* at work at the end of the nineteenth century in Mexico is shown in Figure 3-3a, and its date does not detract from the fact this was the same *ingenio* [machinery] that had been used since the seventeenth century throughout New Spain.[418]

The key to amalgamation lay in achieving the maximum surface area of ore in contact with the chemicals of the recipe.[419] The finest mesh sizes were only achieved using *arrastres*, also called *tahonas,* after first passing the raw ore through a *mortero* or *molino*.[420] Such was the attrition suffered by the *arrastre/tahona* stones (*voladoras*) that they could add up to 10% of the weight of the material obtained after grinding (Figure 3-3 b and c).[421] Humboldt declared

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416 Margaret E Rankine, "The Mexican Mining Industry in the Nineteenth Century with Special Reference to Guanajuato," *Bulletin of Latin American Research* (1992): 43.

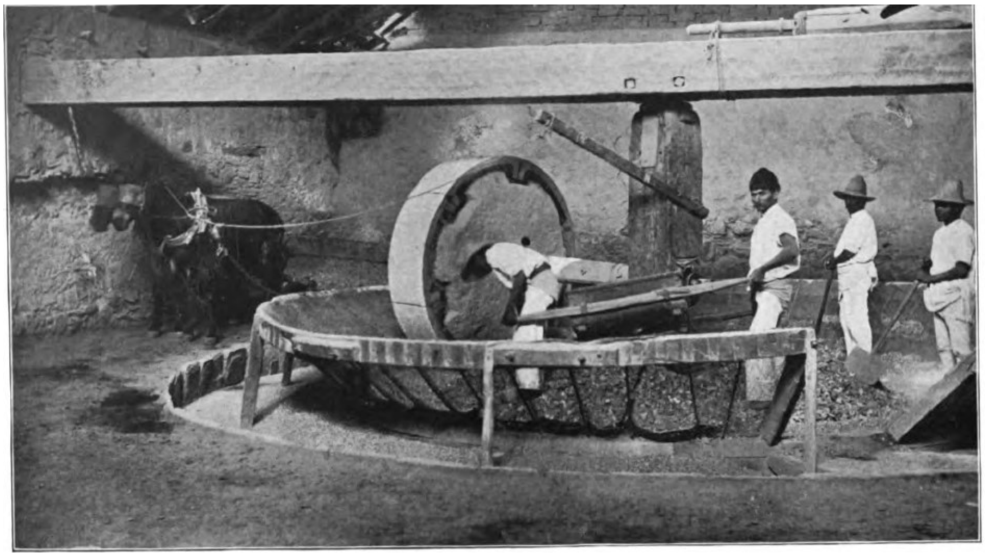
417 Inventory of an *hacienda* owned by the Conde de Santa Rosa, 22 June 1706, AHEZ Poder Judicial-Civil C05-E17, 9r,v; auction of the inventory of the Hacienda San Jose de las Perlas, 9 November 1761, AHEZ Serie Civil C38-E02, 18r.

418 T. A. Rickard, *Journeys of Observation* (San Francisco: Dewey Pub. Co., 1907), 123 (facing).

419 The importance of milling for the success of amalgamation is so high that it has been argued that amalgamation began in Sultepec because that is the location of the first water-powered stamp mills in New Spain built by Germans. West, *The Parral Mining District*, 16. Not all mining districts aimed for the same mesh size, and in the nineteenth century it was Guanajuato who claimed the finest milled ores, according to Duport, *Métaux précieux au Mexique*, 250.

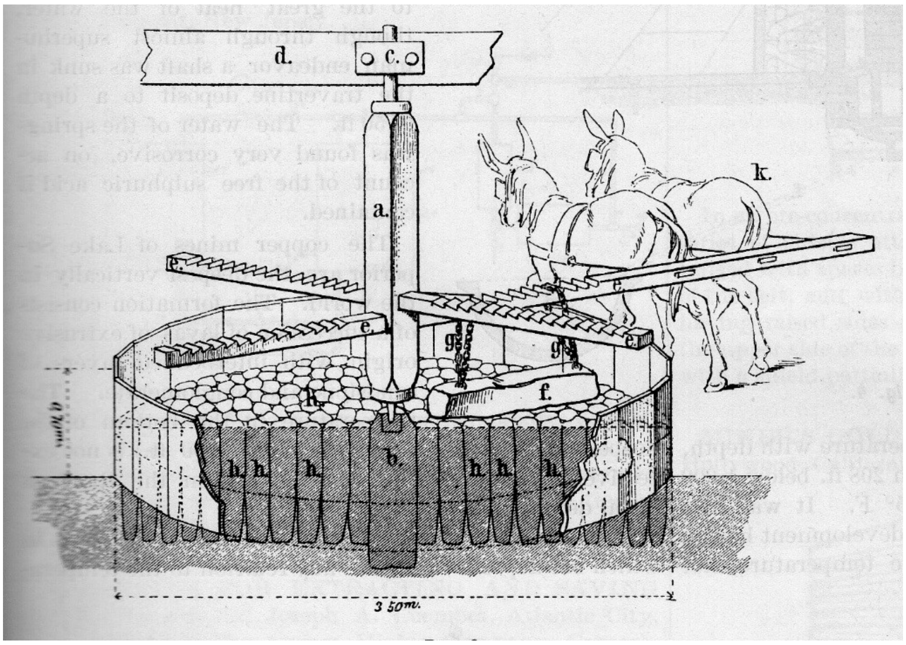
420 The drawing of an *arrastre* has been taken from Bernard MacDonald, "Old Mexican Methods " *Mining and Scientific Press* (1907): 125. For the equivalence of the terms *tahona* and *arrastre* see Hermosa, *Manual de Laboreo de Minas*, 196. The word *taona* or *tahona* does not figure in the documents of Zacatecas reviewed for this chapter of the seventeenth century. The term *arrastre* appears in documents of the eighteenth century of Guanajuato, for example in the sale of the Hacienda San Pedro, 7 December 1739, AHUG, Protocolo de Minas libro 1732-1739, 315v; rental agreement for the Hacienda San Gerónimo (de Capetillo), 10 May 1747, AHUG, Protocolo de Minas libro 1744-1747, 220r to 221r; rental agreement for the Hacienda de Nuestra Señora de Guadalupe, 22 Octubre 1760, AHUG, Protocolo de Minas libro 1757-1761, 43r,to 44v.

421 Egleston, *The Metallurgy of Silver*, 279.



(a)

(b)



(c)

(d)

Figure 3-3. a) a horse-powered *Molino* in Mexico, late nineteenth century reproduced from footnote 418 b) example of the pit of a *molino*, from where the finer grains that have been shovelled through the mesh in a) are withdrawn via the arched tunnel and taken to the *tahonas*/*arrastres*. Photo taken in the ruins of the *Hacienda* San Juan Nepomuceno, Marfil, Guanajuato c) drawing of a *tahona* /*arrastre*, showing its four *voladoras,* reproduced from MacDonald, footnote 420 d) photo of a wasted *voladora* stone, over 1.6 m in length, taken at the home of the Morrill family, previously the *Hacienda* Bustos, Guanajuato.

he had never seen in Europe silver ores ground so fine as those he observed in an *hacienda* of Guanajuato in New Spain.[422] Power was supplied by water or animals.

3.6.2 The amalgamation reactor, or patio.

This was the operational area of greatest extension in an amalgamation *hacienda* of New Spain. It was a courtyard (*patio*) covered in tightly fitting planks of wood or paving stones to minimize loss of reagents through seepage to the soil (Figure 3-4a).[423] Humboldt suggested that the patio floor should be lined instead with iron or copper, an idea that was never taken up but that represented a unique opportunity to have introduced the first major change in the process since Barba.[424] His idea would have decreased substantially the consumption of mercury during the process, both on chemical grounds and by interposing a better barrier to seepage to the soil. According to local weather or custom it would have a roof or remain open to the elements. It comes as a surprise to observe that at least in the nineteenth century the amalgamation slurries were not necessarily laid out in arrays of neat circular *tortas* (cakes), but could be set out in square areas or simply take up all the available space in the *patio* (Figure 3-b and c).[425] The use of animals instead of workers to tread over the slurries reduced but did not eliminate the human exposure to the chemicals in the slurry.[426] The primitive nature of the scenes in Figure 3-4 should not obscure the fact that the *patio* was an open-air industrial

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[422] Humboldt, *Essai politique*, Tome IV, 57.
[423] Hermosa, *Manual de Laboreo de Minas*, 207. The paving stones can be observed in the photo of a patio área that appears in Francisco Antúnez Echegaray, *Monografía histórica y minera sobre el Distrito de Guanajuato* (Mexico: Consejo de Recursos Naturales No-Renovables, 1964), 389. The paving stones are also clearly depicted in Piedro Gualdi's painting (1846) of the patio reactor of the Hacienda Nueva de Fresnillo. http://www.sothebys.com/en/auctions/ecatalogue/2012/latin-american-art-n08907/lot.15.html.
[424] Humboldt, *Essai politique*, Tome IV, 82.
[425] Berenice Pardo Hernández and Oscar Sánchez Rangel, *Mineral de la Luz. La obra fotográfica de John Horgan Jr. en México* (Guanajuato: Editorial La Rana, 2010), 210.; Rickard, *Journeys of Observation*, 145.
[426] Horses are said to have been introduced in Guanajuato haciendas by 1770. Ada Marina Lara Meza, *Haciendas de beneficio de Guanajuato. Tecnología y usos del suelo 1770-1780* (Guanajuato: Presidencia Municipal de Guanajuato; Dirección de Cultura y Educación, 2001), 82. Their legs had to be carefully washed to avoid the generation of cracks in the skin due to the corrosive action of the amalgamation chemicals. No mention is made on the fate of the workers feet. Amador, *Tratado práctico de haciendas de beneficio*, 71. It is reported that

a

b

c

Figure 3-4 a) patio of the *Hacienda* de San Xavier, Guanajuato, photo reproduced from Antúnez Echegaray, footnote 423 b) *patio* of the *Hacienda* de La Luz, Guanajuato, photo reproduced from Hernandez and Rangel, footnote 425 c) *patio* of unidentified *hacienda* in Guanajuato, photo reproduced from Rickard, footnote 426.

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amalgam was recovered from the stomach of these horses. Horse manure was used as joint sealer within the patio area. Rickard, *Journeys of Observation*, 136-37. What has not yet been studied is the effect of horse manure and urine on the chemistry of amalgamation.

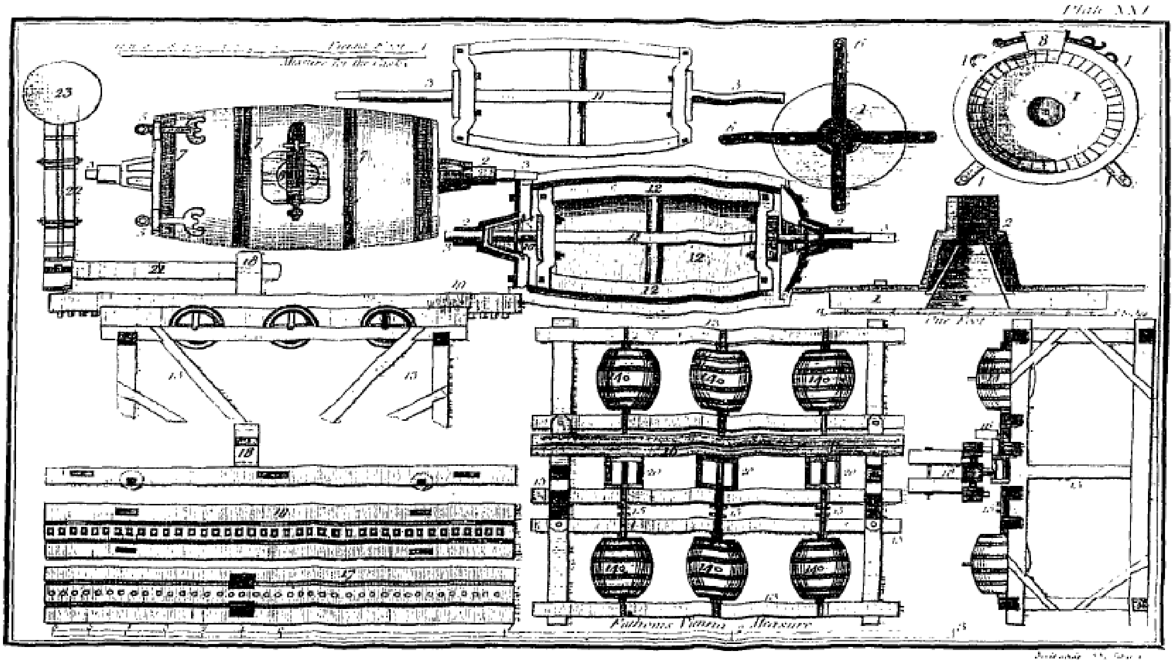

Figure 3-5. Amalgamation in 'fixed casks', Born's variation on Barba's cazo process. Illustration reproduced from footnote 427.

chemical reactor of uncommon flexibility. In an amalgamation *hacienda* the operator enjoyed great freedom in fixing the size of his batches, thus eliminating the usual handicap faced by modern batch industrial processes based on a fixed reactor size. While Figure 3-4 does not relay the same impression of scientific progress as the ordered sets of barrels driven by gears depicted in Born's work (Figure 3-5), the real contrast lies between the simplicity and flexibility of the former compared to the rigidity and complexity of the latter, a complexity that needs to justify itself on costs and efficiency and not simply on the basis it visually indicates change, which can be confused with progress.[427] The range of operational flexibility offered by a *patio* reactor at a minimal capital and maintenance cost can only be underestimated at the cost of altogether missing the point of the industrial process that took place for over three hundred years in New Spain / Mexico.

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[427] Plate XXI, Born, *Born's New Process of Amalgamation*, following 178.

With regards to the amalgamation recipes, water, salt, mercury, a soluble copper additive, iron or copper, and lime make up the usual list of ingredients. Exact quantities vary with location and period and are well reported in the historiography on amalgamation. In Chapter 4 I will be addressing a case study with details on the ingredients and quantities employed. I will only point out that little if any assaying of ores took place, so that reagents were added on the basis of the total amount of ore in a *torta*, and not on its silver content, and even the size of the *tortas* varied according to each mining district. While mercury is always added on the basis of a ratio to the silver in the ore, the absence of assaying made this an exercise either in guesswork or an example of very uniform silver content in most ores for amalgamation. Salt was usually added in excess, while copper sulphates were not, and water was always present to avoid the cakes drying out.[428]

3.6.3 The handling of mercury within the *hacienda*.

There is one reference to mercury stored in barrels in the mercury room (*aposento de azogue* or *azoguería*) in a Zacatecas *hacienda*.[429] By the nineteenth century iron flasks became the norm, so in transit and storage losses would have been reduced substantially.[430] There remained two major steps that required direct contact with mercury by the workers. The first was the manual addition of mercury to each amalgamation *torta*. This was done by squeezing mercury carried in a leather or cloth pouch, weighing between 5 to 9 kg.[431] The second direct manipulation of mercury took place whilst the amalgam was being separated from the mineral

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[428] Sonneschmidt and de Fagoaga, Tratado de la amalgamación de Nueva España, 30-32.; Amador, Tratado práctico de haciendas de beneficio, 73-75.; Hermosa, Manual de Laboreo de Minas, 209-29.

[429] Rental agreement by Antonio de Larrinilla, 13 December 1682, AHEZ, Notarías/Colonia, Number 8 (Blas Nunez Hurtado 1682 - 1683), 5r to 8r.

[430] A document from Zacatecas dated 17 July 1807 refers to 104 iron flasks storing 78 quintales of mercury, as cited in Suarez Arguello and Von Mentz, *Epistolas y cuentas Vetagrande*, 606.

[431] Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 24.; Egleston, *The Metallurgy of Silver*, 286.

slurry, washed, and then placed within a cylindrical cloth (the *manga*) where it was left to stand, then squeezed or hit with paddles until gravity and brute force had forced the excess of mercury out of the amalgam.[432] The white, twisted cylinder observed to the right in the background of Figure 3-6 is the cloth *manga* used to strain mercury from the amalgam.

Note also the presence of the scale, a vital piece of equipment that figures in every historical itemized description of an amalgamation *hacienda*, an indication of the careful accounting of mercury throughout every stage.[433] A typical description from the seventeenth to early eighteenth century in Zacatecas would read thus: ‘a room for mercury and within it seven *quintales* of liquid mercury = a large table = weighing scales [various sizes of bronze and iron weights] = a wooden pine box with keys to store mercury = a *manga* to separate mercury with its iron hoop, [support?] and cloth’.[434] Two hundred years or more separate similar descriptions from the view in Figure 3-6, but apart from the iron flasks now used to store mercury lining the floor of the *azoguería,* the infrastructure remains the same.[435]

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[432] Hermosa, *Manual de Laboreo de Minas*, 235-37.
[433] According to West, refiners had to keep books with mass balances of mercury being used that were checked by officials. West, *The Parral Mining District*, 113.
[434] ‘*un aposento que sirve de azogue y en el siete quintales de azogue en caldo = una mesa grande = un peso de cruz con sus balanzas [pesas varias de hierro y bronce] = una caxa de pino con su llave que sirve para guardar azogue ... una manga para desazogar con su aro de fiero, contramanga y paño de azogue*’ in the inventory of an hacienda owned by the Conde de Santa Rosa, 22 June 1706, AHEZ Poder Judicial-Civil C05-E17, 10v to 11r.
[435] Plate 11, Percy F. Martin, *Mexico's Treasure House (Guanajuato)* (New York: The Cheltenham Press, 1906), 52-54.

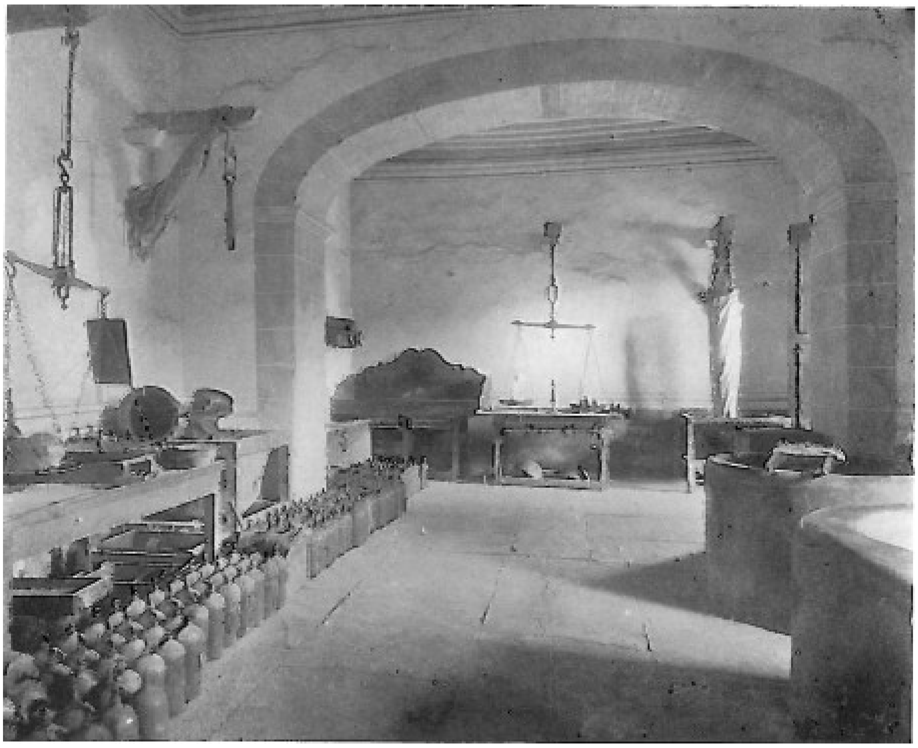

Figure 3-6. Photo of an *azoguería* (mercury room), showing mercury flasks, scales and vertical white manga held by chains from a beam to the right of the background. Original photo from footnote 435.

3.6.4 Planillas

Once the amalgamation process within a *torta* was deemed by the master amalgamator (*azoguero*) to have run its course, the next stage in the process required separating the heavier amalgam from the lighter fraction of the mineral matrix (gangue) in the slurry, minimizing the potential collateral loss of amalgam, excess mercury and unreacted silver ore. All these valuable components in the slurry of the *torta* could be entrained with the water used to wash away the mineral matrix that made up over 99.6 % of the solid content of the slurry. The historiography describes in detail the vats and stirring paddles used to wash away the mineral matrix (gangue) of the slurry.[436] The description of the *labadero* is also given in great detail in

[436] Hermosa, *Manual de Laboreo de Minas*, 229-35.

legal documents that describe the infrastructure of amalgamation *haciendas*.[437] The washings were voided into a canal (*cárcamo*) that run through the *hacienda* until it voided into a nearby stream. Along the way a sediment was deposited within this *cárcamo* which was regularly scooped out and washed in the *planillas*, an inclined plane on which the *planilleros*, women and men, patiently spooned water and sediment over the *planillas* (Figure 3-7).[438] The aim was to separate by gravity the heavier fraction of mercury, amalgam and silver ore entrained in the washing water, allowing the finer silt to be washed away.[439] The visual evidence of the physical reality of the process is important for the later discussion on the stages of the amalgamation process where physical losses of mercury were most likely to occur.

3.6.5 Desazogaderas or capellinas and the recycling of mercury.

The description and understanding of the recovery of mercury from the amalgam is critical for the analysis of the historical environmental impact of silver refining by amalgamation. The previous sections have shown via photographs the conditions under which mercury was handled in the *patio* area. After days or weeks of treading and shovelling a slurry made up of over 99.6 % of waste material, the process had now separated the two most valuable components, mercury and silver. The equal importance of both to the refiner is reflected in inventories of *haciendas* that single out the wooden chests with locks where both were stored, side by side.[440] The first time that mercury is again handled in a closed environment is within

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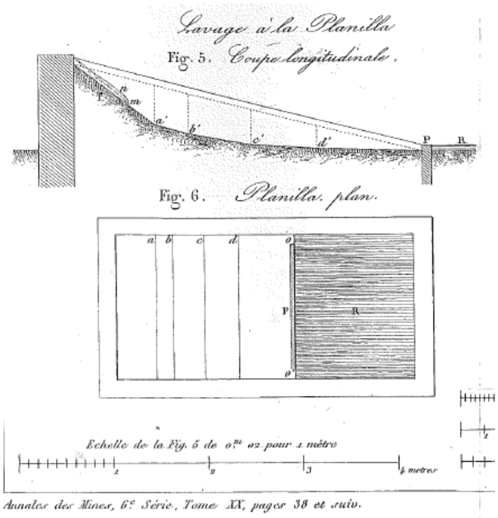
[437] See documents in footnote 416.

[438] See photograph in Bordeaux, *Mexique mines d'argent*, facing p. 160.

[439] Amador, *Tratado práctico de haciendas de beneficio*, 82-84, 89-91. For a drawing of a cross-section of a planilla see Laur, "De la metallurgie de l'argent au Mexique." Plate II, Figures 5 and 6.

[440] For example, '*dos caxas grandes con sus llaves una en que se guarda el azogue otra en que se guarda la plata*' in the rental agreement by the Jesuits for an hacienda, 20 December 1664, AHEZ, Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 4, 141 r, v; similar mention in the rental agreement by Mateo de Herrera, 15 July 1645, AHEZ Poder Judicial-Civil C01-E40.

(a)



(b)

Figure 3-7. a) cross section of a *planilla*, reproduced from Laur, footnote 439 b) photo of *planilleros* at work, showing the *cárcamo* running with the waste water from the washings, the inclined *planillas* and the scoop made from a bull's horn in their right hand. Reproduction of illustration in footnote 438. It seems to correspond to a larger image from where a more reduced area has been reproduced in a photograph by Charles Waite titled 'Washing the Tailings, Guanajuato', 1907, number 16 in the series *Tema y Tecnología* (CIG-AGN).

the *azoguería* (mercury room), and a comparison between Figures 3-6 and 3-7 indicates the quantum leap regarding the degree of control over operational losses. Now the amalgam, having been carefully washed free of any remaining sediment, is strained through a *manga* so as to separate as much as possible the excess of liquid mercury. In New Spain the pliable amalgam was removed from the *manga* and moulded into flat disks or small spheres that could be stacked, separated by layers of ashes, for the most important step of separating mercury from silver, the heating of the amalgam and the recovery of mercury.

The amalgam was never heated over an open fire, contrary to what is observed in modern artisanal gold amalgamation practice. The recycling of mercury always took place under controlled conditions within a closed recipient whose only outlet was to a water trap that cooled and condensed the mercury vapour. The twentieth-century historiography has employed very loose terminology in describing this critical stage. For example, even though there is never a direct contact between flame and mercury, the stage has been described as 'burning' of amalgam.[441] The efficiency of the method to recycle mercury is questioned without providing any evidence, as for example: 'to distill off the mercury ... which could **in part** be recovered' (emphasis added).[442] A claim has been made that 'the resulting pina [amalgam] … was then smelted to vaporize any remaining quicksilver. It was at this point in the production process that tons of mercury were released in … Potosí and breathed in by its inhabitants each year'.[443] It is not only a question that refining terms are being employed incorrectly (it is incorrect to state that the amalgam was smelted), but an operational stage is being misrepresented in the modern historiography and major conclusions on the environmental history of silver refining are derived from the unproven assumption that the major mercury loss vector was volatilized mercury.

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[441] Brading, *Miners Bourbon Mexico*, 138.
[442] Bakewell, *Silver Mining in Zacatecas*, 22.
[443] Robins, *Mercury, Mining and Empire*, 11.

To understand the care taken to operate an efficient recovery of volatile mercury from the amalgam it is necessary to review in detail the four types of heating/condensing assemblies as described in the historiography up to the nineteenth century:

Caperuzas: the early versions of the recycling apparatus used to recover mercury from the amalgam was described and illustrated by Barba (Figure 3-8). The lower part was an iron vessel in which the amalgams, called a piña due to their cone shape, were placed on an iron tray. The upper part was a *caperuza* or lid resembling a Venetian plague mask, whose nozzle ended in the water trap. Both parts had to fit snugly to avoid losses of mercury vapour, and the joint was sealed with a mixture of ash and other components. The assembly was placed on top of a furnace, much like a kettle on a wood-fired stove. Barba complained that *caperuzas* made from ordinary clay in the late sixteenth century were too porous, and that ideally either a special clay as for crucibles, or better still iron or copper should be used instead in order to lessen the loss of mercury in this stage.[444]

Desazogadera: in New Spain it appears that this term was more common than *caperuza*, and the use of metal ones appear cited as early as the 1600s.[445]. In a non-exhaustive survey of contracts drawn up in Zacatecas during the seventeenth century, *desazogaderas* (literally removers of mercury) or as equipment for *desazogar* are the terms utilized, as for example: 'and a room that is used to remove mercury … an iron tray and small plate to remove

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[444] Barba, *Arte de los metales*, 99-104, 169-70. The dictionary on mining and refining terms compiled in Potosí in 1609 by Garcia de Llanos also mentions the use of *caperuzas* made from fired clay. Garcia de Llanos, *Diccionario*, 38. The complaint by Barba that mercury vapour could traverse these primitive and porous *desazogaderas* may be the source of a similar claim made by Robins to justify his proposal that 85% of mercury was lost as volatile mercury during the historical heating of amalgams. Otherwise Robins does not state the experimental or historiographical basis for his proposal that: 'the porous nature of the clay facilitated the escape of mercury, as did the generally inefficient and artisanal nature of the entire process' Robins, *Mercury, Mining and Empire*, 88.
[445] 'the apparatus to remove mercury of metal, copper or bronze'- '*desazogadera de metal, de cobre o bronce*' Gómez de Cervantes, *Nueva España siglo XVI*, 153.

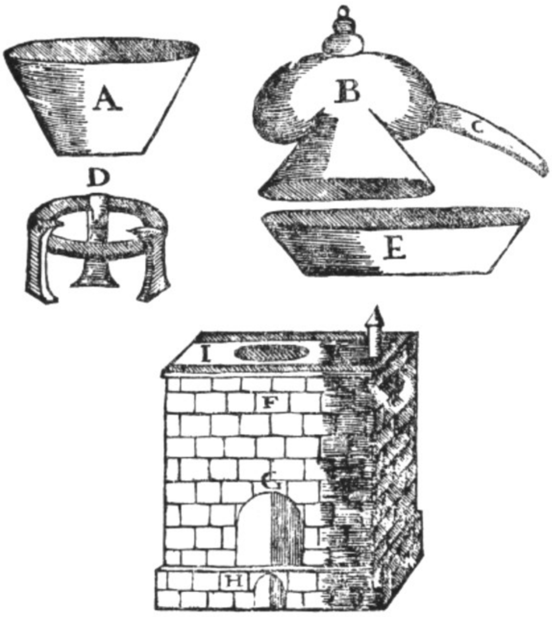

Figure 3-8. Barba's illustration of the apparatus used at the end of the sixteenth century to recycle mercury from the amalgam. A is the iron vessel where the amalgam is placed, B is the *caperuza* (clay or metal) that fits on top of A, with a nozzle (C) that ends below the surface of the water placed in tank E. The whole assembly sits on the ring D on top of the brick furnace. Figure from Barba, reproduced from footnote 444.

mercury'.[446] The number of *desazogaderas* could reach four or more, and some are described as embedded in the ground.[447] The latter implies a heating arrangement as applied to *capellinas* (see below). The fact they do not figure in every inventory of the seventeenth century in Zacatecas, or are listed as incomplete, especially of those *haciendas* that have not been

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446 '*y un aposento que sirve de desogadera … yten un candelero de fiero para desazogar y un platillo'* Rental agreement by Mateo de Herrera, 15 July 1645, AHEZ Poder Judicial-Civil C01-E40. Also in the, inventory of Hacienda Santa Catalina Mártir, 7 June 1651, AHEZ, Notarias/Colonia, Number 4 (Manuel Rodriguez), 73r to 74r.

447 '*el aposento de desazogar que sigue al dicho de azogue con quatro desazogaderas*' in the inventory of an hacienda owned by the Conde de Santa Rosa, 22 June 1706, AHEZ Poder Judicial-Civil C05-E17, 10v to 11r; '*Dicho aposento … de desazogadera … con su puerta y un candado grande con llave … y en el dicho aposento dos ollas enterradas para desazogar*' in Rental agreement by Antonio de Larrinilla, 13 December 1682, AHEZ, Notarías/Colonia, Number 8 (Blas Nunez Hurtado 1682 - 1683), 5r to 8r.

operating, is unexpected due to their important role in the process.[448] Either they were inexpensive to make (for example if they were made of clay) and so did not merit a special mention as a capital asset and/or when made from metal they were readily pilfered from abandoned *haciendas*.

Capellina: in New Spain the term *capellina* appears regularly in documents from the eighteenth century of Zacatecas and Guanajuato. It is made up of two halves, a lower vessel with a rounded base made of metal, in which is placed an iron tray that will hold the stack of flat amalgams separated by layers of ashes. A metal bell (hence the name *capellina*) fits snugly onto this base, with the joint sealed by a combination of ashes and the weight of the *capellina*.[449] A tube channelled the mercury vapours through the bottom of the assembly onto a water trap where mercury condensed and could be recovered. Copper, bronze and iron *capellinas* figure prominently in the inventories of amalgamation *haciendas* in Zacatecas and Guanajuato at least as early as the 1720s.[450] By the nineteenth centuries large *capellinas* appear, weighing as much as 500 kg or more, requiring a pulley to be manoeuvred into place.[451] Thus

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[448] A good example of incomplete equipment listed in an inventory is the following: 'the equipment to remove mercury with two vats and without the receivers' - '*la desazogadera con dos piletas y sin recividoras*' in the auction of the inventory of the Hacienda San Jose de las Perlas, 9 November 1761, AHEZ Serie Civil C38-E02, 18r.

[449] According to Hermosa, 23 to 34 amalgam disks (*marquetas*), weighing 1 arroba each (11.5 kg) were placed in rows of six under a *capellina*. Hermosa, *Manual de Laboreo de Minas*, 238-39.

[450] '*una desazogadera de cobre*' in rental agreement for the Hacienda San Antonio, 1 January 1726, AHUG, Protocolo Cabildo 1726, Libro 30, 331r; '*una desazogadera de cobre*', inventory of Hacienda San Antonio, 15 March 1737, AHUG, Protocolo de Minas libro 1732-1739, 200r; '*una dessasogadera de cobre*' in inventory (*Memoria de los apegos*) attached to rental agreement for the Hacienda San Antonio, 17 March 1741, AHUG, Protocolo de Minas libro 1740-1741, 83r; '*una desasogadera de cobre*' in the rental agreement for the Hacienda San Antonio, 5 Junio 1755, AHUG, Protocolo de Minas libro 1754-1756, 152r; 'the cavity for two capellinas with their corresponding vat'-'*el hueco de dos capellinas con su pila correspondiente*' in the inventory for the Hacienda la Sangre de Christo, 4 October 1784, AHUG, Minería, Caja 15 expediente 547; '3 copper *capellinas* with 938 lbs [of copper]'- '*3 capellinas de cobre con 938 libras*' in the valuation of inventory of an hacienda (incomplete), 2 July 1788,AHEZ, Poder Judicial Civil, C45-E18. Other examples of metal *capellinas* are given in Table I.

[451] 500 kg in Fresnillo, according to Duport, Métaux précieux au Mexique, 269. Over one ton in Regla, Chapter Four; '*Capellinas*: 1 iron bell weighing 900 lbs [approx. 400 kg]' –'*Capellinas: 1 campana de fierro con peso de 900 lb*' in inventory of the Hacienda de Dolores de Granadita, Primer semestre de 1884, Protocolo de Minas, Tomo 1884, 157r. For a detailed description of how the stack is set up within a capellina see Amador, Tratado práctico de haciendas de beneficio, 84-88.

metal *capellinas* are in use during the two centuries that produced nearly 90% of the total silver coming from New Spain / Mexico from the sixteenth to the nineteenth century. Figure 3-9a is a cross-section of a *capellina* assembly from the nineteenth century.[452] Heating was always indirect, piling hot embers around the side of the *capellina*, and according to one account the cycle was monitored by the sounds emanating from within or by the quantity of mercury recovered.[453] After up to 30 hours, depending on the size of the amalgam stack, the recovery of mercury was complete.[454]

In Guanajuato *capellina* was the name also given to a two-storey building that housed the *capellina* assembly in its upper part, and a tube for the condensing mercury vapours reached to the lower part of the structure where it was cooled by water and mercury collected. The lower floor could be either below or above ground level (Figure 3-10).[455]

Finally, Collins describes at the end of the nineteenth century a very simple arrangement used by small refiners in Mexico and South America, based on clay water bottles, though empty metal mercury flasks fitted with a screwed-on pipe were used as well (Figure 3-11).[456] The amalgam is rammed into the bottom of each bottle, up to 35 lb at a time, and the bottle inverted so that the open end now lies below the water level in the tank below. Heating is applied indirectly through hot embers heaped around the inverted bottles.

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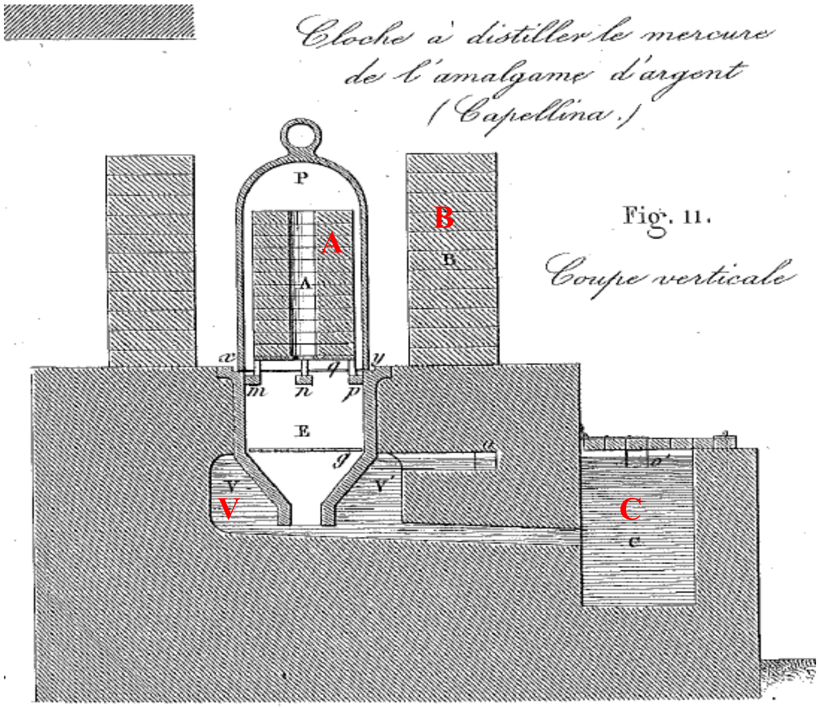
[452] Laur, "De la metallurgie de l'argent au Mexique," Plate II, Fig. 11.; MacDonald, "Old Mexican Methods," 126. The drawings that appear in MacDonald's article are reproduced from a report drawn up in 1886 by E. Tillmann, Royal Commissioner of Mines in Prussia, who visited Guanajuato. I have not been able to locate the original report which would provide very valuable lithographs on the patio process as practised in the late nineteenth century. The same drawings are reproduced in Rickard, *Journeys of Observation*.

[453] Hermosa, *Manual de Laboreo de Minas*, 238-39.

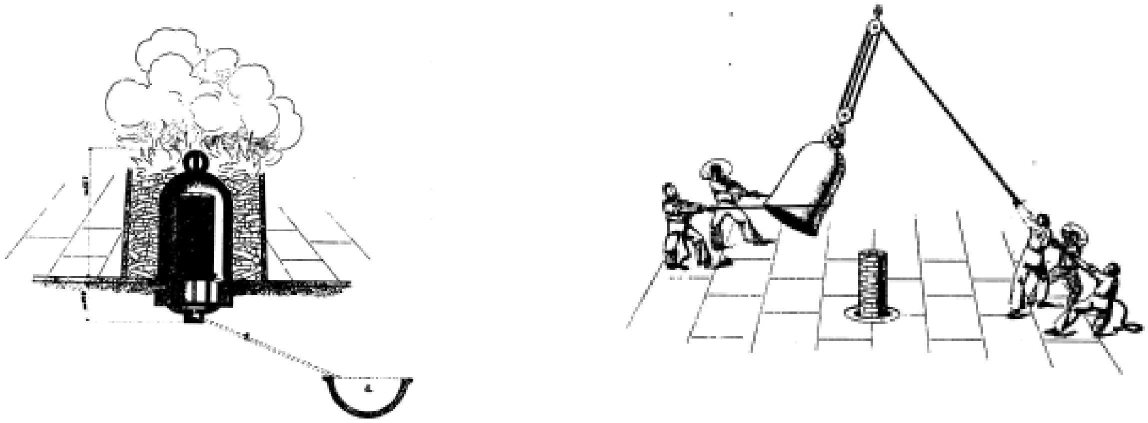
[454] Descriptions of the *capellina* and the recycling of mercury can be found in Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 49-51.; Hermosa, *Manual de Laboreo de Minas*, 237-39. Amador, *Tratado práctico de haciendas de beneficio*, 84-89.; Percy, *Metallurgy*, I 627.; Kerl, Crookes, and Röhrig, *Prof. Kerl's Metallurgy*, 327.

[455] For a detailed cross-section of a two-story structure for a *capellina* see Egleston, *The Metallurgy of Silver*, 328.

[456] Collins, *Metallurgy of Lead & Silver*, Vol. II, 136-38.



(a)



(b)

Figure 3-9. a) Cross-section of *capellina* used by nineteenth century in Mexico. The stack of amalgam disks (A) is covered by the *capellina*. A temporary wall made of bricks (B) surrounds the *capellina*, and embers are placed in the space between the two. Mercury condenses in the water basin below the *capellina* assembly (V) and is collected via the main water channel (C). Adapted from illustration in Laur, footnote 452 b) indirect heating of *capellina* and use of pulleys to manoeuvre *capellina* into place, original lithographs by Tillmann, as reproduced in Macdonald, footnote 452.

Whether the pioneer retort described by Barba, the humble assembly mentioned by Collins or the elaborate *capellina* illustrated by Laur, every one indicates the care taken to constrain the mercury vapour produced by an indirect heating of the amalgam within an enclosed space, so that it would only condense on contact with water. Of all the stages in the process, this was the most easy to control with regards to losses of mercury. The simplicity of an arrangement that requires no special furnace, no direct contact of the flame with the amalgam, and minimal operational oversight within an isolated working area, made this stage extremely efficient with regard to the recovery of mercury from the amalgam at a minimal loss during normal operational practice (see section 3.10 below).

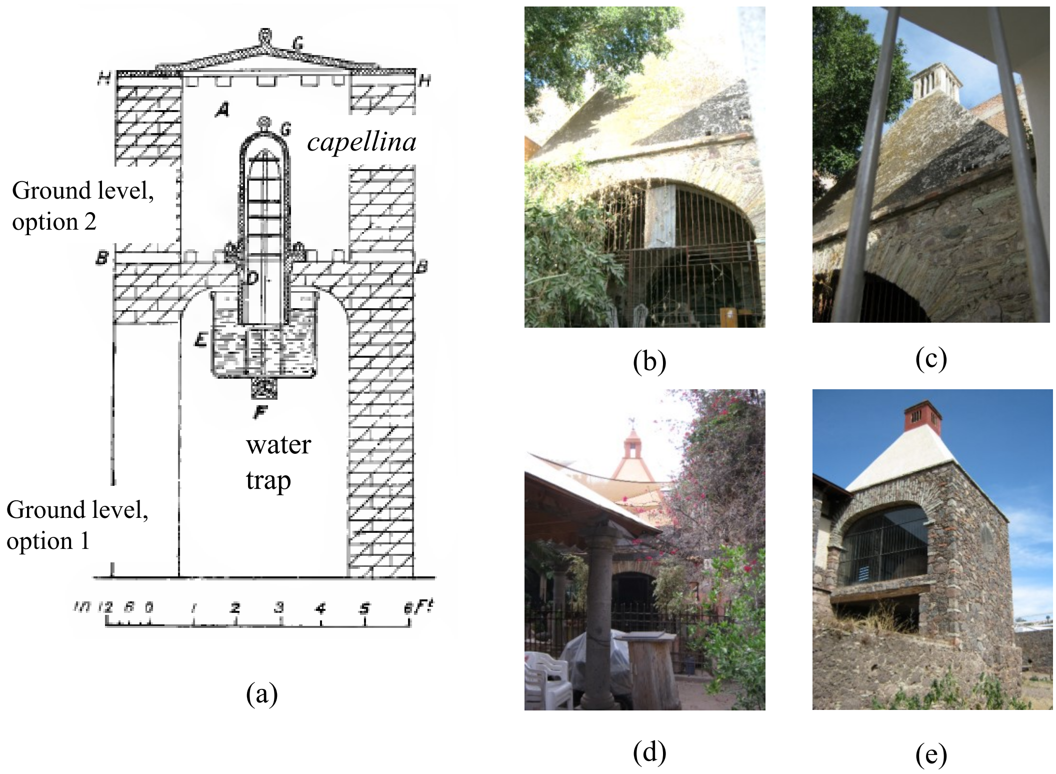


Figure 3-10. a) schematic cross section of a *capellina* building in Guanajuato, original illustration from footnote 455 with annotations added b) and c) *capellina* building, option 2, within the historic *Hacienda* La Escalera, Guanajuato, at present part of a private dwelling, used as a storage shed d) *capellina* building, option 2, renovated by the Morrill family and converted into a studio, previously the *Hacienda* Bustos, Guanajuato e) reconstruction of a *capellina* building, option 1, at a museum on mining on the grounds of the Real de Minas hotel, Guanajuato. The museum was not functioning as of February 2013.

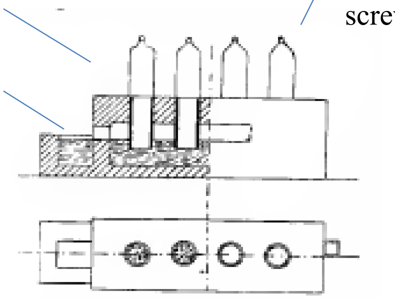


Figure 3-11. Simple recycling assembly of mercury from amalgam, based on inverted clay water bottles. Original illustration from footnote 456, with labels added.

3.7 Amalgamation: the human factor

The *patio* amalgamation process presented the advantage of hiding the complexity of its chemical reactions behind an easy-to-follow operation carried out for the most part at ambient temperature. The labour was either chokingly dusty or cloggingly wet, always back-breaking, and for the *planilleros* as mind-numbing as for a modern factory worker staring at a never ending stream of parts on a conveyor belt.[457] The heating stages (roasting of ores in some locations, heating of the *capellinas* and the final casting of silver bars) were very simple compared to the requirements of smelting. The responsibility for the operation lay in the hands of the *azoguero*, literally the mercury man, who in the absence of assaying controlled the amalgamation process using organoleptic triggers.[458] All the rest was the repetitive application of a well-known recipe that had the seal of approval of centuries of production, 'neither does

[457] '*planilleras*, that is how we call those that wash the fine silt, since only women, with their patience and capacity for waiting, can do such distressing work' - '*planilleras, que asi llamamos a las que lavan los polvillos, porque solo las mujeres, con su paciencia y espera, pueden hacer trabajo tan penoso*' in Juan Moreno y Castro, *Arte o nuevo modo de beneficiar los metales de oro y plata* (Mexico: Imprenta Biblioteca Mexicana, 1758), 24.
[458] *Azoguero* has a more technical, operational, connotation in New Spain compared to Peru, where it was also applied to the rich entrepreneurs involved in the silver mining and refining business.

it require … trained and experienced workers; they can be easily and readily trained in all that is necessary'.[459]

Little is known of the *azogueros* of New Spain, the human lynchpin for the *patio* amalgamation process, if they were only Spaniards, or if they could also be indigenous artisans or even African slaves entrusted with the operation.[460] Subject to the size of the *hacienda* there could be more than one *azoguero* in charge of the *patio* operations. As all pragmatic artisans, they were wary of novelty:

'those that call themselves A*zogueros* … are men … so ordinary as their common birth and customs since they never know how to discourse, nor wish to treat any important subject … [the] Owners continue to use this same method … telling us : Sir. Here have come many Artists with great enthusiasm, but useless'.[461]

Barba's desire that an exam filter out the least trained of refiners had still not materialized by the early nineteenth century, though not all *azogueros* could be as flawed as this one:

'Vetagrande [Zacatecas], September 12 of [18]06, Señor Don Antonio de Bassoco. My dear sir: In the *hacienda* del Buen Sincero the administrator and *azoguero* is Don Lorenzo de Ovalle, who not only does not have the capacity and skill required to carry out both jobs, but also has the vice of an incurable gambler'.[462]

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459 '*tampoco exige ... peones prácticos y enseñados; pues en un instante se adiestran para todo lo necesario, con facilidad*'. in Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 92.

460 Salazar Soler states that the *azoguero* was either a Spaniard or a *mestizo*, of inter-racial heritage, but does not furnish further background information on this issue. Salazar-Soler, "Innovaciones técnicas, mestizajes y formas de trabajo en Potosí de los siglos XVI y XVII," 147. They were housed within the hacienda compound, for example 'vivienda para el azoguero' in the auction of the inventory of the Hacienda San Jose de las Perlas, 9 November 1761, AHEZ Serie Civil C38-E02, 17v. I have found no mention of slaves or indigenous workers as *azogueros*.

461 '*los que se llaman Azogueros ... son unos hombres ...tan ordinaria, como la plebeya de su nacimiento y costumbres pues nunca saben discurrir, ni quieren materia alguna importante… [los] Duenos siguen este mismo método ... diciendo como nos han dicho: Senor, Aquí han venido varios Artistas con muchos entuciasmos, que de nada sirven*' in Dominguez de la Fuente, *Leal Informe Politico-Legal*, 133. See also Mendizábal, *La mineria mexicana*, 306.

462 '*Vetagrande, septiembre 12 del [18]06, Señor Don Antonio de Bassoco. Muy señor nuestro: En la hacienda del Buen Sincero se halla de administrador y azoguero Don Lorenzo de Ovalle, quien además de no tener la extensión y habilidad necesaria para cumplir con ambos empleos, tiene el vicio de tahúr irremediable*' as quoted in Suarez Arguello and Von Mentz, Epistolas y cuentas Vetagrande, 530.

The role of the human actors of *patio* amalgamation is still virgin territory in the historiography. The learning curve for each type of amalgamation recipe seems to have been fairly brief, though the modes of propagation of the amalgamation recipe are as yet undetermined. How the technical recipe spread remains to be studied. Secrecy had marked the initial development of refining techniques in Europe: 'there are no written accounts of the technique [of assaying] before 1500, probably as a consequence of the traditions of secrecy operating in medieval metal production'.[463] Why refiners in the New World were able to obtain relatively quickly details of innovations that represented huge market advantages is still an open question. Did the Spanish authorities play any role in guaranteeing the spread of skills in the use of mercury, or was this left to private enterprise that by nature would be reticent to sharing any knowledge that would help the competition? The role of the indigenous workers in this transmission process needs clarification, and the absence of written instructions would have made even more attractive a process with easy to follow manual steps, to avoid aggregate errors of interpretation of an orally transmitted technology.

Amalgamation also revealed the ethical context of the silver refining industry in the New World. Bribery up to the highest levels was a normal part of the process of procuring sufficient mercury quotas from the monopoly exercised by the Crown authorities, but even goodwill payments could not guarantee its supply.[464]

'the royal officials were given a gift of 1000 pesos each one for the assignment we were given of 600 quintales of mercury; and maybe we will be favourably served in other instances in relation to the last distribution of the remaining ingredient. It is our impression that they have remained grateful'[465]

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[463] Bartels, "Production of Silver in Harz Mountains," 87-89. The spread of the new copper liquation process was hampered initially because it was treated as an entrepreneurial secret by Thurzo Fugger, according to Kellenbenz, "Final Remarks Silver Production," 310.
[464] Bribery of the Viceroy to obtain mercury supplies is mentioned in Brading, *Miners Bourbon Mexico*, 141.
[465] Extract from letter dated 3 October 1806 sent by Isidoro Sarachaga and Manuel de Libron to Don Antonio de Bassoco, one of the rich and powerful mine and hacienda owners of Zacatecas though he lived in Mexico City: '*los señores oficiales reales quedaron obsequiados de 1000 pesos cada uno por la asignación que nos hicieron*

The glimpse offered by this correspondence extends beyond mercury supply into the overall problem of mercury and silver contraband which in turn places a healthy measure of doubt on the reliability of official silver and mercury data for the whole colonial period. I will return to this issue in Chapter 6, when I present an overall balance of minimum levels of chemicals issued to the environment, a base line that in reality would have been higher than that which is projected from the official statistics.

3.8 The architecture of *patio* amalgamation

Three architectural features stand out when visiting the amalgamation *haciendas* that still survive in Mexico: the imposing height of their perimeter walls, the industrial magnitude of some of these *haciendas*, and their clinging like limpets to the banks of streams. The first is the consequence of pioneer mining characterized by 'isolation and insecurity … for many years and even centuries at the mercy of warrior hordes'.[466] The imposing outer shell of the *haciendas* have been ascribed to the fortress mentality of the '*arquitectura del temor*', the 'architecture of fear', the legacy of mining and refining carried out within a '*territorio de Guerra*', the frontier lands where indigenous groups still battled the Spanish conquerors, even as late as the nineteenth century.[467]

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de 600 quintales de azogue; y acaso nos sirvan gustosos en las demás ocurrencias relativas a el ultimo repartimiento que hagan de dicho ingredient que existe y demás. Nos parece han quedado agradecidos', quoted in Suarez Arguello and Von Mentz, *Epistolas y cuentas Vetagrande*, 535. They were wrong, in February of 1807 no mercury was allocated to them, which forced them to offer up to 12 pesos more than the official price if 600 quintales were available. Ibid., 571-72.

[466] '*aislamiento e inseguridad …estuvieron por muchos años y aun siglos a merced de las hordas guerreras*', in Mendizábal, *La mineria mexicana*, 45.

[467] Aurelio de los Reyes, *Los caminos de la plata* (Mexico: Universidad Iberoamericana, 1991), 13. In the north 'the Spanish miner continually on guard against attack … the reales de minas … were virtual military garrisons' in West, *The Parral Mining District*, 4-7. 'in general all the advanced [mines] in territories still held by non-conquered tribes … were protected by small forts or *reales*; from which the generic *name Real de Minas*'- '*en general todas las de avanzada en territorio poblado por tribus no sometidas … eran protegidas por fortines o reales; de donde tomaron el nombre genérico de Real de Minas*' in Bargalló, *Minería y metalurgia colonial*, 63. For an overview of the Chichimeca wars and mining see Bakewell, *Silver Mining in Zacatecas*, 4-40. '*Incursiones bárbaras*', barbaric incursions, are still cited as taking place in the nineteenth century, cited in Cuahtemoc Velasco Avila et al., *Estado y minería en México (1767-1910)* (Mexico: Fondo de Cultura Económica, 1988), 234.

‘the dearth of towns made the *haciendas* into tiny human centres scattered within the boundless countryside, requiring protection against the sudden attacks not only by chichimecas, but also by bandits and guerrilleros .. a state of permanent insecurity is reflected in the old hulks of the *haciendas*’[468]

Protection from those without and protection for the wealth within that provided the resources to push up stone over stone well beyond five metres in height, massive bastions at times crenelated like the walls of castles (Figure 3-12). The region around Pachuca was rife with brigands even in the late nineteenth century, as is clear from any of the travel diaries cited in Chapter 4. Not only travellers but refining *haciendas* were constantly under threat: ‘Attached to these works [*Hacienda* Velasco] is a handsome house, deserted. No officer dare live in it. Not long since its walls were scaled by a robber band, though they could find but little booty.’[469] The height of these walls not only isolated the *hacienda* from a hostile exterior, in some cases they also helped to encapsulate some of the environmental impact vectors within the confines of each *hacienda*.

With regard to the scale of production of amalgamation *haciendas*, I will use as a guide the case of Guanajuato at the end of the eighteenth century. Guanajuato was the region of New Spain that by the nineteenth century was most renowned for the quality of its amalgamation process.[470] Its refining units have been divided by historians into *zangarros* or *haciendas*, the former defined as a smaller and less permanent production unit than the *hacienda*.[471] The Mexican historians Martin Torres and Lara Meza have analysed the nature and location of these

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468 ‘*la escasez de villas hacía de las haciendas diminutos núcleos humanos esparcidos en la inmensidad del paisaje, necesitadas de protección contra los ataques relámpagos no solo de los chichimecas, sino de los bandidos y de los guerrilleros … inseguridad perenne reflejan los viejos cascos de las haciendas*’ in Reyes, Los caminos de la plata, 19.

469 Gilbert Haven, *Our Next-Door Neighbor: a Winter in Mexico* (New York: Harper & Brothers, 1875), 150.

470 For example see Duport, *Métaux précieux au Mexique*, 263.

471 According to Salazar González *zangarros* was a term also applied to small sugar refining units. Salazar González, *Las haciendas de San Luis Potosí*, 83.

units in and around Guanajuato and Marfil, including an extensive review of ownership, sale and rental values, and the web of interrelated business dealings and circulation of capital that fuelled the sector in the seventeenth and eighteenth century. The average size of each class of refining unit is not established, though they make clear that the term *hacienda* encompasses a very wide range of production capacities.[472]

There are two documents in the historical archives of Guanajuato that shed more quantitative data on this general classification. The first is a list of *haciendas* and *zangarros* that had been supplied (*aviado*) by the *Hacienda* La Escalera in Guanajuato, and now had to prove they had the assets with which to repay a considerable aggregate debt of 556,349 pesos up to the 31st October 1788.[473] The documents first of all highlight the existing hierarchy within the business model of refining *haciendas* in Guanajuato, with La Escalera serving as distribution and credit centre to a constellation of third-party refining units held together by a relationship of supply and credit dependency.[474] In each deposition the debtors under oath set out a list of assets to demonstrate their capacity to repay their portion of the debt, but without validation by an independent evaluator. It is not an inventory of each refining unit, but a selection of assets made by each owner. Some items (silver content of ores, silver in *patio*) are prone to over-estimations, while the inventory of mercury, number of amalgamation *tortas* (cakes) in a *patio*, number of *arrastres* or mules are more difficult to manipulate. I have listed

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472 Lara Meza, *Haciendas de beneficio de Guanajuato*, 53-104.; Martín Torres, *El beneficio en Guanajuato*. The pioneering study on the ownership and business structure of the colonial refining sector in Guanajuato is reported in Brading, *Miners Bourbon Mexico*, 261-302.

473 AHUG, Bienes Difuntos, *Caja* 8, Expediente 57, dated 18 mayo 1791 to 7 julio 1791, 6r to 29v. I have only excluded from Table 3-I the data for the Hacienda Nuestra Señora de Guadalupe that appear in 23r,v since the owner declares he will extract from 80 *montones* more than 4,000 marks of silver, which would imply an ore with 50 marks per montón, five times higher than the average of the other haciendas in the document.

474 The full name is the Hacienda de San Antonio de Escalera, situated within the city of Guanajuato, a photo of its impressive perimeter walls appears Figures 3-11 a) and a surviving *capellina* house in Figure 3-9 d). The grounds of La Escalera belong at present to a private housing condominium.

in Table 3-I some of the assets as reported, though the significance of a missing item may only mean the owner decided not to include it as proof of collateral.

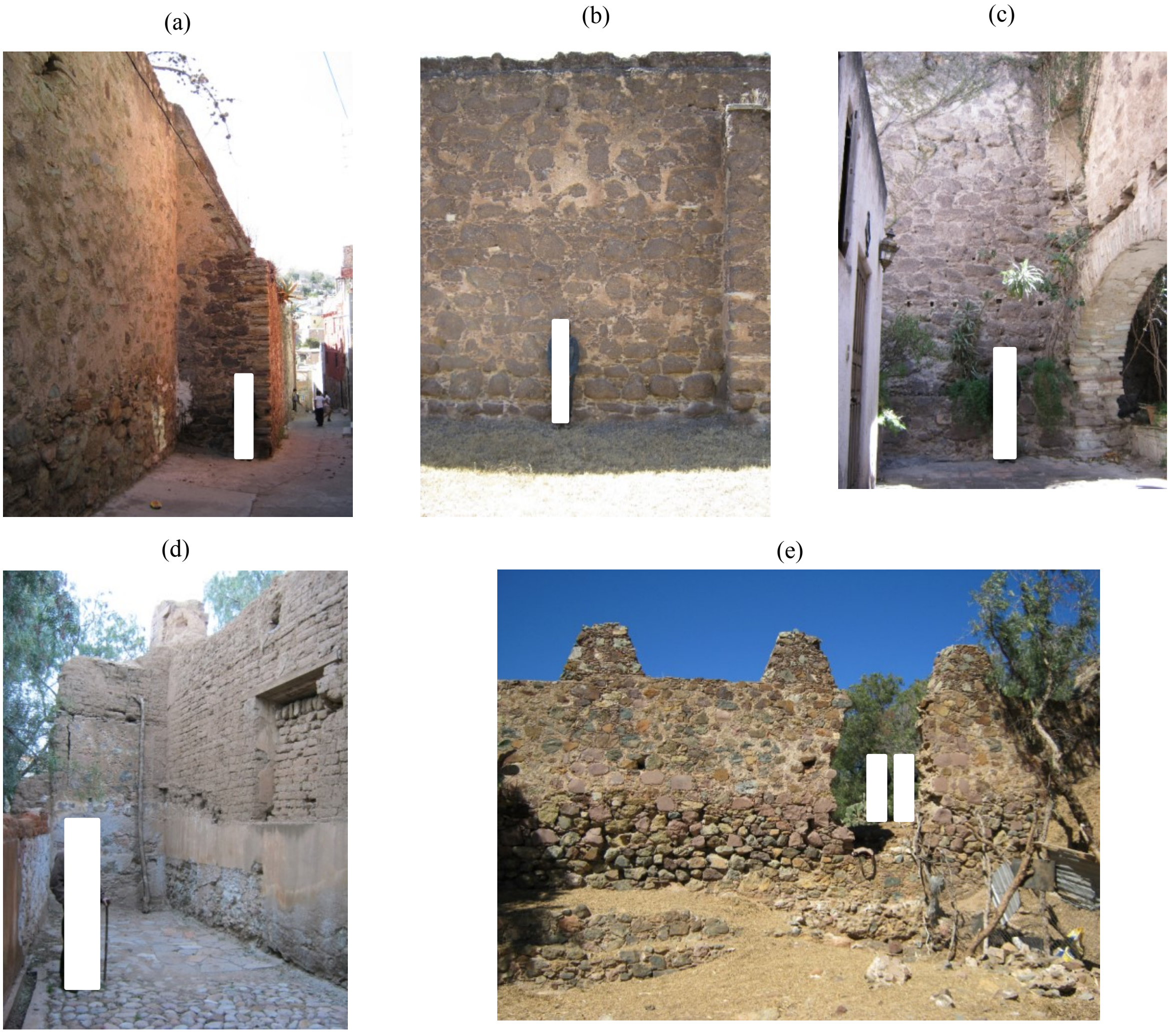

Figure 3-12. Perimeter walls a) *Hacienda* La Escalera, Guanajuato, scale bar 1.6 m b) *Hacienda* San Juan Nepomuceno, Marfil, scale bar 1.6 m c) *Hacienda* Santa Ana, Marfil, scale bar 1.6 m d) *Hacienda* Las Mercedes, Zacatecas, scale bar 1.7 m e) *Hacienda*, name unknown, Pacumo, Zacatecas, scale bars 1.7 m.

From the data in Table 3-I, I conclude that as a rule of thumb *zangarros* on average handled in their reactor *patio* 20 *montones* of 10 *cargas* each, less than 30 t of ore, about one third smaller than the average of the units listed as *haciendas* in the table.[475] The *haciendas* being supplied by La Escalera had on average in their *patios* around 650 marks of silver value (approx.. 150 kg silver), in just three *tortas* of 20 *montones* each, for a total of 600 *cargas* of ore, or approximately 83 t. The data on mercury incorporated into each *patio*, around 800 kg on average, is indicative of the amount of liquid mercury to which the skin of the indigenous workers was exposed every month, starting with the initial addition of mercury to the *tortas*. The information on the number of *molinos* and *arrastres* is more limited, but an average of 12 *arrastres* and one *molino* is given by the data in Table 3-I. If these *haciendas* worked on the basis of a four week amalgamation period, the annual revenues would be in the range of 60,000 pesos, and the annual throughput of ore around 1,000 t, based on a silver content of not more than 0.2%.[476]

With respect to La Escalera there is a second document that places it among the industrial-size *haciendas* of New Spain of this period. It is a short accounting book that has registered the monthly amounts of silver produced at four *haciendas* in Guanajuato, between May 1791 and March 1792.[477] Figure 3-13 tracks the monthly amounts in marks of silver, resulting in an average monthly production of 4,039 marks (929 kg) of silver for La Escalera. This is a scale of production approximately half of that by Regla (Chapter 4) and one fifth of the *Hacienda* Nueva de Fresnillo (Zacatecas) in the nineteenth century (see below). Two other *haciendas* show a level of silver production higher than those of Table 3-I: *Hacienda* San Antonio, with a monthly average of 1447 marks of silver (333 kg) and La Purísima with 1218

[475] This would make a *zangarro* more formal than the 'occasional sheds' described by Brading. He estimates between 200 to 300 *zangarros* and 50 to 75 *haciendas* in the Guanajuato/Marfil area in the period from 1780 to 1803. Brading, *Miners Bourbon Mexico*, 282. Martin also treats *zangarros* as very primitive and non-permanent units, but he does not go further into their analysis. He provides a list of 64 *haciendas* in the Guanajuato area that existed between 1686 and 1740. Martín Torres, *El beneficio en Guanajuato*, XII-XIII, 154.
[476] Lara Meza, *Haciendas de beneficio de Guanajuato*.; Martín Torres, *El beneficio en Guanajuato*.
[477] AHUG, Minería, *Caja* 15, Doc 551, 1r to 5v, initial date 7 May 1791.

marks of silver (280 kg). Finally the *Hacienda* San Juan Nepomuceno presents a monthly average within the range of Table 3-I, with 544 marks of silver (125 kg). It is interesting that

Hacienda	*montones* in *patio*	*tortas* (cakes)	mercury in *patio*, lbs	silver content marks / *monton*	value of silver in *patio*, marks	inventory mercury, *quintales*	*capellinas* number, weight	*arrastres*	mill	mules
Santísima Trinidad	66	3	2,000	10	*660*	35	2			96
Nuestra Señora de los Dolores del Presidio	42	3	1,218	8	*336*	7		6		150
San Juan	78		2,028	9	*702*	17	1, 380 kg	15	1	113
San José	67		1,004	10	*670*			12	1	63
Nuestra Señora de Guadalupe de Rocha	45		1,904		*405*	32	2, cost 500 *pesos*			72
de Cuevas			2,500		800	15	3, copper, 506 kg, 288 kg and 161 kg			265
San Nicolás	48			15	*720*	36	1, copper, 357 kg			65
Nuestra Señora de Guadalupe	46		1,100	15	*690*	19				32
San Antonio		3			600					
San Ignacio	15	3	2,400		800	36				124
San José	120				1,100	30		14	1	124
de Mota	110		1,100		550	30				65
Durán	50			7	350	40				
average	62	3	1,695	11	645	27		12	1	106
Zángarro	*montones* in *patio*	*tortas* (cakes)	mercury in *patio*, lbs	silver content marks / *monton*	value of silver in *patio*, marks	inventory mercury, *quintales*	*capellinas*	*arrastres*	mill	mules
San Buenaventura	16		432				1, copper, 276 kg			24
San Miguel	50			10	*500*	6	1, copper, 288 kg	8	1	60
El Cantador	5		200		80					
San José	9			16	*144*	4				12
Nuestra Señora de Guadalupe	21		500		220	6				20
Señora de los Dolores						12		4		12
average	20		377	13	236	7		6	1	26

Table 3-I. List of debtors on supplies provided by the *Hacienda* La Escalera, Guanajuato, with their estimate of selected assets offered as collateral to the debt, as of 1791. Raw data from footnote 473. Numbers in italic have been calculated by author from original data.

the accounting of silver states the amount in marks but also in number of *pinas*, and in one case for La Escalera in number of *capellinas* (2 *capellinas* producing 551 marks, or approximately 64 kg of silver per *capellina*).

What would have been the architectural footprint of an average amalgamation *hacienda* such as in Table 3- I? The number of historical plans of amalgamation *haciendas* of New Spain is nil, as far as I have found.[478] In the case of Guanajuato Lara Meza confirms there are no

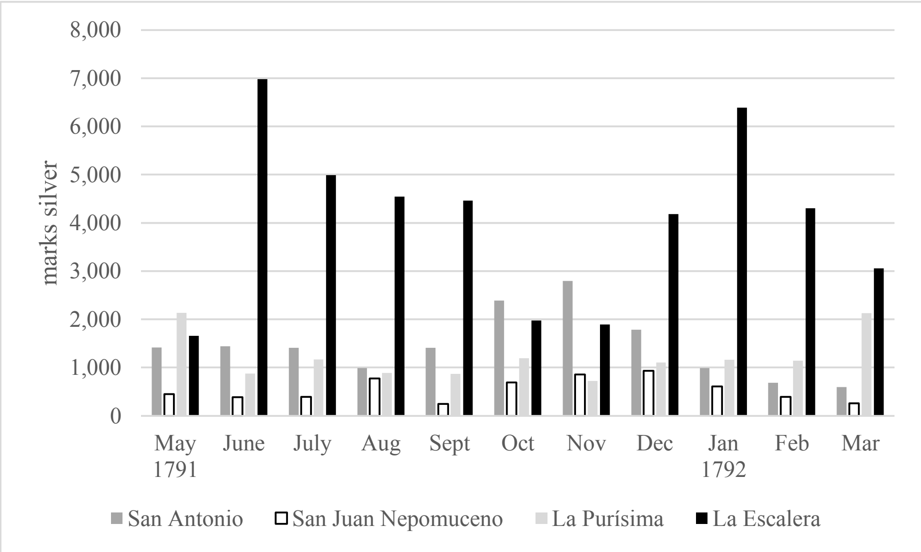

Figure 3-13. Monthly silver production for four amalgamation *haciendas* in Guanajuato, calculated from data in footnote 477.

extant plans dating from the eighteenth century.[479] For the nineteenth century I have found only four historical plans of amalgamation *haciendas*, two of which were located in Guanajuato and two in Zacatecas. The first is a drawing in ink on paper dated 19th May 1885 of the *Hacienda* Casas Blancas situated in Marfil, close to Guanajuato, where many refining *haciendas* were located on the banks of the stream named the Quebrada de Marfil (Figure 3-14; the plan has been redrawn in Figure 3-15 to aid its interpretation). The plan was drawn up by José M. Lira,

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[478] The earliest detailed plans of the complete layout of an amalgamation hacienda dates from Arzans' description of life in Potosí around mid seventeenth century. His drawings correspond to amalgamation carried out in *buitrones* (rectangular vats) and provide a very useful guide to operating conditions (some of the Spanish overseers seem to be carrying whips) and spatial distribution of the process stages, even though they are not drawn to scale. See for example Arzáns de Orsúa y Vela, *Villa imperial de Potosí*, 91.
[479] Lara Meza, *Haciendas de beneficio de Guanajuato*, 124. She presents in her work a reconstruction of the Hacienda de Salgado as of 1775. A generic version of a plan for an amalgamation hacienda in Mexico was published in the nineteenth century in Amador, *Tratado práctico de haciendas de beneficio*, no page number.

Civil Engineer, and identifies the work spaces together with their main dimensions.[480] Even though it indicates smelting areas, it is an amalgamation *hacienda* and these may correspond to the casting of silver bars or an occasional smelting run. I have no information on the background to this *hacienda*, and a visit to the existing structure, which cannot be accessed, did not add to the information in the plan.

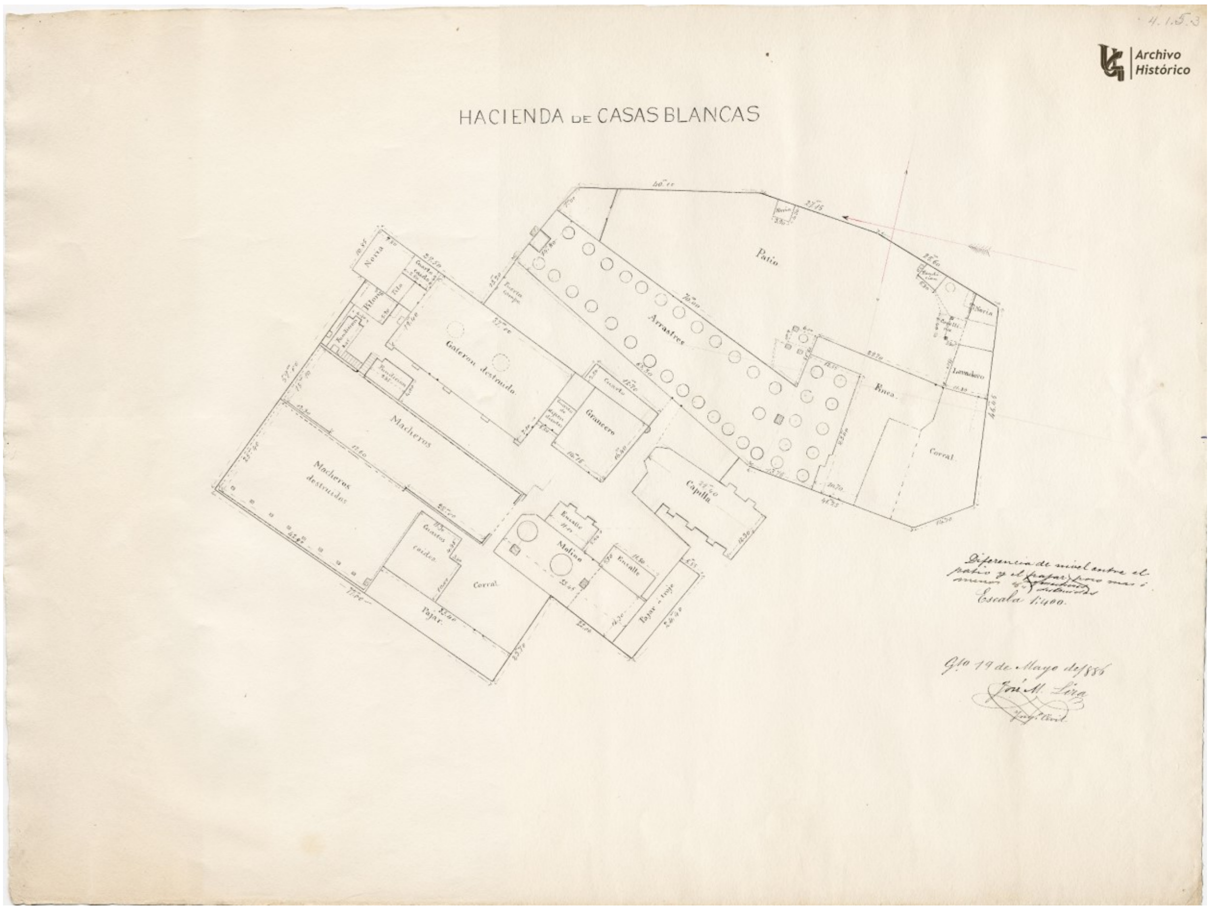

Figure 3-14. Plan of the *Hacienda* Casas Blancas, Marfil, 1885, AHUG, Mapoteca, Hda. Casas Blancas, 5p3. Digital image supplied by AHUG.

The second is a reproduction of the 1866 lithograph depicting the layout of the *Hacienda* de Rocha that occupied the grounds of what is at present the Hotel Reales de Minas

480 AHUG, Mapoteca, Hda. Casas Blancas, 5p3.

in Guanajuato (Figure 3-16). The original lithograph was part of a technical report on amalgamation *haciendas* in Guanajuato by the German mining expert E. Tilmann.[481] In 1850 the *Hacienda* de Rocha was purchased by a Scot, Alexander Cumming Langton, whose son Carlos Ignacio Cumming would establish Cummings y Jimenez, a long-running partnership that in addition to the *Hacienda* de Rocha would be involved in other mining projects. The *hacienda* is described as 'the best equipped of its time'.[482] The perimeter walls depicted in the inset are as usual imposing. For the sake of clarity I schematize the main process areas in Figure 3-17.

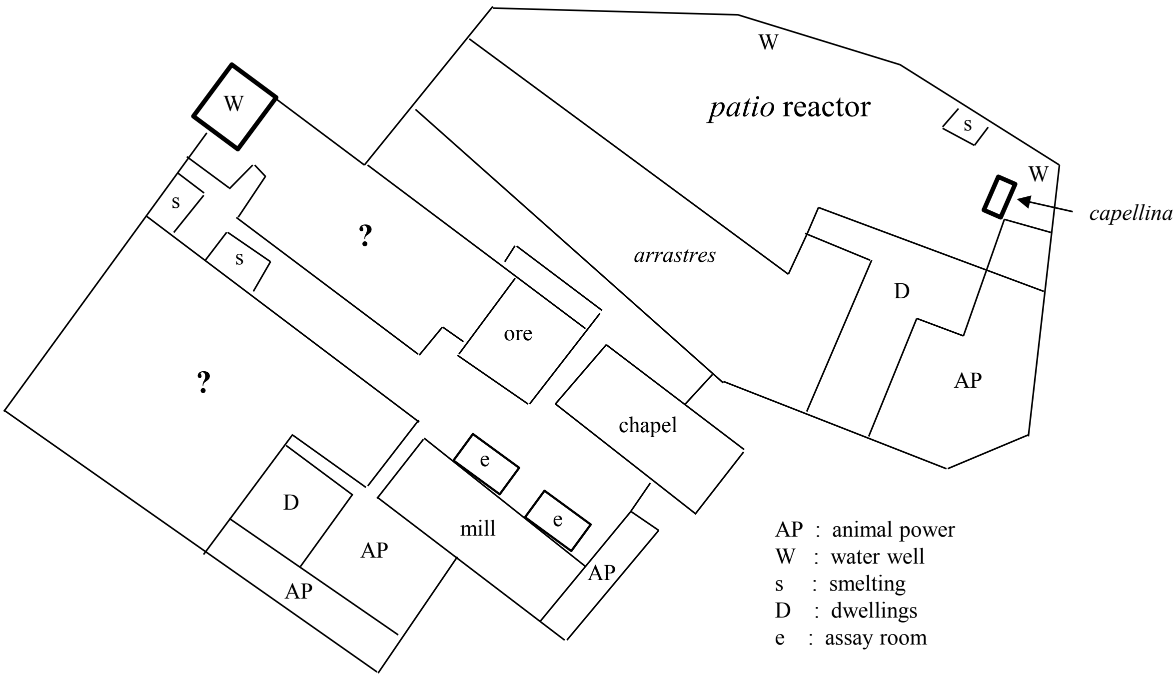

Figure 3-15. Main process areas identified in Figure 3-14.

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[481] The plan of the Hacienda de Rocha is reproduced in MacDonald, "Old Mexican Methods," 123. The original report by Tilman, titled *Der Bergbau und das amalgamations. Distrikte von Guanajuato in Mexico*, was printed in 1866 and commissioned by Guillermo Brockmann as part of a fund-raising effort in Germany to interest investors in the refining industry in Guanajuato, which ultimately failed, as cited in Rankine, "The Mexican Mining Industry in the Nineteenth Century with Special Reference to Guanajuato," 40.

[482] Amor Mildred Escalante, "Redes familiares empresariales en la ciudad de Guanajuato, México, 1877-1911," in *XXI Jornadas de Historia Económica* (Caseros, Argentina: Asociación Argentina de Historia Económica, 2008).

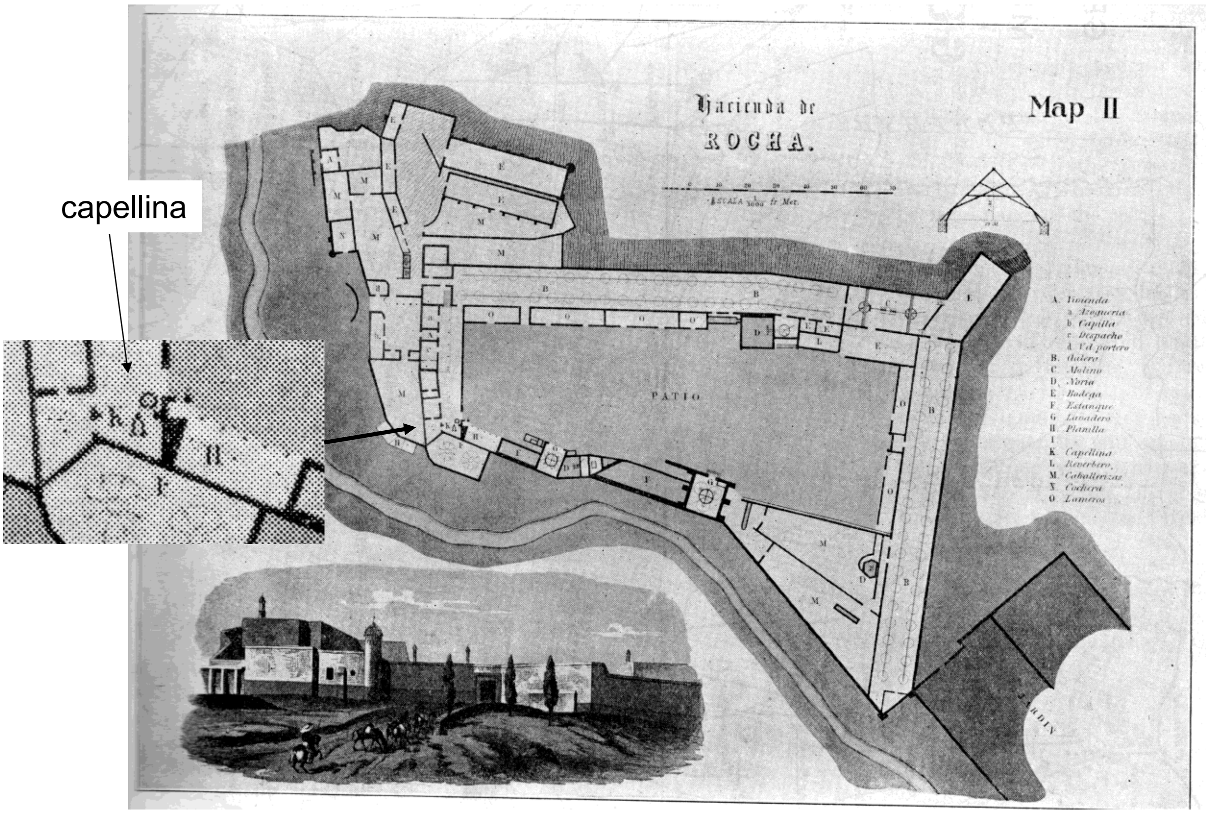

Figure 3-16. Historical plan of the *Hacienda* de Rocha, Guanajuato, reproduction in MacDonald, footnote 481, from an original lithograph in a report by E. Tillmann of 1866.

The third example is the plan of the *Hacienda* de Las Mercedes, on the outskirts of Zacatecas, from the mid nineteenth century.[483] The *hacienda* was to be sold by auction in 1850,

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[483] I found the original drawing in the AHEZ, Fondo Mapas e Ilustraciones, Serie V: Planos Siglos XVIII al XX, number 16, 3 July 1850. The drawing was originally part of the report on the evaluation of the assets of the Hacienda that is located under Notarias: Fernandez y Ferniza, Juan; 6 January 1850 to 22 December 1850, foja 158. I afterwards learnt that the existence of the plan had been made public by a Mexican historian, Antonio Ramirez Ramos, during the *V Reunion de Historiadores de la Minería Latinoamericana*, held in San Luis Potosí in 1997. His presentation was titled 'Aplicación y vigencia del procedimiento de amalgamación en la ciudad de Nuestra Señora de Zacatecas'. Since I have not been able to access his presentation paper I have opted to carry out my own analysis. According to Lara Meza he described the plan and the activities carried out at the hacienda. See Lara Meza, *Haciendas de beneficio de Guanajuato*, 47.

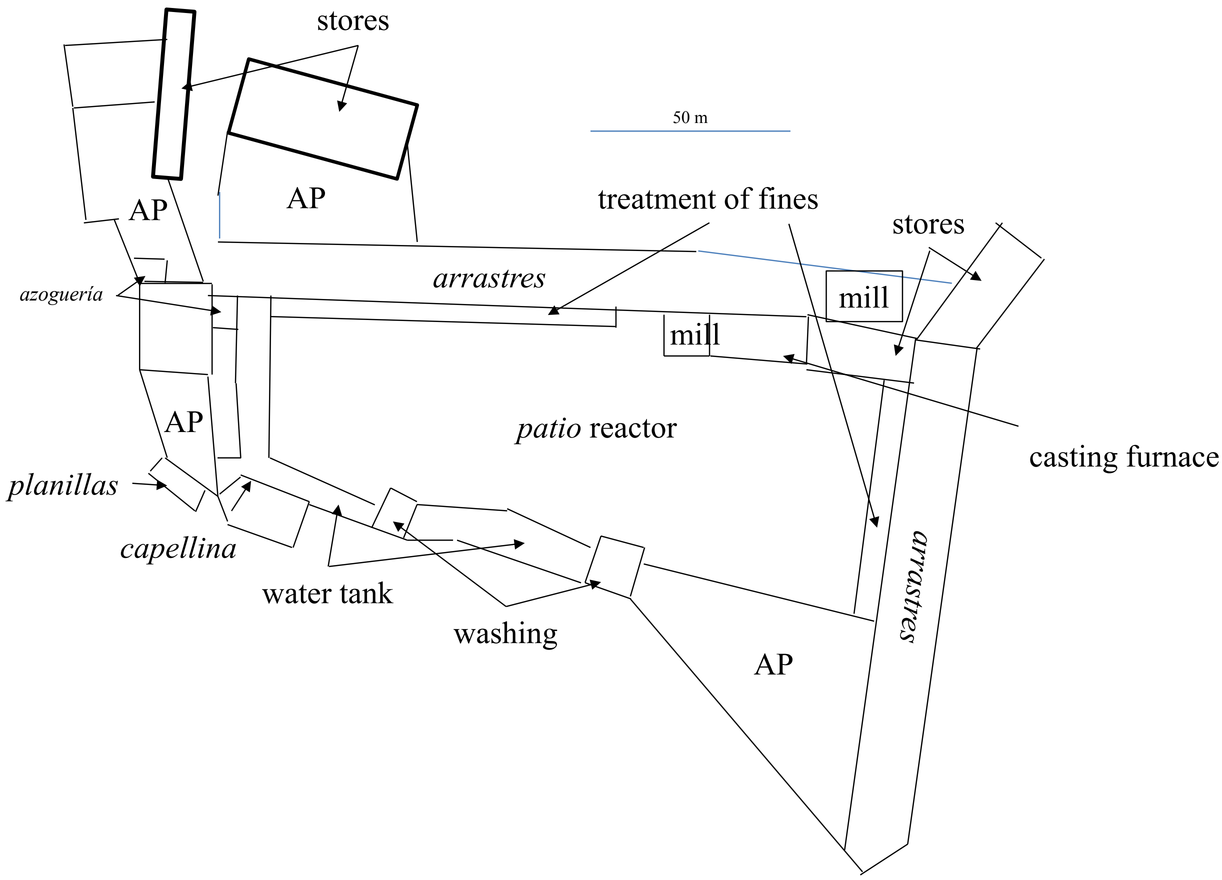

Figure 3-17. Main process areas of the *hacienda* de Rocha, according to Figure 3-16.

so a survey of its value was carried out, including the drawing of its architectural footprint, together with dimensions and the identification of its functional areas. It is a unique document in the historiography since it contains more detailed information (dimensions, building materials, equipment, values) than the previous plans. Figure 3-18 is a digital image of the original map, which I have re-drawn in more schematic form in Figure 3-19. The three areas where mercury and silver are being isolated and refined (see grey circles in Figure 3-19) are close to each other, as expected from Amador's dictum that these areas should always be placed

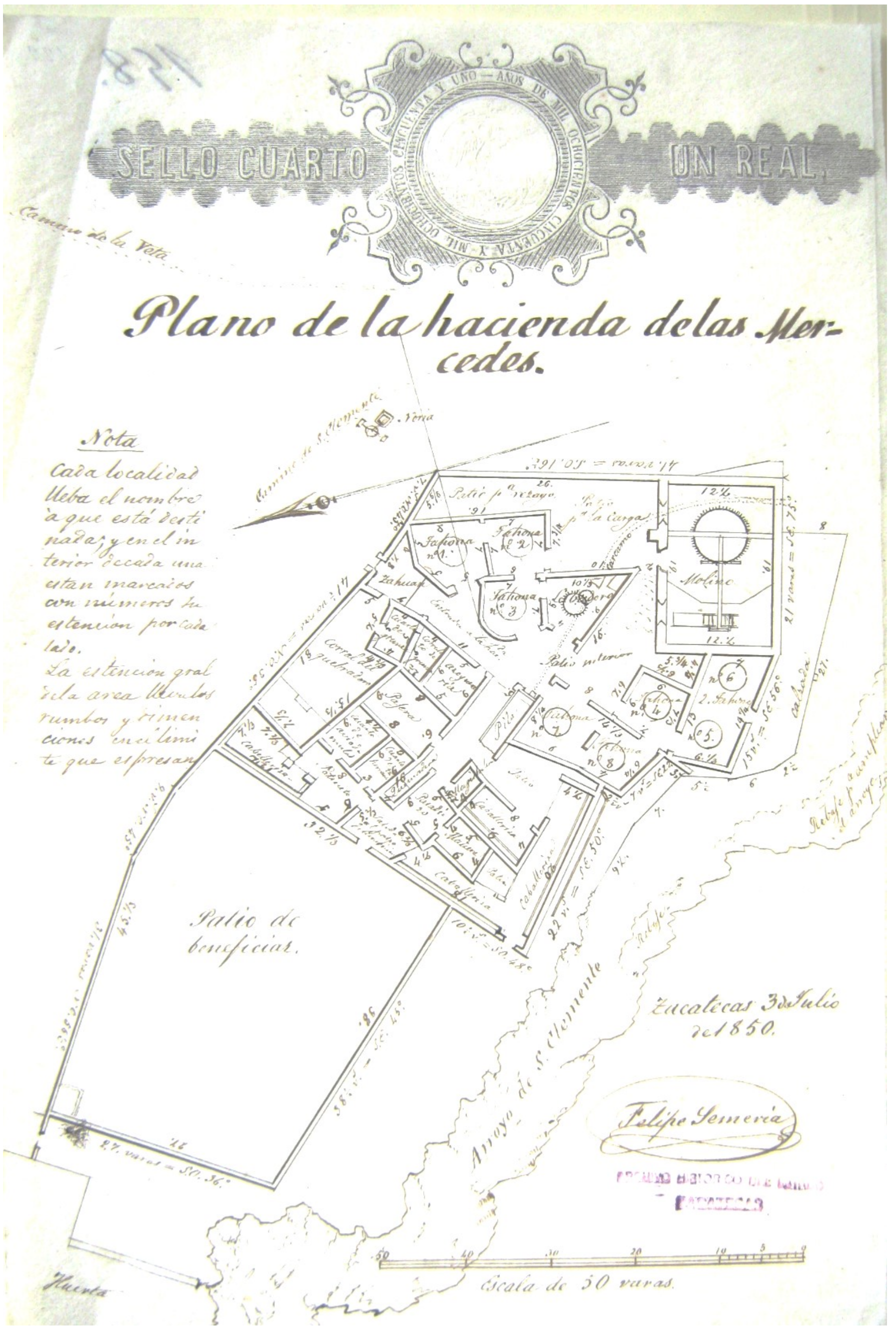

Figure 3-18. Digital image of the original hand drawn plan, ink on paper, of the *Hacienda* Las Mercedes, AHEZ, Fondo Mapas e Ilustraciones, Serie V: Planos Siglos XVIII al XX, number 16, 3 July 1850.

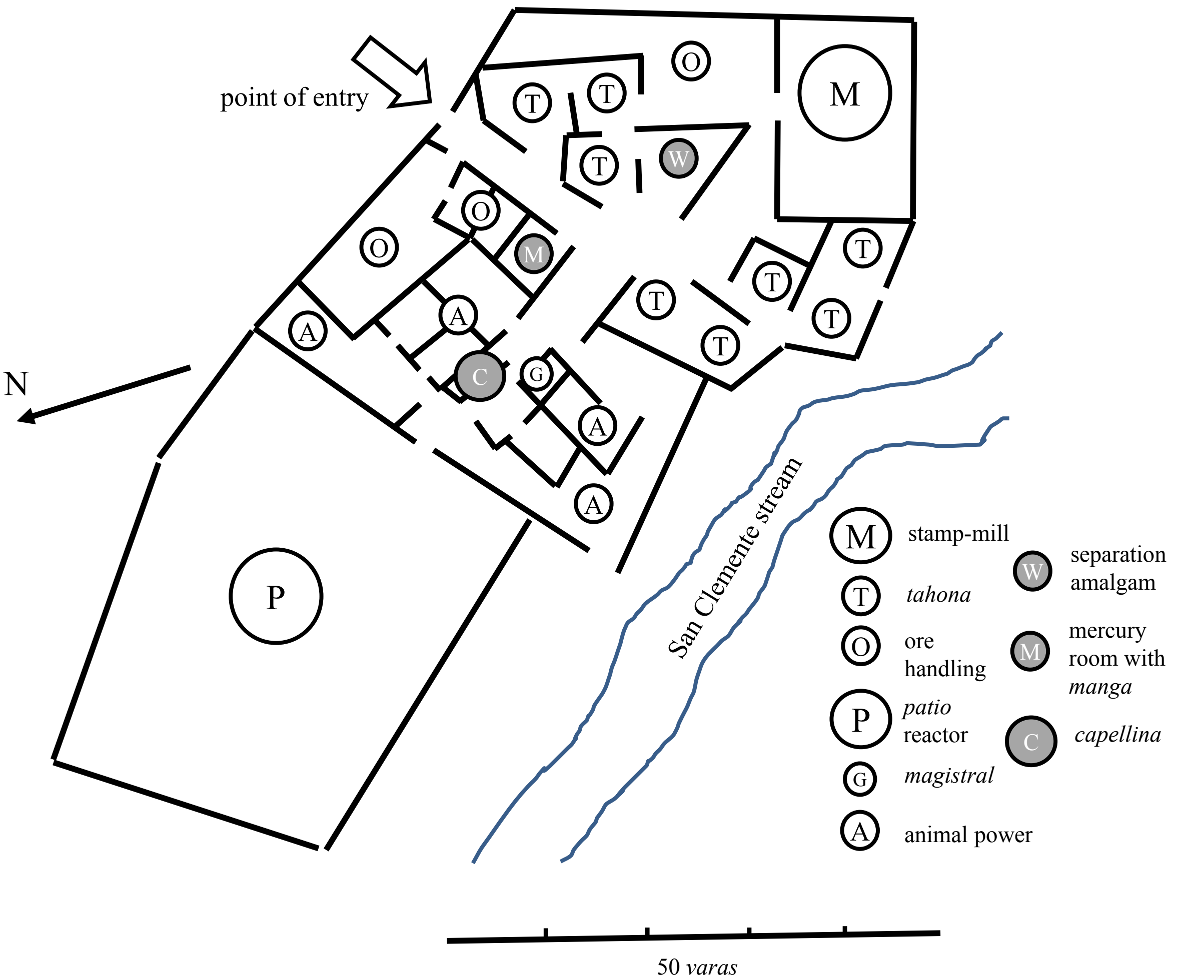

Figure 3-19. Schematic plan of the main process-related areas of the *Hacienda* Las Mercedes, adapted from Figure 3-18.

so as to facilitate their vigilance by the *hacienda* overseers.[484] These three areas, separation of the amalgam from the slurry (W), mercury room where the excess mercury is squeezed in the manga (M) and the space where the *capellinas* are heated (C) require just 3% of the total area of the *hacienda*. The space required just by the *capellinas* is only 0.5% of the total area. No mention is made of a furnace to cast the final silver bars, or of any chimney structure for the heating area of the *capellinas*. The valuation report rendered by Felipe Semeria arrives at a

[484] Amador, *Tratado práctico de haciendas de beneficio*, 70.

total value of just under 6,800 *pesos* for the *hacienda* proper (which at the time was not active), plus another 700 *pesos* for nearby dwellings and orchard.

The largest of these industrial amalgamation *haciendas* of the nineteenth century is the *Hacienda* Nueva de Fresnillo, Zacatecas, whose plan is the only one more readily available in the historiography (Figure 3-20), built to process the ores from the nearby mines of Proaño. The plan printed by the Escuela Práctica del Colegio de Minería in the mid-nineteenth century shows a geometrical array of spaces and equipment reminiscent of the colonnades of a Greek or Roman temple.[485] Even without the benefit of a scale it is evident that the three areas dedicated for the *capellinas* and the one area for the smelting of silver bars are a minor fraction of the total operational area of the *hacienda*.

The capital cost of the *Hacienda* Nueva de Fresnillo, including steam engines, by 1844 was just over one million pesos.[486] This flagship of amalgamation *haciendas* in Mexico could accommodate 64 *tortas* in its *patio*, each one of 120,000 lb, for a total of 3.5 t of ore at any one time. This is approximately 40 times the average capacity of the *haciendas* in Table I. Duport states there were 314 *arrastres* (*tahonas* in the plan by the Escuela de Minería), though only 200 were in use at any time. The *hacienda* also had 12 *molinos*. Animal power was furnished by 1,500 horses and mules. The diameter of the *tortas* was approximately 15 m, with a height

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[485] There are two sources for the plan of the Hacienda Nueva de Fresnillos. One is the plan drawn by Luis Pozos Rosas Fito, Escuela Práctica del Colegio de Ingeniería, 1857 (MMOB, Colección General, Estado de Zacatecas, Varilla CGZAC03, Numero de control 12780-CGE-7241) and printed by Litografía Salazar, prepared for the Escuela Práctica del Colegio de Minería. On the top right hand corner it states 'Lam. [Lámina] 9', which implies it is one of series, but there is no other information on the content of the other engravings. There is another reference to a plan of the Hacienda Nueva in the plates at the end of Duport's book on silver refining in Mexico, but unfortunately the plates have been removed from the copies of Duport's work available for consultation. According to Duport he obtained his copy of the plans from a French engineer, M. Doy, who worked at the hacienda. Duport, *Métaux précieux au Mexique*, 261. Silliman reproduces the plan published by Duport, in Benjamin Silliman, *Sketch of the Great Historic Mines of the Cerro de Proaño at Fresnillo, State of Zacatecas* (New Haven, Conn.: Tuttle, Morehouse & Taylor, 1883), 33. The Escuela Práctica of the Colegio de Minas to be situated in Fresnillo was created by decree in 1853, according to http://www.palaciomineria.unam.mx/recorrido/dir_jose_maria_tornel.htm. Thus it is most probable the plan in Duport's book is the original version.
[486] *Great Historic Mines of the Cerro de Proaño*, xvii.

of 28 cm. The copper *capellinas* measured approximately 90 cm high and 45 cm in diameter, and weighed 500 kg. In 1841 approximately 32,500 t of ore were amalgamated, producing over 51 t of silver.[487] It indicates a refined silver content with an average over 0.16%. Figure 3-21 shows an internal view in perspective of the *patio* reactors, an interesting mix of traditional technology together with nineteenth-century innovations, such as steam powered *tahonas* and

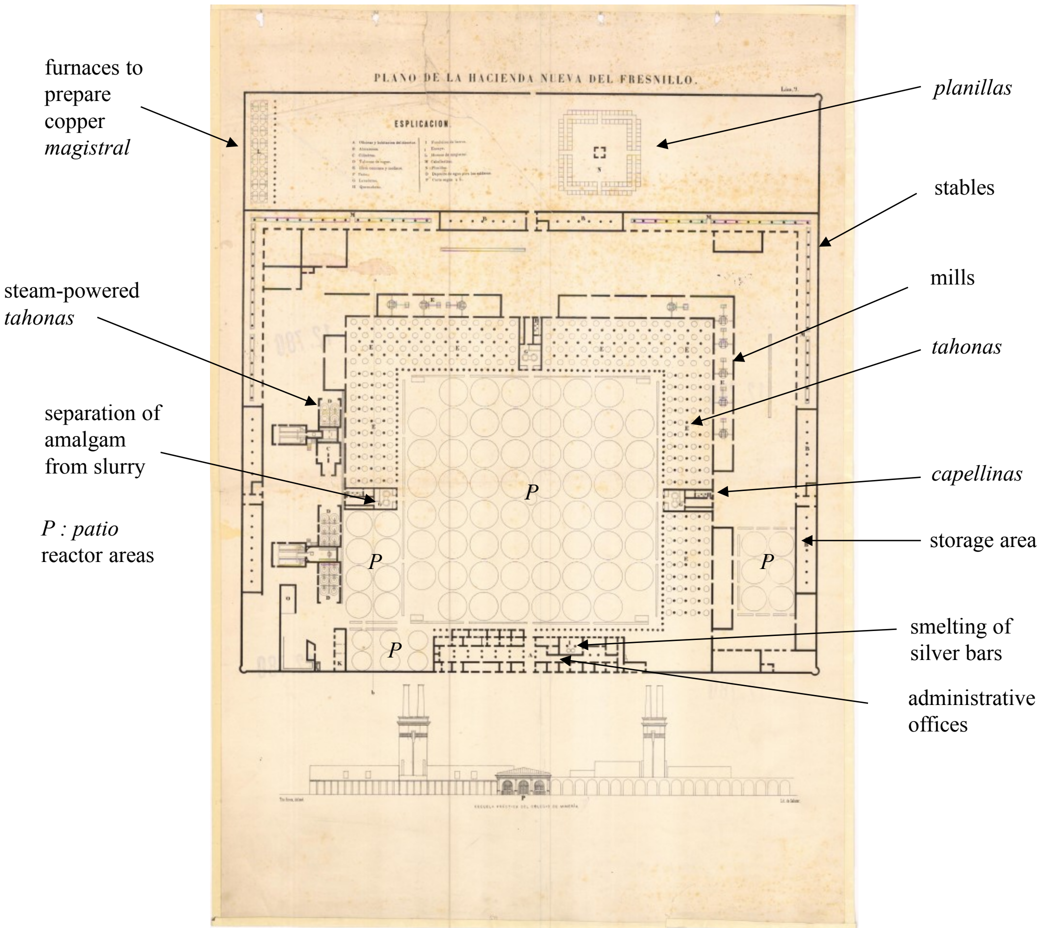

Figure 3-20. Plan of the *Hacienda* de Proaños, Fresnillo, Zacatecas, annotations added to the digital image supplied by MMOB, Colección General, Estado de Zacatecas, Varilla CGZAC03, Numero de control 12780-CGE-7241. No scale is supplied in the drawing.

[487] Duport, *Métaux précieux au Mexique*, 260-83.

railtracks and canals acting as conveyor belts for the fines. Though all these additions to the traditional process would have eased some of the back-breaking manual and animal labour, the heart of the operation remained the *patio* reactor.

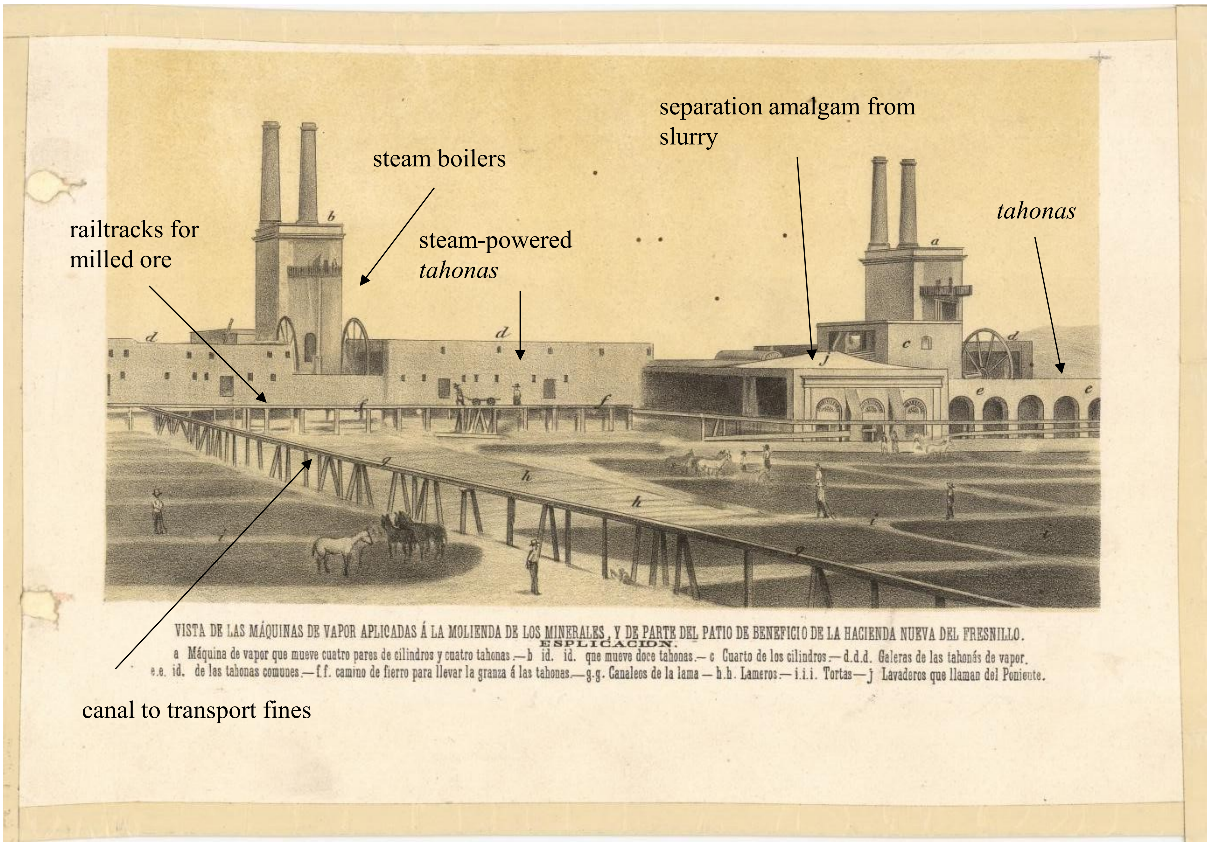

Figure 3-21. A perspective of the *Hacienda* Nueva de Fresnillo, annotations added to the digital image supplied by MMOB, Colección General, Estado de Zacatecas, Varilla CGZAC03, Numero de control 12780-CGE-7241.

To compare the main features of these four *haciendas* I have placed in Table 3-II the main spatial and operational characteristics that can be measured from the plans, together with additional information on processing capacity or infrastructure reported in the historiography or in the primary sources. I have complemented this information with my estimate of their production capacity (when not provided by other sources), using a formula based on their reactor *patio* area (see Section 4.4.3 of the next chapter). Of the four, the *Hacienda* Las

Mercedes is closest to the *haciendas* listed in Table 3-I, which probably represent the average amalgamation *hacienda* of the colonial period, though not enough data has been reported to establish this for certain. At the other extreme the *Hacienda* Nueva de Fresnillo represents a scale of industrial silver refining output that I have not found matched elsewhere in Mexico up to the mid-nineteenth century.[488] The disproportion in operational areas required at both extremes of the process (*patio* and milling vs the tiny area reserved for the *capellinas*) is indicative of the extremely reductive nature of the whole refining process in terms of volume and mass, a characteristic that will become more apparent in the next chapter which analyzes in detail the *Hacienda* de Regla, of a magnitude similar to that of Rocha.

Hacienda	Approximate area	mills	*arrastres*	approximate *patio* reactor area	Ore processed	Silver production	Approximate distribution of operational areas (% of total)				
	m2	number	number	m2	t/m	t/m	*patio* reactor	mills, *arrastres*	animal power	storage	*capellinas*
Casas Blancas	10,500	1 to 2	37	1,900	*< 300*	*0.3 to 0.6*	18	16	10		~ 0.2
Rocha	23,000	2	84	7,000	*<1,000*	*1 to 2*	30	18	19	9	~ 0.1
Las Mercedes	2,700	1	8	1,000	*< 150*	*0.15 to 0.3*	36	29	11	6	~ 0.5
Nueva de Fresnillo		12	314		2,700	4.3	no scale in plan				

Table 3-II. A comparison of some of the main spatial and operational features of amalgamation *haciendas* in Mexico, nineteenth century. Data in italics have been estimated, other data are derived from plans or from sources in text.

[488] The recognition that amalgamation haciendas in general were industrial units has been made in the historiography: for example, West, *The Parral Mining District*, 26.; Lara Meza, *Haciendas de beneficio de Guanajuato*, 31. Other examples of industrial amalgamation haciendas are: at Sombrerete the Fanoaga family mill had 84 *arrastres* and 14 furnaces, according to Brading, *Miners Bourbon Mexico*, 140.; at Sauceda, Zacatecas, in the 1770s, 3000 *quintales* of ore per week (approx.. 600 t per month) were processed in the Hacienda La Sagrada Familia, built by Jose de la Borda, with 70 *arrastres* and 10 stamp mills, as reported in Brading, "Mexican Silver Mining," 672-73. In the 1780s the haciendas (number unknown) of the Marques de Valle Ameno refined 3200 quintales of ore every two weeks, approximately 300 t per month. Moreno y Castro, *Arte de beneficiar los metales*, 12.

From an environmental point of view the economy of scale in the largest industrial *haciendas* did not translate into an economy of waste. Regardless of size, from the *zangarro* to the *Hacienda* Nueva de Fresnillo, over 99.6% of all the solids that entered each unit were eliminated as waste via the nearest available stream. Whatever efficiency was translated into a lower consumption of reagents per kg of silver produced paled in comparison to the magnitude of the mineral matrix, the gangue, that held no economic interest for the refiner. In contrast to the case of smelting *haciendas*, this waste from the process did not form a belt of lunar landscape around them but was flushed constantly downstream, converting the streams that nurtured these *haciendas* into their waste-disposal unit. If natural water streams were not available or sufficient, water pumped from mine shafts was diverted to these *haciendas*, at times even through other *haciendas* without permission, via aqueducts whose remains in the more arid Zacatecas dot the hills like dismembered vertebrae of ancient monsters.[489] Water played a vital role in keeping the surrounding areas of the amalgamation *haciendas* free of mounds of debris, so that as well as providing power to the mills, keeping the slurries wet so the chemical reactions could take place, washing the ore slurries, slaking the thirst of the animals that ploughed blindfolded through the *tortas*, and for the workers as well, it was water that washed away the mounds of silt and the calomel, mercury and excess salt and other chemicals generated by these industrial units.

3.9 The mass balance of amalgamation: the role of the *correspondencia*

There is one mathematical constant to the history of amalgamation in the New World. Barely five years after this process was being applied in New Spain, it became an established

[489] Lawsuit brought by the Hacienda San Tadeo against the Hacienda La Sauceda for constructing an aqueduct without permission across their land to bring water from the mines in Vetagrande (Zacatecas) to the Hacienda La Sauceda, 11 February 1808, EHEZ, Poder Judicial Civil C56-E07.

rule of thumb that two weights of mercury were consumed for every weight of silver extracted.[490] What is remarkable is that Duport in the mid nineteenth century commented that the 'loss' of mercury per mark of silver reported from 1570 to 1585 was the same he observed on average in Mexico some three hundred years later.[491] The authorities quickly took advantage of this inherent ratio of the process and used it as the benchmark in their apportioning of mercury to the refiners, to attempt to control the production of contraband silver. This benchmark was called the *correspondencia* and it is usually expressed as marks of silver produced per *quintal* of mercury consumed. The rule of thumb value for the *correspondencia* was usually 100 marks of silver to one *quintal* of mercury, a weight ratio of 2:1 (mercury to silver), but in practice it varied according to location. This consumption of mercury was broken down in amalgamation lore into one part of mercury consumed for one part of silver produced, and the remainder was deemed to be the physical loss of the process. 'The principle that the loss of mercury was at least equal to the weight of silver obtained, is a prejudice so embedded in most of the *azogueros*, that it is a waste of time to discuss with them on this issue'.[492] The

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[490] 'with a quintal of mercury they only extract half [a quintal] of silver' - '*con un quintal de azogue no sacan mas que medio de plata*', letter from the Viceroy of New Spain to the King, 30 July 1561, as quoted in Castillo Martos, *Bartolomé de Medina*, 145. In the discussion that follows the point of reference is *patio* amalgamation. Barba's *cazo* process shows very low levels of mercury consumption because the underlying chemistry during refining is completely different.

[491] 12 oz of mercury per mark of silver. Duport, *Métaux précieux au Mexique*, 144. At the close of the eighteenth century Garcés y Eguía had already commented upon the theoretical implications of a common value of mercury consumption in relation to the aleatory nature of human operational skills: 'the particular luck or misfortune of this or that miner [refiner] cannot question the result of calculations, since these arise from a standard behaviour of all the body [of refiners]; so that the consumption of mercury does not depend on this or that individual, but on all together … unless it can be proved that there is a problem common to all the body' – '*la fortuna o desgracia particular de uno o de otro Minero, no puede hacer falible el resultado de los cálculos, porque estos proceden según la regularidad de todo el cuerpo; al modo que los del consumo de azogue no penden de este o aquel individuo, sino de todos juntos … mientras no se verifique un mal que comprehenda a todo el cuerpo*', in Garcés y Eguía, *Nueva teórica del beneficio de plata*, 3. What in fact was common to all the body was the chemical underpinning to the *correspondencia*.

[492] '*Le principe d'une perte de mercure égale au moins au poids de l'argent obtenu, est un préjugé tellement enraciné chez la plupart des azogueros, que c'est peine perdue de discuter avec eux sur ce point'*. Duport, Métaux précieux au Mexique, 119.

obstinacy of this myth of a one to one conversion betrays its alchemical roots in the assumption that mercury is transmuted into silver during amalgamation.

For the majority of silver ores refined in the New World the need to constantly replenish mercury stocks destined for the amalgamation process was mainly due to the chemical reaction that transformed it into calomel, the chemistry of which was indicated in Section 3.4 above. By the nineteenth century chemical knowledge had matured to the point it became possible to quantify this chemical consumption of mercury. In 1872 Manuel Maria Contreras calculated the weight of mercury transformed into calomel as 1.85 times the amount of silver recovered, and conditioned this ratio to the absence of competing reduction routes for silver chloride. Though the author recognized that the physical losses during washing would alter this value, he did not proceed further into the consequences of his quantitative analysis.[493] The more recent historiography has not echoed his analysis, and has treated the *correspondencia* as a useful number to estimate silver production by amalgamation, for the lack of a better alternative.[494] And yet the *correspondencia* factor is not just a number whose only discernible connection to

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[493] Manuel Maria Contreras, "Empleo de los ensayes de pella y de residuos para determinar los adelantos y fin de la amalgamacion de la plata en el beneficio de patio.," in *Historia de la ciencia en México: Estudios y textos.*, ed. Elias Trabulse (Mexico: Conacyt y Fondo de Cultura Economica, 2003), 721-38. The original paper was published in *Anales del Ministerio de Fomento de la Republica Mexicana*, Imprenta de Francisco Diaz de Leon, tomo X, México, D.F., 1872. Contreras fought against the North American invasion of Mexico when he was 14, then graduated as a mining engineer, was named assayer of the Casa de la Moneda, became a politician (member of Congress and Senator), a noted mathematician and author of textbooks on mathematics and geometry. There is a small town in Mexico named after him, in the State of Veracruz, and also a street in Ciudad de Mexico. http://biblioweb.tic.unam.mx/diccionario/htm/biografias/bio_c/ contreras_manuel.htm. At the turn of the century Humboldt had written that 'if, in the patio process, all the silver extracted was due to a decomposition of silver chloride by mercury, the ratio of mercury lost to that of silver in the chloride would be approximately 4:7,6, since that is the respective oxidation [value] of the two metals' - '*Si, dans le procédé por patio, tout l'argent retiré étoit dù à une décomposition de muriate d'argent par le mercure, il se perdroit une quantité de mercure que seroit à celle de l'argent dans le muriate, à peu près comme 4 :7,6, car cette proportion est celle des oxidation respectives des deux métaux.*'. Humboldt, *Essai politique*, Tome IV, 80-81. Humboldt was therefore the pioneer in this correct chemical approach to the problem of mercury consumption during amalgamation, but reverses the weight ratio so that it stands at 1 to 1.9, mercury to silver. In another part of his work he states that the mercury loss was between 1.4 to 1.7 per kg silver in patio, and around 0.2 in the barrel process. Ibid., Tome IV, 68. Whether the inversion in the first ratio was an editing mistake, an ambiguous reading of the original in German or an error in the 'oxidation' values he adopts for silver and mercury is not clear, but Humboldt may have predicted the theoretical basis for the mercury to silver weight ratio as early as the 1800s.

[494] One of the most recent examples is in Lacueva Muñoz, *La plata del Rey*, 204.

the amalgamation process is a spurious stability in value throughout three centuries of refining history in the New World. On the contrary, it is a number with a sound theoretical base, the mathematical consequence of the chemical correlations inherent to the amalgamation process, and of the physical losses of mercury incurred, as I will argue in the following paragraphs.[495]

The observation that a relatively constant weight ratio applied to the consumption of mercury per kg of silver refined is strongly indicative that the underlying reason is the stoichiometry of the chemical reaction that involves both mercury and silver.[496] Returning to the sequence of reactions specified in Section 3.4, the two steps of the basic amalgamation reaction, once the silver sulphides present in the ore have been converted into silver chloride, can be condensed into the following equation:

$$(n + 2)Hg(l) + 2AgCl(s) \rightarrow Ag_2Hg_n(l) + Hg_2Cl_2(s)$$ **Reaction 4**

This chemical equation tells us that in the absence of native silver in the ore, of iron or copper metal, and excluding other side reactions of mercury or physical losses, for every mole of silver (107.87 g) refined by amalgamation, one mole of mercury (200.59 g) will be consumed in its transformation into solid calomel.[497] In this scenario, the theoretical weight ratio of mercury consumed to silver produced using amalgamation would be 1.86. This is equivalent to a *correspondencia* of just over 110 marks of silver per *quintal* of mercury under the conditions cited above. A selection of historical *correspondencia* values reported for Peru and

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[495] The main results presented in this section have been published in Saúl Guerrero, "Chemistry as a Tool for Historical Research: Identifying Paths of Historical Mercury Pollution in the Hispanic New World," *Bulletin for the History of Chemistry* 37, no. 2 (2012).

[496] Stoichiometry: in chemistry, the determination of the proportions in which elements or compounds react with one another. *Encyclopaedia Britannica*, 15th ed.(Chicago: Encyclopaedia Britannica, Inc., 1992), Micropaedia, 11, 279.

[497] The presence of native silver, which does not react chemically with mercury, will reduce the consumption of mercury. This fact is remarked upon by Egleston, *The Metallurgy of Silver*, 307.

New Spain during the period of interest is summarized in Table 3- III.[498] The mercury to silver weight ratios have been calculated for each *correspondencia* value, and have all been given equal weight to arrive at an average value of 1.8 ± 0.3. This historical average is very close to the theoretical value of 1.86 calculated above, taking into account that an additional physical loss of mercury was also taking place.

To incorporate the effect of physical losses on the *correspondencia* value I start with a very simple mass balance for an ore that contains no native silver and where no physical losses are involved (Figure 3-22). Mercury was added to the ore in a range between 5 to 10 times the deemed amount of silver estimated to be extracted in the ore. I will use as a starting point a proportion of seven to one in weight.[499] Thus if I begin my amalgamation cycle using 100kg of mercury, that means I am treating a total quantity of ore that holds 14 kg (to the nearest integer) of silver in the form of chlorides or sulphides. It is not necessary to know the total quantity of ore treated or the exact proportion of either silver compound. According to Reaction 4, for each kilogram of silver extracted, the amalgamation reaction converts 1.86 kg of mercury into calomel. It is irrelevant for this exercise whether the silver chloride that is reduced by mercury was present originally in the ore or is the result of the conversion of silver sulphides

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[498] The sources for the data in Table 3-III are the following: a) G. Cubillo Moreno, "Los dominios de la plata: el precio del auge, el peso del poder. Empresarios y trabajadores en las minas de Pachuca y Zimapán, 1552-1620,"(Col. Divulgación, Serie Historia, Instituto Nacional de Antropología e Historia/Consejo Nacional para la Cultura y las Artes, México, 1991). b) Gómez de Cervantes, *Nueva España siglo XVI*. c) Peter J. Bakewell, "Notes on the Mexican Silver Mining Industry in the 1590's," in *Mines of Silver and Gold in the Americas*, ed. Peter J. Bakewell (Aldershot (GB); Brookfield (Vt.): Variorum, 1996). d) "Registered Silver Production in the Potosi District 1550-1735," *Jahrbuch für Geschichte Lateinamerikas* 12 (1975). e) complaint by miners on the price of mercury, 26 April 1679, AHEZ Notarías/Colonia, Number 5 (Felipe de Espinosa 1653 - 1680), expediente 9. f) lawsuit against the Count of Santa Rosa, for mercury debt to the Royal Treasury, 6 December 1692, AHEZ, Real Hacienda- Judicial 1690. g) *Silver and Entrepeneurship in Seventeenth-Century Potosí. The Life and Times of Antonio López de Quiroga* (Dallas: Southern Methodist University Press, 1995). h) Newson, "Silver Mining Honduras." i) Brading and Cross, "Colonial Silver Mining: Mexico and Peru." j) Arduz Eguía, *Minería altoperuana*. k) Mendizábal, *La mineria mexicana*. l) Burkart, "Mines de Veta-Grande." m) Duport, *Métaux précieux au Mexique*.

[499] Five to six parts of mercury to one of deemed silver content according to Amador, *Tratado práctico de haciendas de beneficio*, 75. ; Hermosa, *Manual de Laboreo de Minas*, 216.; ten parts of mercury to one of silver in Duport, *Métaux précieux au Mexique*, 269.

according to Reaction 3. The critical assumption is that only mercury reduces the silver chloride to elemental silver.

Mercury	Silver	Location	Period	Hg/Ag	Source
1 *quintal*	100 mark	Pachuca, New Spain	16 c	2.1	a, 165
1 *quintal*	115 mark	Pachuca, New Spain	end 16 c	1.8	a, 184
1 lb	1mark	New Spain	1580s	2	b, 154-155
1 *quintal*	115 mark	New Spain	1590s	1.8	c, 175
1 *quintal*	150 mark	Potosí, Peru	1588	1.4	d, 82
1 *quintal*	160 mark	Potosí, Peru	1635	1.3	
300 *quintales*	36,000 marks	Zacatecas, New Spain	1679	1.7	e, 63r
165 *quintales*	16,500 marks	Zacatecas, New Spain	1690	2	f, 33r
13,000 lb	7800 lb	Potosí, Peru	colonial era	1.7	g, 59-60
1 *quintal*	80 mark	New Spain		2.6	c, 175
1 *quintal*	140 mark	New Spain		1.5	
1 lb	1 mark	Honduras		2	h, 53
1 *quintal*	100 mark	New World best practice		2.1	i, 556
1 *quintal*	85 mark	Bolaños, New Spain		2.4	
1 *quintal*	125 mark	Guanajuato, New Spain		1.6	
1 *quintal*	112-126 mark	Zacatecas, New Spain		1.6-1.8	
		Potosí, Peru	1750s	1.5	j, 105
1 *quintal*	120 mark	New Spain	1770s	1.7	k, 75
1 *quintal*	80 mark	San Luis Potosí, Sultepec, others, New Spain		2.6	
1 *quintal*	125 mark	Guanajuato, New Spain		1.6	
		Zacatecas, New Spain	1835	1.5	l, 80
12 oz	8 oz	Guanajuato, New Spain	mid 19 c	1.5	m, 118
10-24 oz	8 oz	Guanajuato, New Spain		1.2-3	m, 119
1 lb	1 mark	New Spain	1836	2	m, 134
12 oz	8 oz	Catorce, New Spain	mid 19 c	1.5	m, 143
15 oz	8 oz	Zacatecas, New Spain		1.9	m, 251
12-14 oz	8 oz	Fresnillo, New Spain		1.5-1.8	m, 275, 279
8-13 oz	8 oz	Guadalupe, New Spain		1-1.6	m, 319, 328

Table 3-III. Historical values of Hg/Ag weight ratios calculated from values of correspondencia reported in the historiography. Sources from footnote 498.

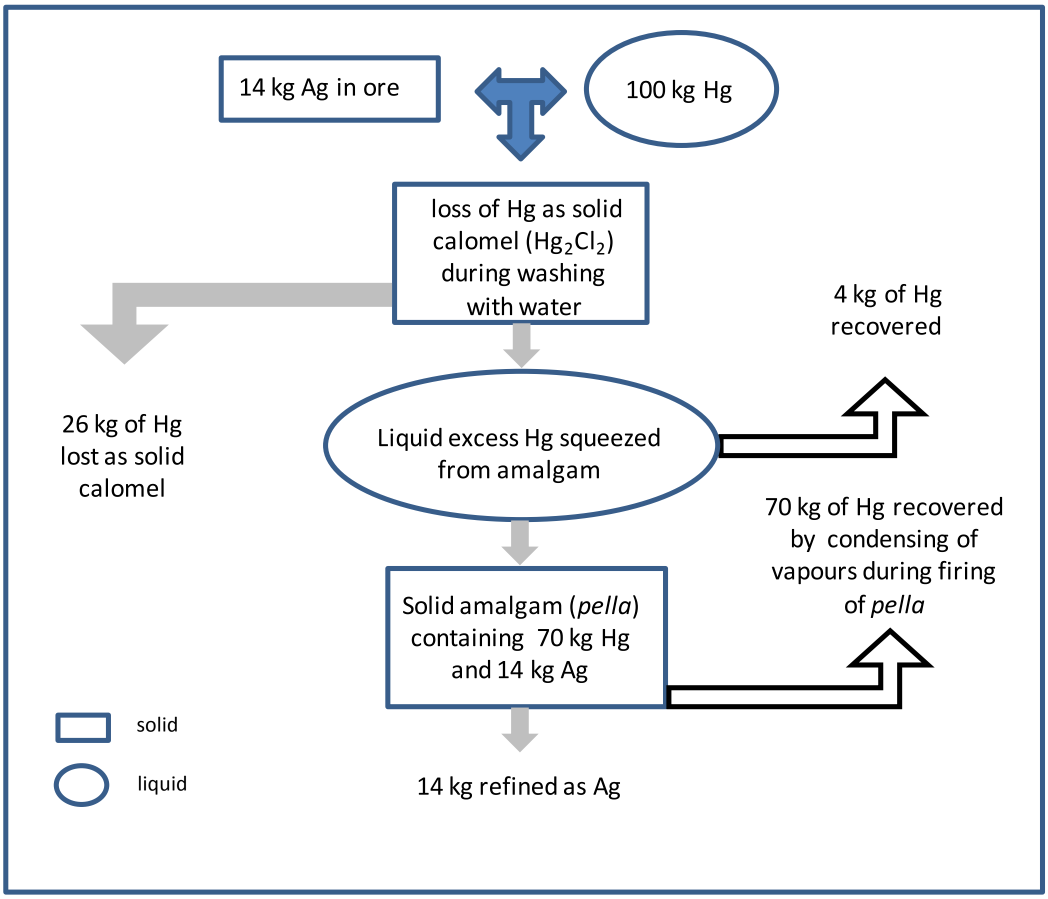

Figure 3-22. Simplified mass balance of amalgamation process

I further assume that in a single cycle I extract the totality of the 14kg of silver, which then implies a total chemical conversion of 26 kg of mercury into calomel. All throughout this exercise I only refer to the weight of mercury lost as calomel, not to a weight of calomel produced. The composition of the amalgam after the excess mercury was extracted was approximately 5 parts mercury to one part silver.[500] The amalgam is assumed to contain 14 kg of silver and 70 kg of mercury, while 4 kg of mercury were extracted in the *manga*.

[500] This is an average proportion, that is found at both ends of the historical period under study. For example see Capoche, "Villa Imperial de Potosi," 124.; Amador, *Tratado práctico de haciendas de beneficio*, 75.

In summary, this simple mass balance shows that after extracting 14 kg of silver there are 74 kg of mercury recovered in two different batches, one by a simple operation of squeezing a liquid amalgam through a cloth, and the remainder by heating the amalgam in the mercury recycling assemblage (*caperuza*, *desazogadera*, *capellina*) and condensing the mercury vapours. In addition 26 kg of mercury are converted to solid calomel. I will now designate by f_a the fraction of silver present as silver chloride or silver sulphide in the ore, with values between 0 and 1. It is important to underline that the variable f_a is not the silver content in the ore. In fact, the same f_a value can apply to two silver ores with quite different silver content. Thus the weight ratio of mercury lost as calomel to silver refined for ores containing native silver as well as silver chlorides and sulphides can be expressed in the following manner:

$$[Hg/Ag]_{\text{calomel loss}} = 1.86\ f_a$$

If the silver content in the ore is made up of pure native silver, f_a is equal to zero and no mercury is lost as calomel. If the silver content is made up only of silver chloride and sulphide, then the weight ratio of mercury lost to silver extracted will be 1.86. I am ignoring further chemical losses in the form of secondary reactions between mercury and excess copper *magistral* that can produce calomel or mercury with sulphur to produce cinnabar, but they could be factored into the equation in an analogous manner.

The most simple way to include the effect of physical losses on the weight ratio is to assume a single physical loss factor (f_b) between zero and unity that encompasses both mercury lost through volatilization and mercury lost through washings and spills. By taking this approach the exact amount of mercury remaining in the amalgam does not need to be known. Based on the amalgamation recipe of seven parts mercury to one part extracted silver from the ore, the weight ratio of mercury to silver due to physical losses of mercury will then be:

$$[Hg/Ag]_{\text{physical losses}} = [\ 7 - 1.86\ f_a]\ f_b$$

The term between brackets on the right-hand side of the equation corresponds to the weight ratio after eliminating the chemical loss. It would be possible to separate ‘cold’ losses of mercury (spills, washings) from ‘hot’ losses (volatilization) but for the purpose of this exercise I will continue using a single loss factor, f_b.

The total weight ratio, taking into account both chemical and physical losses, can now be expressed as:

$$Hg/Ag = 1.86\ f_a + [\ 7 - 1.86\ f_a]\ f_b$$

where

Hg/Ag = weight ratio of mercury lost to silver extracted

f_a : weight fraction of silver chloride and sulphide in the silver present in the ore, between 0 and 1

f_b : total physical loss of mercury during amalgamation, expressed as a weight fraction between 0 and 1

The ratio Hg/Ag, as well as the *correspondencia*, is independent of the total silver content of an ore.

The relevance of the equation is that it demonstrates that the values of the Hg/Ag ratio (as representing the *correspondencia*), silver content (as chloride and sulphide) and physical losses are not three independent variables. Thus each of the three constrains the values the other two can adopt. It is easier to visualize this interdependence in Figure 3-23. Each value of the Hg/Ag ratio can be calculated from different pairings of f_a and f_b values. Three values of this ratio are plotted as curves in Figure 3-23: 1.5 (lower limit of standard deviation of historical average), 1.8 (historical average) and 2.1 (upper limit of standard deviation of historical average) respectively. The only pairings of f_a and f_b values that are relevant to the present discussion are those that fall between the bottom and top curves representing the two extremes of the historical Hg/Ag ratio. In addition, the silver ores treated by amalgamation were the *negrillo* ores, rich in silver sulphide and low in native silver, which would therefore have f_a values that tend to unity. I will assume as a working figure that the most likely range of f_a for these ores lies between 0.75 and 1. As can be seen in Figure 3-23, this in turn would limit the values of f_b to below 0.15. The rectangle in grey visualizes the 'boxing in' of f_b imposed by the value of f_a and the range of observed Hg/Ag ratios.

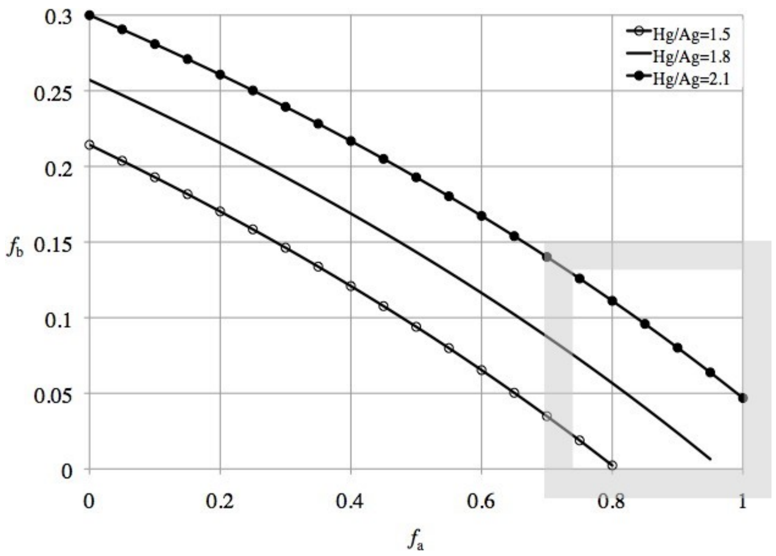

Figure 3-23. Sensitivity of Hg/Ag weight ratio to the fraction of silver chloride and sulphide of the total silver present in the ore (fa) and on the fraction of physical loss (fb). Reproduced from footnote 495.

If for the treatment of *negrillos* (assumed range of f_a values between 0.75 and 1) higher physical losses are assumed, i.e. values of f_b well over 0.15, the mercury to silver weight ratio would quickly reach values much greater than 3, well above the historical range reported in Table 3-II. This is illustrated by the plots in Figure 3-24, where the grey area denotes the average range of observed Hg/Ag ratios. Only ores very rich in native silver (low to zero f_a

values, not shown) would mathematically allow a high physical loss of mercury, but since these were smelted rather than amalgamated, they do not represent a historically representative case.

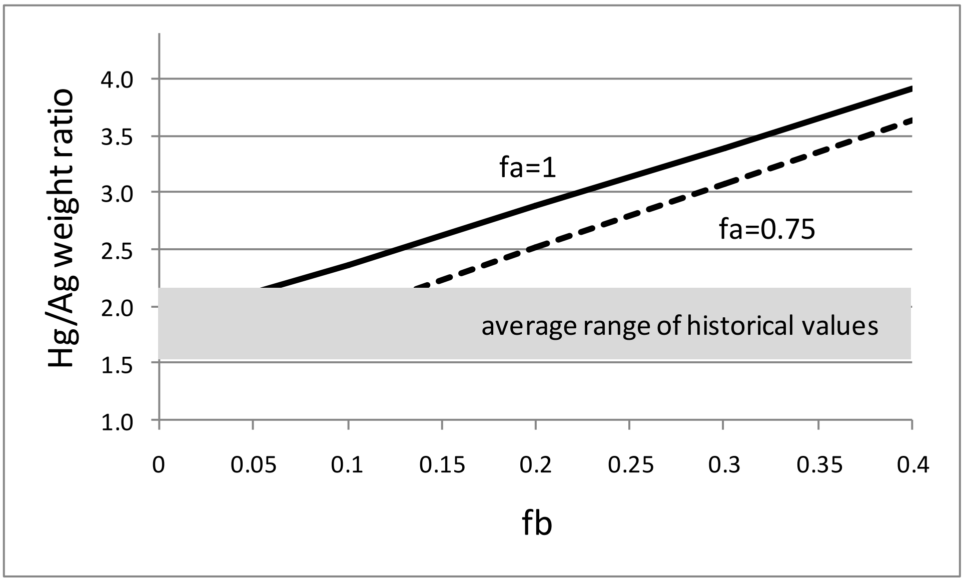

Figure 3-24. Sensitivity of the Hg/Ag weight ratio to f_b values, for the range of f_a values expected from ores refined by amalgamation. Reproduced from footnote 495.

To calculate the breakdown between mercury consumed in its transformation to calomel and mercury lost through physical causes the following equations apply:

$$\% \text{ Hg consumed as calomel} = \frac{1.86\,fa}{(1.86\,fa + (7 - 1.86\,fa)fb} \text{ x } 100\%$$

$$\% \text{ Hg physical loss} = \frac{(7 - 1.86\,fa)fb}{(1.86\,fa + (7 - 1.86\,fa)fb} \text{ x } 100\%$$

The expected range for total physical losses of mercury during amalgamation is calculated using these equations from approximately 10 to 30%, subject to the value of the *correspondencia* (Table 3-III). The values in Table 3-IV have been obtained by fixing the value of the mercury to silver weight ratio, and choosing a range for f_a consistent with the historical reality that it was *negrillo* ores (silver sulphide) which were destined primarily for amalgamation.

f_a	0.75	0.75	0.85
f_b	0.13	0.02	0.05
Hg/Ag	2.1	1.5	1.86
% mercury converted to calomel	69%	91%	85%
% mercury physical loss	32%	10%	15%

Table 3-IV. Percentage breakdown of mercury losses to the environment as a result of the refining of silver ores with mercury.

Since the values of *correspondencia* are not the result of an aggregate of contingent human errors of operation but are dictated mainly by the chemistry of the reactions during amalgamation and the nature of the ore, it converts this index from a passive mirror of operational empiricism into a theoretically solid tool of historical analysis.

3.10 The environmental impact vectors of amalgamation

Of all the components of an amalgamation recipe applied to silver ores, the usual environmental suspect that springs to the forefront for a modern reader is mercury. The historiography of the period also focused most of its attention on the consumption of mercury, but for other reasons. Within the lore of amalgamation it was accepted that there was a fixed one to one ratio between the weight of mercury 'destroyed' during the process and the weight of silver refined. This was called '*el consumido*', or the consumption of mercury. Any additional need for mercury was due to operational losses ('*el perdido*') during the process.[501] Thus from the very beginning the total consumption of mercury was interpreted as the sum of two processes, one chemical (the consumption as a transformation of matter), and one physical (the loss of liquid mercury due to mechanical causes).

The historiography was also well aware of the dangers posed by mercury to the workers exposed to its vapours, and Chapter Six will review the historiography on the risk to the health of workers posed by mercury during this historical period. Barba criticizes the careless use of equipment to heat the amalgam, so that if joints are not properly sealed and a poor quality clay is used to make the recipients there is a danger of volatile mercury escaping to the environment.[502] Barba also goes on to strongly suggest the use of iron or beaten copper recipients as the most secure means to recover the mercury from the amalgam.[503] The warning on the accidental exposure of amalgamation workers to heated and volatile mercury continues throughout the period in question.[504] It was not only the health of the workers that spurred this concern. As Gomez de Cervantes recognized very early, the economic importance for a careful husbandry of mercury stocks from the point of view of the refiner merited a strict supervision of the efficiency of the recycling stage:

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[501] Laur, "De la metallurgie de l'argent au Mexique," 163.
[502] Barba, *Arte de los metales*, 100.
[503] Ibid., 101.
[504] 'In all these works he who is present should always place himself upwind of the furnaces, so that if a vessel should break... the smoke of the mercury will not cause harm ... which is very great.'-'*En todas estas obras se ponga siempre, el que a ellas asistiere, a barlovento de los hornos, por el riesgo de que quebrandose algun vaso ... no cause el humo del açogue los daños ... que son muy grandes*' in ibid., 170. According to Sonneschmidt the older type of clay vessels could break easily, so that workers who came to dampen the embers were at risk of mercury poisoning: 'I have found various individuals that in such circumstances have been poisoned by mercury, and fell to the floor senseless' -'*He encontrado a varios sugetos que en tales circunstancias se han azogado, y cayeron en el suelo privados de sentidos*'. Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 51.

'If mercury is lost and the loss cannot be remedied … this is the greatest loss that can be had, and it can happen to a miner during the refining process; and when it happens, not even the value of the silver [refined] can match the value of the mercury that is lost'.[505]

The successful control of the loss of volatile mercury during the heating stage of the amalgam is amply commented upon in the technical descriptions that are available for New Spain. Thus Born states that by the end of the eighteenth century iron vessels [*capellinas*] were used to recycle mercury using a water channel such that 'all the quicksilver is recovered without loss'.[506] Humboldt does not even mention volatile losses of mercury during the heating stage of the amalgam in his analysis of the possible causes of the physical losses of mercury.[507] Sonneschmidt states that when carried out correctly the losses during the *capellina* stage are minimal.[508] Duport cites total mercury losses during the recycling stage of mercury of just 0.06%.[509] According to Laur 'except in case of accidents, or negligence, the losses of mercury caused by the operation [the *capellina* stage] are of little importance [around 0.001%]'.[510] Losses of volatile mercury could occur through accidents, but the available historiography up to the end of the nineteenth century concurs that normal practice did not incur a regular loss of volatile mercury to the air of any relevant magnitude.

If mercury was not lost to the air, how did contemporary observers interpret the fate of the c*onsumido* and the *perdido*? For the former, I have conjectured on the alchemical roots for the notion of an equivalent weight of mercury required to be transmuted into silver. However, beyond the lore of the *azogueros* that exasperated Duport, by the nineteenth century it was

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[505] *'Si se pierde el azogue y no se puede remediar ... es la mayor pérdida que puede haber y sucede al minero en el dicho beneficio; y cuando sucede, no llega el valor de la plata al azogue que se pierde.*' Quoted from Gomez de Cervantes (1599) in Bargalló, Minería y metalurgia colonial, 245-46.
[506] Born, *Born's New Process of Amalgamation*, xxi, 133.
[507] Humboldt, *Essai politique*, Tome IV, 80-81.
[508] Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 53.
[509] One ounce (28 g) per quintal (46 kg), in Duport, *Métaux précieux au Mexique*, 117.
[510] '*a moins d'accidents, d'ailleurs fort rares, ou de négligence, les pertes de mercure causes par l'opération sont peu importantes ... [1.3 to 1.75 per thousand]*' in Laur, "De la metallurgie de l'argent au Mexique," 176.

clear that the formation of a salt of mercury was responsible for the chemical consumption of mercury, as I reviewed in Section 3.9 above. As to the *perdido*, its ultimate fate was the waterways and the soil, according to the historiography up to the nineteenth century. The physical loss that was caused by entrainment in the water used to wash the slurries or ore in order to separate the amalgam extended also to unextracted silver and amalgam. On the heels of the implementation of amalgamation, the observation was made in 1571 on 'the loss or at least the greater part of *quintales* of mercury and silver that is taken by the river … in this New Spain'.[511] In the 1740s Dominguez de la Fuente would write:

'the drawbacks of the present refining process [*patio* amalgamation] run manifesting themselves in the creeks and streams close to the *haciendas*, from where the women regularly extract silver, and who are known by the title of '*Plomilleras*' … the first is from the same silver that comes from the washing vats of the *haciendas*, the second is potential silver … that dust … from which these women extract it [silver] by fire'.[512]

In 1802, the same concern persists in New Spain, where Jose Antonio de Ortega proposes to use '*buzos*' (divers) or dams to collect the sediment and recover the silver lost in this manner :

'[I] denounce to Your Excellency the Gold, and Silver, that incorporated in Mercury, exists, in the depths and natural deposits, exists, in the Rivers, of this Kingdom [New Spain], and in that of Peru, proceeding from the washing vats of the refining of said Metals in *Haciendas* that existed and exist'.[513]

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[511] '*la perdida o alomenos gran parte de los quintales de azogue y plata que se lleva el rrio … en esta Nueva España*', extract from a *merced* awarded in New Spain in 1571 by the Viceroy of New Spain to Fernando de Portugal y Leonardo Fragoso for their method to increase the efficiency of recovering silver and mercury from the washings, AHSLP, Colección Powell, catálogo p. 94, Patronato 18 2 ramo 42, rollo 166-7-50 21; AGN, Instituciones Coloniales, Mineria, 28304, Volumen 17.

[512] *'la insuficiencia del presente beneficio, corre manifestándose por las canadas y Arroyos, vecinos de las Haziendas, de donde sacan regularmente las Mujeres plata, que se conocen por el titulo de Plomilleras … la primera es de la misma plata que arrojan de los lavaderos de las Haziendas, la segunda, es de la plata potencial … aquel polvillo ..[que] estas mujeres la sacan de el, por fuego*' in Dominguez de la Fuente, Leal Informe Politico-Legal, 136.

[513] '*denuncio a la Superioridad de Vuestra Excelencia el Oro, y Plata, que incorporado en Azogue, existe, en las profundidades y depositos naturales , existe, en los Rios, de este Reyno, y en el de Peru, procedentes de los labaderos de veneficio de dichos Metales de la Haciendas que existieron y existen'*, AGN, Instituciones Coloniales, Minería, 28304, Volumen 17. Ortega was a member of the Royal Basque Society and collector of

Humboldt concluded that the consumption of mercury during amalgamation was due in greatest part to its entrainment in solids carried away in the water washings.[514] Laur sums up the views held by the end of the nineteenth century that the causes of the consumption of mercury are two, chemical reactions inherent to amalgamation and mechanical losses during the washing of the slurry due to the extreme fineness of the particles of ore.[515]

With respect to losses of liquid mercury to the soil, there are references to the soil of abandoned amalgamation *haciendas* being excavated in the 1670s to recover the mercury contained within them:

> 'Nicolas de Villareal, of this city [Zacatecas] stated that when digging into the foundations of the old houses that belonged to General Agustin de Zavala … within the soil that he dug from the place where the *hacienda* of the General used to be, he found samples of mercury and because if he washes more soil he may recover more quantity of said substance … [he requests] that your lordships decide how best to serve [the interests] of His Majesty'.[516]

Hermosa, another first-hand observer of the process, proposes that the main routes for the physical loss of mercury is seepage to the soil and entrainment in the water washings.[517] Referring to amalgamation mills in the United States of America of the nineteenth century, Egleston writes: 'By far the greater loss [of mercury] is mechanical. The ground under some of the old-fashioned [silver refining] mills was richer in mercury than a quicksilver mine'.[518] Sonneschmidt is one of the few in the historiography to doubt that much mercury was lost in

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taxes in Oaxaca, '*socio Benemerito de la Real Sociedad Bascongada, Administrador de las Reales Rentas del Partido de Villa Alta, Oaxaca*'.

514 Humboldt, *Essai politique*, Tome IV, 81.

515 Laur, "De la metallurgie de l'argent au Mexique," 163.

516 '*Nicolas de Villareal vzo de esta ciudad dijo que abriendo unos cimientos en las cassas viejas que fureon del Gral Agn de Zavala … entre la ttierra que se a sacado de ellas en el cittio donde hera la hazienda que el dicho Gral tuvo parece apinttado algunas muestras de azogue y porque puede ser que lavando otras tierras se recoga alguna canttida de dicho genero … vms dispongan lo que mas sea del servicio de su Magestad*', dated 29 March 1673, AHEZ, Real Hacienda 1673, document with lower right hand corner missing.

517 Hermosa, *Manual de Laboreo de Minas*, 239.

518 Egleston, *The Metallurgy of Silver*, 398.

this manner, stating that on lifting the lining of the *patio* he could not find evidence of mercury droplets, though he does not state how deep in the soil he searched.[519]

The mention of mercury losses in the historiography up to the nineteenth century does not mean there was an interest on the impact these losses would have on the communities or on nature around the amalgamation *haciendas*. As a case in point, Duport's excellent review of silver refining in Mexico does not address any environmental issue. Though the main historical concern was to explain the disappearance (or waste for some observers) of an expensive and limited reagent critical to refine silver, some degree of care for strict operational guidelines that would lower the risk of inhaling mercury vapours is also evidenced. The other component of the amalgamation recipe that received attention was the amount of solids voided into the waterways. In the case of Guanajuato, where the amalgamation *haciendas* were clustered close to the town and around the main waterway that ran through it, the consequences of dumping the fine mineral silt from the constant washing of the amalgamation *tortas* caused problems that had to be addressed on a yearly basis:

'the water from the river that run through the city was used by the refining *haciendas* … a city whose mining activity regulated the economic life of its inhabitants generated waste inherent to the refining process, these were thrown into the river causing it to flood'.[520]

These wastes would be dug out of the river bed and sent to landfills around the city, as is clear from the instructions sent by the Viceroy of New Spain to the Cabildo of Guanajuato requiring it to estimate a budget and plan for:

'the cleaning of the River … the solid fill and filth that will have to be removed … the land where they are to be deposited, without affecting the public, as well as the retaining walls that

[519] Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 128.
[520] '*el agua del río que atravesaba la ciudad era utilizada por las haciendas de beneficio de metales ... una ciudad cuya actividad minera regía la vida económica de la población generaba desperdicios propios del beneficio de metales, estos eran arrojados al río causando su desbordamiento*' in Alma Linda Reza, Guanajuato y sus miasmas. Higiene urbana y salud pública, 1792-1804 (Guanajuato: Presidencia Municipal de Guanajuato, 2001), 40.

will be required to contain the landfills so that they do not cause harm to the city or return to the causeway of the River'.[521]

The historiography of the twentieth century introduced a major change in the portrayal and analysis of the environmental legacy of historical silver refining in the New World.[522] It was the field of environmental science that provided the first novel interpretation of the consumption of mercury during the historical amalgamation process practised in the Americas. Nriagu's landmark one-page note to the journal Nature in 1993 based its analysis on the premise that all the consumption of mercury during the period of historical silver refining by amalgamation was due to a 100% physical loss of mercury, of which 60 to 65% were deemed to be due specifically to volatile losses of mercury. No mention was made of calomel. In the same note Nriagu mentions that the consumption of mercury in the colonial amalgamation of silver is very similar to that observed for the modern amalgamation of gold in the Brazilian Amazon region. Further, he states that the fraction of mercury lost to the air during colonial refining of silver ores is comparable to the 65 to 83% range of mercury losses during gold amalgamation measured in modern times in the Amazon.[523] The mainstream historiography has followed Nriagu's paper to propose similar ranges of loss for volatile mercury, up to 85%

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[521] '*en la limpia del Rio … los atierres e immundizias que habran de extraerse … los parajes en que harán de depositarse, sin perjuicio del publico, como también los pretiles o calicantos que a caso sea necesario hacer para contener los citados atierres que no hagan daño a la ciudad ni vuelvan a la Caja de dicho Rio* ' in AHUG, Actas de Cabildo, 5 December 1782, 153v to 156r.

[522] One of first modern works to bring attention to the harm caused by mercury to the indigenous communities as a consequence of mining and refining of silver was Eduardo Galeano, *Las venas abiertas de América Latina* (Buenos Aires: Siglo Veintiuno, 1982), 62. The value of this work as an objective appraisal of historical events should be judged in the light of the author's recent comments during the II *Bienal del Libro* in Brasilia, Brasil, held in April 2014. Galeano confessed that 'I would not be able to read the book again. That traditional left-wing prose is too boring … I did not have the necessary knowledge [to write it]. I do not repent having written it, but it was a stage that, for me, has long been over.' - '*yo no seria capaz de leer el libro de nuevo. Para mi esa prosa de izquierda tradicional es pesadísima … yo no tenia la formación necesaria. No estoy arrepentido de haberlo escrito pero fue una etapa que, para mi, fue superada*' as reported in http://es.brasil247.com/es/247/sociedad/1199/Galeano-la-realidad-cambi%C3%B3-no-leer%C3%ADa-m%C3%A1s-Las-venas-abiertas.htm

[523] Nriagu, "Legacy of Mercury Pollution," 589.

in the latest proposal by Hagan et al and Robins in 2011.[524] The formation of calomel continued to be excluded from these analyses. Though mercury salts as by-products of amalgamation are mentioned in some modern historical texts on silver refining in the New World, the majority view is that overall it was volatile mercury that constituted the main cause for the consumption of mercury in the New World.[525]

The omission of calomel as a principal factor in the consumption of mercury not only ignored the chemistry of the process and the historical texts of the nineteenth century, but it implied a magnitude of historical air deposition of mercury around refining sites that could not be corroborated by new results from research on historical mercury depositions from the atmosphere. In 2011 Cooke, Balcom, Kerfoot, Abbott and Wolfe published the levels of mercury deposited in the sediment of Laguna Lobato, some 6 km west of Cerro Potosí, from 600 to 2000 CE. High initial levels of mercury up to ca. 1300 CE are explained as coming from pre-Columbine smelting of native silver found on the surface of the Cerro Potosí. From that date to the present the levels of airborne mercury deposits decrease continuously throughout the historical period that saw amalgamation used on a massive scale in Potosí and surrounding areas. In contrast, levels of airborne lead are seen to spike around the period large-scale smelting was introduced by Spain in Potosí.[526] This result contradicted the assumption that major losses of airborne mercury took place in Potosí as a consequence of amalgamation. In

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[524] Julio A. Camargo, "Contribution of Spanish–American Silver Mines (1570–1820) to the Present High Mercury Concentrations in the Global Environment : A Review," *Chemosphere* 48(2002).; S. Strode, L. Jaeglé, and N.E. Selin, "Impact of mercury emissions from historic gold and silver mining: Global modeling," *Atmospheric Environment* 43, no. 12 (2009).; Nicole Hagan et al., "Estimating historical atmospheric mercury concentrations from silver mining and their legacies in present-day surface soil in Potosí, Bolivia," ibid.45, no. 40 (2011).; Robins, *Mercury, Mining and Empire*.

[525] An example is the following discussion on historical mercury losses from amalgamation: 'other losses resulted from binding of mercury in insoluble compounds to sulfides, chloride or other salts in the ore. Some, perhaps most, of the losses occurred in vaporization of mercury', from Richards, *The Unending Frontier: An Environmental History of the Early Modern World* 370.

[526] Cooke et al., "Pre-Colombian Mercury Pollution Associated with the Smelting of Argentiferous Ores in the Bolivian Andes."

2012 I published the results presented above in Section 3.9.[527] In 2014, a review paper by Engstrom et al. argued that the evidence from a world-wide survey of historical mercury airborne depositions is not consistent with the assumption of large scale volatile mercury losses from historical periods of silver refining by amalgamation, and they proposed a shift in the paradigm applied to the interpretation of historical mercury emissions, in line with the mathematical results of the model I proposed based on calomel (Section 3.9).[528]

With regard to the amount of liquid mercury that seeped into the soil as a result of historical silver refining, the research is still at an early stage. In present day Potosí, disturbing the topsoil by excavating down to 50 cm in locations where amalgamation units used to located will liberate very significant amounts of mercury to the air. In contrast, undisturbed sites show very low levels of mercury in the air. The authors propose that this is due to mercury being present in different chemical forms according to depth, thus making it less susceptible to be airborne when in the topsoil.[529] The oral history of San Luis Potosi, Zacatecas and Guanajuato confirms in a qualitative way the presence of mercury in the soil. The Director of the Historical Archive in San Luis Potosi, Don Rafael Morales Bocardo, recounted to me that when excavations were being carried out on the floor of the assaying room of the Casa de la Moneda, he saw the newly exposed soil weeping globules of mercury. Mrs. Maria del Socorro Cardoso Girón, the local Historiadora [designated resident historian by the provincial government] of the village of Pánuco, close to Zacatecas, told me that many of the historical *haciendas* lay in ruins, with only remnants of some perimeter walls standing, because in the past these *haciendas*

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[527] Guerrero, "Historical Mercury Pollution in the Hispanic New World."

[528] Daniel R. Engstrom et al., "Atmospheric Hg Emissions from Preindustrial Gold and Silver Extraction in the Americas: A Reevaluation from Lake-Sediment Archives," *Environmental Science & Technology* 48, no. 12 (2014).

[529] P. Higueras et al., "Mercury vapor emissions from the Ingenios in Potosí (Bolivia)," *Journal of Geochemical Exploration* 116(2012): 6.; P. Higueras et al., "Multielemental pollution of soils at the Ingenios, decommissioned mineralurgical sites in Potosí (Bolivia)," (2010).

had been bought just for the value of the mercury in the soil. Once all the impregnated soil had been scraped from the grounds of the *hacienda*, and carted off to be processed elsewhere, it was left as an empty shell. Finally in Guanajuato, both Mr. Morrill, owner of one of the few standing *capellina* buildings which he has now converted to a studio, and Doctor Virgilio Fernandez del Real, the venerable Spanish owner of the *Hacienda* Santa Ana in Marfil, currently the Museo Gene Byron, gave me independent reports of trees that grow normally until one day their roots strike what they believe to be a mercury rich section of the earth under the *patios* and suddenly wither away and die.

The fate of calomel washed away together with the mineral silt from the washed *tortas* awaits future research. In the case of Guanajuato the modern city retains physical evidence of historical landfills from the waste dredged from its waterways where both mercury and calomel may reside. Figure 3-25 shows the Observatorio Metereológico, of the Comisión Nacional del Agua and University of Guanajuato, built on a hill made up from a landfill of the waste recovered from the river.[530] How much of the total waste voided initially into rivers was returned as landfill to the land remains to be established. In other locations such waste would have been deposited along the bed of each river, to an extent that remains to be studied.

[530] Personal communication, Lic. Silvano Pozos Suarez, in charge of the Observatory. The hill of mineral waste on which the Observatory was built lies over the road in front of the grounds of the historic Hacienda de Rocha. I have not been able to determine if the present road was built over the historic trace of the stream that run along the hacienda.

Figure 3-25. The Observatorio Metereológico of Guanajuato (Conagua and Universidad de Guanajuato), sited on a landfill of waste from refining *haciendas*. Photo taken from the grounds of the historic *Hacienda* de Rocha (at present the Hotel Reales de Minas).

In summary, the relevant environmental impact vectors for *patio* amalgamation can be grouped into four sets: calomel and mercury, the water-soluble reagents (salt and copper *magistral*), the waste solids from the ore and finally fuel. Waterways, not air, are the main conduit of the environmental impact vectors for *patio* amalgamation. Within the *hacienda*, mercury was consumed and transformed into calomel during the *patio* amalgamation process, and the solid and insoluble calomel was washed away into the adjoining waterways together with the portion of the mineral ore that had no economic value to the refiner. In this waste water were present the excess salt, iron and copper compounds used in the recipe. A huge amount of solid waste, over 99.6% of all the ore that was processed in each *hacienda*, was suspended in the washing water voided into the streams.[531] Soil was the second major conduit for the

[531] For the haciendas producing 600 marks of silver per month this represents approx. 75,000 kg of solids voided per month into a waterway. For an *hacienda* of the size of La Escalera, it would have reached approximately 450,000 kg in the 1790s.

physical loss of mercury and water-soluble components of the amalgamation recipe, whether from spills during transport or storage, or more important from seepage during the wet slurry phase of amalgamation.

The only stage of the amalgamation process where air-borne particles of any nature would have been a daily significant environmental issue would have been close to the *molinos* and *tahonas / arrastres*. This area would have been the source of very high background levels of dust and noise, with a direct impact on the workers handling the ore.[532] As to losses of volatile mercury, it is only during the casting of silver bars that any residual mercury not recycled during the *capellina* stage would have been issued to the air.[533] A loss of one percent of the total weight of silver cast into bars was judged to be a standard of good practice, and the figure is validated by the operational accounting data I present in the next chapter.[534] Losses of mercury by direct volatilization from the *tortas* are in theory possible but in practice would have been negligible.[535] Any losses of volatile mercury during the heating of the amalgam would be the result of accidents and not a consequence of normal operating conditions. Even in such a case, the mercury that escaped would quickly deposit itself on any surface in the immediate area, as can be deduced from the following description of artisanal gold refining practices in the Amazon:

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532 According to Egleston the use of stamp mills imparted a radial, upward movement to the particles of crushed ore. Egleston, *The Metallurgy of Silver*, 176.

533 30 kg silver bars have been described as cast from moulds the Hacienda de Loreto (Pachuca) into which melted silver has been poured using an iron ladle which was dipped into a vessel full of molten silver. Collins, *Metallurgy of Lead & Silver*, 141.

534 Laur, "De la metallurgie de l'argent au Mexique," 180.

535 A very approximate idea can be gained using the results published by Winter on the loss in mass of a 0.2 g spherical drop of mercury exposed to a ventilated room, away from direct sunlight and winds, at an ambient temperature around 20^0 C. He measured a maximum weight loss of 7 µg per hour. For the sake of argument, if 6 million such drops could be assumed to exist within an average *torta*, it would lose 14 kg of mercury in two weeks. Since only a minority of mercury droplets would be exposed to sun and wind, I will assume that 5% of this theoretical total was the effective loss, less than 1 kg per month per *torta*. Thomas G. Winter, "The Evaporation of a Drop of Mercury," *American Journal of Physics* 71 (2003).

'the hot flame would burn off the mercury. It would dissolve and rise as a vapor – looking indeed like white water vapor- to a height of about two to three metres, before condensing again and settling back down. In this process of first rising as vapor and then settling as droplets, the mercury would settle on any object at hand- including on men's eyebrows, and the hair on their heads, their moustaches, even on their forearms, as a form of eery looking white mist.'[536]

A more important area of constant human contact with mercury would be during the addition of liquid mercury to the *tortas,* since the workers did not use any gloves or other implements to avoid prolonged mercury to skin contact. The same applies to the treading of the slurry with or without the aid of horses and mules.

Figure 3-26 represents a schematic pathway for the main losses of calomel and mercury. In the absence of iron or copper, and with a *correspondencia* of 1.8, the transformation of mercury into calomel would have accounted for around 85% of the total consumption of mercury during the *patio* amalgamation. The majority of the remaining 15 % would have been physically entrained by water or seeped to the soil. A minor amount, not exceeding 1 %, would have been lost as volatile mercury, in a regular manner each time silver bars were cast, or in isolated accidents during the heating of the *capellinas*. The addition of iron to the recipe could lower the *correspondencia* to 1.3, but the percentage breakdown of the consumption of mercury remains similar. In Chapter 4 I will be analysing in greater detail the specific mass balance of the process as carried out in a major amalgamation *hacienda*, including the directionality of all these vectors.

[536] Helmut Waszkis, *Mining in the Americas: Stories and History* (Cambridge: Woodhead Publishing Limited, 1993), 202-203.

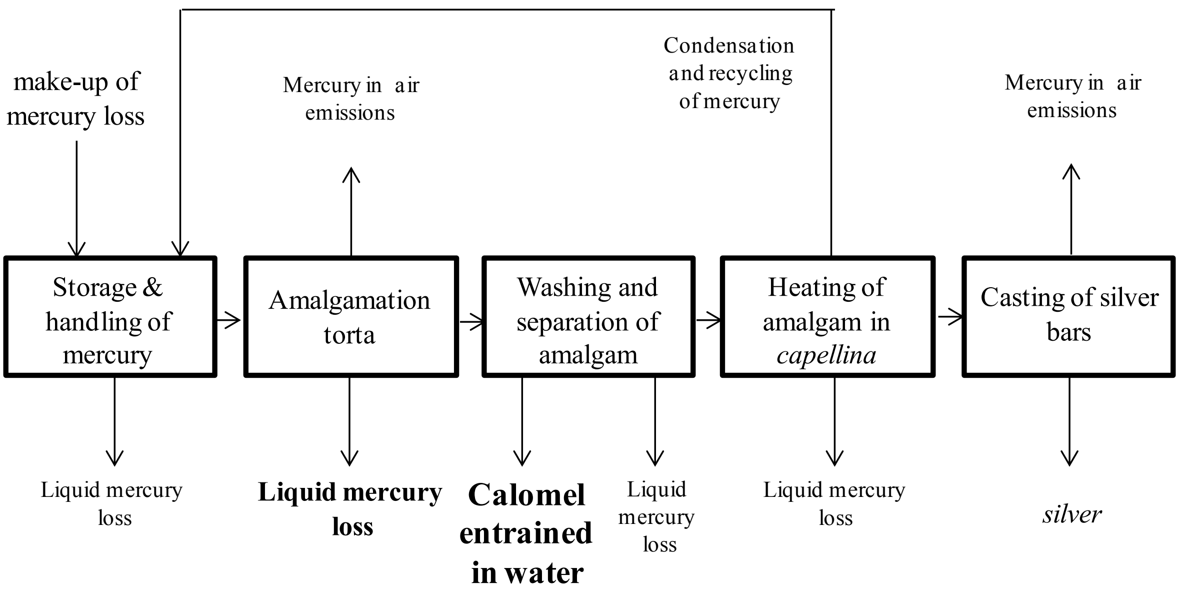

Figure 3-26. Main loss vectors of calomel and mercury

3.11 Final remarks

I have argued in this chapter that the chemical reactions that are an inherent part of the amalgamation process of silver ores lead to the formation of calomel in the majority of historical scenarios, as was pointed out by all nineteenth century sources. Thus the environmental legacy of the *patio* amalgamation process in New Spain / Mexico lies dispersed and deposited along the riverbeds and water basins where millions of tons of waste solids from the washings of the amalgamation *haciendas* were voided, or in any landfills that were formed from these wastes. It was the chemistry of amalgamation, and not its physical facet, that consumed the greater fraction of the mercury required by the process, converting liquid mercury into solid and insoluble calomel. Much less important was the physical loss of mercury, a lower fraction lost in the washings or seeped into the soil where it lies dormant until disturbed, within the high walls that still contain the spoor of past chemical processes. The minor part that was volatilized was lost mainly during the final casting of the silver bars, while the loss during the heating of the amalgam was negligible under normal conditions. The best evidence for the control over the consumption of mercury during the process is the impressive immutability of the *correspondencia* ratio over 300 years. The total consumption of mercury did not simply depend on the skill and experience of each *azoguero* but was determined to a great extent by a chemical reaction common to all amalgamation locations and historical periods, together with the extreme care taken in conserving the scarce and expensive mercury.

I have complemented the chemical and mathematical analysis of the amalgamation process with a much-needed visual reminder of the conditions under which amalgamation was carried out. *Patio* amalgamation was for most of the time a large-scale wet and messy process where it would have been impossible to completely control a small but constant physical loss of mercury and other components of the amalgamation recipe by seepage to the ground or entrainment in the waste water. No amount of *planilleros* or paving stones could control the inherent leakage of this watery matrix, though minimize it they did. Each photo of a *patio* conjures up the sucking and slurping noises of an ever-present mud tugging at the feet of men and animals, a watery medium constantly seeking cracks or trickling into waste channels, its puddles ever-present in paintings and photographs. The only stages of the whole process where the operators could exercise the highest control over physical losses took place outside the *patio*, once all the water had been separated and they could work with kilograms and not tons of material. The careful handling of mercury and silver took place in the controlled environment of the mercury room that housed the *manga* for squeezing dry the amalgam, during the heating of the *desazogueras* or *capellina* ensembles that could be as heavy and solid as a compact car, and finally in the casting of the silver bars. To propose that up to 85% of the consumption of mercury took place during the heating cycle of a *capellina* , as do Hagan and Collins, is to ignore the reality of the nature and conditions under which *patio* amalgamation took place.

Any photo of an amalgamation *patio* is also a Rorschach test for the biases of the viewer. For many it represented a long and primitive process that did not evolve over centuries, proper to a country and people untouched by progress. On the other hand Humboldt grasped the true nature of this space when he suggested covering its floor with iron or copper. An amalgamation *patio* is no less than an open-air chemical reactor, symbol of an impressive solution to the challenge of refining silver sulphide ores that were poor in lead, a unique example of a batch industrial process carried out in a reactor that could extended laterally or contract as needed, a pioneer vision of industry perfectly suited to the available level of human skills and materials. It is a sign of strength, not of weakness, that the chemical maturity of the process was reached by the end of the sixteenth century, and that it lasted for three hundred years until a new chemical process based on cyanide displaced it.

Amalgamation required from the start a careful planning of inventory of reagents, starting with salt and mercury, the two chemical linchpins of the process. Even copper sulphate could have been supplanted if necessary by roasting the sulphides with salt prior to amalgamation. The amalgamation *haciendas* came in a wide range of sizes, from the small *zangarros* of Guanajuato to the industrial behemoth at Fresnillo, but their capacity to pollute the environment did not offer an economy of scale. The bigger *haciendas* may have been more efficient in some aspects of the operation, but both they and their smaller brethren voided into streams over 99.6% of all the solid ore they received, accompanied by smaller fractions of calomel, salt and copper compounds. The imbalance of these different components of the amalgamation process is reflected in their architectural footprint, the patio and milling areas greedy for space, while the final stages of the separation of the amalgam, mercury and silver appear huddled together to control pilfering, until the areas of the *capellinas* are all but forgotten spaces, dwarfed by the other spatial needs of the process. Dry ore and water, not fire, set the tone for the arrangement of working areas. Where furnaces merit a mention in the legal documents it is in the context of preparing *magistral* amd roasting rebellious ores, never in the context of recycling mercury.

The narrative of this chapter has paid significant attention to clearing up issues that may not appear relevant to the environmental history of amalgamation of silver ores. Apart from a desire to tie up evident loose threads, how critical is it to seek the roots of amalgamation in European alchemy or to question the credibility of a fully-fledged amalgamation recipe sprouting from the metallurgical virgin forehead of Medina? The reason lies in human choice, or its absence. If amalgamation had no roots in previous alchemical or refining experience in Europe, then it would be possible to argue that neither the Crown nor the refiners knew a priori what its effects on the workers and their communities would be if applied on a major scale. Furthermore, if 1555 is anointed as the *annus mirabilis* of amalgamation in the New World, after which little of technical importance took place, it casts a shadow of inevitability over the whole history of amalgamation. If amalgamation was indeed the only technical key to unlock silver from its New World ores, then there is little point in searching for the role of human agency in the charting of its historical course.

The alternative is to reconstruct the roots of amalgamation via alchemy and European metallurgy, two areas that overlapped with pragmatic ease in the sixteenth century. What was good for gold was equally good to extract silver, and though the chemistry of the two processes is totally different, the simple amalgamation formula happened to work on the mounds of discarded ore left by the first waves of ignorant miners. The same geological luck of the draw that allowed ignorant conquerors to easily smelt ores rich in native silver and silver chloride, also allowed a simple gold amalgamation recipe of water, salt and mercury to extract silver from the huge stockpiles of a similar type of ore that had been discarded by the impatience born of that same ignorance. The success of the group of refiners of the Andes in the 1580s in creating an amalgamation recipe specifically tailored for silver sulphides is in fact the real starting point of the history of amalgamation in the New World. As to the contention that without mercury there would have been no silver from the New World, the evidence so far presented is that from a technical point of view smelting with added lead would have been able to refine the type of ore found in New Spain. In Chapters 5 and 6 it will be argued that even though the choice of refining method was first and foremost determined by the chemical nature of the ores, under certain historical scenarios both refining processes would have offered the same economic incentive to refiners.

One of the major challenges facing any historian in attempting to reconstruct the historical environmental impact of silver refining in the New World is the dearth of hard data. If the original architectural plans are not available (and I have set out the very limited selection of historic plans that can be found for now, of which none correspond to smelting *haciendas*), then the ruins of the existing *haciendas* are too dilapidated or altered by modern conversions to be of much assistance. Similarly, as yet no surviving account books have been found from New Spain to establish the mass flow within the *haciendas* with an existing architectural plan, without which it is impossible to project the environmental impact of their operations. In the following chapter I will present an important exception to this state of affairs. These are the very detailed accounting records of the commercial operations carried out in the *Hacienda* Santa Maria de Regla, which practised in parallel both smelting and amalgamation. Though again no historical plan has been found for this *hacienda*, its imposing historical remains allow for a straightforward reconstruction of its operational areas. The wealth of quantitative information for this *hacienda* will provide in the next two chapters a much needed window into the detailed operational and economic structure of a silver refining *hacienda*, and its impact on the environment.

4 *Hacienda* Santa María de Regla.

'Over there – one argued to oneself – was Chichen Itza and Mitla and Palenque, the enormous tombstones of history, the archaeologist's Mexico ... and for the businessman the silver mines of Pachuca ... for the priest prison, and for the politician a bullet'. Graham Greene, *The Lawless Roads* (1939)

'One should view it as we did, in a thunderstorm, for it has an air of vastness and desolation, and at the same time of grandeur ... down in a steep barranca, encircled by basaltic cliffs, it lies : a mighty pile of building ... all is on a gigantic scale: the immense vaulted storehouses for the silver ore; the great smelting furnaces and covered buildings where we saw the process of amalgamation going on; the water wheels- in short, all the necessary machinery for the smelting and amalgamation of the metal'. Fanny Calderón de la Barca, *Life in Mexico* (1843)

4.1 Introduction

The chemistry of the refining of silver ores remained constant from the sixteenth to the end of the nineteenth century, when amalgamation with mercury is replaced by the use of cyanide to extract silver from ores using a wet process. Though the chemical recipes did not change, the physical trappings of each process did evolve with time, as seen in the substitution of clay by metal *desazogueras* or *capellinas*, or the increasing height of smelting chimneys, and the switch from *hornos castellanos* to more efficient blast furnaces. What did change substantially was the amount of silver produced in each of the centuries that span this period. Though the environmental history of silver refining by amalgamation and smelting in the Americas covers nearly four centuries of continuous production, the greater part would take place in the nineteenth century when Mexico had already become a republic.

Mexico began its struggle for independence from Spain in 1810, the year that as the Vice-Royalty of New Spain, it was providing 'three-quarters of all profits from Spanish

American holdings'.[537] Eleven years of fighting would pass before the first Republic, the *Estados Unidos Mexicanos* was created in 1821. It would survive an invasion by Spain in 1829 after which 'Mexican history teetered between simple chaos and unmitigated anarchy'.[538] Between 1821 and 1876 seventy five different Presidents would hold that office in Mexico. In the north, the other *Estados Unidos* would annex half the territory of Mexico by 1848 (present day Texas, New Mexico, Arizona, California, among others) and in the process access the remaining subduction deposits of silver and gold in the American Cordillera. This would catapult the U.S.A. from being a nonentity in silver production to being the leading producer of silver in the world by 1872.[539] Faced with a dwindling treasury, Mexico would declare a moratorium on all repayments of foreign debt in 1861, leading to a blockade of Mexican ports by France, Great Britain and Spain. France would then proceed to invade Mexico and install an Emperor, Maximillian Joseph. The Republic would be restored by 1867, and the French-backed Emperor shot by a firing squad. The toll on Mexico's development of such a long period of unrest, violence and foreign intervention is obvious. In 1860 Mexico had only 150 miles of laid railway track, compared to over 30,000 miles in the U.S.A. When Porfirio Diaz embarked on his drive to modernize Mexico (a period known as the Porfiriato), 'in 1876, except in a few of the larger cities, the country had scarcely been touched by the scientific, technological and industrial revolution, or the material conquests of the nineteenth century'.[540]

The impact of these events in the maintenance of mines and refining *haciendas* has been commented upon in the historiography, highlighted by the fact that many of the main mining districts to the north of Mexico (San Luis Potosi, Zacatecas, Guanajuato) figure

[537] Michael C. Sherman William L. Meyer, *The Course of Mexican History* (New York: Oxford University Press, 1979), 196.
[538] ibid., 205-49.
[539] Merrill, *Summarized Data of Silver Production* 7.
[540] Meyer, *Mexican History*, 262-323.

prominently in the struggle for Independence and in the political turmoil of the nineteenth century.[541] And yet the overall data as reported in Figure 4-1 shows a remarkable resilience of silver production in the midst of a society being violently uprooted every few years during this century. Wars did not end with the declaration of independence or when the invading army of the United States of America left Ciudad de México. The *Hacienda* de Regla whose data sustains this chapter continued to produce silver even during the French occupation of Mexico in the 1860s, during which it was forced to loan money to the invading French army quartered in the region.[542] This is a significant measure of the sturdy nature of the refining processes involved. A silver refiner of the seventeenth century transported to the year 1870 could not have understood the political reality around him. The expulsion of the Spaniards from Mexico, an Emperor imposed by France and shot by a Mexican government firing squad, a member of the Zapotec indigenous group elected as President of the Republic, a Catholic Church with much reduced power, Mexican miners taking industrial action, all these issues involved concepts that were not conceivable or did not even exist in the age where he came from.

In sharp contrast, this same individual would have had no problem putting his technical skills to good use at any of the silver refining *haciendas* of Mexico in 1870. The amalgamation process had remained virtually unaltered, and did not require imported machinery or foreign know-how to process the silver ores. Production would not otherwise have survived the sequence of foreign intervention into Mexico or the negative balance of payments that characterize most of this century. Even the loss of Spanish subsidized mercury did not strangle

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[541] ibid., 252-62.
[542] The period in question is 1863 to 1866, and loans were repaid. Fighting did not end with the retreat of the French, between 1876 and 1877 the revolution of Tuxtepec took place. Rocio Ruiz de la Barrera, "La Empresa de Minas del Real del Monte (1849 - 1906)" (Colegio de Mexico, 1995), 200-201, 231.

production. The major boom in silver production observed all over North America (Mexico and U.S.A.) in the nineteenth century up to the 1900s, was based on the same chemical reactions stumbled upon by trial and error in the South American Andes in the 1590s.

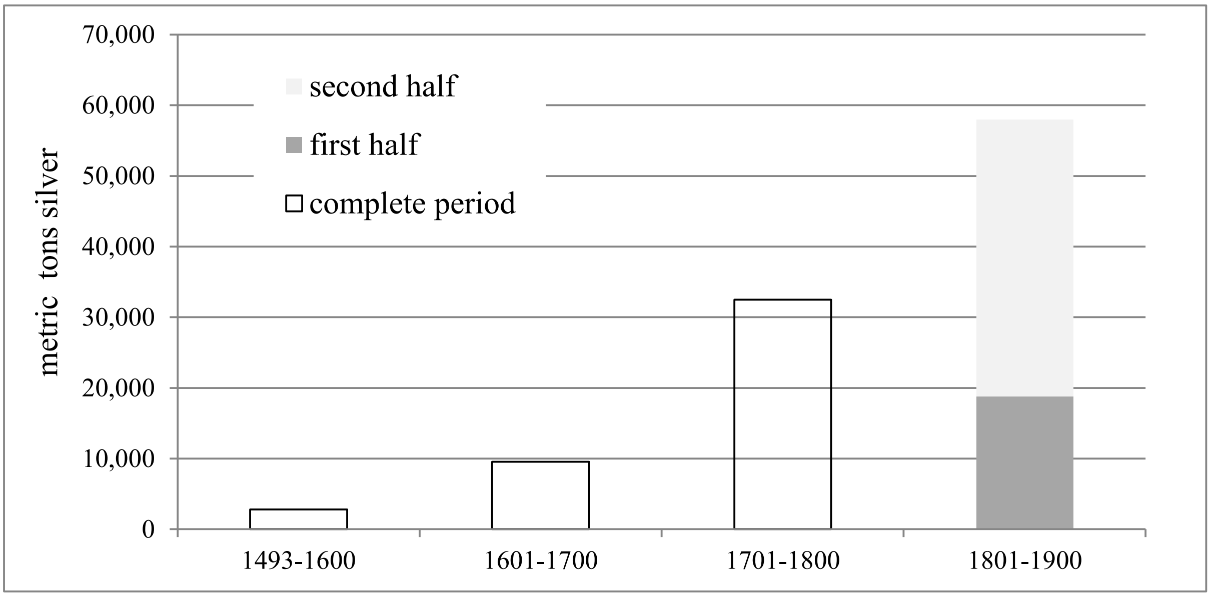

Figure 4-1. Production of silver in metric tons, from 1493 to 1900, adapted from footnote 543.

The curve of silver production in Mexico for the nineteenth century reflects the short-term influence of the political turbulence. The entry of foreign capital into the mining sector took place from the mid-1820s, while by the 1850s many of these ventures had collapsed. Overall Mexico would produce in the nineteenth century more silver (1.9 x 10^9 fine ounces, nearly 58,000 t) than the sum total produced in the three previous centuries by the Vice-Royalty of New Spain (1.4 x 10^9 fine ounces, nearly 45,000 t). Nearly two thirds of this production took place in the second half of the nineteenth century, making the period of 1850 to 1900 nearly as productive in silver as the whole colonial period.[543]

The arguments presented in the previous paragraphs lead to the two propositions that sustain the analyses made both in this and the following chapter. First, the immutability of the amalgamation and smelting processes from a chemical point of view makes it possible to profit from the wealth of operational and accounting data of a major silver refining *hacienda* operating in the late nineteenth century.[544] Since the chemistry did not change, then the period of time between the seventeenth and nineteenth centuries would only have increased the efficiency of the various operational steps, thus decreasing the quantity but not the nature of the chemicals generated per kg of refined silver that had an impact on the environment. Therefore the nineteenth century values can be interpreted as a historical minimum, a baseline with regards to emissions per unit of silver produced and other operational variables. Second, the environmental impact of silver refining in Mexico from 1850 to 1900 would have been more intense on a yearly basis than at any other period since the arrival of the Spanish silver refiners. The total emissions from silver refining from the last fifty years of the nineteenth century would have been chemically identical and quantitatively close to the total emissions from the sixteenth to the eighteenth century.

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[543] Merrill, *Summarized Data of Silver Production* 8, 10. Merrill's data gives a total from 1493 to 1799 of 1,441 million fine ounces, 44,833 t, which correlates well with the total of 44,211 t for an equivalent period reported by TePaske and Brown, *Gold and Silver*, 113. For the purposes of this chapter Merrill has the advantage of reporting production for the nineteenth century which coincides with other data sets in the historiography, as reviewed in Chapter 6, section 6.3.14. He reports the data for the first and second half of the nineteenth century, which therefore smooths out over 50 years both the fall in silver production during Independence and the boom of the latter part of the century.

[544] The realm of chemistry follows Einstein's observation that 'the distinction between past, present, and future is only an illusion, however persistent'. The quote is from a letter of condolence sent to the family of a friend, Michele Basso, recently deceased, dated 15th March 1955. Einstein would die just over one month later, on the 18th April 1955. As cited in The Oxford Dictionary of Quotations (Oxford; New York: Oxford University Press, 1979).

Any conclusion on the environmental impact from silver refining as a whole in New Spain / Mexico obtained from a case study from the latter half of the nineteenth century is as relevant as any other example within the whole 350 year period. This chapter will therefore reconstruct the material balances for amalgamation and smelting as practised in the second half of the nineteenth century at the Hacienda de Regla, situated near Pachuca in the modern state of Hidalgo. The mass balance of these processes is a very powerful tool to estimate the emissions of heavy metals and other substances to the environment as a result of the refining of silver. In modern environmental impact studies it is possible to measure in-situ and in real time the amounts of chemicals voided into the environment, but this option is obviously not possible in the study of historical industrial pollution sites. The existence of detailed accounting books that track the consumption of all materials including energy, concurrently with the production of silver, provide the only option to arrive at an order of magnitude of historical emissions to the environment that can be calculated with great precision down to the daily, weekly or monthly level at any time from the sixteenth to the nineteenth century, if the extant records can be found. This level of detail of specific historical periods is impossible to achieve with current methods that determine the historical deposition of elements in the soil through the dating and analysis of cores of soil samples.[545]

The method is based on the principle of the conservation of matter: the weight of all materials consumed in the *hacienda* is equal to the weight of all materials produced at the *hacienda*, silver and waste products. Though none of the historic accounting books used in this chapter track waste produced (in modern industry all waste has to be accounted for and monitored), they do register in detail all materials consumed and the silver produced, which

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[545] For a very technical discussion on the advantages and limitations of the current methods of dating samples see for example Merritt R. Turetsky, Sturt W. Manning, and R. Kelman Wieder, "Dating Recent Peat Deposits," *Wetlands* 24, no. 2 (2004).

leaves a simple subtraction to arrive at figures on waste. It is of critical importance to correctly identify the chemical reactions taking place and the physical causes of loss, which explains the role of the previous two chapters in the development of my argument, so as to be able to allocate with confidence the weight of waste according to each chemical species voided to the environment.[546]

In addition, the detailed knowledge of mass balances provide a quantitative fleshing out of the physical structures observed in the architectural remains of silver refining haciendas. The data give credibility to spaces designated as storage areas, establish the importance of clear transit corridors, and connect milling infrastructure with required monthly throughput capacities. In aggregate they allow a more informed analysis of the internal distribution of areas as observed in the plans of the previous chapter and of the reconstruction carried out in this chapter for Regla. Correlations can be established between the areas of amalgamation patios and the refining output of an *hacienda*, a very valuable indicator since patio areas are usually the only remaining physical evidence of these historical production units. The accounting information will also provide needed insights on the average silver content of the ores, the composition of amalgamation *tortas* and the technical reasons for the amalgamation periods adopted. Finally, the following sections leave no doubt as to the efficiency of the workforce and managers without which these historical units would not have been capable of producing such major amounts of silver on a continuous basis for over three centuries.

[546] I have not come across a similar study for other historical polluting industries based on accounting records, but I cannot affirm this is the first example of the method.

4.2 The Adventurers in the Mines of Real del Monte

At first reading it is not evident why Graham Greene would have chosen to single out the silver mines in Pachuca in his book on travels in early twentieth-century Mexico.[547] Guanajuato would have been a better example from a business point of view.[548] It seems that like the Cornish-inspired pasties that are now staple fare for Mexicans in Pachuca, a snippet of its past held on and managed to flourish in Greene's mind, whispers of 'that second South Sea delusion, the Anglo-Spanish American mining fever' that some one hundred years earlier had surged, then burst, among mining investors in England.[549] After all, the mines of Pachuca would have lost their English investors some $5 million by mid-nineteenth century.[550] Unfortunately for those caught up in the investment fever, the munificence of the Pachuca mines occurred both before the English arrived with their steam engines, Cornish miners, and substantial overhead costs, and after they left all the infrastructure to the gain of the Mexican owners who took over.

The impressions set down by previous English travellers to the *Hacienda* de Santa Maria de Regla, with its imposing walls and vaults reflecting roots of great opulence, may also have left their imprint on the mind of the writer. The proximity to the Mexican capital (Figure 4-2) and the lure of silver mining were by themselves sufficient reason to attract foreigners

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[547] Graham Greene, *The Lawless Roads* (London: Longmans, 1939), 23.

[548] 'The two greatest British concerns had their offices in Guanajuato-the Anglo-Mexican Company and the United Mexican Company' in Percy F. Martin, *Mexico's Treasure House (Guanajuato) An Illustrated and Descriptive Account of the Mines and their Operations in 1906* (New York: The Cheltenham press, 1906), 211.

[549] Robert Anderson Wilson, *Mexico and Its Religion; with Incidents of Travel in that Country During Parts of Years 1851-52-53-54* (New York: Harper & Bros., 1855), 354. Cornwall and Pachuca would cross paths because the General Manager of the English Company that would invest in Real del Monte believed firmly in the advantages of dressing an ore prior to refining, and in his opinion the experts in dressing ores in England were only found amongst the tin miners of Cornwall. John Taylor, *Selections from the Works of the Baron de Humboldt, Relating to the Climate, Inhabitants, Productions, and Mines of Mexico with Notes by John Taylor* (London: Printed for Longman, Hurst, Rees, Orme, Brown, and Green, 1824), xxv.

[550] John H. Buchan, *Report of the Real del Monte Company, Mexico* (London: Taylor, Printer, 1855), 2. For a history of the English investment in the Real del Monte Company see Robert W. Randall, *Real del Monte: a British Mining Venture in Mexico* (Austin: The University of Texas Press, 1972).

travelling in Mexico to visit the Pachuca area.[551] The unique architecture of the *hacienda* built by the first Conde de Regla in the latter half of the eighteenth century, nestled amongst unique scenery, left its mark not only in the diary of Fanny Calderón de la Barca:[552]

'the *Hacienda* de Regla ... forms the most extraordinary mass of buildings I ever saw in my life ... the prison-like castle, with its mining works – a gigantic, strong, irregular pile of household building, over dungeons, vaults, and tunnels, with magazines, spires or turrets, courts, back yards, furnaces, smelting and amalgamation works'.[553]

'nothing can exceed the fairy-like vision which the situation of this place presents. It is entirely surrounded, except at its entrance, by the most superb amphitheatre of perpendicular basaltic columns that I ever beheld; far superior to anything that I saw two years ago at the Giant's Causeway in Ireland '[554]

'on the following morning we rode to Regla ... it is now an immense ruin, crowded with monstrous arches of masonry, which appear as if they had been constructed as if to support the world... preparations of a more useful nature were now in forwardness amongst the mighty ruins but nothing could relieve the air of desolation, which gave the *Hacienda* the appearance of a battered fortress. It lies deep in a precipitous Barranca, fenced in by fine basaltic cliffs, of which so much has been said; and close above it is the celebrated Fall of Regla [El Salto] ... the ravine is one of the most beautiful and perfect basins of basalt in the world' [555]

The massive walls and arches of the *Hacienda* de Regla that so impressed the visitors of the nineteenth century had in fact been built at the end of the eighteenth century by Pedro de Terreros, first Conde de Regla.[556] It was named after the *Virgen de Regla*, the 'sanctuary

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[551] Charles Bunker Dahlgren, *Historic Mines of Mexico. A Review of the Mines of that Republic for the Past Three Centuries* (New York: Printed for the author, 1883), 184.
[552] Fanny Calderón de la Barca, ed. *Life in Mexico; the Letters of Fanny Calderón de la Barca, with New Material from the Author's Private Journals* (Garden City, N.Y.: Doubleday, 1966), 240-41.
[553] William Parish Robertson, *A Visit to Mexico, by the West India Islands, Yucatan and United States, with Observations and Adventures on the Way* vol. II (London: Simpkin, Marshall & Co., 1853), 221.
[554] Henry Tudor, *Narrative of a Tour in North America Comprising Mexico, the Mines of Real del Monte, the United States, and the British Colonies : with an Excursion to the Island of Cuba : in a Series of Letters, Written in the Years 1831-2* (London: J. Duncan, 1834), 309-10.
[555] Capt. Lyon visited Regla in 1826 when English investment was rehabilitating its processing infrastructure, G. F. Lyon, *Journal of a Residence and Tour in the Republic of Mexico in the Year 1826 with Some Account of the Mines of that Country* (London: J. Murray, 1828), 153-55. For other glowing descriptions of Regla see Wilson, *Mexico and Its Religion*.p. 363.; Thomas Unett Brocklehurst, *Mexico To-day: a Country with a Great Future, and a Glance at the Prehistoric Remains and Antiquities of the Montezumas* (London: J. Murray, 1883), 144-45.
[556] Two biographies of the first Conde de Regla are: Francisco Canterla y Martín de Tovar, *Vida y obra del primer Conde de Regla* (Sevilla: Escuela de estudios hispano-americanos, 1975).; Edith Boorstein Couturier, *The Silver King : the Remarkable Life of the Count of Regla in Colonial Mexico* (Albuquerque: University of New Mexico Press, 2003). By coincidence *terreros* was the mining term for tailings in Spain.

...[that] was located on the last spit of land visible to ships leaving Cadiz towards America'.[557] Having placed his destiny in the hands of the Virgin on leaving Spain, he made up for the many favours received by erecting in her honour a massive temple of stone to refine his ores. Peak production was reached towards 1770, using ores from the mines at Real del Monte, and also lead-rich ores fit for smelting from the mines at Zimapán.[558]

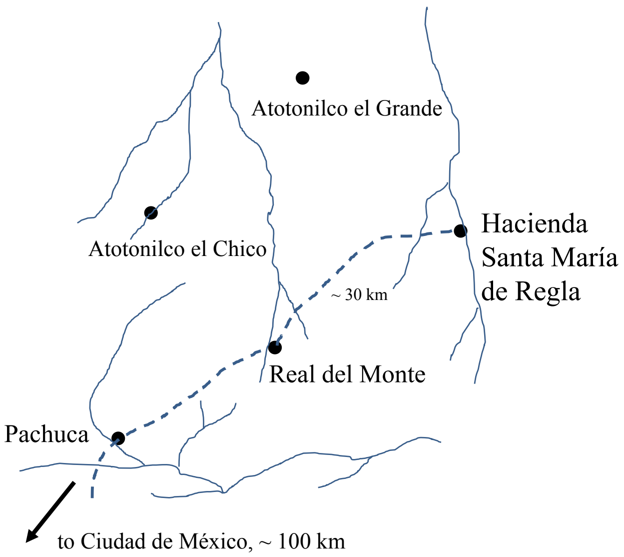

Figure 4-2. The *Hacienda* de Regla in relation to Real del Monte, Pachuca and Ciudad de México. Map adapted from footnote 551.

From Canterla's data it is possible to calculate that from 1761 to 1768 the annual average reached 22 t of silver while from 1776 to 1781 it decreased to 12 t/y. In both periods 85% was obtained by amalgamation and 15% by smelting. Couturier's figures give a yearly average of 14 t and a peak production in 1770 of 30 t of silver.[559] Either set of data place Regla among the major silver refining *haciendas* of the whole period (see Chapter 3, Section 3.8). By

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[557] *The Silver King*, 20.
[558] On the silver-rich lead ores of Zimapan see Miguel Othon Mendizábal, "Los minerales de Pachuca y Real del Monte en la época colonial," *El Trimestre Económico*, no. 2 (1941): 263.
[559] Canterla y Martín de Tovar, *Vida y obra del primer Conde de Regla* 41.; Couturier, *The Silver King*, 157.

the time the first English group arrived at Pachuca in the mid-1820s to rehabilitate the mines and *haciendas*, this first stage of silver bonanza had long been over.

This functionally unwarranted but visually impressive pile of buildings, surrounded by the most beautiful of natural settings one can choose for any industrial production site, would be rehabilitated by the Adventurers in the Mines of Real del Monte as of 1824. By the early nineteenth century both water and political turmoil had taken their toll on the infrastructure that had proved so profitable to the first Conde de Regla. The mines had become flooded and the refining *haciendas* stripped of contents and in ruin, so that production of silver had plummeted. The new republic made it possible for foreign investors to enter the mining industry in Mexico, and the allure of this historically lucrative sector attracted English capital that until then had been barred from the Spanish colonial empire in the New World.[560]

The English investment would not be profitable, with revenues of $10.5 million against expenditures spiralling to $15.4 million up to 1847.[561] The new Mexican owners took possession of the existing assets of the failed English Adventurers for less than 1% of the total expenditures incurred by the Adventurers.[562] They named as General Manager the same

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[560] Taylor, *Selections from Humboldt*, i-iv.; H. G. Ward, *Mexico*, vol. I (London: H. Colburn, 1829), 418.; Henry English, *A General Guide to the Companies Formed for Working Foreign Mines with their Prospectuses, Amount of Capital, Number of Shares, Names of Directors, &c* (London: Boosey & Sons, 1825), 55.; Wilson, *Mexico and Its Religion*, 355.; Randall, *Real del Monte*, 34.

[561] Buchan, *Report Real del Monte*, 41. An anonymous letter signed 'Visitor' printed in England and translated in Mexico placed the blame of the losses on the 'notorious extravagance … incapacity and madness of the persons on which trust was placed, and not on any fault of the deposits [of silver]'- '*a la notoria ... extravagancia, incapacidad y locura de las personas a quienes fueron confiados sus intereses, y no a la falta de mérito y bondad de los Criaderos en cuestión'*. According to the writer the fault lay on the very costly and bad management in London, bad choice of employees, bad agents sent to Mexico, and even on their lack of Spanish. Viajero, "Las Minas de Mexico," *Revista de Minas* Tomo I (1861): 177. All these faults apply equally well to modern transnationals and the high costs incurred by expatriates who at times rarely speak or integrate themselves into the local communities.

[562] Buchan states in his report that the new capital invested by the year 1854, six years after the Adventurers had dissolved their company, comes to $538,484, but does not include payments for transfer of rights or liquidation of debts previously incurred. According to Robertson, the Adventurer's Company was liquidated for just $130,000, of which three-quarters were used to liquidate existing debts. Thus the shareholders in London would receive approximately $30,000 in cash, and the new investors a very significant plant infrastructure in mines and

Englishman who as representative of the Adventurers had been responsible for obtaining the best price for their assets in Mexico, John H. Buchan.[563] Buchan's penchant for accounting set a precedent within the new Company that has made the present chapter possible:

'I commenced by arranging the entire system of accounts on such a plan, that every week's result, in each mine and reduction-work, might be clearly shown, and the economy of the different departments thus fairly compared against each other'.[564]

Thanks to Buchan the *Hacienda* Santa María de Regla, or simply Regla as it is referred to in the accounting books, offers unique advantages to a historian reconstructing the environmental history of historical silver refining. Without a detailed operational mass balance of the amalgamation and smelting process it is impossible to arrive at a quantitative impact of

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haciendas for just $130,000. Buchan, *Report Real del Monte*, 32,42.; Robertson, *A Visit to Mexico*, II 172. For a more detailed breakdown, see Randall, *Real del Monte*, 200-209.

563 The conflict of interest for Buchan in selling the English assets of the Company he represented at such a low price to a new Company where he held an evident interest is just one part of a chapter that may be more complex than a straightforward change of ownership. Velasco Avila et al have been very critical of the business practices of the new Mexican owners of the Compañia de Real del Monte in the 1850s. The new owners, amongst which figured Nicanor Beistegui, Alejandro Bellange and Manuel Escandon, were also at the time leasing the *Casa de la Moneda* (Minting House) in Ciudad de México and the monopoly on tobacco sales (*Estanco del Tabaco*). Their speculative business practices, which included buying but leaving idle mines that did not immediately provide a bonanza, and their strategy of expanding upstream (agriculture, salt mines, water sources, real estate) so as to control the prices of consumables in the refining process, together with a constant pressure on the government to provide them with special exceptions, have led Velasco et al to brand them 'vampires of the Treasury'. Velasco Avila et al., *Estado y minería en México*, 48, 141-143,246- 248. The new owners were very successful even under conditions that included the French invasion of Mexico. Though they would soon lose the lease to the *Casa de la Moneda* in Ciudad de México, which had given them the advantage of faster cash flows on silver remitted, the *Compañia Real del Monte* would produce between 30 to 60% of all silver rendered to the *Casa de la Moneda* in Ciudad de México. The Company is said to have produced around 8% of all the silver in Mexico between 1849 and 1861. The combination of business practices, government contacts, the bonanza of the Rosario mine and the decrease in mercury prices (see Chapter 5) made the *Compañia Real del Monte* one of the leaders of the Mexican silver refining industry. Ruiz de la Barrera, "La Empresa de Minas del Real del Monte," 3, 14, 37, 73-77, 284-85.; Elvira Eva Saavedra Silva and María Teresa Sánchez Salazar, "Minería y espacio en el distrito minero Pachuca-Real del Monte en el siglo XIX.," *Investigaciones Geográficas, Boletín del Instituto de Geografía*, no. 65 (2008): 91-92.;Velasco Avila et al., *Estado y minería en México*, 49.;José Alfredo Uribe Salas and Rubén Darío Nuñez Altamirano, "Depreciación de la plata, políticas públicas y desarrollo empresarial. Las pequeñas y medianas empresas mineras mexicanas de Pachuca y Real del Monte," *Revista de Indias* LXXI (2011): 463.

564 Buchan, *Report Real del Monte*, 43. John Buchan states he was sent to Pachuca in 1848 to wind up the affairs of the Adventurers. Robertson and Randall associate Buchan with the Adventurer's Company as of 1825. Robertson speaks highly of Buchan, explaining he was came from a 'good Scotch family but an Englishman by birth and education'. Buchan was accompanied by his wife, 'a lady of beauty and animation .. lively disposition ... warm heart .. good sense ... cultivated mind'. His brother-in-law Thomas R Auld will appear in managing positions of the Mexican company in the following sections. Ibid., 39.; Robertson, *A Visit to Mexico*, II 163-65.; Randall, *Real del Monte*, 201.

each process on the environment. Regla provides a rich source of accounting data for the period from mid-1872 to mid-1888 which allows very detailed mass and energy balances to be established on a weekly and monthly level for most of this period, both for *patio* amalgamation and for smelting. The fact that the same Company and *hacienda* carried out in parallel both processes in the same location establishes a level playing field when comparing the process variables of both refining processes. The long time series available for the data even out spurious correlations and eliminates the risk present when single years are chosen to determine the long-term mass and energy balance of a process.

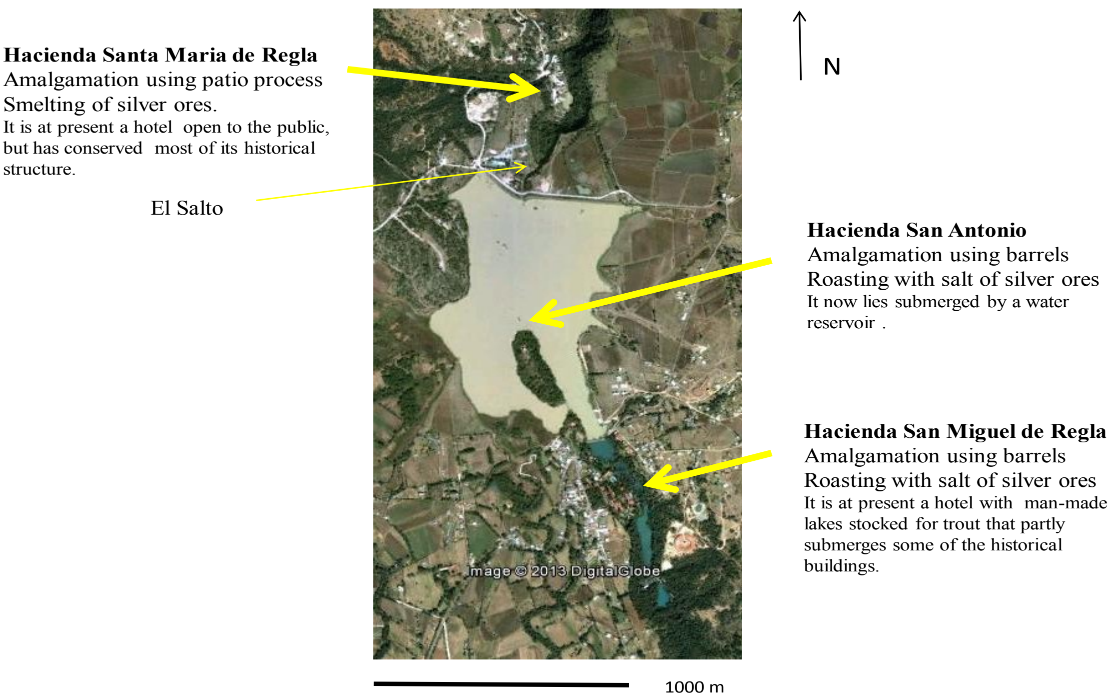

Figure 4-3. The locations of three of the historical silver refining *haciendas* operated by the Compañia Real del Monte in the second half of the nineteenth century, on the outskirts of present day Huasca de Ocampo, Hidalgo State, Mexico. Adapted from Google Earth © 2013 DigitalGlobe, reservoir location 20° 13' 36" N 98° 33' 46" W.

While the neighbouring *Hacienda* San Antonio de Regla now lies beneath a man-made reservoir lake with only a chimney stack signalling its presence beneath very murky waters, and San Miguel has many of its historic buildings knee-deep in a new recreational lake (Figure 4-3), Regla can be visited, measured and reconstructed on paper, thanks to the solid pile of buildings left by the first Conde de Regla.

4.3 The *Hacienda* de Regla.

Regla stands at an elevation around 2000m, some 20 km from the present town of Huasca de Ocampo, in the modern state of Hidalgo. The first refining *hacienda* to be built in the basalt-lined gorge was called "El Salto", and was bought by Terreros in 1753 'from the son of another local miner, Isidro Escorcia'.[565] The location was assured of an ample supply of water from an *Ojo de Agua* (water spring) that compensated for the transport of silver ores some 30 km by mule trains over rough tracks from Real del Monte. As amply commented upon by travellers, it is situated in a *barranca* (gorge), in whose southernmost point a waterfall (*El Salto*) provides the water required by the *hacienda*. The construction of the modern reservoir makes it impossible to judge what the original volume of water cascading down El Salto may have been. Three *haciendas* were fed by the *Ojo de Agua* in the second half of the nineteenth century: San Miguel de Regla, San Antonio and Regla (Figure 4-4). The gorge of Regla pales in comparison with the cleft in the landscape that nestles the town of San Sebastián.[566]

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[565] Couturier, *The Silver King*, 67.

[566] The reproduction of the lithograph of the terrain and haciendas in the area of Pachuca and Real Monte from which I have reproduced the section in Figure 4-4 was provided in digital form by the MMOB where it is classified under: '*Colección Orozco y Berra, Hidalgo, Varilla OYBHG001, Numero Clasificador:1233-OYB-7246-A-002, Litografía a Color, Perfiles 1 y 2 de Pachuca a Real del Monte (sobre las vetas del Xacal y Vizcaina, y por la Cañada, del Real del Monte hacia Omitlan y la Hacienda de Regla, Autor desconocido, Ano: 1700, Escala: en varas, medidas: 24x126 cm*'. The year indicated (1700) is wrong for three reasons: there was no Compañia Real del Monte in 1700, the refining haciendas that appear did not exist, and the artist, Hesiquio Iriarte, was signing his work as *Litografia de Iriarte y Compañia* as of the 1850s as reported in Manuel Toussaint, *La litografía en México en el siglo XIX : sesenta y ocho reproducciones en facsímil* (México: Estudios Neolitho, 1934), 8. This lithograph accompanies the text of Burkart, "Memoria Real del Monte."

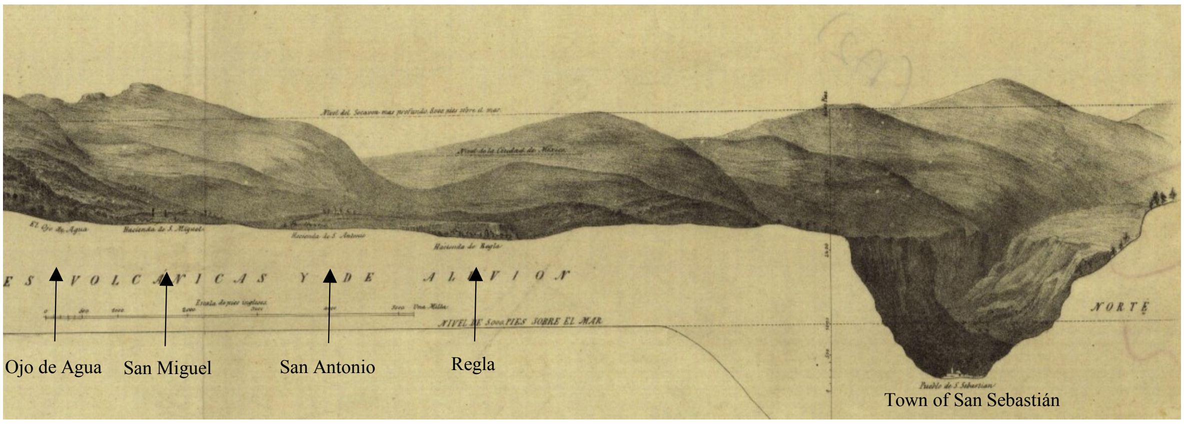

Figure 4-4. Section of the lithograph that shows the location of the three refining *haciendas* (San Miguel, San Antonio and Regla) with respect to the Ojo de Agua that provided the guaranteed water supply for their processes. Reproduced and adapted from footnote 566.

Regla had been constructed in the late eighteenth century to refine ores both by *patio* amalgamation and by smelting, and this dual functionality would persist under its new English and then Mexican owners. In fact it would be singled out as the only *hacienda* of the Company Real del Monte to refine ores by smelting. It does not surprise then that the Englishman in charge of Regla in 1851 was the chief smelter of the Company, a Mr. Bell of Durham.[567] The extravagance of the first Conde de Regla and the relative isolation of the site has made it possible for most of the *Hacienda* de Regla to have withstood the erosion of time, in contrast to the case of most historical *haciendas* in San Luis Potosi, Zacatecas or Guanajuato. Since no historical or modern architectural plan could be found of Regla, it has been necessary to reconstruct the various operational areas within the *hacienda*. I have used as my initial guide

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[567] Robertson, *A Visit to Mexico*, II 223. In 1828 the chief smelter at Regla was of German nationality. Letter from Charles Tindal to Wllima Dollar, dated 4th October 1828. AHCRMyP, Sección: Correspondencia, Subserie: Correspondencia General, 12-2: 20 Julio 1827- 6 Julio 1832

both the nature of the processes, the extant visual evidence (paintings, watercolours, engravings, on-site photographs, historical photographs and satellite images), on site measurements and travellers' accounts.

Figure 4-5 is a Google Earth satellite image of the grounds of Regla, as they stood in the year 2004. The outline of the *hacienda* resembles the shape of a Space Shuttle, and the distance between the nose cone on the right and the top of the tail on the left is around 300 m. At its widest point the *Hacienda* spans approximately 75 m. Figure 4-6 is the general assignment of main process areas of Regla, which are given in greater detail in the plan of Figure 4-7. The main operational areas are straightforward to identify when they retain furnaces or circular milling areas. The spaces identified for storage comply with three conditions: proximity to the process area where the stored materials will be used, a degree of protection commensurate with the nature of the material, and the area assigned must suffice to store the levels of inventory carried at Regla.[568]

The first impression of Regla on one of the first English members of the group sent by the Adventurers to visit the *haciendas* of Regla, San Antonio and San Miguel, in June 1824 was not flattering. 'The buildings upon them must have cost great sums, but they are now in a state of decay. They are ill planned, and appear placed at random. The architect, whoever he was, was a sworn enemy of right lines and angles'.[569] This was a most sweeping and dismissive indictment that came from an observer who was looking at his first industrial site designed expressly for a joint *patio* amalgamation / smelting process. The unknown artificer-architect of

[568] The detailed calculations are set out in Appendix C.
[569] Anonymous, "Journal Descriptive of the Route from New York to Real del Monte by Way of Tampico," *The London Magazine* 1826, 167.

Figure 4-5. Satellite image of Regla. The lake is the most evident of modern additions. The photograph is aligned on a South to North axis from left to right. Google Earth © 2013 DigitalGlobe, 20° 14’ 15” N 98° 33’ 42” W.

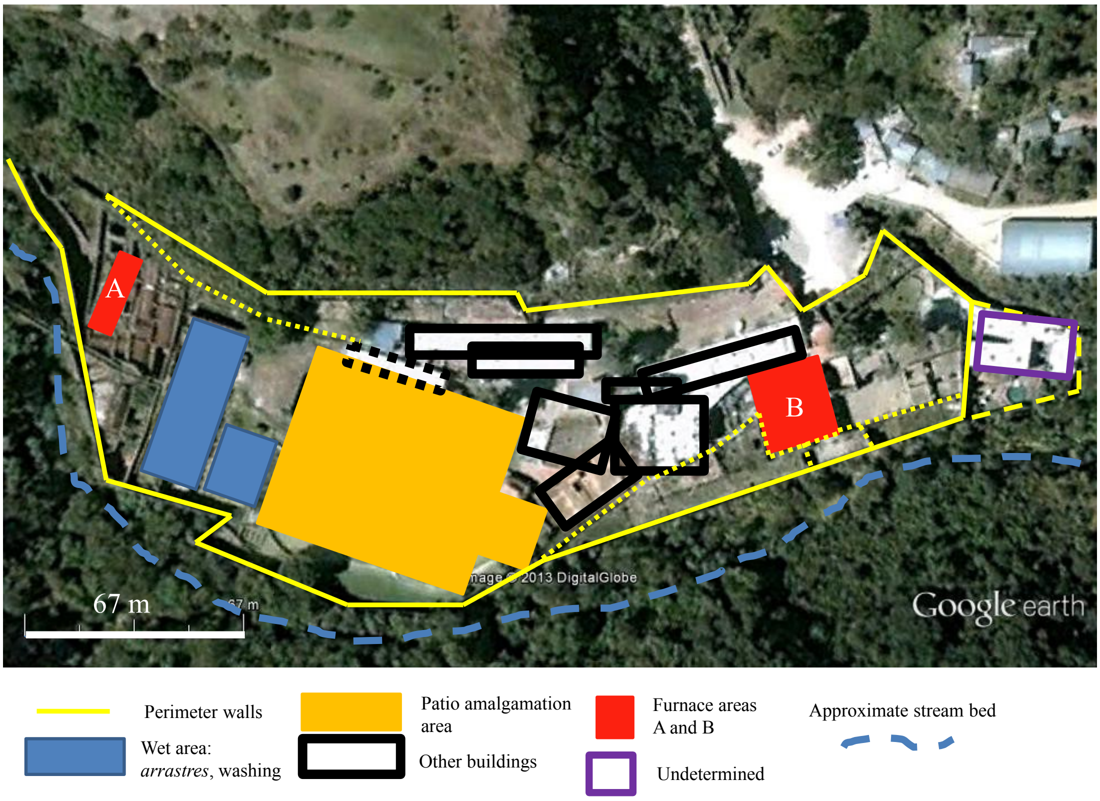

Figure 4-6. Assignment of general process areas of Regla. Satellite image from Google Earth © 2013 DigitalGlobe.

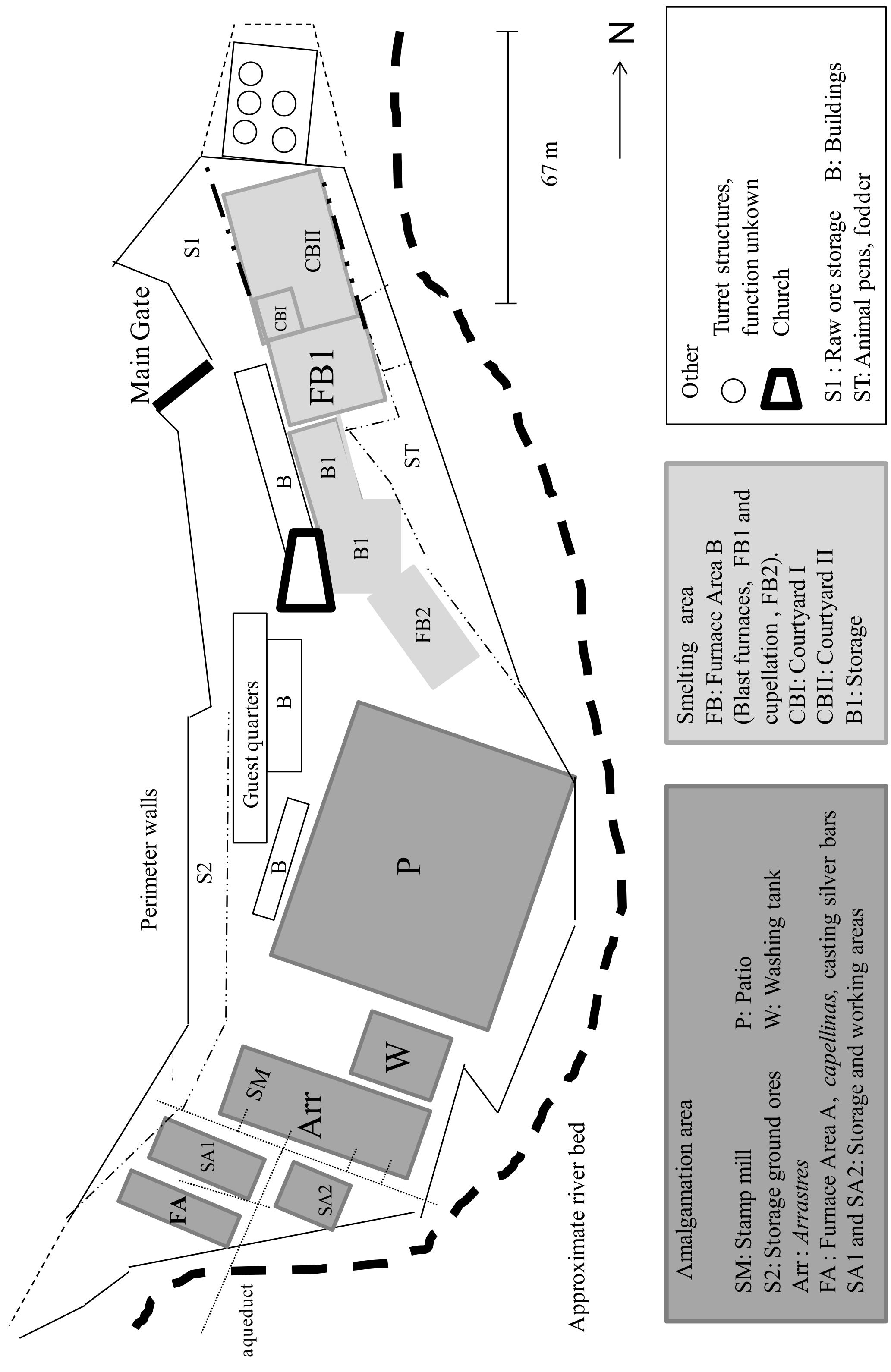

Figure 4-7. Reconstruction of main functional areas at Regla (see text for details).

Regla had managed to snuggle his massive walls and buildings between the basalt prisms and the waterway, as close to the waterfall as possible in order to retain the full potential of its hydraulic power.[570] The merits of his scheme will become apparent as I analyze each of the process areas in detail.

4.3.1 Ore reception and stamp mill

There was only one main entrance to Regla though which entered all the raw ore, reagents and fuel required for the refining of the silver ores. Raw ore, both for amalgamation and for smelting, would have been stored close to the main gate (S1: all abbreviations refer to Figure 4.7). This would isolate the transit corridor for 600 mules (or the requisite number of carts) periodically delivering raw ore, from the internal workings of the *hacienda*. From this common storage area the flow of materials would separate into two distinct transit and work corridors. Materials and silver ores for amalgamation would have been transported through the arches straight ahead from the Main Gate to the amalgamation work areas, including Furnace Area A. Materials and ores for smelting from the mid 1830s would have been sent to be processed at Furnace Area B. The painting by Johan Moritz Rugendas shown in Figure 4-8 gives the artist's impression of the scene on entering by the Main Gate in the year 1832. The tall building observed on the right with the prominent corridor houses the accommodation quarters for guests. The loaded mules are being taken though the massive arches to the amalgamation areas in the southern part of the *Hacienda*.[571] Blueish smoke eddies from the hidden chimney stacks of Furnace Area A still in use in the background of the scene.

[570] According to Couturier 'contemporaries asserted that Pedro Terreros himself had planned this great hacienda' but provides no primary source. Couturier, *The Silver King*, 69.
[571] The use of the word *trapiche* for the title of the painting is an aid to identifying the work spaces. '*Entrada a los trapiches*' in the plural signals the entrance to an area of mills, in the plural. The trapiche in a sugar refining hacienda is the place where the sugar cane is crushed Another painting by Rugendas titled '*Trapiche del ingenio de Tuzamapa*' shows the grinding of sugar cane in a crusher powered by the circular motion of horses. Renate

With regards to the mills, in 1771, due to the workers strike, it is claimed that 'the five magnificent waterwheels at Regla had nothing to grind'.[572] An inventory from 1824 states: 'Grinding establishment.- One wheel in working order. Five stamp heads'.[573] One year later the British Chargé d'Affaires in Mexico, H.G. Ward, would observe that:

'the whole [Regla] is in a tolerable state of repair, with the exception of the stampers, for braying the ore, which are now in ruins. These are to be replaced by a water-wheel constructed by the Company, which is thirty–six feet in diameter, and is to put in motion forty-eight stamps'.[574]

Figure 4-8. '*Entrada a los trapiches de la hacienda Santa Maria de Regla*', by Johan Moritz Rugendas, oil on cardboard, 24 August 1832. Image reproduced with permission from the web portal of the Universidad de las Artes, Aguascalientes, Mexico: http://www.aguascalientes.gob.mx/ temas/cultura/ webua/catalogo/ johanmoritz.html (accessed 9 May 2013).

Moyssén Löschner, Xavier Echeverría, and Mario de la Torre, El México luminoso de Rugendas (Mexico City: Cartón y Papel de México, 1985), 49. *Trapiche* has also been used to refer to the *molino*. Egleston, *The Metallurgy of Silver*, 269.

[572] Doris M. Ladd, *The Making of a Strike : Mexican Silver Workers' Struggles in Real del Monte, 1766-1775* (Lincoln: University of Nebraska Press, 1988), 147.

[573] Randall, *Real del Monte*, 218.

[574] H. G. Ward, *Mexico* vol. II (London: H. Colburn, 1829), 140.

By 1855 the stamping equipment has again changed. Buchan reports that the new Mexican company has installed two water-wheels (of unknown dimension) providing power to thirty stamps (of unknown size).[575] The logistics of an efficient amalgamation process requires that the stamping mill should be located as close as possible to the *arrastres* (area marked Arr)*,* powered by water supplied by the internal system of water channels. There is at present a rectangular structure in the area designated SM that would have accommodated one large vertical waterwheel. The proximity of the proposed stamping area SM to the living quarters may explain the following extracts: ‘a poor woman [the wife of the English manager at Regla], living all alone ... with no other sound in her ears from morning till night but the roar of thunder or the clang of machinery’.[576]

Or as expressed more explicitly:

‘The works are on the patio system ... the noisy stamping-mills working night and day. To me they had a peculiarly musical charm. It happened that in the middle of the night two or three of the nearest stamping-mills stopped on account of something being wrong with the water-wheels, and Bishop and I, who slept in adjoining rooms, both awoke and called to each other, wondering what had happened’.[577]

No mention is made of clouds of dust emanating from the stamping operation, which may imply that water was added during stamping in the 1880s.[578]

4.3.2 *Arrastres* and water power in the *Hacienda*

The circular vats in Figure 4-9 correspond to where the *arrastres* used to be located at Regla, a total of sixteen units arrayed in two sections of eight each. Another two circular vats

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[575] Buchan, *Report Real del Monte*, 13.
[576] Calderón de la Barca, *Life in Mexico*, 243.
[577] Brocklehurst, *Mexico To-day*, 145.
[578] Hermosa, *Manual de Laboreo de Minas*, 196.

are observed in the topmost terrace which correspond to the traces of two *molinos*. The *arrastres* were powered by water-wheels, possibly two *arrastres* to one water-wheel. The diameter of the well of each *arrastre* at present is approximately 3 m.

Figure 4-9. View of the sixteen circular vats of the *arrastres*. The remains of two *molino* tracks are hidden by the cactus leaves on the lower right-hand corner.

Figure 4-10 is a photograph of a water-powered *arrastre* from an unnamed hacienda in Mexico in the nineteenth century.[579] Fanny de Calderon may have been referring to all these water-wheels in her description of the Hacienda (see quote at the beginning of the chapter). Ward mentions that 'eight of the old arrastres, (worked by water) had been repaired' and also states that in the mid-1820s there were 'twenty-four Arrastres, worked by horizontal water-wheels'.[580] That only eight required repair after a decade of neglect prior to the 1820s implies

[579] Rickard, *Journeys of Observation*, 242.

[580] Ward, Mexico, I 424.;Mexico, II 140. Humboldt makes the unexpected commentary that arrastres were unknown at Regla, where ores were ground by stamp mills only. '*Dans quelques grandes usines de la Nouvelle-Espagne, par exemple a Regla, on ne connoit point encore les arastras*'. Humboldt, *Essai politique*, Tome IV, 59. Castelazo's account of the mining around Real del Monte, first published in 1820, states that the second Conde

a robustness of structure for these wet grinding units. The upper terrace in Figure 4-9 which at present holds two rectangular tanks may have originally contained another eight circular vats.

Figure 4-10. Photograph of water-driven *arrastre*, from unnamed *hacienda* in Mexico, photograph reproduced from footnote 579.

According to Randall, an inventory from 1849 includes 'forty water-powered *arrastres* capable of reducing 120 tons per week'.[581] The grinding capacity is consistent with the

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de Regla built masonry arrastres of Regla at a cost of more than 100,000 pesos, but does not provide a date. Mining and refining in the area would progressively halt after the death of the second Conde in 1809. '*el Segundo Conde ... en atención a la necesidad que tenia de habilitar las haciendas para beneficiar los metales que produjeran, juzgando suficiente las de S. Antonio, S. Miguel y Regla, determinó repararlas ... construyendo en ellas nuevas* y *costosas oficinas, particularmente en la primera y última, cuyos arrastres de solida mampostería le tuvieron de costo mas de cien mil pesos'*. Jose Rodrigo Castelazo, Manifiesto de las riquezas que han producido y actualmente contienen las celebradas minas de las vetas Vizcaina y Santa Brigida ubicadas en el Real del Monte, jurisdicción de Pachuca, de las grandes obras que en ellas se hicieron y del estado en que actualmente se hallan (Mexico: Imprenta de D. Mariano Ontiveros, 1823), 15. The third Conde visited Regla, whom he referred to as 'Babylonia', the 31st January 1810. According to his journal for that day, '[it] is the only one still functioning, even if partially, since only three [stamp] mills are working, eight smelting furnaces, twelve of the twenty four [*ar*]*rastras* that it possesses' *'[es] la única que esta en ejercicio, aunque incompleto, porque solo andan tres morteros, ocho hornos de fundición, doce rastras de las veinte y cuatro que tiene'*. Manuel Romero de Terreros, "El condado de Regla en 1810," *Historia Mexicana* 4, no. 1 (1954): 110. If Humboldt was not mistaken this would confirm that *arrastres* are not installed in many haciendas of the late eighteenth century.

581 Randall, *Real del Monte*, 219.

amalgamation activity at Regla, but it is not evident where the additional *arrastres* according to Randall would have been located within the compound. By 1855 there are only 16 *arrastres* included in the description by Buchan of the infrastructure at Regla, plus one *molino*, which corresponds well to the modern image in Figure 4-8.

The guarantee of a constant large flow of water was necessary to provide power, both to the stamp mill and to the *arrastres.* The main aqueduct enters the *Hacienda* on the south side (Figure 4-11), fed by water retained in a small pool at the bottom of the waterfall (Figure 4-12).

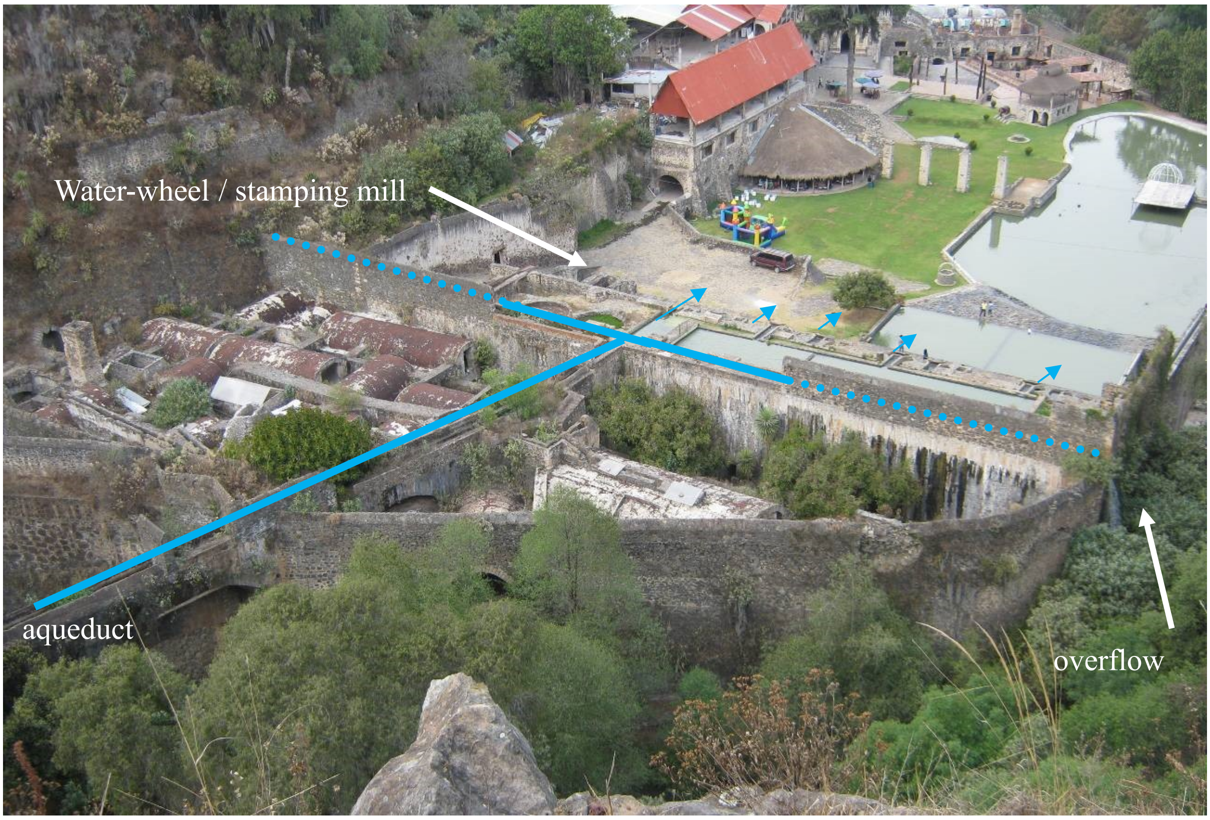

Figure 4-11. Water distribution channels and overflow outlet in the southern area of the *Hacienda*. The four pillars on the grassy area may be the remnants of the structure that sustained a roof over the *patio* area.

The presence of this reservoir would have cushioned the *Hacienda* from an irregular flow from the spring. The opening in the perimeter wall pointed out in Figure 4-11 acts as an overflow outlet to regulate the total volume of water supplied to the various process areas of the *Hacienda*. Large quantities of water would also be required to prepare the amalgamation slurry, to replenish the water lost by evaporation from the *tortas*, to wash away the mineral matrix of the slurry and separate the amalgam and for the consumption of the workers and animals (from 100 to 300 mules and horses kept within the *Hacienda* towards the latter part of the nineteenth century, see below).

Figure 4-12. The pool at the foot of 'El Salto'.

4.3.3 The *patio* reactor.

The ore, now milled to a very fine powder in the *arrastres*, could have been transported in barrels or discharged directly from the *arrastres* to the *patio* reactor.[582] The *patio* reactor at Regla went through two quite distinct stages. Initially the inventory from 1824 describes a 'Patio for quicksilver reduction, with forty-five masonry arches to support roofs, now in ruin. Wooden floor partly serviceable, partly in ruin. Pillars supporting arches partially worn away at base, due to salt'.[583] The English Company opted to retain the roof, since by 1829 Ward mentions 'two covered Patios, each about 200 feet in length, in which the process of amalgamation is carried on'.[584] Figure 4.11 shows four pillars still standing at present, which may correspond to the type of column mentioned in the 1824 inventory. However, neither of the paintings shown below include these pillars. The practice of using wooden planks to floor the *patio* area has been mentioned in Chapter 3. By 1835, according to Randall, Commissioner John Rule decided to adopt the "Guanajuato" method, and decided to keep the *patio* area uncovered and unheated except by the sun.[585] By 1855 Regla has an open *patio* 'all carefully floored in beams', and the area available for amalgamation is claimed to cover one and a half acres (approx. 6,000 m^2).[586] The impact of rain on a *patio* reactor without a roof is well illustrated in a letter from R. Bell at Regla to Mr. Auld, General Manager of the Real del Monte Company, dated September 30th 1865, reporting that:

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[582] It is claimed that transport in barrels was more efficient than discharging each *arrastre* through an outlet, with two workers discharging via shovelling into barrels the contents of 4 *arrastres* in half an hour. Hermosa, *Manual de Laboreo de Minas*, 207-208.
[583] Randall, *Real del Monte*, 218.
[584] Ward, *Mexico*, II 140.
[585] A technical report drawn up for the Directors of the Company in London refers to the amalgamation process carried out in Guanajuato as reaching "the highest state of perfection". Randall, *Real del Monte*, 115-16.
[586] Buchan, *Report Real del Monte*, 9. The patio reactor area in Figure 4.7 corresponds to over 5,000 m^2.

'the weather is dreadfull here, it began raining on Wednesday night & it has rained incessantly ever since, our Patio is a complete lake, we cannot work it. The salt and sulphate must be all washed out by this time, & I have not a grain of salt about the place to replace the loss'.[587]

It is this new open *patio* area that is prominent in two paintings of the *Hacienda* de Regla. The collection at the Soumaya Museum in Mexico City houses a painting by Eugenio Landesia that depicts the *Hacienda* in almost photographic detail (Figure 4-13). It was commissioned to be painted from the location of the *arrastres* when Thomas R. Auld was managing Regla in 1854.[588] It is a view to the north of the *hacienda*, showing some fifteen circular *tortas* being trod upon by teams of horses and men. '[the mixture] is ... pounded and trampled upon, by both bipeds and quadrupeds ... men and mules are seen, in most singular combination, performing this dirty but essential operation'.[589] Some of the *tortas* are depicted as being fenced in using provisional planks to the sides. What can only be appreciated in the original painting are the small mounds of copper sulphate with their tell-tale intense blue colour, waiting to be added to each *torta*.

There is also an anonymous, unidentified and undated painting reproduced in black and white, in the textbook on the history of Mexico by Meyer, Sherman and Deeds.[590] It is again a view facing north, but takes in the whole *Hacienda*, having been painted presumably from the heights of the *barranca.* The uncovered patio area places the date after the mid-1830s. As can be seen in Figure 4-14 the *arrastres* appear covered with small roofs and some ten *tortas* are

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587 AHCRMyP, Sección: Correspondencia, not classified, 1865. Auld was the family name of the wife of John Buchan, the first General Manager under the new Mexican-owned company established in 1848.
588 Alfonso E. Pérez Sánchez, Benito Navarrete Prieto, and Gustavo Curiel, *Tesoros del Museo Soumaya de México : siglos XV-XIX* (Madrid: BBVA, 2004), 213-15.
589 Tudor, *Narrative of a Tour*, 298.
590 Meyer, *Mexican History*, 150.

Figure 4-13. '*Patio de la Hacienda de Regla*' by Eugenio Landesia, 1857, oil on canvas, 46 by 64 cm. Image reproduced from footnote 588.

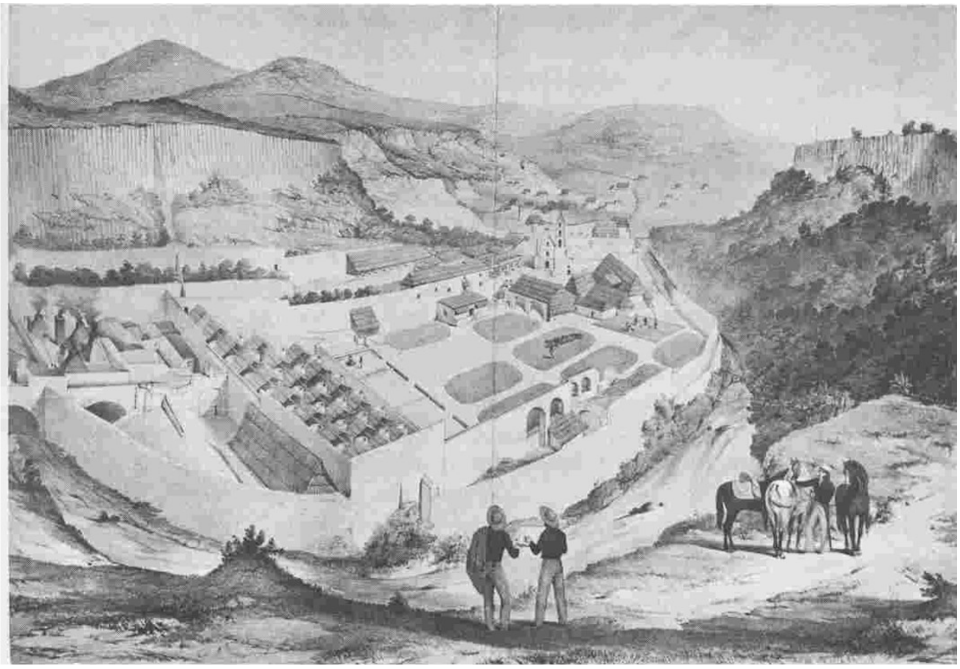

Figure 4-14. The *Hacienda* de Regla, from an unidentified illustration in footnote 590.

being worked on the *patio*. The only smoke seen in the painting is coming from Furnace Area A, in the most southern area of the *Hacienda*. Should any doubt remain as to the identity of this *Hacienda*, the facade of the Church and the rendering of the basaltic prisms in the cliffs of the background complete its identification. The width of the stream indicates a significant volume of water at the time of the painting.

4.3.4 Furnace Area A: Capellinas and the recycling of mercury

Furnace Area A is currently designated as the site of the 'Spanish Furnaces', where the original smelting furnaces built in the eighteenth century were located. Though the English investors built the new blast furnaces to the north of the hacienda (Furnace Area B), Furnace Area A remained the location where approximately 85% of all the silver of Regla was finally separated from the amalgam. The initial separation of the mercury amalgam from the ore slurry in the washing tanks (WT) was a milestone in the process. For the first time a product with a very high tangible monetary value per unit weight has now been isolated into a relatively small mass of mercury and silver. From this moment on, each stage of the process would require an increasing amount of vigilance and control.[591] Away from the open *patio* area there are three process areas I have designated in Figure 4-15 as SA1, SA2 and FA (Furnace Area A). SA1 I have assigned to a covered work and bulk storage area for two water-soluble high bulk additives, salt and copper sulphate. SA2 I assign to a secure storage area for premium materials such as the amalgam, mercury and intermediate storage of spongy silver from the *capellinas*.

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[591] 'in the [washing] vat the men handle the pella [amalgam] just a short time, at the most two hours; during this time the guards are overseeing [them], and yet many thefts are detected … those who know of the tendency to steal by the workers in mines and haciendas, will be able to appreciate this reasoning' - '*en la tina los hombres manejan la pella un corto rato, que quando mucho llega a dos horas; en este tiempo están los Mandones de guardas de vista, y sin embargo se averiguan muchos robos … quienes tengan conocimiento de lo propensas que son al robo las gentes operarias de minas y haciendas, sabrá graduar el peso de esta razón*' in Garcés y Eguía, *Nueva teórica del beneficio de plata*, 137. The overall level of tension between the workforce in the mines and haciendas, their overseers and the first Conde de Regla is the subject of Ladd, *The Making of a Strike*.

It would also include the *azoguería*, the mercury room with *manga* and scales such as depicted in Chapter 3.

From the 1830s, in Furnace Area A at least two heating operations took place: the separation of mercury from silver in the *capellina*, and the casting of silver bars. Buchan includes one distilling furnace (*capellina*) and one bar casting furnace in his description of the amalgamation infrastructure at Regla in the year 1855.[592] I have tentatively assigned the circular bed observed in Figure 4.16 as housing the lower part of a *capellina*, with its channel for cooling water that runs to the back wall. It was not possible to measure directly the diameter of the bed since the area is at present off-limits to the public.

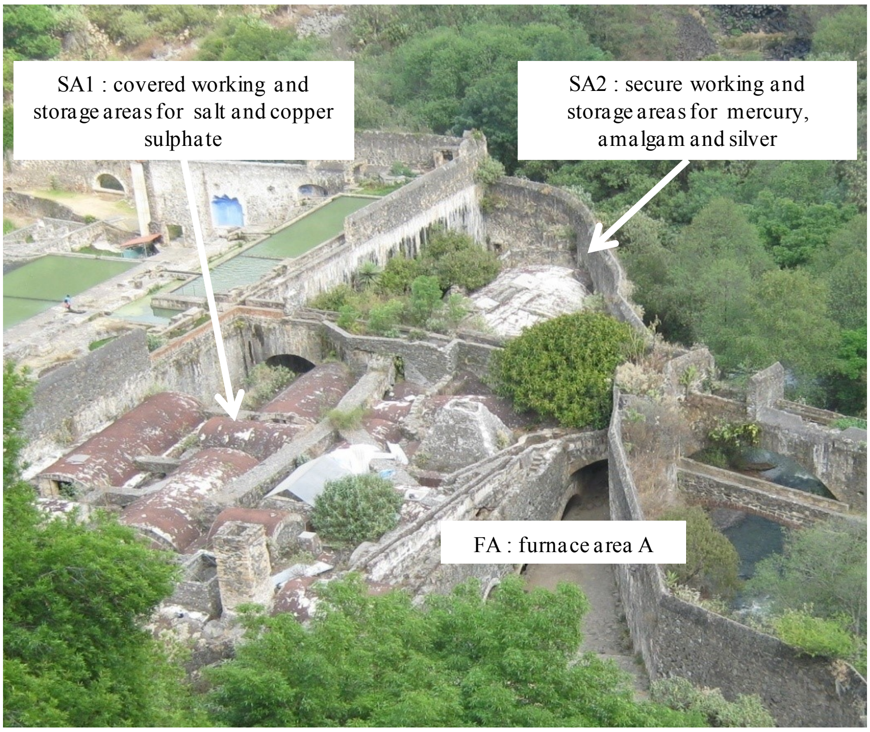

Figure 4-15. Proposed assignment of dry process areas related to the amalgamation process in the southern part of Regla.

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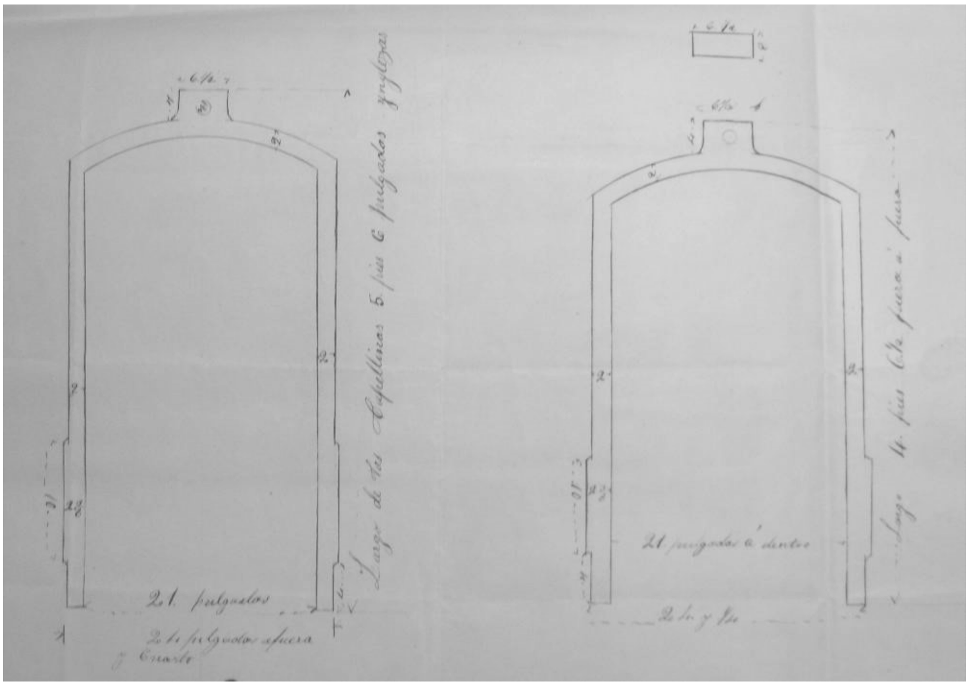
[592] Buchan, *Report Real del Monte*, 9.

Figure 4-16. Tentative location for a *capellina*, showing the channel for cooling water. This picture was taken in March 2013. Further excavation around this location has been carried out by November 2014.

I estimate a diameter well over 1 m. The external diameter of the *capellinas* used at Regla in the second half of the nineteenth century was 0.61 m, according to engineering drawings of the Compañia Real del Monte from this period (Figure 4-17).[593] This dimension would be sufficient to fit the rounded base of an assembled *capellina* and leave space for the fuel used for heating. Once assembled, the *capellina* loaded with stacked amalgam *pellas* inside

[593] At the beginning of the nineteenth century the most common copper *capellinas* measured approximately 40 cm (half a *vara*) in width and up to 80 cm (one *vara*) in height, according to Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 48.



a

b

Figure 4-17. a) Drawing with the engineering specifications for the construction of iron *capellinas* in the workshop of the Compañia de Real del Monte (date unknown). The left-hand *capellina* has a height of ‘5 pies 6 pulgadas ynglesas’, 5 feet 6 english inches, an internal diameter of 21 inches and an external diameter of 24 inches. The *capellina* on the right has the same width but a height of 4 feet and 6 ½ inches. Digital image of undated drawing courtesy of AHCRMyP, Sección: Administración Interna, Serie: Departamento de Ingenieros, Subserie: Croquis y Planos, Vol 204 Carpeta 1. b) Photo of *capellina* in the entrance to the Hacienda Santa María de Regla, photo courtesy of Mr. Josue Soto Samperio, November 2014. Original height impossible to ascertain since *capellina* has been embedded, but at least over 1 m.

would have weighed approximately two tons. I arrive at this figure because just the weight of the iron hood, based on the smaller model in Figure 4-17 a, would be approximately 700kg.[594] As to the contents, I have used as a guide the fact that in the four weeks ending May 26th 1878, a total of 11 *capellina* runs were carried out and 66 silver bars cast, equivalent to approximately 7 bars cast from the silver refined from each *capellina* run.[595] This means that at least 210 kg of silver and 840 kg of mercury (both contained in the amalgam) were loaded into each *capellina*, making a total weight approaching two tons.[596]

Since the *capellina* cycle took approximately one day, a single *capellina* installation would have been enough, as also observed in the plan of the *hacienda* de Rocha in Chapter 3. From an architectural point of view the method required sufficient overhead space to allow the *capellinas* to be lifted by pulley and manoeuvred into place, and the channelling of a guaranteed flow of cold water at floor height. The water channels that supplied the constant stream of cold water required to condense the mercury vapours during the heating of the amalgam can also be clearly identified running the length of the roof of this area in Figure 4-18.

The placing of religious inscriptions over the original placing of these furnaces conform to their deemed Spanish roots: *Las ordenes de Christo*, The Orders of Christ (Figure 4-19 a) and *Nuestra Señora de los Dolores*, Our Lady of the Sorrows (Figure 4-19 b). At least one other placement for a furnace can be observed at the end of the corridor of Furnace Area A

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[594] Based on estimating the volume of iron used for the hood (diameter, length and thickness as given in Figure 4.16) and using the density of iron to calculate the weight.

[595] AHMP, Memorias No. 19 - 21 de los Gastos de la Hcda de Regla.

[596] A 4:1 mercury to silver weight ratio in the amalgam after straining in the *manga* is indicated in Hermosa, *Manual de Laboreo de Minas*, 236. My calculation for Regla coincides with the following generic description: 'bricks of amalgam ... were pressed together ... one ton of these was piled on iron supports, over a stone tank filled with water to nearly the top of a copper or iron bell, *capellina*, which is 0.90 m high and 0.45 m diameter ... the yield of silver was about 200 kilos., and the charcoal used about 250 kilos. per charge.' Egleston, *The Metallurgy of Silver*, 304. The *capellina* run of 1761 cited in Chapter 3, Section 3.8, corresponded to a silver content of around 60 kg, which confirms the increase in the size of the *capellinas* from the eighteenth to the nineteenth century.

(Figure 4-19 c), to the right of which lie a succession of vaulted chambers which I have assigned tentatively to the storage of salt and copper sulphate, both of which needed protection from the rain. It is significant that the anonymous painting of Regla (Figure 4-14) shows at least four heavily smoking chimneys in this area, three with pyramidal stacks and one with a rectangular stack. At present one pyramidal and one rectangular stack can still be observed (Figure 4-20). Other chimney flues can be found in this area, where reverberatory furnaces used to cast silver bars may have been located:[597]

'The retort silver [from the *capellina*], *plata pasta*, is refined in a small reverberatory furnace built of adobes, and heated with wood, which receives a charge of 300 kilos. of the crude bullion. This charge is refined for four hours. A little litharge and lead are added to remove the impurities'.[598]

Figure 4-18. Stone water channels (just to the right of the pyramidal chimney stack) on the roof of the Furnace Area A corridor, that distribute water supplied by the external aqueduct for the condensation of mercury. The shrubs in the foreground hide the connection to the furnace topped by the rectangular chimney stack.

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[597] 'reverberatory furnaces to cast silver into bars'-'*hornos de reverbero para fundir plata en barras*'. Hermosa, *Manual de Laboreo de Minas*, 250.
[598] Egleston, *The Metallurgy of Silver*, 306.

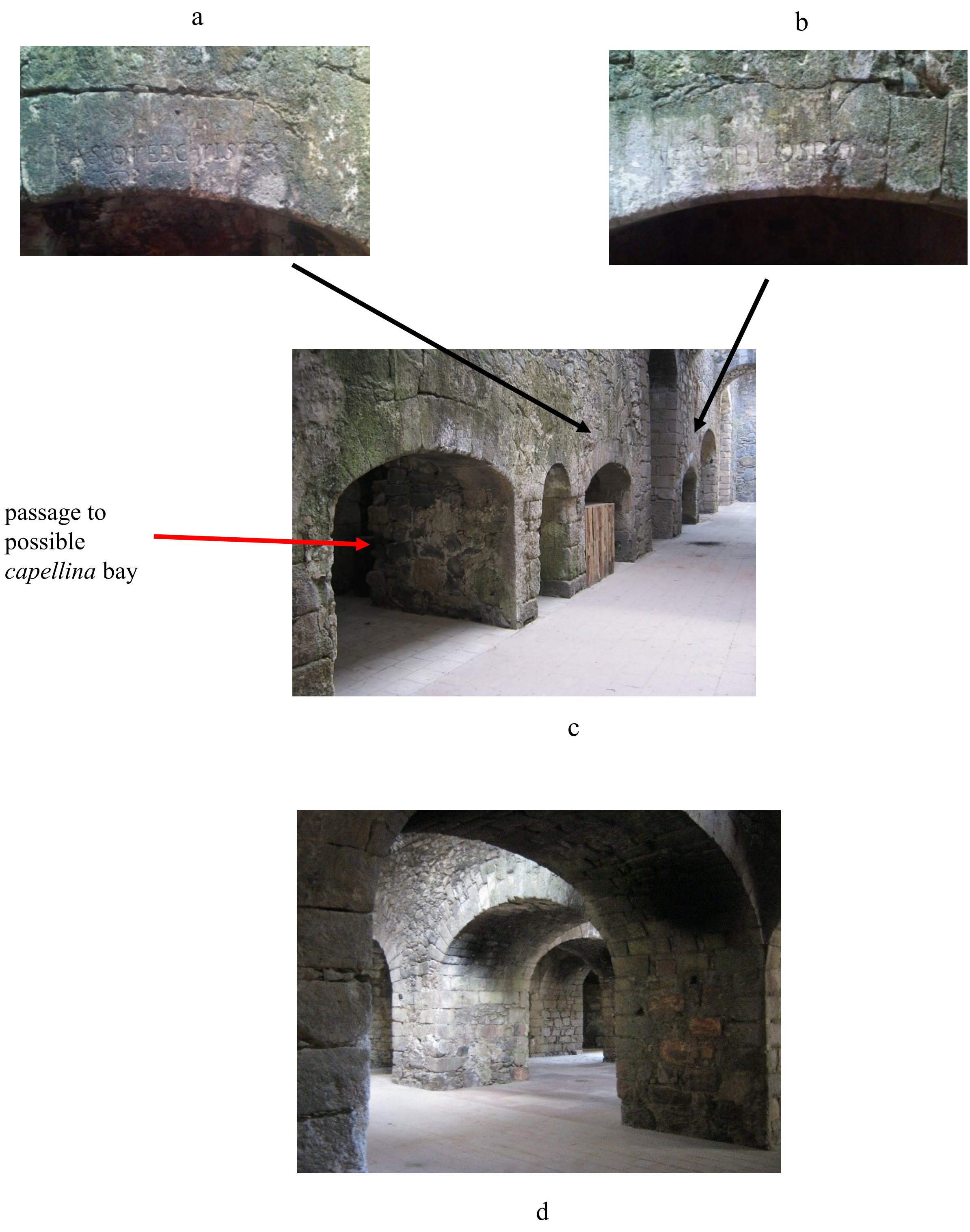

Figure 4-19. a) *Ordenes de Christo* b) *Nuestra Señora de los Dolores*, inscriptions over arches where *hornos castellanos* are deemed to have been located to the left of c) Furnace Area A corridor, to the right of which d) the vaults of the proposed storage areas for salt and copper sulphate. Photos 4-19 a) and b) courtesy Mr. Josue Soto Samperio.

Figure 4-20. Extant chimney stacks, date unknown, but similar in location and shape to two of the five depicted in Figure 4-14.

I have also found engineering drawings for kettles used at Regla and designated as '*ollas para dissolver la plata*', kettles to dissolve silver, dated the year 1880. These would have been used to melt the spongy silver and then to ladle it into moulds.

I have not found a detailed description of areas FA, SA1 and SA2 from a visitor to Regla. In particular, area SA2 would have stored or manipulated much of the wealth generated at Regla, in the shape of mercury, silver amalgams and silver from the *capellinas*, so it may have been off-limits in any case to the visits by the tourists of the nineteenth century.

4.3.5 Furnace Area B

Smelting of lead-rich silver ores from Zimapán had been carried out since the 1770s at Regla, most probably using *hornos castellanos* in the location described in the previous section, Furnace Area A. The third Conde de Regla stated in the journal entry for his visit in 1810 that at the time there were eight smelting furnaces still in place, though unfortunately he does not state where.[599] This is important to point out, to avoid the impression that smelting was introduced at Regla by the English investors in the 1820s. By the time they arrived in the area in 1824 'all the machinery in the large reduction works, formerly employed for extracting silver from its ores, was gone'.[600] It is also true that the Europeans came with smelting firmly in their plans. By 1826, when Ward visited Regla, he was able to report 'a number of furnaces for smelting' already functioning, though it is a pity he was not more specific on the technicalities of the same.[601] In the notes written in 1824 by the person who would be the General Manager of the Adventurers in the Mines of Real del Monte until its dissolution, John Taylor, he lays out his ideas regarding the furnaces to be used in Mexico for smelting: 'by a better application of fuel either in good reverberatory furnaces, or in the blast hearths used in the north of England, the silver ores may be smelted with a certain quantity of lead'.[602] I have not been able to establish the exact year of installation of the blast furnaces in Furnace Area B. Events on the ground soon changed the plans of the Company, for which I quote at length from Randall:

'Once it was clear ... they could not make a rapid and dramatic change from amalgamation to smelting as the sole method for ore reduction at Real del Monte ... [the company decided to] operate patio amalgamation plants at both the Regla and Sanchez *haciendas* ... [and] pressed ahead with efforts to construct a superior smelting establishment at the Regla mill ... John Taylor ... reporting to the June 1831 stockholder's meeting : "I believe that this important branch of economy is more advanced [at the Regla mill] than in any other part of Mexico" ... accordingly, blast machinery, intended to put more smelting furnaces into operation at the Regla mill, were purchased in England and dispatched [to Mexico in 1833, 1834]'.[603]

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599 Terreros, "El condado de Regla en 1810," 110.
600 Buchan, *Report Real del Monte*, 38.
601 Ward, *Mexico*, II 140.
602 Taylor, *Selections from Humboldt*, xiv.
603 Randall, *Real del Monte*, 111-12. The text quoted from Randall correlates well with a letter dated 21st March 1834 where R. Mackenzie at the headquarters of the company in Real del Monte, after consultation with John Rule, disregards the doubts raised by A. Mackintosh at Regla on the wisdom of extending the smelting facilities at Regla, since equipment had already been purchased and labour force assigned. AHCRMyP, Sección: Correspondencia, Serie: Compañía a Varios, Subserie: Correspondencia General, 33-11: 20 Marzo 1834 – 20 Abril 1835.

Just one year later, in 1835, Commissioner John Rule would begin the change in strategy from smelting to amalgamation, arguing for a rehabilitation of the San Antonio *hacienda* in order to achieve sufficient refining capacity, or "*hacienda* power". 'Smelting would not again be considered the technical key to success for the Real del Monte Company'.[604]

According to the 1849 inventory, at the time Regla was returning to Mexican ownership, the contents included a 'foundry with ten furnaces, iron-cylinder blast powered by water; capable of smelting from 27 to 30 t per week ... [and a] four-cylinder engine to provide blast for furnaces'.[605] It would seem that both water and steam engines had been used to provide the blast for the furnaces. By 1851 Regla was running its own Mexican version of the dark satanic mills of the English Industrial Revolution:

'Mr. Bell conducted us to the great smelting works of Regla, which were at the time in actual operation. The vault or cavity into which a row of huge furnaces disgorged their contents, was about two hundred feet in length, and eighty to a hundred in width, smoke-dried, black and rough. The scoria from the ores came out of the furnaces, in soft, ductile cakes; and as they gradually cooled, they were thrown on heaps of now vitrified masses, misshapen and strange in their conformations. To look into the heated furnaces, would have been something terrific to such as had not visited our own manufacturing districts, more particularly those of Staffordshire.; and, adding the blackened visages of the workmen, with their long iron implements for handling the glowing materials of their Vulcan-like home; the scene was one of almost satanic grandeur'.[606]

In the 1855 report by Buchan, he makes reference to 'the smelting works of Regla, with a powerful cylinder blast, and eight high furnaces'. In a table he adds to these eight furnaces another two refining furnaces in the list of infrastructure for smelting.[607] At present only six

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[604] Ibid., 112-14.
[605] Ibid., 219.
[606] Robertson, *A Visit to Mexico*, II 224-225. The dimensions correspond to the areas designated as FB and CBII in Fig. 4.7.
[607] Buchan, *Report Real del Monte*, 9, 13.

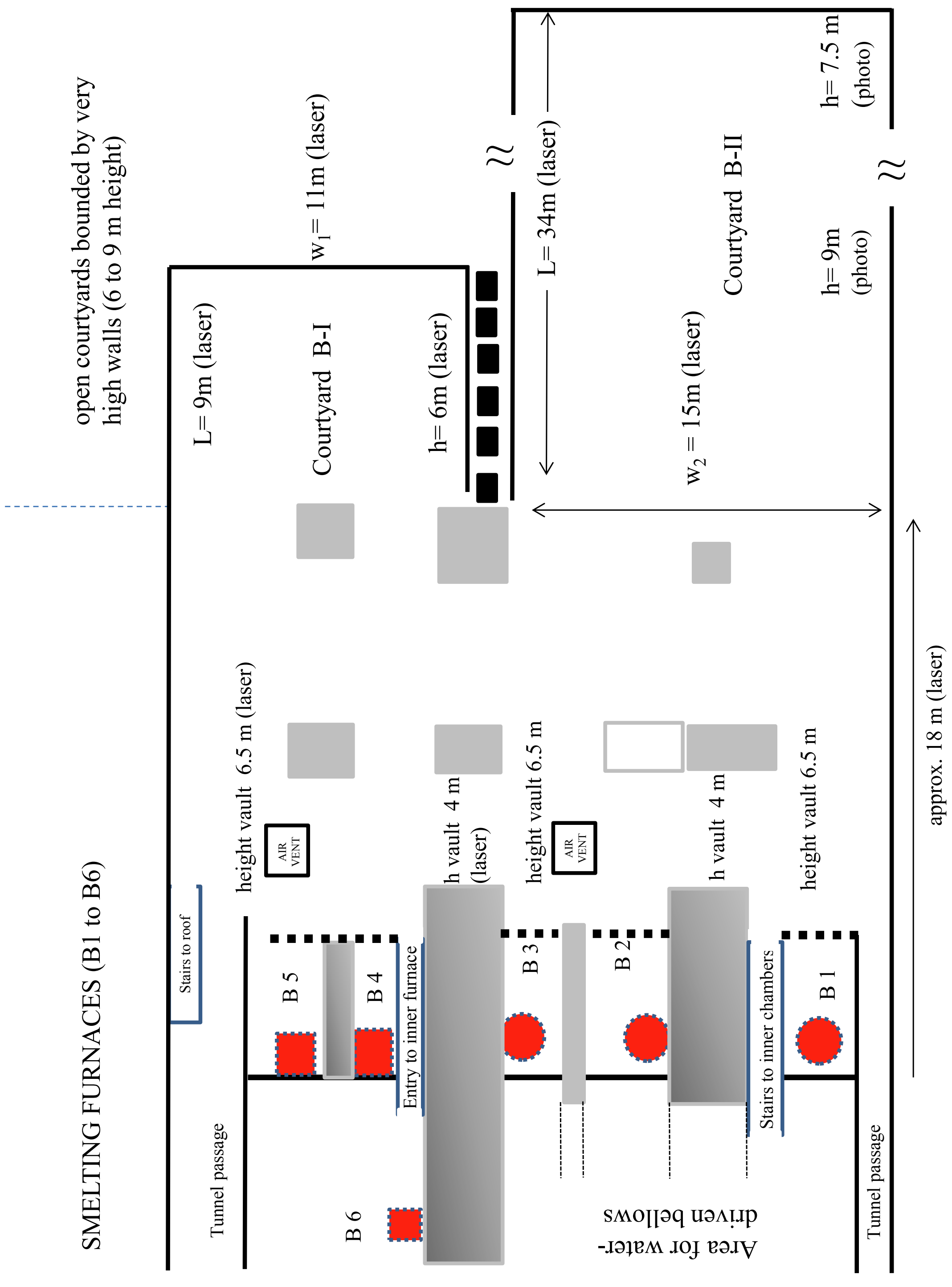

Figure 4-21. Plan of Furnace Area B, floor level including courtyards.

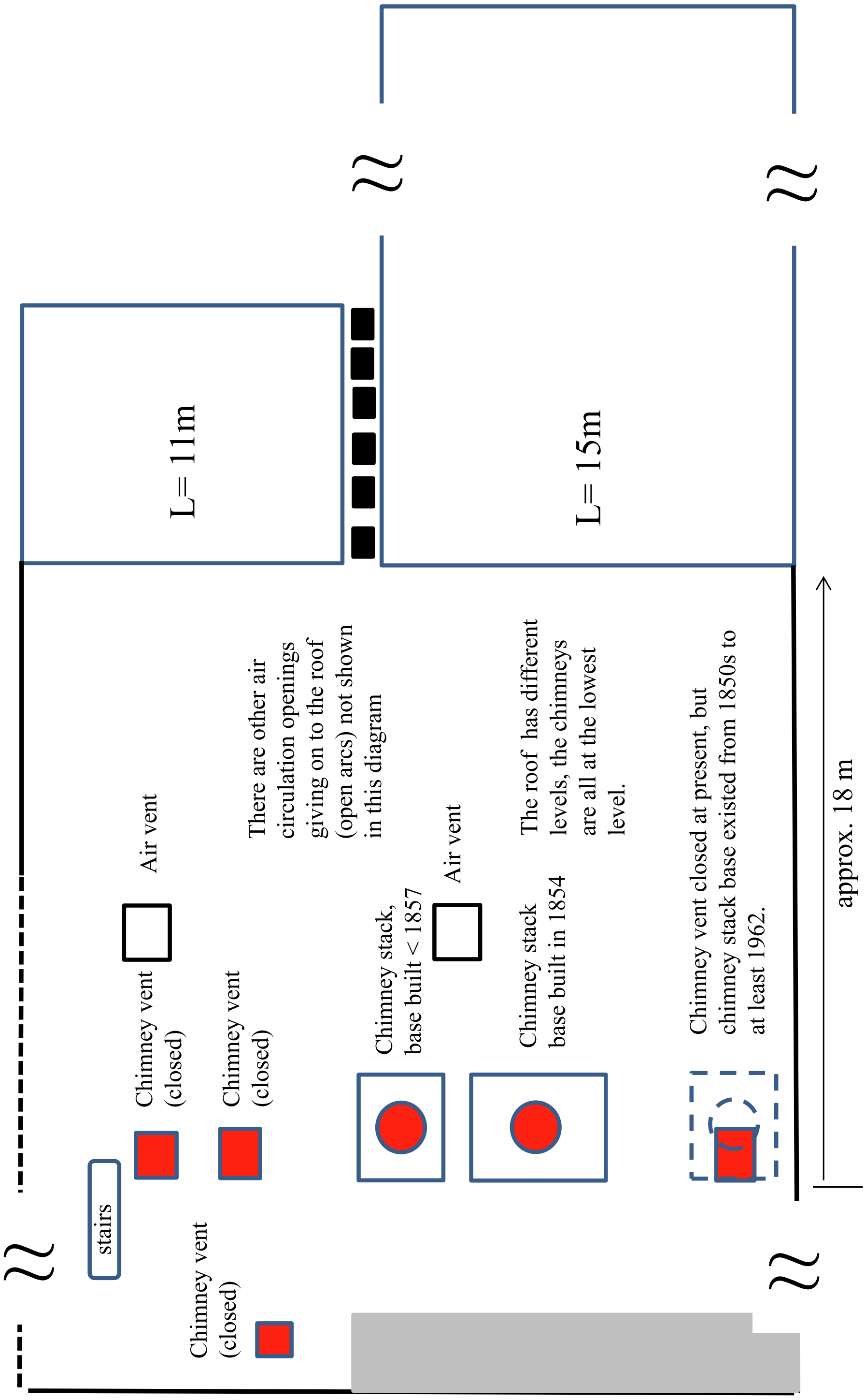

Figure 4-22. Plan of loading floor of Furnace Area B, at present without a roof.

remains of high furnaces are found in the area I have designated as Furnace Area B.[608] At present this area is designated by the term '*hornos ingleses*', English Furnaces, but the documents detailing the reasons for installing the new blast furnaces at this location in the hacienda have not yet come to light. Figure 4-21 and 4-22 are a plan of Furnace Area B, floor level and loading floor level, as measured by the author on-site.[609] It comprises a lower level vaulted area where the furnaces, cylinder air blasting equipment and storage rooms would have been located. In contrast to the other five, furnace B6 lies within a closed internal chamber, its dimensions as yet undetermined.[610] The other five furnaces (B1 to B5) give onto walled-in open courtyards, and are all covered by a roof that served as an upper-level loading area as well as providing an outlet for air vents and skylights. Since the present roof was the loading floor for the charge on each furnace, it is very probable there was originally a provisional roof structure over the load floor to provide a round-the-clock working environment.

The spacing of the furnaces complies with the observation by Iles that blast furnaces should be set not less than 1 m apart to avoid crowding the operations around them.[611] The five accessible furnaces present extensive damage to the lower portion of their structure, most probably due to the extraction of all components made from iron once Regla was taken out of commission in the early twentieth century.[612] Furnaces B1 to B3 were fitted under the new

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[608] The possible location of the two other blast furnaces mentioned by Buchan is unknown.

[609] Measurements were carried out wherever possible using a Bosch Laser GLR225. Where sunlight made this impossible, photographs were taken and a notebook used as scale. If none of these options was available, approximate measurements have been used either using Google Earth images or by visual evaluation of relative heights in photographs.

[610] The inner chamber where furnace B6 is located is unlit and no measurements could be taken. A photograph taken with the aid of a flash shows a furnace hearth very different from the other five.

[611] Malvern Wells Iles, *Lead-Smelting The Construction, Equipment, and Operation of Lead Blast-Furnaces, and Observations on the Influence of Metallic Elements on Slags and the Scientific Handling of Smoke* (New York; London: J. Wiley & Sons; Chapman & Hall, 1904), 80.

[612] According to the description by Iles of nineteenth century blast furnaces, iron plates or jackets covered a major portion of the lower surfaces of blast furnaces, in the form of water jackets that reached up to nearly 2 m in height, crucible plates, iron floor plates around the outside of the furnaces and cast iron binding rods. Ibid., 39, 54-55, 60, 80. Residual silver may also have been sought in the materials extracted from the furnaces.

Mexican ownership with a pyramidal chimney stack and loading aperture. These brick chimney stacks for furnaces B2 and B3 still stand at present, though it is unknown if their height was adjusted during the second half of the nineteenth century (Figure 4-22). I can state that furnace B1 had a similar configuration as B2 and B3 because the visual evidence supports the presence of a third stack as early as mid 1850s and still existing in 1962.[613] From Landesia's painting it is clear that the Mexican company did not install similar stacks for furnaces B4, B5 and B6.[614] This may reflect a decision not to invest in such structures if the level of smelting output after the 1850s did not justify it. I have seen no evidence for flue-ducts to capture the lead fumes coming from the smelters, as was already the custom in England since the eighteenth century, or of bag-houses as were installed in similar smelting facilities in the U.S. by late nineteenth century.[615] Finally, close to Furnace Area B there should be an area reserved for the waterwheel that drove the blast iron cylinders, but this space I have not been able to identify.

The second major furnace operation carried out at Regla was the cupelling of the silver-rich lead obtained from the blast furnaces. The observations from a visitor to Regla in the 1850s confirms the use of a reverberatory furnace for this stage:

> 'The mass of molten lead and silver is drawn off, and placed in a large oven with a rotary bottom, into which tongues of flame are continually driven until the lead in the compound has become once more oxydized, forming litharge, and the silver is left in a pure state. A little beyond the furnace is a series of tubs, built of blocks from broken columns of basalt [the arrastres]'.[616]

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[613] A photograph of Regla taken in 1962 shows the third stack, Calderón de la Barca, *Life in Mexico*, 578.
[614] This assumes the date 1854 refers to a completely new structure, and not the rebuilding of stacks built by the English.
[615] As discussed in Chapter 2, the presence of lead in the fumes was well known in England in the nineteenth century, and flue systems attached to lead smelting furnaces existed in Derbyshire as of the late eighteenth century, as reported in Willies, "Derbyshire Lead Smelting," 13-14.
[616] Wilson, *Mexico and Its Religion*, 366.

a

b

c

d

Figure 4-23. a) Blast furnaces B2 and B3, h = 4m and w = 6m; distance from hearth front to front furnace wall: ~2 m, distance to exposed back furnace wall: ~2.7 m. b) trough in front of furnaces, possibly for water. The photo was taken in March 2013. By November 2014 this trough had been demolished as part of alterations underway in this area by the hotel c) furnace stacks, with opening to charge the furnace; the left stack is taller, notebook in lower corner served as scale for photo measurements, strong sunlight precluded laser measurements d) right hand stack was built in 1854.

This would be the cupelling furnace for *afinación*, distinct from the blast furnaces, mentioned by Buchan in his listing of 1855. The statement that 'a little beyond the furnace' lie the *arrastres* can be interpreted in two ways: either the cupelling furnace for the silver-rich smelted lead was situated in Furnace Area A, or it was placed within the building with a smoking chimney to the east of the Church as shown in Landesia's painting (Figure 4-24). It communicates with the area of the blast furnaces through indoor passages and is isolated from the open *patio* area by a high wall. The high lintels would indicate either increased air circulation or the manipulation of equipment requiring a high overhead clearance. Finally, the fact that 'poor' lead is mentioned as being sold at Regla during the period when smelting was carried out raises the question as to how, and where, this silver-poor lead was produced. The Pattinson process had been introduced in England in the 1830s as a means to enrich the lead from the smelter prior to cupellation, while at the same time producing a 'poor' lead that could be sold.[617] If the Pattinson process was not used, then silver-poor litharge had to be reduced in a reverberatory furnace. The English historian David Cranstone makes the distinction in the refining of silver in England between 'a cupellation furnace [and] the more sophisticated processes such as Pattinson's or Parkes', which would surely be used in any new mid 19th century silver refinery'.[618] The exact location for either of these two processes within Regla remains to be established.

To the north of the row of blast furnaces of Furnace Area B were located two courtyards, one small and enclosed, B-I, the second one much larger and on two levels, B-II. Both were surrounded by walls that measured up to 9 m in height (see Figure 4-25). The height

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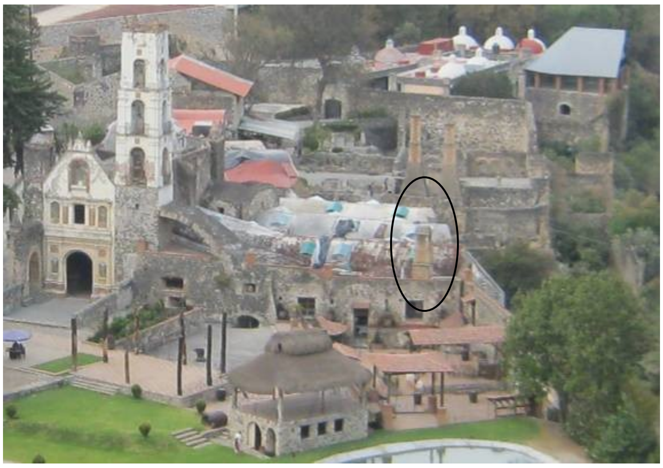
617 For details on the process, see Percy, *Metallurgy of Lead*, 121-148.

618 David Cranstone, "Excavations at Old Gang Smeltmills: an Interim Report," in *Boles and Smeltmills: Report of a seminar on the History and Archaeology of Lead Smelting*, ed. Lynn Willies and David Cranstone(Reeth, Yorkshire: Historical Metallurgical Society, 1992), 29. Since none of the account books mention the purchase of zinc, I have ruled out the option that Parke's process was used at Regla.

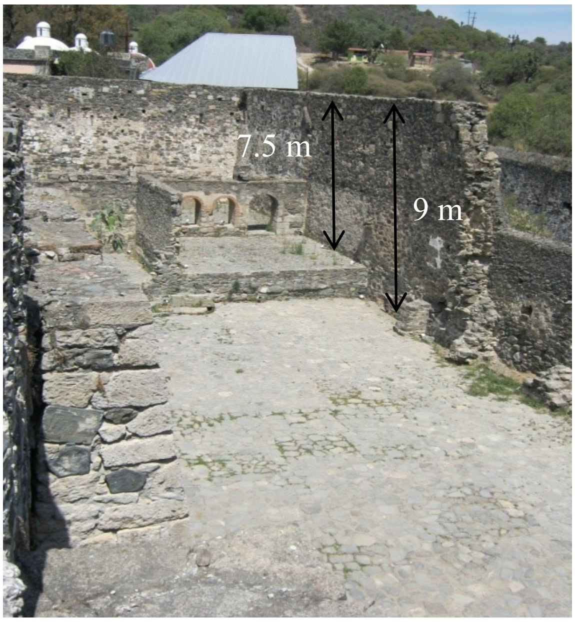
a



b

Figure 4-24. a) Detail of Landesia's painting of the *Hacienda* de Regla in 1857, showing the presence of three stacks in Furnace Area B. The single chimney in the foreground is assigned to reverberatory furnaces b) probable location of same chimney stack in modern Regla.

of these walls means that fugitive emissions of lead in this area would tend to be trapped in these courtyards. The apparent defensive nature of these walls may reflect that the ore with the highest silver content was kept in this area. Between courtyard B-II and the outer perimeter wall lies an area that I have very tentatively assigned to animal pens or to store fodder and other general materials in use at Regla (see Figure 4-7). By November 2014 the space corresponding to Courtyard B-II had been transformed into modern bathing pools and toilets, and the crenelated wall measuring 6 m in height shown in Figure 4-25 had been half demolished, in a process of further adaptation of this historic hacienda into a hotel.



b

a

c

Figure 4-25. a) Courtyard B-I. This photo was taken in March 2013. By November 2014 this crenelated wall no longer exists, having been half demolished in alterations being carried out by the hotel b) Original view in March 2013 of Courtyard B-II. By November 2014 the area has been converted to a set of pools and toilets c) View of courtyard B-II from vaulted furnace area. Photo taken in March 2013. In November 2014 this arch was being filled in using stones from the demolished interior walls

4.3.6 Final comments on the architectural layout of the *Hacienda* de Regla

The Church at Regla remains one of its iconic features, its buttressed facade hopefully having provided some blessing to the hard labour of the workforce. Just to the west of the Church the housing of guests took place in the tall building with a corridor (see painting by Rugendas, Figure 4-8). The height at which the living quarters are perched gives it a modern look. The corridor facing the rooms provided an excellent viewpoint from which to oversee the operations in the *patio* area:

'We lean over the balcony of our hospitable quarters, awaiting breakfast, and see the horses tread out the silver. A yard eighty rods square, *poco mas y menos*, is laid down to this work ... beds of black mud are located over it ... two hundred horses are engaged in tramping out the silver. Their tails are shaven, the mud has splashed up to their heads and backs ... they look ... as if their labor were degrading ... eighty of these march round one circle, five abreast ... over three hundred and fifty are owned by the company, and sometimes all of them are put into service at once'.[619]

If the work was deemed degrading for the horses, no similar sentiment is expressed as regards the local workforce. According to Ward the English investment of the 1820s in Regla covered 'stabling completed for 500 mules and horses'.[620] By the late nineteenth century the number of horses and mules dropped to around one hundred, with a monthly mortality rate of around 5%.[621] Animals, fodder and secondary materials would all be kept within the perimeter of the *hacienda*, as well as areas for iron-working and carpenters, but their exact locations have not been identified. It is possible that orchards also occupy some internal spaces, judging from the anonymous painting in Figure 4-14. A fresh-water source, uncontaminated by the

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619 Haven, *Winter in Mexico*, 155.
620 Ward, *Mexico*, I 424.
621 Informe Mensual Regla, 29 Jun 1872 – 27 Oct 1888.

operations of the *Hacienda*, would also have been required. The cluster observed at the most northern tip of the *hacienda* comprises at least five circular structures capped by cupolas, but their function and date of construction have not been identified.

4.4 The mass balance of the amalgamation process at Regla, 1872 to 1888

The main archival source for the data on consumption of materials and production of silver at Regla for this chapter is the single tome accounting ledger that registers the mass consumption of materials and production of silver by month, the *Informe Mensual Hda. Regla, 29 Jun 1872 – 27 Oct 1888* (hereon referred to as *Informe Mensual*). The ledger identifies each *torta* with a number, states the origin of the silver ore according to the mine it was extracted from, registers the quantity of each type of ore that is treated in each *torta*, the initial silver content of the ore that makes up each *torta*, the amount of silver extracted from each *torta* or from each of the ore components of the *torta,* the corresponding percentage loss of silver, and the consumption of mercury per *torta* or per ore component of the *torta,* and at times the consumption of copper sulphate. The amount of data cover a fifteen year interval, though the year 1874 was found to have been subject to major interruptions in production, to the point of making it non-representative of the period.[622] In total this represents a sample of 180 monthly data sets from which a representative average can be derived for the most critical parameters of the amalgamation process. I have not come across any similar set of published results in the historiography of silver refining in Mexico or Peru up to the nineteenth century.

The raw accounting data, once checked for evident mathematical errors at source wherever possible, are used to construe a mass transit profile on a monthly timeline for the amalgamation process, both on an absolute and a relative basis using as common denominator

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[622] see Appendix B. The reasons for the atypical behaviour in 1874 is discussed in Chapter 5.

the production of one kilogram of silver. This profile is required to estimate the environmental impact of the process as a consequence of solid, liquid and air emissions.

The time series on the inventory carried by Regla of the main materials required for the process are reported in Appendix C, together with the assignment of spaces based on inventory levels. The way the inventory was handled also provides insights on how the operational management coped with the challenges of supply and forward planning of operations. The numbers in the following sections define a very busy hive of physical activity, sounds and emanations, day and night, converting mountains of ore into small silver bars whose final volume paled into insignificance in the light of the tonnage of waste that every month was dispersed into the environment.

4.4.1 Silver ore received for amalgamation.

The most important solids handling operation at Regla revolved around the amalgamation process. Figure 4-26 shows the monthly amounts of ore received at Regla from the mines in the Real del Monte area and earmarked for amalgamation. It is virtually identical to the total sum of ores received at Regla. Among the mines that supplied silver ore to Regla during this period were Guatimaztin, Dificultad, Aguichote, Jesus Maria, Moran, Rosario, Porvenir, Sta. Ines, Sta. Brigida, Viscaina, Perro, San Genaro and Milanesa.[623] Most of the ore came from mines owned by the Compañia Real del Monte, though at times silver ore was classified as '*ajeno*' [belonging to another], indicating that tolling was carried out. Ores from the same mine show a wide range of silver content. No information is provided in the accounting ledger as to the nature of the silver minerals in the ore.

[623] No attempt has been made in this analysis to calculate the amount and quality provided by each mine, and the silver produced, though this information can be gleaned from the data in the ledger and from other primary sources at AHCRMyP.

The average supply of total ore to Regla in this period was of 7,304 *cargas* per month (1,008 t/m), of which an average 7,175 *cargas* per month (990 t/m) were milled for amalgamation. The profile of deliveries over time shows a marked negative correlation in the time series, a reflection of the contingent nature of a total mine production distributed over different refining *haciendas* at the discretion of a central management.[624] This average and the whole time series in Figure 4.26 lies below the level indicated by Ward for Regla at the end of the eighteenth century, when he claims 'in 1795 five thousand cargoes of ore were received there weekly', though it is probable that he may have just been repeating an exaggerated claim.[625] The average inventory of raw ore for the period is 5,091 *cargas* (703 t) per month.

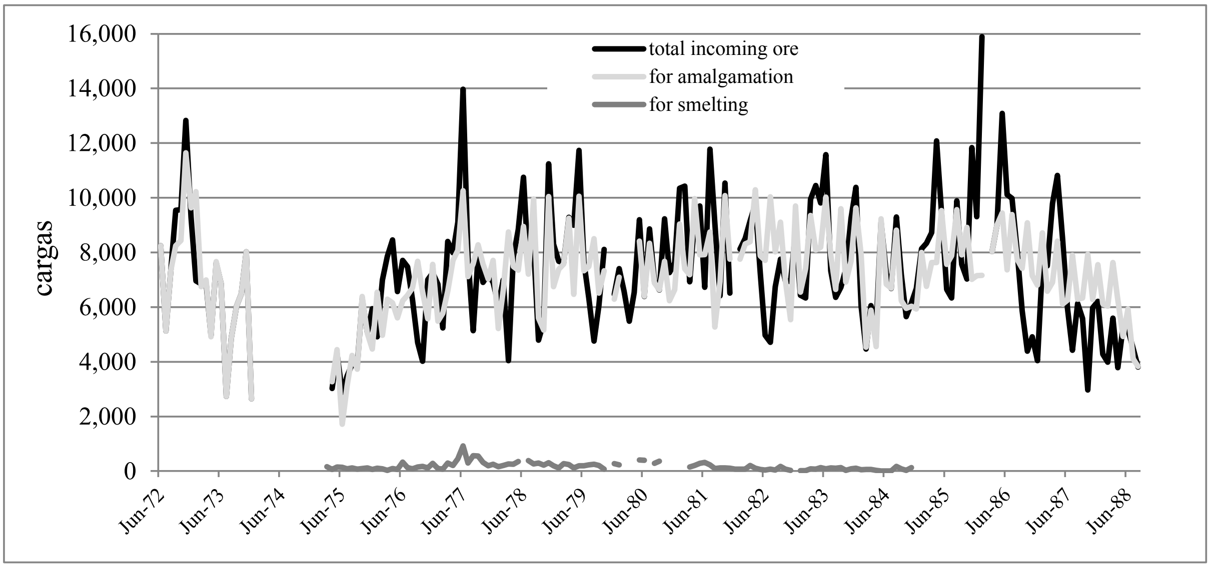

Figure 4-26. Monthly deliveries of raw ore to Regla. Data adapted from *Informe Mensual.*

[624] Negative correlation is the term applied to a sequence of high and low consecutive values within a time series, or in more colloquial terms, the spikiness of a plot.
[625] Ward, *Mexico*, II 140-41. Average silver production from Regla was higher over 1872 to 1888 than the average amount of silver registered by the first Conde de Regla prior to 1795.

4.4.2 Milling of silver ore destined for amalgamation.

The raw silver ore destined for amalgamation was processed through the stamp mill and the *arrastres* at an average monthly rate during this period of 7,239 *cargas* (999 t), as reported in Table 4-I.[626] In an era without electric power it is interesting to determine if water supply was assured year-round or if the dry season (November to February) had an operational impact on Regla, which did not use animal power to drive its *arrastres*.[627] 'Water in all new mining countries is an exceedingly uncertain reliance, and a mill depending on it alone will generally lie idle from a quarter to half a year'.[628] This was not the case at Regla. There is no evident correlation between monthly grinding output and the month of the year over the period under analysis, as seen in Figure 4-27. The data show that the location of Regla was well justified by offering a reliable source of hydraulic energy year round. The data in Table 4-I also underline the operational flexibility shown by the milling units, since the values range from a minimum of 1,714 *cargas* (237 t) in June 1875 to a maximum of 11,650 *cargas* (1,608 t) registered in November 1872. In modern industrial terms, a turn-down capacity of one seventh the maximum output for a batch processing plant is not common and represents a great operational advantage to any production unit.

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[626] 11% is the additional solids content from the erosion of the *voladora* stones in the *arrastres* of Regla according to Laur, "De la metallurgie de l'argent au Mexique," 112. I have not made any corrections to the accounting data since it does not include information on the erosion rate of the stones with which to cross-check Laur's figure. An error of at least plus or minus 5% should be assumed for all mass data.
[627] The impact of climate on monthly production of silver in New Spain is also explored in Bernd Hausberger, *La Nueva España y sus metales preciosos* (Frankfurt am Main: Vervuert, 1997), 113-25. Since his analysis is centred on the amounts of silver registered at the regional *Cajas* (Treasuries), where factors such as distance from refining centres, travel conditions, working hours of the *Caja* and other factors come into play, there is no direct comparison between his data and the behaviour presented in this section for Regla. It is significant that in his opinion 'for our purposes it would be more useful to have analyzed the accounts of a refining hacienda. Unfortunately I do not have at hand such an account' - '*para nuestro propósito seria de mayor utilidad el análisis de las cuentas de una hacienda de beneficio. Desafortunadamente una cuenta de ese tipo no tengo a mi disposición*'. Ibid., 135.
[628] Egleston, *The Metallurgy of Silver*, 442.

	1872	1873	1875	1876	1877	1878	1879	1880	1881	1882	1883	1884	1885	1886	1887	1888
Jan		10,228		6,546	5,482	5,214	7,388	7,096	9,039	7,759	6,552	7,916	8,000	7,157	8,715	6,117
Feb		6,751		4,971	5,780	6,616	7,579		7,392	8,315	7,409	4,529	6,755	5,755	6,582	6,033
Mar		6,990		6,292	6,583	8,749	9,253	4,439	7,179	8,387	9,355	5,882	7,626	8,032	6,907	7,633
Apr		4,919	3,276	6,160	7,713	7,486	6,468		9,970	10,295	8,094	4,556	7,627	9,012	8,410	6,265
May		7,664	4,440	5,602	8,076	7,348	10,061	8,417	7,915	7,872	8,196	9,225	9,538	9,445	6,108	4,922
Jun	8,244	6,862	1,714	6,238	10,265	8,950	7,327	6,400	7,918	7,705	10,027	6,842	7,569	7,365	6,256	5,934
Jul	5,129	2,739	3,123	6,432	7,115	7,202	7,483	8,331	8,753	10,036	7,894	6,695	7,880	9,382	7,905	4,114
Aug	7,337	4,860	4,234	6,700	7,587	9,960	8,507	6,885	5,269	8,022	6,647	8,820	9,570	7,741	6,286	3,830
Sep	8,241	6,022	3,734	7,681	8,283	5,599	6,508	6,640	6,942	9,102	9,599	6,234	7,907	7,421	6,330	
Oct	8,438	6,493	6,390	6,554	7,577	5,162	7,325	7,677	10,085	6,977	6,919	5,957	8,921	9,082	7,935	
Nov	11,650	8,020	5,040	5,579	7,023	10,049	9,017	6,236	7,759	5,535	7,672	6,028	7,014	7,154	6,273	
Dec	9,631	2,643	4,463	7,566	7,712	6,752	6,295	6,639	9,940	9,698	9,633	5,927	7,156	6,809	7,553	
max	11,650	10,228	6,390	7,681	10,265	10,049	10,061	8,417	10,085	10,295	10,027	9,225	9,570	9,445	8,715	7,633
min	5,129	2,643	1,714	4,971	5,482	5,162	6,295	4,439	5,269	5,535	6,552	4,529	6,755	5,755	6,108	3,830
monthly average over period = 7,190 cargas																

Table 4-I. Monthly amounts, in *cargas*, of ore ground for amalgamation. Raw data from *Informe Mensual.*

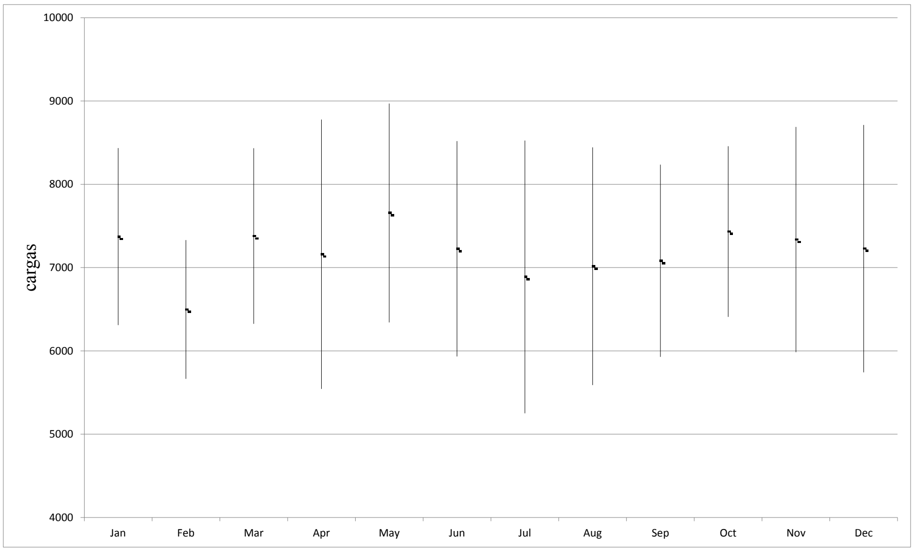

Figure 4-27. Average monthly values and standard deviation of ground silver ore destined for amalgamation, in the period mid 1872 to mid 1888. Data calculated from Table 4-I.

Once the raw silver ore was ground in the stamp mill and in the *arrastres*, the average monthly inventory over the whole period was 6,405 *cargas* (884 t) of ground ore. There is no indication of major interruptions after 1874 up to 1888, and overall it shows a regular operation. The level of inventory covers nearly one month's milling production (see Table 4.I), which would cover for short-term maintenance shut-downs or interruptions in the reception of raw ore.

What do these levels of output say about the stamping capacity at Regla? The daily milling capacity per stamp at a stamp-mill in the U.S. in the nineteenth century is said to 'generally be from one to four tons per stamp in twenty-four hours, depending upon the character of the rock and the weight and velocity of the stamp [and whether it is dry or wet stamping]'.[629] Assuming that the same 30 stamps reported in 1855 were still the number operating in the 1870s (a major assumption), they would have needed to process over one ton per stamp per day. Taking into account maintenance down times, an installed capacity of 2 t/d would have allowed them to work at around 60% of total installed capacity, which seems a more viable level. Based on these figures, each *arrastre* at Regla would have needed to process a daily average of up to 10 *cargas* of ground ore (1.34 t) discharged from the stamp-mills. This is a higher output from *arrastres* than the generic 9 quintales per day (0.4 t) mentioned by Hermosa, but it is difficult to compare without knowing the mesh size of the ore being fed to the *arrastres*, the hydraulic energy employed and the weight and nature of the *voladora* stones employed.[630] *Arrastres* with a 10 ft diameter (~ 3m) as in Regla were said to be able to grind 1 t/d if operated on a continuous 24 h basis.[631]

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[629] Ibid., 184, 185, 187.
[630] Hermosa, *Manual de Laboreo de Minas*, 199. 1.5 to 3 m is the diameter given in Laur, "De la metallurgie de l'argent au Mexique," 111. Hermosa's output coincides with that of Humboldt, who in addition states that *arrastres* had a diameter between 9 to 12 m, though his dimensions for *arrastres* do not match most other sources. Humboldt, *Essai politique*, Tome IV, 58. A discussion on milling equipment in use at the end of the nineteenth century for silver refining in Nevada can be found in Donald L. Hardesty, *Mining Archaeology in the American West: A View from the Silver State* (Lincoln: University of Nebraska Press, 2010), 64-69. It focuses on how the colder weather of Nevada required heating of the amalgam in pans, and shows how the physical structures of milling and amalgamation had evolved prior to the introduction of the new cyanide process.
[631] Egleston, *The Metallurgy of Silver*, 24.

4.4.3 The amalgamation *tortas* (cakes).

Once milled in the *arrastres*, the next step was the preparation of the *tortas*, the cakes which required the mixing of the ground silver ore with water to make a slurry, together with added salt, copper sulphate and mercury. Figure 4-28 indicates a very coordinated process, with a match within 1% between the monthly amounts of ore ground for amalgamation, and the amount processed by amalgamation each month. The monthly average for the period is 7,166 *cargas* (989 t) processed by amalgamation.

With the exception of the year 1874, when production was seriously interrupted for much of the year, it shows from 1877 to 1887 a period of relatively steady throughput during production, the exceptions being the periods at both extremes. In 1855 the newly formed Mexican company was aiming for an amalgamation capacity at Regla capable of processing 50,000 *cargas* in a year.[632] By the 1880s the company was amalgamating over 60% more than that initial target. If the size of the *patio* area did not change, nor the quality of the ore, what can explain this major jump in output?

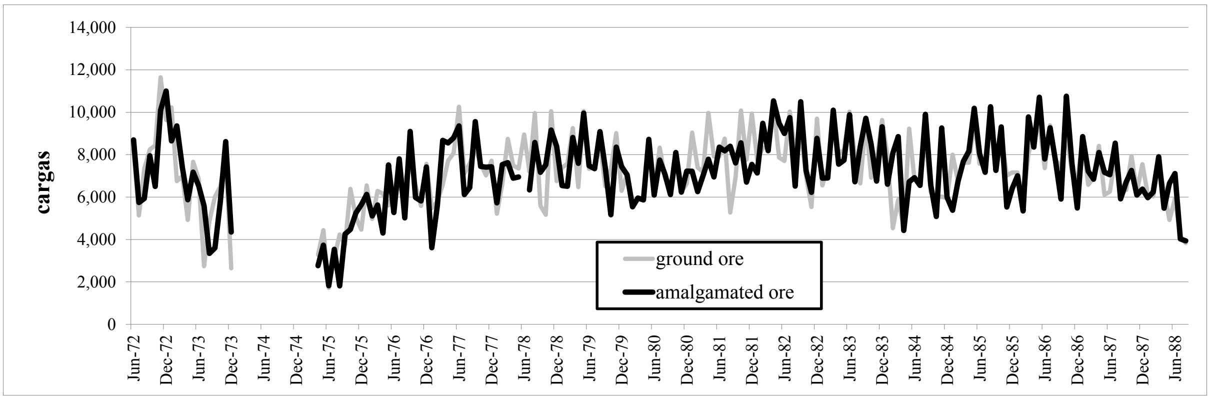


Figure 4-28. The monthly amounts of silver ore ground for and processed by amalgamation. Data from Table 4-I and the *Informe Mensual*.

[632] Buchan, *Report Real del Monte*, 9.

The output in silver of the *hacienda* is a function not only of its milling capacity but of the time it took to complete an amalgamation run for each *torta* on its *patio* reactor so as to free space for the next batch. It is fortunate that the accounting data from October 1872 to December 1873 also included the amalgamation period for each *torta*.[633] Figure 4-29 is a histogram of the days it took to complete the amalgamation runs during this period. On average it required 13 days, with some runs as short as eight days and the longest at 18 days.[634]

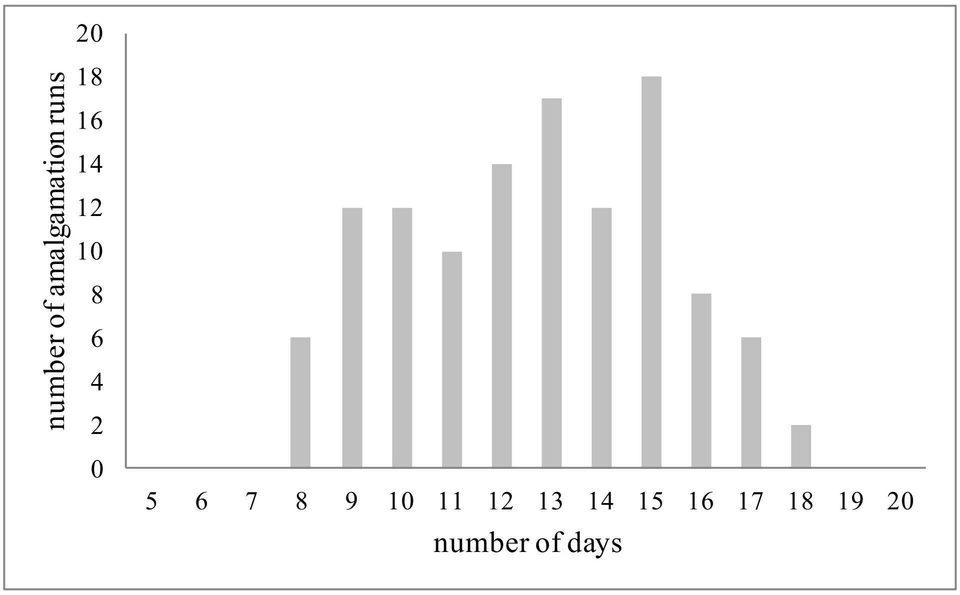
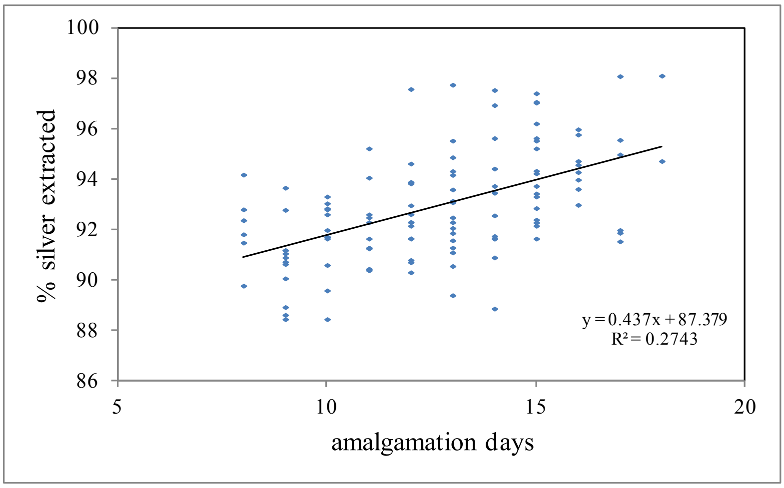


Figure 4-29. Histogram of the days required for amalgamation, as recorded over the period October 1872 to December 1873. The average amalgamation run lasted 13 days. Raw data from *Informe Mensual*.

Thanks to the accounting data it is also possible to follow the extraction of silver as a function of the time allowed for amalgamation. According to Figure 4-30 on average

[633] From 1874 to 1888 no further data are registered regarding the amalgamation days required for each *torta*.
[634] One run was recorded at 24 days in December 1873, but I have not included it in the data set, one datum point out of a total set of 118 data points.

approximately 93% of silver had been extracted after two weeks. I have plotted the raw data as a scatter graph and also as averages. The linear regression analysis gives nearly identical results



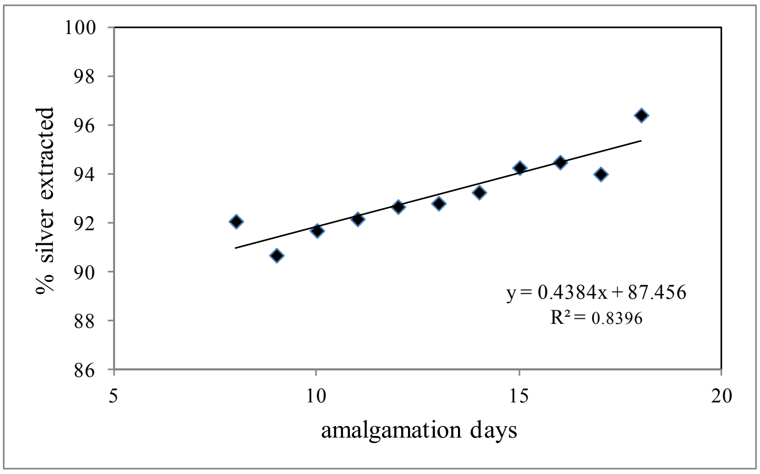


Figure 4-30. Scatter graph and plot of averages as measured at various amalgamation periods that show an evident correlation between the percentage of silver extracted and the number of days for an amalgamation run. Raw data from *Informe Mensual*.

in both cases, though the plot of averages makes it easier to visualize the correlation. If I assume that the extraction process was linear, 100% extraction of silver would occur on average after an amalgamation period of 30 days. For the moment I will ignore the real possibility that the amalgamation process is not linear throughout but becomes asymptotic towards its final stage.[635] The question is whether it made business sense to aim at 100% extraction of of silver by waiting another two weeks, or to optimize the use of the *patio* reactor by amalgamating two batches of ore within the same period of time. 93% of the silver of two batches of ore is better than 100% of silver from just one batch. The law of diminishing returns applied after a two week amalgamation period. Under a scenario of sufficient and continuous ore supply, there was little incentive to carry out the amalgamation reaction to its final conclusion.

The profile of the histogram in Figure 4-29 is a reflection of this operating strategy as carried out in the 1870s, but it was not always the case at Regla. In 1855 Buchan reported that 'amalgamation lasts from thirty to fifty days'.[636] At some point in the intervening years the operators at Regla had realized it made little economic sense to wait beyond the two week period, and this explains the increase of over 60% in the amount of monthly amalgamated ore, assuming all other operating variables were kept equal.[637]

Among the advantages of the *patio* process was that instead of using a batch reactor of fixed capacity, like a barrel, the slurry was spread out into one or more *tortas* of whatever size was needed. The amount of silver ore processed in each *torta* thus varied widely, and constituted the operational flexibility of this process. Figure 4-31 shows the histogram of the

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[635] Data already reported in the nineteenth century point to an asymptotic extraction rate for silver during patio amalgamation, see Laur, "De la metallurgie de l'argent au Mexique," 157-58.

[636] Buchan, *Report Real del Monte*, 9. The patio process has been criticized both by its contemporaries and by later historians for the long periods required to complete the extraction of silver from the ore. The data from first-hand observers indicate a process taking weeks, in some special cases up to two months, and then only subject to the difficulty of the ore to be amalgamated. For example, 8 days to more than 2 months, in Dominguez de la Fuente, *Leal Informe Politico-Legal*, 93.; 8 days to 2 months, Sonneschmidt and de Fagoaga, Tratado de la amalgamación de Nueva España, 32.;18 to 60 days in Duport, *Métaux précieux au Mexique*, 267.;10 to 25 days, according to the nature of the ore, ambient temperature and degree of mixing during amalgamation, in Hermosa, Manual de Laboreo de Minas, 233. Periods longer than 2 months cited in the secondary literature should be treated with caution, such as the five months cited in Humboldt, *Essai politique*, Tome IV, 66.

[637] Ruiz states that the frequency of mixing each *torta* at Regla was increased, which led to a shorter amalgamation period. There is not enough information to determine the order of factors that led to the use of a shorter turn-around time for the *tortas* in the *patio* reactor. Ruiz de la Barrera, "La Empresa de Minas del Real del Monte," 309.

size of *tortas* according to their charge of silver ore. The minimum number of *cargas* per *torta* in this period was 18 (2.5 t of silver ore), the maximum 2,059 (284 t), with an average of 753 *cargas* (104 t) per *torta*.

How many *tortas* on average could be amalgamated at Regla during one month? It ranged from one to sixteen, of different sizes, with an average of 9.4 *tortas,* indicating this patio reactor had an average capacity of one thousand tons of ore at any one time. The different amalgamation periods dictated by the *azoguero* in charge of the process, even within the limits observed in the histogram of Figure 4.28, would in time introduce a natural and unpredictable staggering of the runs.

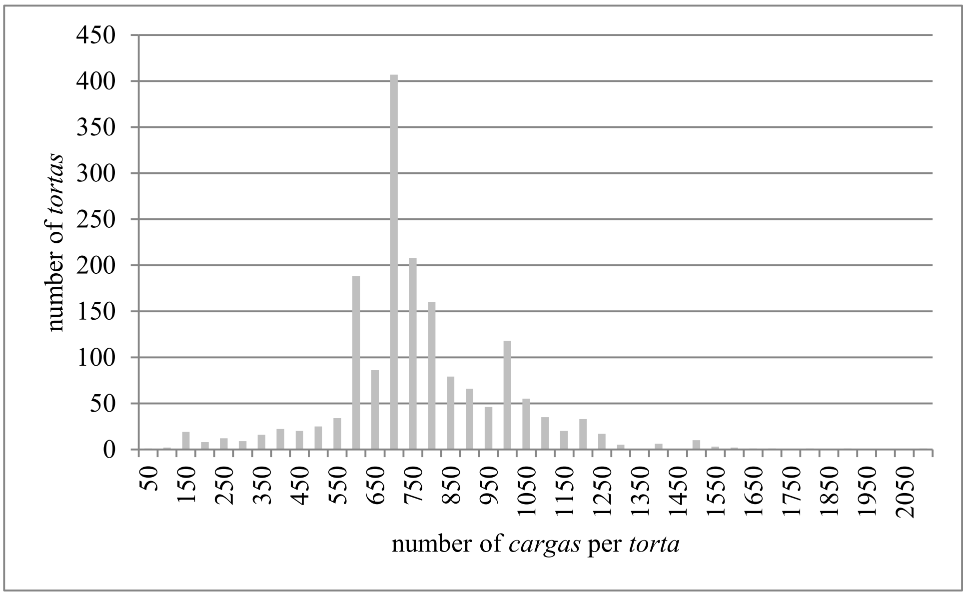

Figure 4-31. Histogram of the number of *cargas* per *torta* as practised at Regla (1872 to 1888). Source data from *Informe Mensual*.

Is it possible to relate the area of the *patio* reactor to the refining capacity of an amalgamation *hacienda*? The majority of the surviving silver refining *haciendas* in Mexico are reduced to ruins, with no or limited extant written records to provide a clue to their production. What does sometime survive to the extent of being measureable is the area of the *patio* reactor, or a close approximation to the original space. A rule of thumb can be established using the data from Regla. Taking Buchan's figure of the area of the *patio* reactor at Regla of 6,000 m^2, we have seen it process on average 1000 t of ground ore per month. Thus the processing of one ton required a *patio* reactor area of 6 m^2. Assuming a 93% extraction rate for silver in two weeks, total production can be estimated from the area of a *patio* reactor according to the following equation:

Monthly production silver in tons = 0.93 × (area of *patio* reactor in m^2 ÷ 6) × (% silver in ore by weight) × (0.5 ÷ average amalgamation period in months)

4.4.4 The silver content of ores used for amalgamation.

The accounts provide two sources for the silver content of the ores processed by amalgamation. As an example, Table 4-II is a transcription of the raw data as reported for the five weeks ending the 28th November 1885.[638] Over the whole period from 1875 to 1888 the silver content per *monton* of incoming ore can be used to prepare a histogram such as Figure 4-32, which indicates a bimodal distribution due to the overlap of two different distribution curves over the period. The average of 11.2 marks per *monton* of 10 *cargas* corresponds to 0.19 % of silver by weight.[639] The other value of interest is provided by dividing the total silver refined during these years (303,334 kg) by the total weight of ore processed by amalgamation (178,287,306 kg), in which case an average value of 0.17% is obtained. The difference

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[638] Monthly runs were accounted for in periods of either four or five weeks, and the date registered in the ledger is the last day of any such period.

[639] According to Humboldt, the silver content of the lowest quality ore from the Vizcayna vein at the start of the nineteenth century had been 4 marks per *monton*, just 0.06% silver by weight. The data from Regla place the ore quality for amalgamation in the latter part of the century above what Humboldt had classified as the second tier silver ores (0.16%): '*dans le district des mines de Pachuca ...les minerais de la seconde classe, 7 a 10 marks ... les plus pauvres, qui forment la troisième classe, ne sont évaluées qu'a 4 marks d'argent par monton*.' Humboldt, *Essai politique*, Tome III, 370. In 1882, silver ores with less silver content were being amalgamated in the United States. For example, ores with 41 ounces of silver to the ton (0.12%) were refined with mercury at Tombstone Mill, in Arizona. Egleston, *The Metallurgy of Silver*, 422.

corresponds to the amount of silver left unextracted (approximately 10%), if the values for the raw ore can be trusted (see Section 4.5.3). Furthermore, if these values of refined silver are now plotted by month over the same period, it can be observed that the percentage of refined silver decreased over the period, as seen in Figure 4-33, pointing to a lowering of the quality of the ore over time. Table 4-II also shows how varied was the mix of ores used to constitute an amalgamation *torta*, with silver contents per *monton* of some of the constituent ores reaching up to 61 marks (1 % silver by weight) in this example.

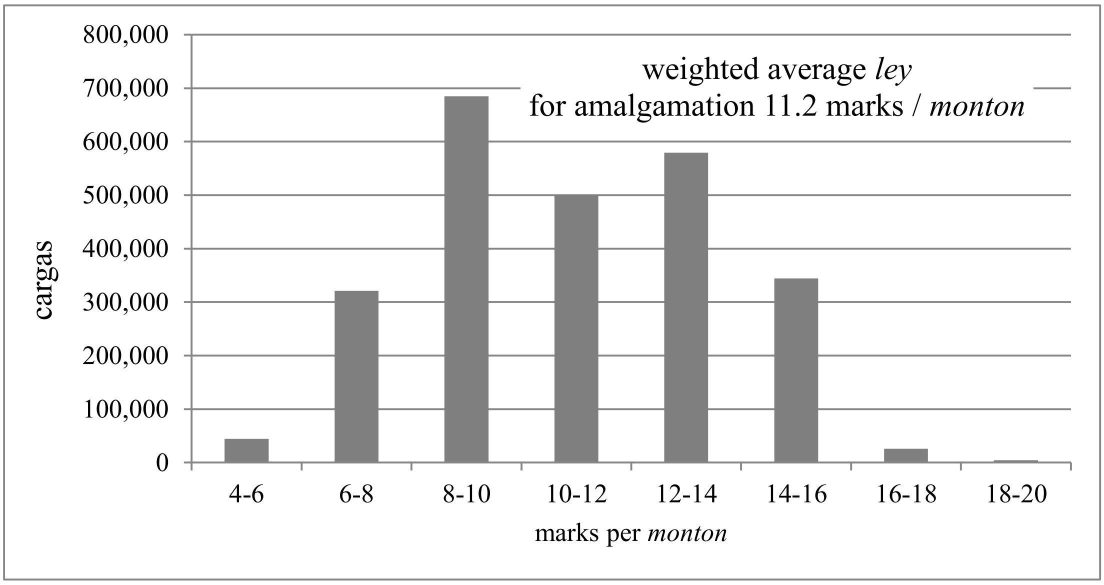

Figure 4-32. Histogram of ore quality refined by amalgamation. Raw data from *Informe Mensual*.

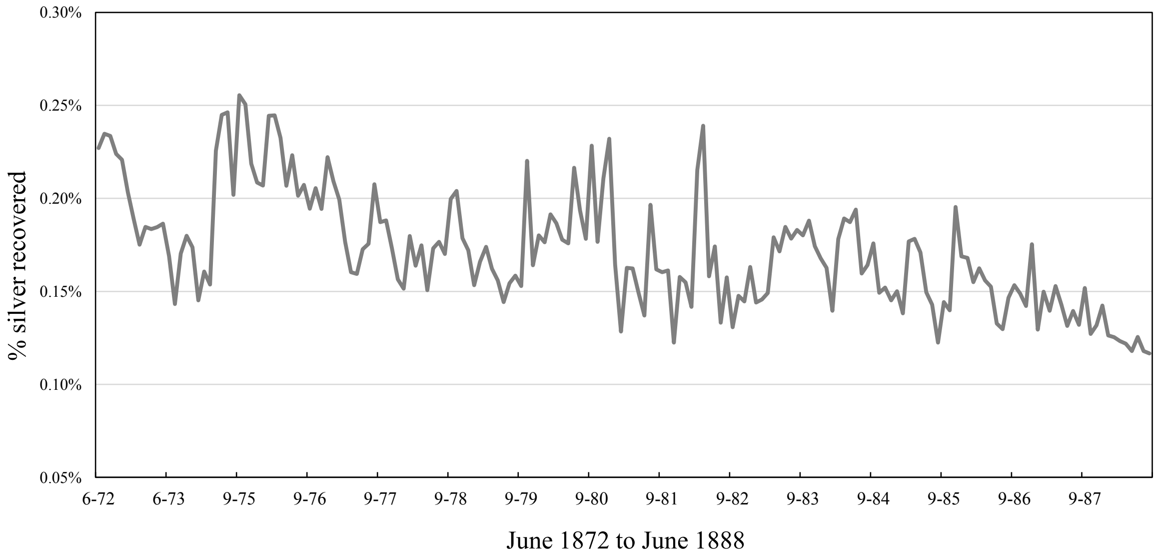

Figure 4-33. Decrease in percentage of refined silver from the ores processed by amalgamation. Percentage calculated from raw data in *Informe Mensual.*

4.4.5 Interlude: pizzas or juggling acts.

As discussed in Chapter 3, a *torta* once formed from all its ingredients would be expected to be a whole entity, an amorphous slurry subject to the constant mixing of its components thanks to the tread of humans or animals. Thus, once the seven different silver ores that comprise *torta* number 3397 in Table 4-II have been mixed with the ingredients of the amalgamation recipe, it seems an impossible task to be able to measure the specific amount of silver recovered from each ore fraction, or the specific amount of mercury losses that can be assigned to each type of ore present in the *torta*.[640] To argue otherwise would require the concept that not all *tortas* were equal, that some *tortas* could somehow be sectioned like a pizza into different ore flavours, each slice kept meticulously apart during the whole process, from wet area to refined silver, and its consumption and production data carefully accounted for at

[640] The same statement applies to detailed accounting of salt and copper sulphate consumption according to ore type in hybrid *tortas*.

Account of refined ores [*Cuenta de metales beneficiados*]												
REFINED ORES [*METALES BENEFICIADOS*]		CARGAS	SILVER CONTENT PER MONTON [*LEY POR MONTON*]		SILVER PRODUCED [*PLATA PRODUCIDA*]			LOSSES [*PERDIDAS*]				
			Crude ore [*Metal crudo*]		Total [*Total*]	Per Monton [*Por Monton*]		Of silver [*De plata*]		Of mercury [*De azogue*]		
			Marks [*Marcos*]		Marks [*Marcos*]	Marks [*Marcos*]		Percent [*Por ciento*]		Total [*Total*]	Per mark [*Por marco*]	
3397	Jesus Maria	149	8	52	117	7	85	7	87	90	14	31
	San Miguel	44	7	5	28	6	34	9	68	21	12	-
	Sta Brigida	76	31	97	223	29	34	8	23	170	12	20
	Corteza	13	10	77	13	10	-	7	14	101	12	31
	Aviadero	20	40	-	73	36	50	8	75	56	12	27
	S. Pedro y S. Pablo	16	61	87	91	56	88	8	8	70	12	31
	S. Antonio	1	50	-	5	50	-	-	-	4	12	80
3398	Dificultad	480	11	75	790	11	62	1	13	497	10	7
3399	id	827	8	-	674	8	15	*1*	*81*	437	10	37
3400	Aguichoto	730	12	25	840	11	50	4	4	569	10	84
1	Dificultad	1185	11	-	1180	9	96	9	51	821	11	13
2	Rosario	463	17	25	1018	15	35	11	11	656	10	31
3403	Guatemozin	701	15	50	1050	14	98	3	40	739	11	26
3405	Dificultad	118	10	-	122	10	34	*3*	*39*	95	12	46
	Aguichoto	41	10	-	42	10	24	*2*	*44*	33	12	37
	Guatemozin	17	10	-	17	10	-	-	-	13	12	23
	San Gregorio	5	10	-	5	10	-	-	-	4	12	80
3407	Id id	449	7	25	200	8	3	*10*	*50*	149	11	92
		5535	12	38	6488	11	72	5	30	4434	10	93
Smelting [*Fundicion*]												
	Dificultad	86	112	33	959	111	51	0	72			
	Aguichoto	48	112	29	535	111	46	0	74			
	Perro	16	137	50	219	134	88	0	45			
	Jesus Maria	4	85	-	34	85	-	0	0			
	San Antonio	6	100	-	40	100	-	0	0			
	Rosario	6	131	67	78	130	-	1	27			
	Guatemozin	3	123	33	37	123	33	0	0			
	Jacal	3	110	-	33	110	-	0	0			
	Porvenir	2	85	-	17	85	-	0	0			
		174	114	8	1972	113	33	0	65			

Table 4-II. Partial transcription of data that appear for the five weeks ending on November 28th, 1885, as registered in the *Informe Mensual*. Numbers in italics represent numbers shown in red in original document. The units of silver content are registered in marks and hundredths of a mark.

every stage according to ore components. Either this represents a degree of operational complexity unsuspected in the historiography, or a degree of accounting creativity of the data.

I have placed a grey background on the data in Table 4-II where there is no question it would be obtained from direct measurements: the silver content of each component ore, the amount of each ore weighed and added to the *torta*, and the total amount of silver refined from the whole *torta*. This last quantity is reported in Table 4-II as a segregated quantity according to ore type for the hybrid *tortas*, but it could have been calculated by the accountants.[641] Other notations are more difficult to justify. The ore fraction of *torta* 3397 with a silver content of 50 marks per *monton* is reported as not incurring any silver loss during refining, while the values of silver loss for each of the other ore fractions is different and reported to a high degree of precision, for an average of 8.17%.[642] The data on mercury losses defie a similar calculation to arrive at individual values for each ore fraction. One probable explanation is that for those cases where hybrid *tortas* are registered, an accounting juggling act took place whereby certain boxes were filled with creativity just to arrive at a known average value.[643] The hybrid *torta* of Table 4-II is the occasional exception, since the great majority of *tortas* reported in the *Informe Mensual Regla* are made from a single type of ore.

4.4.6 The mass balance for salt.

After the ore, salt was the major solid being stored and used at Regla. Figure 4-34 plots the monthly consumption of salt required to produce 1 kg of silver, giving an average of 29.9 kg of salt per kg of silver. The sudden increase in salt consumption that is evident at the tail end of this period shows a departure from what had been until then a relatively stable pattern. The cause is not known, and is not repeated for the other components of the recipe. Since the quality of the salt is not registered, I can only surmise that a poorer salt may have been used at

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[641] In the case of *torta* 3405 there is in fact no loss, but a gain in silver after refining. This type of result figures predominantly in the ledger, and is due to errors in determining the average silver content of tons of ore from a very small assaying sample of the ore.

[642] A range of silver losses during patio amalgamation between 12% and 36% is given in Laur, "De la metallurgie de l'argent au Mexique," 186-87.

[643] It also challenges the reader as to why the ore fraction from Corteza should show such an abnormal consumption of mercury registered in pounds, while the corresponding value of consumption of mercury per mark of silver for this ore is clearly wrong. See footnote 125 on Laur's mistrust of nineteenth century accounting practices in haciendas.

the end. On a monthly basis an average of 4,310 *arrobas* (49.6 t) of salt was consumed during the amalgamation process, approximately 5 t per average *torta*. Overall the ratio at Regla is within the range of 2 to 5 % per *torta* suggested in a Mexican operations manual dated 1857.[644] The average inventory value in this period was 18,459 *arrobas* (212 t).

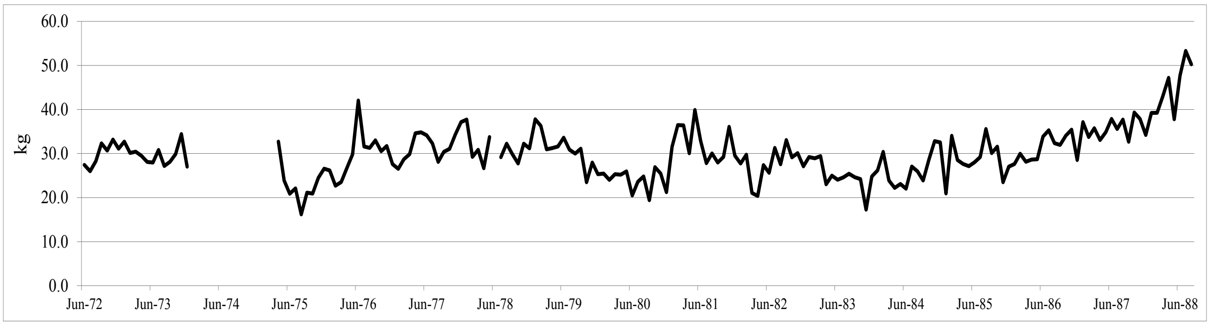

Figure 4-34. Consumption of salt per kg of silver refined by amalgamation (1872-1888). Raw data from *Informe Mensual*.

Based on the chemical reactions set out in Chapter 3, if all the silver refined was present originally as silver sulphide (Ag_2S), then the stoichiometric requirement of salt per kg of silver refined is 2.2 kg.[645] Thus on average over 10 times more salt was being added than was required by the basic chemistry of the conversion of silver sulphide to silver chloride. Since the purity of the salt used at Regla would have been consistently under 100%, this explains in part the higher ratio used. The excess of salt also covers the amount of salt lost as the saline water of the slurry seeped into the soil during the amalgamation period, when water was being constantly added to avoid the drying-out of the cakes.

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644 Hermosa, *Manual de Laboreo de Minas*, 215.

645 According to Reaction 3 in Section 3.4, 2 moles of silver chloride are produced from the reaction of 8 moles of sodium chloride with 1 mole of silver sulphide. Thus 2 moles of silver (215.72 g) require 8 moles of sodium chloride (467.6 g), a weight ratio of 2.2 kg pure salt to 1 kg of silver.

4.4.7 The mass balance for copper sulphate.

The next major additive, as measured in quantity used and stored, was copper sulphate. Figure 4-35 shows the profile of its monthly consumption per kg of silver refined by amalgamation. On average 9,774 lbs (4.4 t) of copper sulphate were used per month, for an average ratio of 2.6 kg of copper sulphate per kg of silver refined. In contrast to the use of salt, it is not only the purity of the copper sulphate that can influence the amount used. Copper sulphate or copper *magistral* was added according to the subjective judgement of the *azoguero* in charge of the amalgamation process. Recommended ranges went from 0.2 to 8 %, reflecting the variety of criteria in its use.[646] At Regla an average of 0.4% was added, based on the weight of the ground ore.

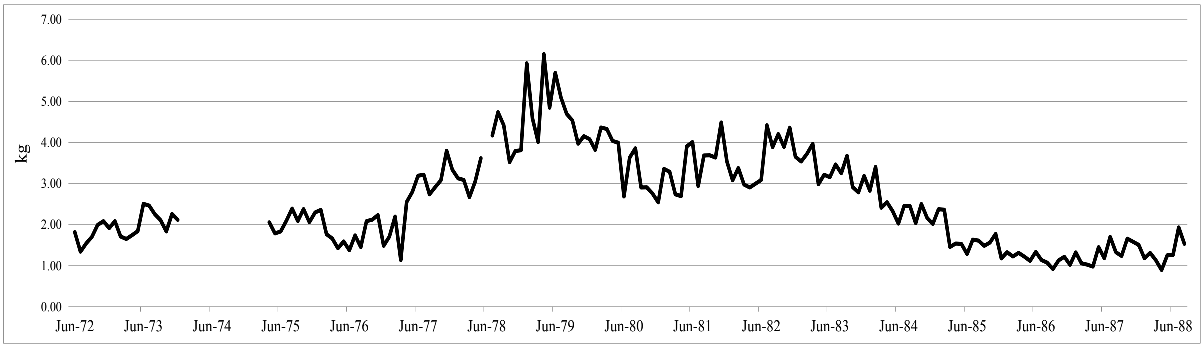

Figure 4-35. Consumption of copper sulphate per kg of silver refined by amalgamation (1872-1888). Raw data from *Informe Mensual*.

If all the silver refined was present originally as silver sulphide (Ag_2S), then the stoichiometric requirement of copper sulphate per kg of silver refined is 2.1 kg.[647] In contrast to salt, operators at Regla were using quantities much closer to the theoretical requirement,

[646] Hermosa, *Manual de Laboreo de Minas*, 216.
[647] According to Chapter 3, 2 moles of silver chloride are produced from the reaction of 2 moles of copper ions with 1 mole of silver sulphide. Thus 2 moles of silver (215.72) require 2 moles of copper sulphate (446.32), a weight ratio of 2.07 kg pure copper sulphate to 1 kg of silver.

taking into account the expected variations in its purity and the losses through seepage to the soil. The presence of native silver or silver chloride in the ore would have lowered the need for copper sulphate, and so may have provided some respite to their recipe. Approximately 0.5 t would have been added to every average *torta* of 700 *cargas*.[648] The level of monthly inventory over this period was 15,109 lbs (6.9 t),

4.4.8 The mass balance for mercury used during amalgamation

The monthly ledger for this period did not register the amounts of mercury added to each *torta*, only the amounts consumed, so they do not provide the total amount of mercury in circulation on a monthly basis at Regla. Buchan stated that 18,000 lbs (8.2 t) of mercury were in use on a monthly basis in 1855.[649] This corresponds to a weight ratio of five parts of added mercury per one part of assumed silver content in the ore.[650] It also indicates the monthly amount squeezed through the fingers of the workers at Regla. The profile of its monthly inventory level provides an insight into how an amalgamation operation was run. Throughout this whole period Regla maintained an average monthly inventory level of mercury of 29,830 lbs (13.6 t). This represents an inventory equivalent to 6.8 months of average mercury consumption at Regla. John Taylor, the General Manager of the Real del Monte Company, was prescient enough to write in 1824 from London:

'I know that it will be necessary for each establishment to keep at all times a large stock of this article [mercury] at the mines; and that thus, besides the risk of plunder and waste, a greater

[648] Humboldt states that 1 to 7 pounds of *magistral* were added for every pound of mercury. In Regla this ratio was just over 2 during the period. Humboldt, *Essai politique*, Tome IV, 64-65.
[649] Buchan, *Report Real del Monte*, 9.
[650] Assuming an average production of 1.6 t of silver produced by amalgamation per month and a recipe of 5 to 6 parts mercury to one part silver in the ore, then approximately 8 to 10 t of mercury would have been added on a monthly basis to the ores under amalgamation. For an average *torta* of 740 cargas, this requires adding near 1 t of mercury during amalgamation. This is the amount of mercury squeezed through the fingers of the workers for each *torta* in the patio. Approximately 80 one-litre flasks of mercury would have been required per *torta*. For the proportion of mercury to silver in the ore, see Hermosa, *Manual de Laboreo de Minas*, 216. Humboldt reports that the weight of mercury added was six times the deemed content of silver in the *torta.* Humboldt, *Essai politique*, Tome IV, 64.

capital than would otherwise be required must be provided and locked up in a distant country'.[651]

Whether by coincidence or intent, Regla always had enough reserves of mercury to jump-start the process if necessary from scratch.

4.4.9 The mass balance for silver.

The only commercial end product at Regla was silver.[652] The average monthly production of silver at Regla during this period via amalgamation was of 7,327 marks (1.7 t). As observed in Figure 4-36, Regla managed a steady production rate from mid 1876 to mid 1887, with just one singular peak in production in early 1882. Regla would cast silver bars from both amalgamation and smelting at an average rate of 64 bars per month, with most bars registering a weight of 140 marks (30 kg). This reflects the account given by Countess Kollonitz in 1864 : '[silver] is cast in very heavy bars ... every fifteen days 28 bars of silver are produced ... twice per month the company guards escort the silver bars to the sea ports, from where they are sent mainly to England'.[653]

How efficient was the *patio* amalgamation process at Regla, how much silver would have been left in these ores irrespective of the amalgamation period adopted? There is no straightforward answer to this question. First of all, the chemical nature of the batches of ore amalgamated at Regla is not reported in the account books and is expected to have changed

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[651] Taylor, *Selections from Humboldt*, xxii.
[652] Very minor amounts of lead were sold occasionally, as well as materials drawn from the storehouse, but none represent amounts of note.
[653] '*se funde en pesadísimas barras ... cada quince días salen 28 barras de plata ... dos veces al mes la guardia de la compañía escolta los lingotes de plata hasta los puertos de mar, de donde son enviados principalmente a Inglaterra*' in Paula Kollonitz, Un viaje a México en 1864 (México: Secretaría de Educación Pública, 1976), 146. Silver bars weighed 31.3 to 35 kg according to Duport, Métaux précieux au Mexique, 117.; Amador, *Tratado práctico de haciendas de beneficio*, 88.

from batch to batch.[654] Second, by curtailing the amalgamation period to approximately two weeks, a sacrifice of at least 5% is made on the maximum operational level of extraction of silver. Third, even though the silver content of the raw ore was measured and registered in the accounts, in many cases it is obviously incorrect, since it is registered as lower than the final

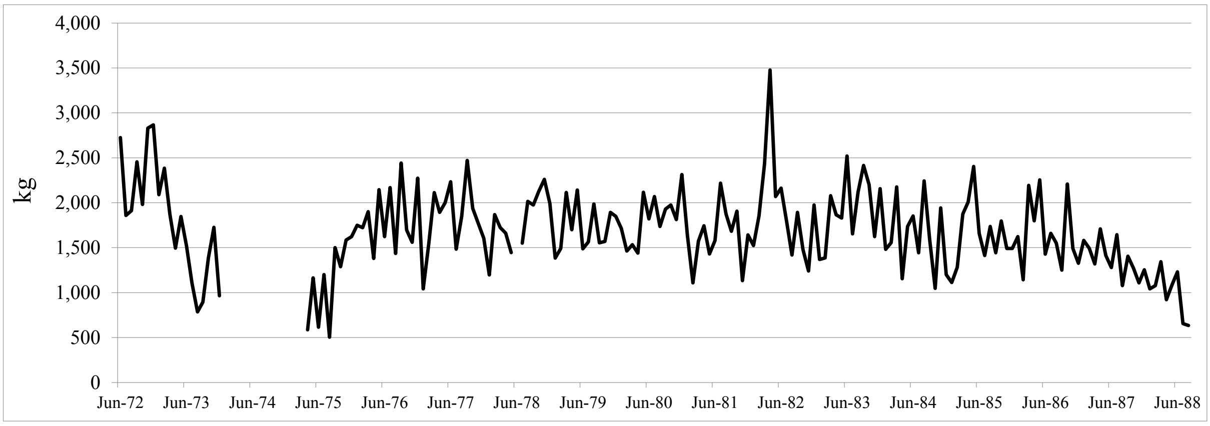

Figure 4-36. Monthly production in kg of silver by amalgamation (1872-1888). Raw data from *Informe Mensual.*

percentage of silver extracted from the ore. The operational challenge of sampling tons of ore so as to obtain a small representative amount that can be analyzed in a cupel for silver content is obvious, and it seems it was not overcome at Regla until the end of the period in question. The ledger for Regla is full of data on silver 'loss' inked in red to indicate this negative territory where more silver is registered as extracted than was measured in the raw ore.[655] When the non-negative values for the loss of silver are plotted, the average 'loss' of silver during *patio* amalgamation at Regla is just 5.1% with a standard deviation of 2.8%, a reflection on the large

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[654] The silver ores of Real del Monte containing manganese, antimony and lead were known to be difficult to amalgamate using the patio process, according to Phillips, *Metallurgy Silver*, 327.
[655] Laur argues that the issue of silver refined by amalgamation being greater than expected from the range of silver assayed in the ores is a result of large-scale manipulation of accounts by the administrators of haciendas to cover for inefficiencies in their operation, including pilfering. Laur, "De la metallurgie de l'argent au Mexique," 183-84.

variations observed in the data. The large gaps in data from 1875 to 1881 in Figure 4-37 correspond mainly to negative values that have been ignored, not to a lack of diligence on the part of the assayers. The average corresponds well to what was expected from an amalgamation *interruptus*.

Finally I have already pointed out the fact that the total amount of extracted silver is approximately 10% less than would be expected from the average silver content of the ore being amalgamated. Of this shortfall, around 5% corresponds to the curtailed amalgamation process, and the remainder could well be the dilution of the ground ore with inert solids from the wear of the *voladora* stones. Overall there is a good match between the data, and any pilfering that took place was hidden within the range of error of the measurements taking place and/or the registers in the accounts.[656]

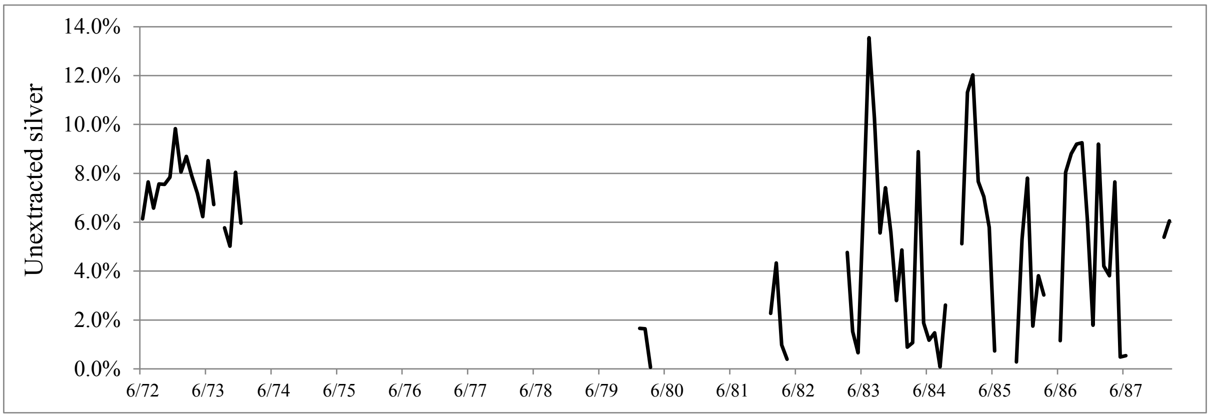

Figure 4-37. Losses of silver, expressed as percentage, during amalgamation (1872-1888), calculated from raw data in the *Informe Mensual*. All negative values reported in the ledger have been excluded.

[656] ‘criminals against the industry’ were thieves of mercury, silver or tools, ‘who could be punished on the spot’. Ladd, *The Making of a Strike*, 69.

4.4.10 The mass balance for mercury consumed

The ledger registers the amount of mercury consumed during the amalgamation process. This detailed bookkeeping requires keeping track of any mercury recovered a) during the separation and washing of the amalgam from the rest of the *torta* b) during the mechanical extraction of mercury from the amalgam in the *manga* and c) during the recovery of the mercury from the *capellinas*. The average monthly consumption of mercury at Regla was 4,638 lbs (2.1 t). When plotted as a function of kg mercury consumed per kg of silver refined, the plot shown in Figure 4-38 shows two distinct sections. The first, at approximately 1.1-1.2 kg of mercury for every kg of silver, is from 1875 to 1878 and at times is surprisingly smooth, not only compared to the other plots of consumption of reagents, but also compared to the time series on either side.[657] After 1878 the plot averages around 1.4 kg of mercury per kg of silver. The average value for this ratio from 1872 to 1888 at Regla comes to 1.25.[658] I have commented upon the fact that lower ranges are a sign of a) ores rich in native silver or b) the presence of iron or copper in the recipe, which are reducing agents of silver chloride that lower the consumption of mercury. The historiography confirms both factors are at work here.

Humboldt mentions that at the beginning of the nineteenth century the ores from the Vizcayna vein of Real del Monte contained silver sulphides mixed with native silver.[659] In his review of historic mines of Mexico, published in 1883, Dahlgren states that as to the ores of Real del Monte mines :

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[657] It is tempting to consider some accounting sleight of hand to explain the smoothness of data that one expects by nature to be more erratic in behaviour. Some data could have been extrapolated, based on the expected values of the ratio together with some coordinated adjustments to inventory and purchase orders. This would only be explained if they were making up for non-existent field measurements.
[658] The amalgamation recipe used in Potosí in 1603 shows a mercury to silver ratio of 1.3 with iron included as an important part of the recipe. Anonymous, "Relaciones Geograficas de Indias - Peru I," 376.
[659] '*Le filon de la Biscaina renferme ….de l'argent sulfuré mêlé d'argent natif*'. Humboldt, *Essai politique*, Tome IV, 16.

'near the surface the usual "Colorados" appeared while as depth was attained Silver Sulphides, native Silver (in quantities which have made this district famous), Dark Ruby and Prismatic black Silver (the "Negros") took the place of the "Colorados". There was some Galena.'[660]

A modern treatise on this mining district also draws attention to earlier ores such that 'native silver … in previous times was very frequent'.[661]

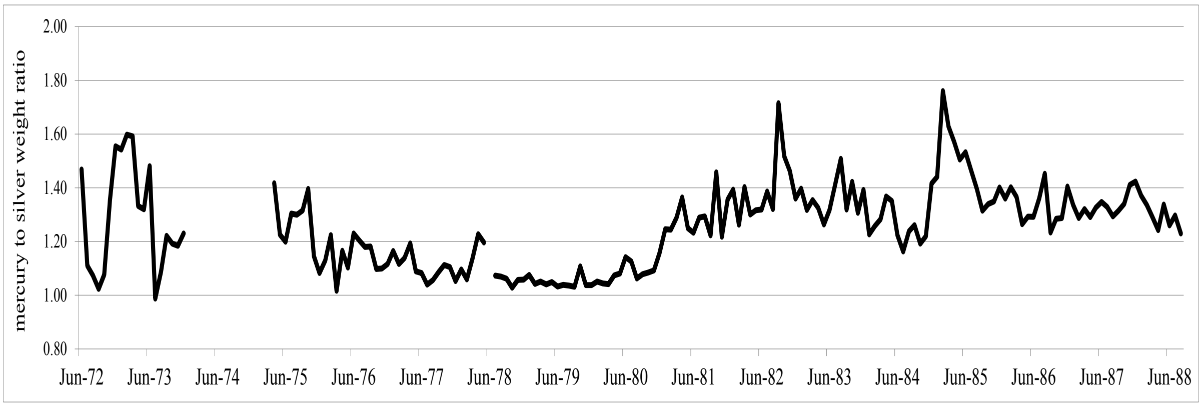

Figure 4-38. Weight ratio of mercury consumed to silver refined by amalgamation (1872-1888). Raw data from *Informe Mensual*.

As to iron, the other *haciendas* of the Compañia Real del Monte were routinely adding it to the amalgamation recipe so as to decrease mercury consumption during the barrel process.[662] Iron appears among the materials consumed at Regla, though it is not possible to discriminate in the accounts the amounts destined for amalgamation, as an additive in smelting and iron for general use in the *hacienda* (Table 4-III).[663] However the very high wear and

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660 Dahlgren, *Historic Mines of Mexico*, 196.

661 *'la plata nativa … en épocas anteriores fue bastante frecuente'* Galindo y R, *Distrito Pachuca-Real del Monte*, 5.

662 Iron was a standard additive in the recipe for the barrel process used in Mexico in the nineteenth century. Laur, "De la metallurgie de l'argent au Mexique," 98.

663 Table V is an extract from the *Memoria No. 19* to *Memoria No. 21 de los Gastos de la Hcda de Regla,* , corresponding to the four weeks ending on the 26th May 1877. It shows that in addition to salt, copper sulphate and mercury, the following reagents were also consumed: *tequezquite* (also spelt *tequesquite*), a naturally occurring salt used as flux for the smelting process; lime, used to control the amalgamation process if the *azoguero* deemed he had added too much *magistral*, and different types of iron. It is widely reported that iron was a

consumption of horseshoes made of iron at Regla raises the possibility that part of the iron that reduced the silver chloride in the slurry came from horseshoes, as the following calculation shows. The number of horseshoes replaced during the period covered in Table 4-III is equivalent to up to 600kg of iron, at 2 kg per heavy duty shoe. The wear on the horseshoes would have been an unwitting but extremely effective source of iron for the reduction of silver chloride. The constant erosion of its surface on a very abrasive ore slurry would have spread finely ground iron into the slurry every time each horse or mule tread his circular path through a *torta*. Even if only 50% of the mass of each horseshoe found its way into the amalgamation slurry, it would have been a very useful if unintended contribution to the observed lower mercury to silver weight ratio. Whole mule and horse shoes were added to the barrel amalgamation recipe mix in the United States in the nineteenth century.[664]

year 1877, week ending	consumption					
	tequezquite	lime	iron slag	english iron	mixed iron	horseshoes
	cargas	cargas	cargas	lbs	lbs	number
05-May	2.3	0	43.5	0	0	114
12-May	2.8	4	27.8	0	0	43
19-May	3.0	0	27.3	993	0	87
26-May	2.8	0	0	0	1,053	78
total	10.8	4	98.5	993	1,053	322

Table 4-III. Additional consumables at Regla, from *Memorias de Gastos* for the four weeks ending on May 26th 1877.

necessary component in the smelting of silver ores, for example Pique, *A Practical Treatise on Silver*, 69.; Phillips, *Metallurgy Silver*, 433.; Willies, "Derbyshire Lead Smelting," 3.

664 Egleston, *The Metallurgy of Silver*, 38. In Potosí in 1603 iron was added in a proportion of 0.5 to 1 with respect to the silver refined, and this was enough to bring down the mercury to silver ratio to 1.3. This would require adding approximately between 1 to 2 t of iron per average *torta* at Regla. At the lower ratio horsehoes could have added inadvertently around 30% of the required iron additive to the recipe.

4.4.11 The overall mass balance for the amalgamation process at Regla

Table 4-IV summarizes the magnitude of the main environmental impact vectors from the amalgamation process as carried out at Regla within the period covered by the accounting ledger. Based on the analysis presented in Chapter 3, Section 3.10, I propose that on average 85% of the total mercury consumption was in the form of solid calomel washed away after amalgamation, and the remaining 15% corresponded to a physical loss of mercury. The chemical transformation of mercury into calomel would consume on average 1.8 t/m of mercury into an insoluble solid that was entrained in the water used to wash the *tortas*, and deposited over an undetermined area in the water basins downstream from Regla. A total of 0.3 t/m of mercury was lost due to physical losses, of which the largest share would be by entrainment in water used for washing *tortas* or in the condensation channel underneath the *capellina,* together with seepage into the soil in the *patio* reactor area, for a total estimated average of 0.28 t/m. Air emissions of residual mercury in silver being cast into bars, 1% of the total weight of silver, represented an average of 0.02 t/m. A loss via evaporation from the *tortas* that will not be taken into consideration (estimated as 0.002 t/m).[665]

According to this scenario, for every kg of silver refined by amalgamation at Regla, approximately 1.1 kg of mercury was lost as calomel, 0.2 kg was lost as liquid mercury in the waste water or by seepage to the soil at Regla, and just over 10 g were lost as volatile mercury from the casting of silver bars. In terms of mass these losses pale in comparison to the 620 kg of solid mineral waste and salts in solution that were washed downstream from Regla for every kg of silver refined by amalgamation.

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[665] If all the mercury was exposed to sun and wind the deemed loss via evaporation would amount to 14 kg of mercury per *torta* in two weeks, or a total of 250 kg for 9 *tortas* every month. Since only a minority of mercury droplets would be exposed to sun and wind, I will assume that 1% of this theoretical total was the effective loss, 2 kg per month. Calculations based on Winter, "The Evaporation of a Drop of Mercury."

The yearly average amounts to approximately 12,000 t of mineral waste and salts, 20t of mercury in the form of calomel, 4 t as losses of liquid mercury and 0.2 t of mercury via air emissions.

amalgamation									
average input		raw ore		salt	copper sulphate	net mercury to be consumed			total
	t/m	989		49	4	2.1			1,045
average output		silver	waste ore	waste additives		chemical loss	physical loss		
							ground and water	air emissions	
						mercury loss as calomel	mercury loss as liquid mercury	mercury from casting silver bars	
	t/m	1.7	987	53		*1.8*	*0.28*	*0.02*	1,045
average input (kg) per kg refined silver		raw ore		salt	copper sulphate	net mercury consumed			
		587		30.0	2.6	1.3			621
average output (kg) per kg refined silver		silver	waste ore	waste additives and byproduct salts (except calomel)		mercury loss as calomel	mercury loss as liquid mercury	mercury from casting silver bars	
		1	587	32		*1.1*	*0.2*	*0.01*	621

Table 4-IV. Overall mass balance for the amalgamation of silver ores as practised at Regla between 1872 and 1888. Data compounded from different sections of this chapter. The numbers in italic denotes a calculated number, not directly derived from the monthly accounting ledger.

4.4.12 The energy balance of the amalgamation process

Patio amalgamation as practised at Regla in this period was not a major consumer of fuel. The only main process requirements for heat came from the c*apellinas* and from the casting of silver bars. A guide to the consumption of fuel is provided in the *Memorias de Gastos* of weekly consumption of wood and charcoal used at Regla (process, cooking, heating), and one example is reproduced in Table 4-V. These *Memorias de Gastos* register both consumption and purchases to re-stock the central warehouse (data in italics), and covers both amalgamation and smelting. Firewood in some *Memorias de Gastos* is explicitly designated as '*leña para afinaciones*', firewood for refining by cupellation. To arrive at a ratio of wood and charcoal per kg of silver refined by amalgamation, the first column in Table 4-V is assigned as fuel for the cupellation stage of the smelting process, while the second I will tentatively assign for the heating of *capellinas*. The charcoal from *ocote* I assign to the casting of silver bars. The final column of charcoal corresponds to the smelting of silver ore. In these four weeks 1,999 kg of silver were produced by amalgamation.[666] It should be noted that cooking and other domestic requirements for fuel would have also been included within these figures, but I have ignored these cosnumptions for want of information.

year 1877, week ending	consumed or *purchased (re-stocked)* , central warehouse			
	firewood	ocote	charcoal (ocote)	charcoal
	cargas	arrobas	cargas	cargas
05-May	366.5	206	27	*189.5*
12-May	50 *81*	146	24.5	*150.5*
19-May	50 *1,183*	118	18.5	*209*
26-May	49 *993*	164	19.5	850 *187.5*
total	515.5	634	89.5	850

Table 4-V. Total consumption of firewood and charcoal registered on a weekly basis at Regla, according to *Memorias No. 19 - 21 de los Gastos de la Hcda de Regla*, for the four weeks ending on May 26th 1877. Data in italics correspond to inventory make-up.

[666] *Informe Mensual Regla*.

My working figures thus err on the high side for the fuel required for amalgamation. According to my assignments, the total energy requirement for amalgamation during the month of May 1877 was 634 *arrobas* (7,291 kg) of *ocote* and up to 89.5 *cargas* (12,351 kg) of charcoal (*ocote*). To arrive at a ratio based on the energy content of charcoal, using a 10% conversion rate of wood to charcoal (see Chapter 2), a maximum of 7 kg of charcoal was required for 1 kg silver produced by amalgamation.

4.5 The mass balance of the smelting process at Regla, 1875 to 1886.

Compared to amalgamation, the solids handling logistics required for the smelting operations at Regla were on a much more modest scale. Ore, *greta* and charcoal sum up the input, while silver, slag and '*plomo pobre*' [desilverized lead] comprise the output. Though Regla was the only designated site to carry out smelting of silver ores for the Compañia Real del Monte, for many periods no smelting was carried out. Thus the smelting data that are analysed in the following sections start at June 1875 and end by January 1886, which still represents approximately one decade of nearly continuous operating data registered on a monthly basis. I follow the same method as for the amalgamation process.

4.5.1 The mass balance for ore

The average quantity of ore received at Regla destined for smelting was 172 *cargas* per month (23.7 t) during this decade. As seen in Figure 4-39 there was a peak reception period, mostly from the Rosario mine, around mid-1877. The gaps in the data reflect the lack of sufficient information in the monthly account to separate ore for smelting from ore for amalgamation. On average a monthly inventory of 216 *cargas* (29.8 t) was carried at Regla, just over one month of smelting throughput.

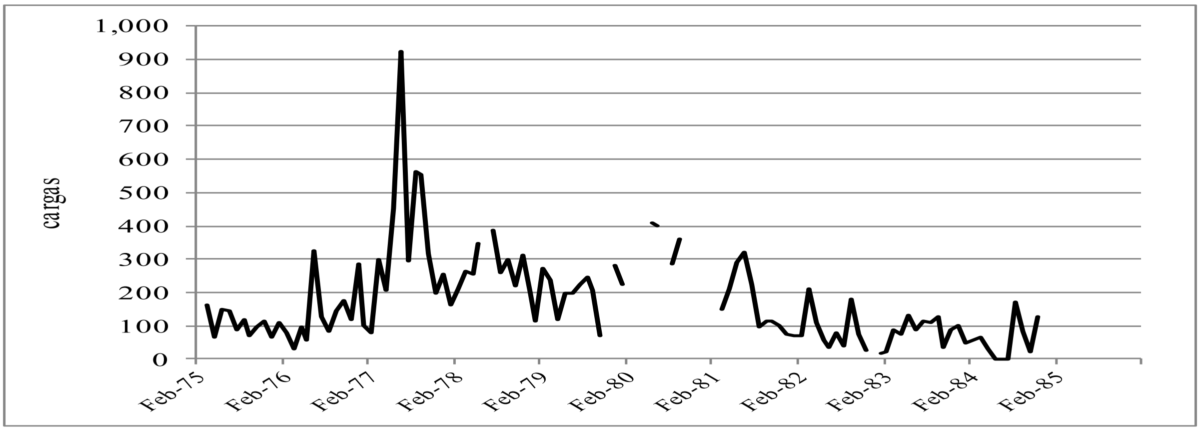

Figure 4-39. Monthly deliveries of ore for smelting to Regla (1875-1886). Raw data from the *Informe Mensual*.

The close correspondence between the monthly amounts of milled ore and then smelted, as shown in Figure 4-40, indicates that once it was ground, the over-design of the blast furnaces would have guaranteed a fast smelting operation.[667] The average throughput for grinding and smelting in both cases is approximately 179 *cargas* (24.7 t) per month.

The ore smelted at Regla had on average a silver content of 116.6 marks per *monton* (1.9% silver) (Figure 4-41). The highest values are of the order of 3.6 % silver. In contrast to the data presented for amalgamation, the average of silver extracted by smelting as calculated from the accounting data (net of silver extracted from recycled slags) is also 1.9%. Losses of silver during refining from the scarce data available are found to be roughly equivalent for amalgamation and smelting (Section 4.5.3 below). One possible explanation is the diluting effect of the erosion of the *voladora* stones for the ore milled prior to amalgamation.

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[667] The smelting capacity of Regla in mid nineteenth century was up to 30 t of ore per week, which implies that the whole Furnace Area B was working in the 1870s and 1880s at one fourth of its capacity. As a comparison, in the roughly same period as analyzed at Regla (1877 to 1891), the Newland blast furnaces in Cumbria (England) run iron ore smelting campaigns from four to twenty-eight months, at the end of which the furnace was 'blown out', as reported in Bowden, *Furness Iron*, 50. In the case of Regla the weekly accounts indicate much shorter runs of days, not months.

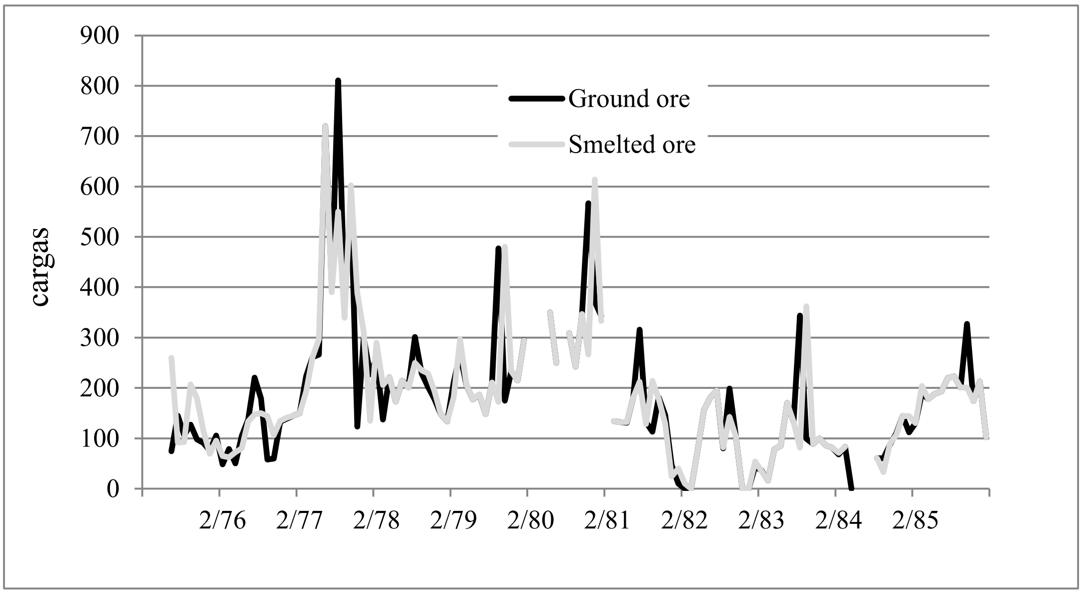

Figure 4-40. Monthly values (1875-1886) of silver ore ground prior to smelting, and the quantities of ore smelted. Raw data from the *Informe Mensual*.

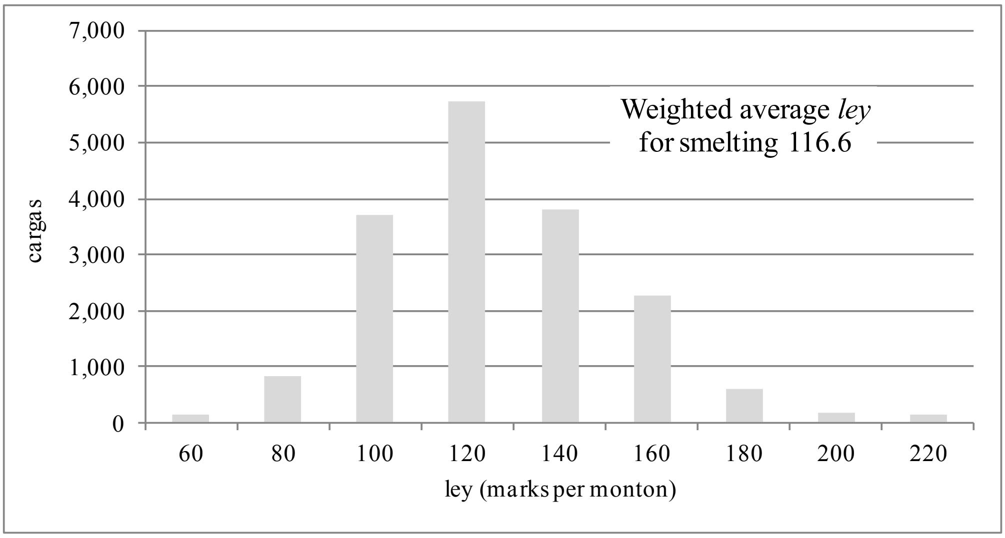

Figure 4-41. Histogram of the silver content of ores destined for smelting at Regla. Raw data from the *Informe Mensual*.

4.5.2 The mass balance for litharge as input

The ores sent to Regla for smelting did not contain sufficient lead to be smelted on their own, so litharge had to be added.[668] Exactly how much litharge was added per smelting batch is not reported in the monthly accounting ledger. One visitor to Regla noted that '[the ore] is mixed up [with] a quantity of lead, bearing an almost equal proportion to the other, and a certain admixture of what is called slag', where the lead is probably litharge, and the slag he refers to may have been *grasas*, or lead slag that still contained silver.[669] As in the case of mercury, what is registered in the ledger is the amount of litharge lost per month.

Regla did not produce lead as a regular commercial product, though it did sell occasionally what the weekly accounts of the *Memorias* term 'poor' lead, de-silverized lead. However it did have an incentive to control as much as possible its losses of litharge, which had to be purchased.[670] After the first major charge to start a smelting cycle, new purchases of litharge would only be required to compensate for losses during the process. The operator would be expected to control losses of lead in the slag, since it would entrain losses of silver as well. In case too much silver and lead was retained in the slag, it was re-smelted occasionally as *grasas*.

4.5.3 The mass balance for silver: output

In the period June 1875 to January 1886, Regla produced on average 1,717 marks (395 kg) of silver by smelting on a monthly basis. When both types of process were being operated

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[668] According to Dahlgren, in 1883 the Real del Monte Co. was the owner of lead and iron mines in Zimapan. Dahlgren, *Historic Mines of Mexico*, 20. According to Laur they supplied the litharge. Laur, "De la metallurgie de l'argent au Mexique," 253. Zimapan does not figure as source of the silver ores in the monthly ledger for the period 1872 to 1888.

[669] Tudor, *Narrative of a Tour*, 298.

[670] Even if the Company owned the source of litharge (for example from Zimapan), it still needed to account for litharge as an expense. In modern terminology the Company was treating each operation as a stand-alone profit centre.

in parallel, smelting would account for 18% of the total average silver production from Regla. When the whole period from 1872 to 1888 is considered, smelting accounted for approximately 14% of total silver production. Compared to the steadier profile of amalgamation refining, the smelting output reflects the uneven sourcing of ore for smelting over the period, as can be seen in Figure 4-42.

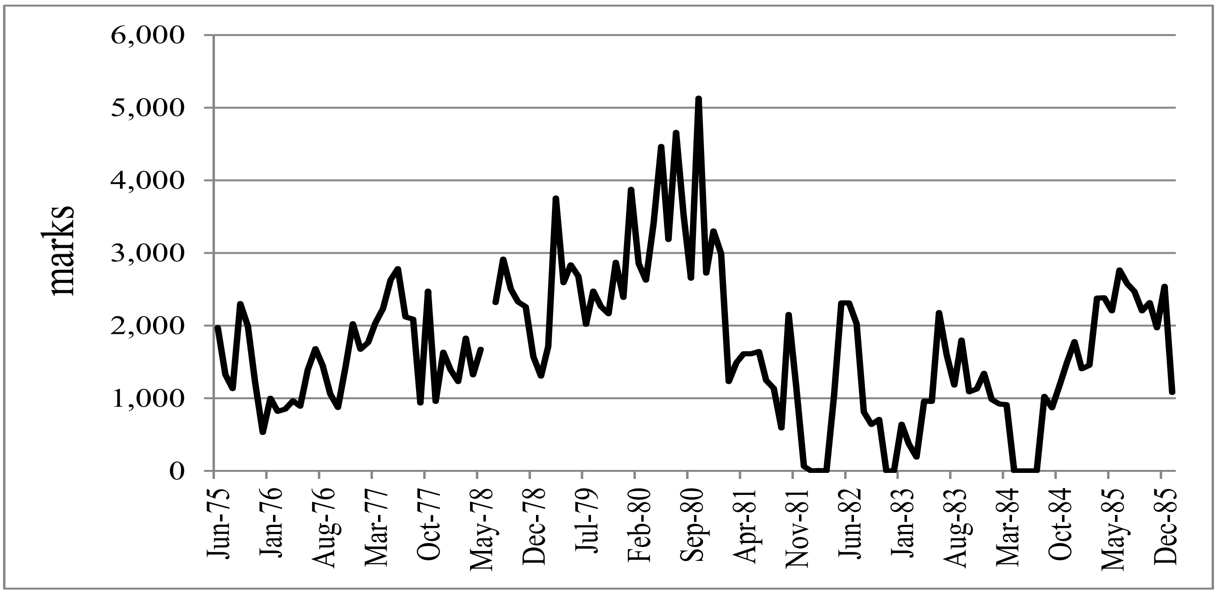

Figure 4-42. Monthly production of silver by smelting (1875-1886). Raw data from the *Informe Mensual.*

The fact that Regla oversaw both amalgamation and smelting provides a singular opportunity to compare the efficiency of each method to extract silver under the operating conditions of a commercial *hacienda*. Figure 4-43 compares on the same graph the data on silver loss from smelting and amalgamation as registered in the monthly ledger at Regla. As was the case for amalgamation, many silver losses for smelted ores appear in red in the monthly ledger, indicating the same lack of sufficient skill to sample and assay correctly some of these ores. Smelting shows a degree of silver losses of 4.7 ± 3.1 %, commensurate with the result for amalgamation already indicated above, of 5.1 ± 2.8 %. The production data from Regla does not indicate that *patio* amalgamation was more efficient than smelting in extracting silver from its ores, for the type of silver ore processed.[671]

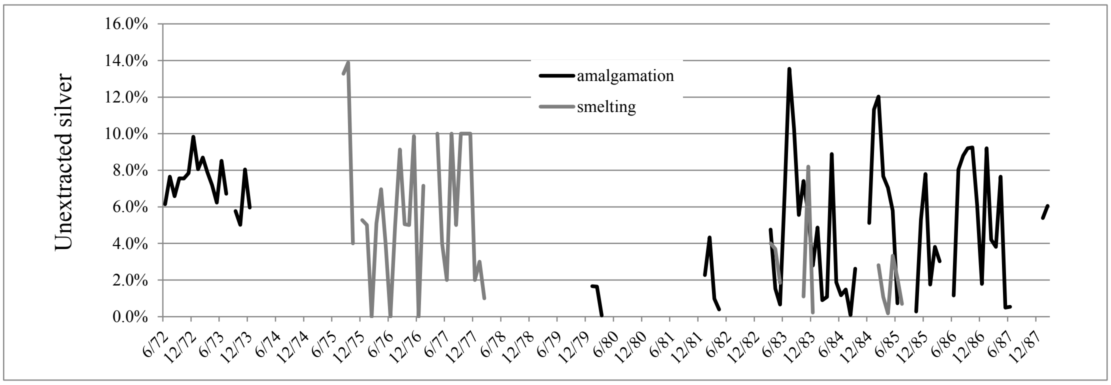

Figure 4-43. Comparison of silver losses incurred during smelting and amalgamation (1872-1888). Raw data from the *Informe Mensual*.

4.5.4 The mass balance for litharge: output

The monthly average consumption of litharge from June 1875 to January 1886 was of 5.4 t (the ledger reports the data for this period first in pounds and then in *arrobas*, so I have converted both to tons). An average of 13.7 kg of litharge was therefore lost for every kilogram of silver obtained by smelting (Figure 4-44).

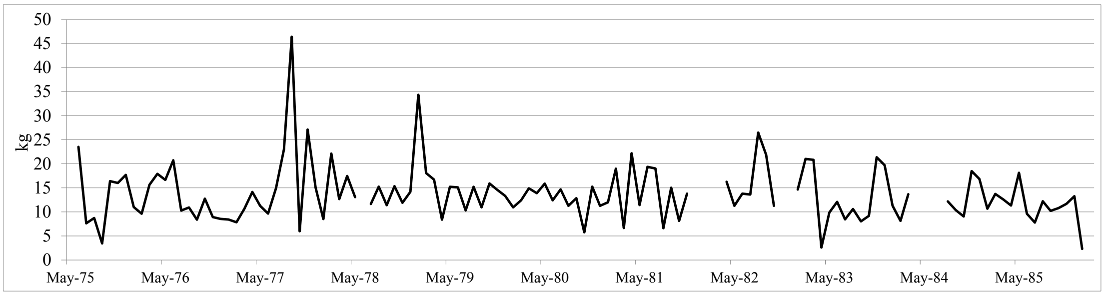

Figure 4-44. Weight of litharge lost per 1 kg of silver smelted (1875-1886). Raw data from the *Informe Mensual.*

[671] In the historiography the contrary is affirmed, as for example: 'amalgamation was a more efficient method of separation than smelting' in Brading, Miners Bourbon Mexico, 156. Since no production data are used to sustain this conclusion, which in any case depends on the nature of the ore, such generic statements should be treated with caution.

4.5.5 The mass balance for smelting at Regla

The average monthly mass balance for lead can be expressed as:

Lead in silver ore + lead in litharge consumed = total lead in air emissions (l_a) + lead in slag (l_s) + poor lead sold (p),

Where l denotes lead, subscript a indicates emissions to the atmosphere, subscript s indicates solid slag and p is poor lead.

The amount of historical lead lost as fugitive losses cannot be quantified so I have excluded it from the right hand side of the equation. The weight of lead in pure litharge is 92.8%, so if 5.4 t/m of litharge are consumed on average, this amounts to approximately 5 t/m of lead contributed by litharge. As a working figure I assume that the occasional sales of poor lead were of the order of 340 lb/m (150 kg/m).[672]. The equation can now be expressed in t/m as:

$$[24.7 \times \% \text{ (lead in silver ore)}] + 5 = l_a + l_s + 0.15$$

$$l_a = [24.7 \times \% \text{ (lead in silver ore)}] - l_s + 4.85$$

The lead content of the silver ores is not reported in the monthly ledger accounts, nor the lead content in the slags. I will therefore deduce a working value for these two variables from a) the amount of non-lead and non-silver content in the ore that I will assume was totally eliminated in the form of slags and b) ranges of lead content reported for historical slags from smelting operations of lead ores. This will allow me to establish a first approximation to the

[672] The weekly *Memorias de Gastos* provide two values for the production of poor lead, 280 lbs (127 kg) for the monthly period that ended the 26th May 1877, and 400 lbs (182 kg) for the monthly period that ended 30th March 1878.

range of monthly losses of lead in air emissions at Regla during the years when smelting was carried out.

A working figure for the average content of lead in historical slag was deemed to be 3% (Chapter 2, Section 2.6.1). The remaining, non-lead, content of the slag can be approximated by calculating the monthly amount of mineral in the ore that was not silver, assuming no lead was present. This is equivalent to:

24.7 t/m of ore x 0.981 = 24.2 t/m

Ignoring losses of the non-lead fraction via volatilization, then the estimated value for l_s is:

$l_s = 0.03 \times 24.2$ t/m = 0.7 t/m

This calculation ignores, for want of data, the amount of iron used in the smelting charge, and it includes by default the unknown amount of lead lost via fugitive losses.[673] The average monthly loss of lead in air, for ores with no lead content, is given by the following mass balance:

l_a = net lead in litharge consumed - deemed loss of lead in slag – sale of poor lead = 4.1 t/m

which corresponds to a 10 to 1 ratio with respect to the average monthly production rate of silver by smelting of 0.4 t/m. This correlates with the upper level of the range deduced

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[673] At Regla the source of fugitive emissions would be particulates blown from the inventory piles of litharge and from work areas around the furnaces. The high walls around the courtyards of Furnace Area B (CB-I and CB-II) would serve to contain and concentrate these fugitive emissions over time. These fugitive losses would add to the monthly consumption of litharge registered at Regla. They would reduce both the level of lead lost as slag and the loss of lead and lead compounds to the atmosphere, but to an extent I cannot at this moment estimate.

in Chapter 2, Section 2.6.1, for the ratio of losses of lead and lead compounds to the atmosphere for every kg of silver refined by smelting.

On this basis Table 4-VI summarizes the overall mass balance for smelting as practised at Regla from early 1875 to early 1886. For every kg of silver, 59 kg of solid waste would be generated, which for my simplified analysis I have converted all to waste slag with a deemed average lead content of 3%. Under this scenario, an ore with zero lead content would produce a loss of lead and lead compounds in the fumes of 10 kg of total lead per kg of silver refined by smelting. Any additional lead in the ore (which in Table 4-VI is set as zero) or any loss of waste ore by volatilization in the blast furnace instead of as slag would increase this baseline level. On a yearly average, at Regla some 50 t of lead would have been issued to the atmosphere during this period, and some 300 t of solid waste in the form of slags.

<table>
<tr><td colspan="9">smelting</td></tr>
<tr><td rowspan="2">average input</td><td></td><td colspan="2">raw ore</td><td colspan="3">net lead in litharge consumed</td><td>lead in ore</td><td>total</td></tr>
<tr><td>t/m</td><td colspan="2">24.7</td><td colspan="3">5.0</td><td>0</td><td>29.7</td></tr>
<tr><td rowspan="3">average output</td><td rowspan="2"></td><td rowspan="2">silver</td><td rowspan="2">waste ore as slag</td><td>ground and water</td><td>air emissions</td><td rowspan="2" colspan="2">sale of poor lead</td><td rowspan="2"></td></tr>
<tr><td>lead in slag and fugitive emissions</td><td>lead in fumes</td></tr>
<tr><td>t/m</td><td>0.4</td><td>24.3</td><td>0.7</td><td>4.1</td><td colspan="2">0.15</td><td>29.7</td></tr>
<tr><td colspan="2" rowspan="2">average input (kg) per kg refined silver</td><td colspan="2">raw ore</td><td colspan="3">net lead in litharge consumed</td><td>lead in ore</td><td></td></tr>
<tr><td colspan="2">59</td><td colspan="3">11.8</td><td>0</td><td>70.4</td></tr>
<tr><td colspan="2" rowspan="2">average output (kg) per kg refined silver</td><td>silver</td><td>waste ore as slag</td><td>lead in slag and fugitive emissions</td><td>lead in fumes</td><td colspan="2">sale of poor lead</td><td></td></tr>
<tr><td>1</td><td>57.5</td><td>1.7</td><td>9.8</td><td colspan="2">0.4</td><td>70.4</td></tr>
</table>

Table 4-VI. Overall mass balance for the smelting of silver ores as practised at Regla between June 1875 and January 1886. Data was compounded from the sections on smelting of this chapter. The numbers in italic were calculated and not obtained directly from the accounting data.

The numbers from Regla can be used to derive a factor whereby the existing mounds of the fields of *grasas* around a smelting *hacienda,* which in theory have a mass that can be estimated, become an indirect guide to the amount of historic amounts of lead and lead compounds that was issued to the air. According to the numbers in Table 4-VI, an order of magnitude of the total mass of lead issued from the refining of silver ores can be approximated by multiplying by a factor of six the estimated weight of extant *grasas* around the ruins of a smelting *hacienda*.

4.5.6 The energy balance of the smelting process at Regla

According to notations made in some *Memorias de Gastos*, the charcoal employed is made from *encino* [oak], the wood of choice both for charcoal and for timbers for the mines. *Ocote* is a Mexican pine tree, used both for firewood and to make charcoal. It is important to note that charcoal for blast furnaces requires certain strength to maintain the physical integrity of a load of ore and charcoal during smelting. Thus charcoal for a reverberatory furnace need not have the same strength as charcoal for a blast furnace, and both could come from different types of wood.

The average ratio over this decade was 204 kg of charcoal per kg of silver (Figure 4-45). A minor amount of additional fuel would be required to cast the smelted silver into bars, but I will consider this included in the discussion on amalgamation fuel requirements. This ratio is one fifth the ratio of approximately 1,000 kg of charcoal per kg of silver reported in the historiography (see Chapter 2).[674]

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[674] A very low ratio of one *arroba* (11.5 kg) of wood to smelt one *quintal* (46 kg) of ore is reported for silver refining in Honduras, but it requires validation. See Newson, "Silver Mining Honduras," 51.

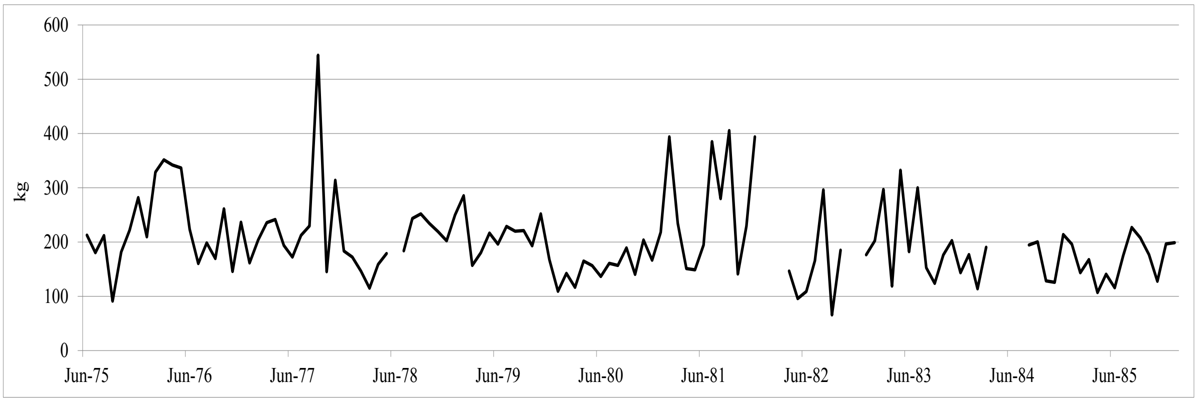

Figure 4-45. Weight of charcoal required to produce on average 1 kg of silver by smelting (1875-1876). Raw data from the *Informe Mensual*.

4.6 The environmental loss vectors in the period 1872 to 1888.

Regla merged the requirements of two completely different silver refining operations into an integrated whole. The challenge faced by whoever designed the *Hacienda* de Regla is illustrated by the mass transit corridors needed to service the two parallel organizations shown in Figure 4-46. These two completely different refining operations shared a somewhat constrained physical location, between a stream and the sheer basalt sides of the gorge. There were no conveyor belts, automatic hoppers or rotary mixers run on steam engines at Regla. Man, horse and mule power received their only help from the endless supply of water coursing through the stone channels, but it was still back-breaking work.[675]

On average every day at Regla over 35 t of materials were entering the compound through a single gate, and another 35 t were in constant motion between the various process areas of the *Hacienda*, some along transit corridors that had to handle two-way traffic. Since both amalgamation and smelting were batch processes, the monthly averages do not fully

[675] Any reader who has had to mix with a shovel just one bag of cement (50 kg) with sand and water will appreciate the severity of the workload at Regla in preparing and handling one average *torta* without the aid of a cement mixer.

convey the peaks of internal mass transport or the intense physical activity whenever a *torta* was prepared or broken up for washing. The constant backdrop to these bursts of activity was the periodic arrival and storage of raw ore and materials, and the continuous feeding of ore to the stamps and *arrastres*, the jaws of this industrial organism. This animal however had a most wasteful metabolism, expelling as useless to its well-being over 99.6 % of what it consumed.

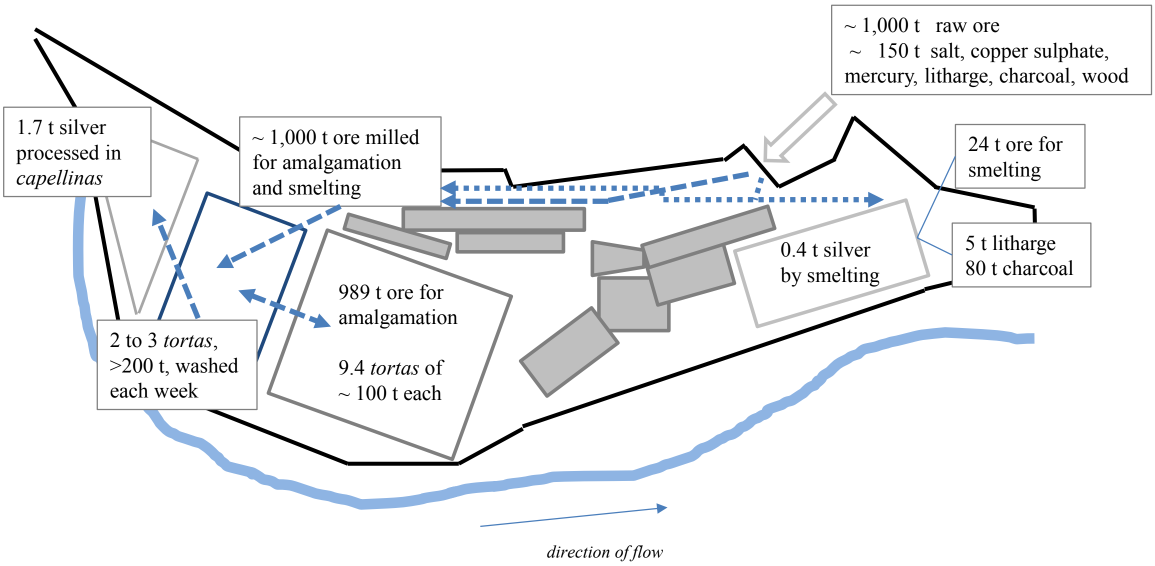

Figure 4-46. Main mass transit corridors at Regla, average monthly quantities in the period 1872/73 and 1875/88 (amalgamation) and Jun 1875 to Jan 1886 (smelting).

The mass balances presented in Tables 4-IV and 4-VI are visually summarized in Figure 4-47. Four areas of the environment were impacted by the refining activities at Regla:

a. The stream flowing past the south and eastern perimeter walls of Regla.

The stream to the side of Regla becomes a tributary of the Rio Metztitlán, which in turn flows until it reaches the natural dam of the Laguna de Metztitlán, approximately 60 km downstream from Regla (Figure 4-48). The mean annual run-off of the river into the lake in the twentieth century is estimated at 1.6×10^8 m^3. Drainage from the bottom of the lake exits to form the Almolón River, at a level 250m below the lake.[676] In terms of mass, the majority of the waste from Regla would be discharged into this stream. In terms of heavy metals, it would be the conduit to dispose of around 90% of all mercury losses, mainly in the form of calomel. The loss of lead via the stream would be minor since there is no textual evidence for the dressing of ores at Regla.

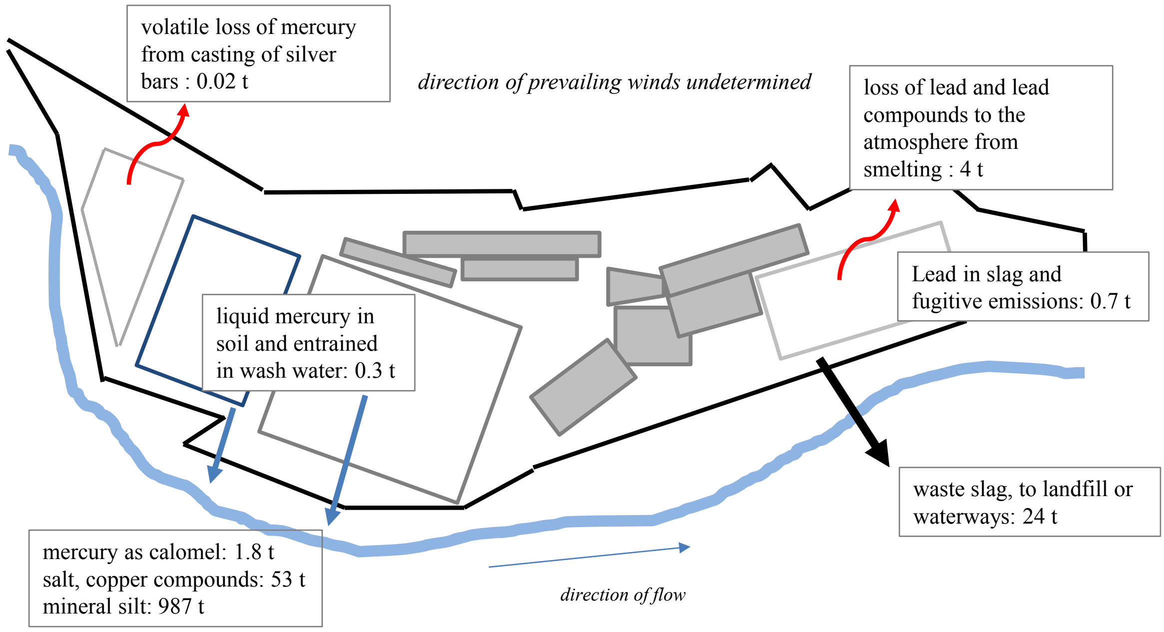

Figure 4-47. Main loss vectors of waste material, monthly average at Regla in the period 1872/73 and 1875/88 (amalgamation) and Jun 1875 to Jan 1886 (smelting).

676 Max Suter, "A neotectonic-geomorphologic investigation of the prehistoric rock avalanche damming Laguna de Metztitlán (Hidalgo State, east-central Mexico)," *Revista Mexicana de Ciencias Geológicas* 21, no. 3 (2004): 397-411.

Figure 4-48. The Valley of the Metztitlan River, Hidalgo State, Mexico. Satellite image from Google Earth Image Landsat. The Lago de Metztitlan is situated at 20° 41’ 04” N 98° 51’ 01” W. The depth of the valley floor relative to Regla is best appreciated in Figure 4-4.

Every year some 12,000 t of solids would be discharged into the stream, to join the waste generated by the *haciendas* upstream of Regla (San Antonio and San Miguel). This was enough material to have covered to a height of 2.5 m the whole *patio* area at Regla. In terms of concentration, just the mercury in the calomel from Regla would represent 0.17% of mercury (1700 ppm) encapsulated within the fine solid mineral silt from the milled ore. Taking into account that the river Metztitlán discharges 160 million tons of water into the Laguna Metztitlán every year, the impact of all these loss vectors would be dissipated as the flow of water approached the lake. For example, even if all the mercury in calomel reached the lake (an improbable scenario), it would be present as 0.1 ppm of the yearly flow of water into the lake.[677] Accumulated quantities over an 80 year production span in the nineteenth century

[677] Modern studies on the presence of mercury downstream from artisanal centres of gold extraction using mercury are detecting it as far away as 600 km from the site of mining. Sarah Diringer et al., "Mercury Biogeochemistry and Artisanal and Small-Scale Gold Mining in Madre de Dios, Peru,"(Poster, 11th International Conference on Mercury as a Global Pollutant, Edinburgh 2013).

would obviously be more significant, but I have not found any studies to date of core samples either from the river beds or the lake sediments in this area.

b. The soil within the perimeter walls of Regla.

The soil of the *patio* area, and of the storage and handling areas for mercury would have been impregnated with mercury that percolated through the *tortas* and through the wood slabs that covered the *patio*. In contrast to the waste continually removed from Regla by the stream, the soil within Regla would become a depository of accumulated liquid mercury, down to an unknown depth. How much of this mercury would have been entrained in the skin and clothes of the workforce and transported to their homes and families is unknown.

Fugitive losses of lead and litharge took place and would also have accumulated within the perimeter of Regla, but I am not able to quantify this amount.

c. Airborne emissions and deposition of airborne particles in and around Regla.

Air was the domain of lead emissions, not of mercury. Up to 170 times more lead (as lead and lead compounds) was issued to the air than mercury during the whole period covered by this chapter. Taking into account that smelting was not carried out during certain years, or that smelted silver only corresponds to 14% of all the silver produced during the period, this is a significant ratio.[678] From the point of view of the workers, lead fume posed a much more concentrated threat in time than the constant but much lower level of mercury emissions.

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[678] A total of 301 t of silver was produced at Regla between 1872 and 1888 by amalgamation and 50 t by smelting. According to my calculations set out in Tables 4-IV and 4-VI, for every 1 kg of silver refined by amalgamation, 10 g of mercury is lost as volatile matter, while for every kg of silver refined by smelting, a conservative estimate is that 10 kg of total lead in lead fume is lost to the atmosphere. Over the whole period I project that approximately 3 t of mercury and 500 t of lead were lost as emissions to the atmosphere during the process.

Within Regla, high ambient levels of lead and lead compounds would permeate the areas around the hearths of the blast furnaces and in the load floor during the charging of the stack. Other areas within and without Regla would be subject to airborne diffusion of lead and lead compounds in particles, and to the deposition of these airborne particles from the furnace stacks. The exact footprint of these lead depositions can only be established on the basis of the prevailing wind direction in the gorge. The isolation of the site and its location within a gorge would have concentrated the impact of its air emissions to the workforce and local dwellings, while minimizing it on the surrounding area.

d. Loss of woodland

Smelting was a much greater cause of deforestation than *patio* amalgamation at Regla. Even with much more efficient blast furnaces at the end of the nineteenth century, charcoal consumption was still thirty times greater for smelting than for *patio* amalgamation, based on the heating energy requirements to produce 1 kg of silver.[679] If the whole period is taken into account, amalgamation at Regla would have required a total of just over 2,000 t of charcoal, compared to approximately 10,000 t for smelting. In Chapter 2 I calculated that approximately 0.04 to 0.08 hectares of woodland could supply 200 kg of an average quality charcoal. The total amount of woodland that would have been deforested in this period in order to supply the heating requirements for Regla would have been in the range of 2,500 to 5,000 hectares, of which more than 80% was due to the smelting process.

In 1855 Buchan reported on the woodlands available to the Company at that time:

[679] Barrel amalgamation as practised at Regla was much more energy intensive than patio amalgamation, and the conclusions drawn in this paragraph do not apply to it (see Chapter 5). For patio amalgamation I have calculated 7 kg of charcoal equivalent for every kg of silver refined. In the case of smelting it is approximately 200 kg of charcoal per kg of silver refined.

'our consumption of wood is not less than 60,000 tons ... *per annum* ... for the supply of this fuel we hold ... some 25,000 acres, for the most part forest ... the nearest of these woods have already, during the last twenty-five years, been much diminished; but we have lately acquired others ... and with due care of the young trees which are reproducing in those portions already many years cut, even our nearest forests are not likely soon to fail; while from a distance ... the supply is inexhaustible'.[680]

Buchan was referring to the total requirement for timber and wood for charcoal for all the operations of the Company, and steam engines and barrel amalgamation were major consumers of energy. Even a deforestation at the lower estimate of 6,000 acres in total over this period just to supply the needs of Regla represents an important fraction of the total forest holdings owned by the company in 1855, even assuming reforestation over 20 year cycles.

4.7 Concluding remarks

Regla must have smelled not of riches but of rich animal manure and the sweat of overworked men and animals, overlaid with the earthy overtones of the dark mud of the silver ore slurry spread out over the *patio*. The smelting runs punctuated with their acrid sulphur the softer background levels of wood smoke from the reverberatory furnaces. Gritty dust must have coated all surfaces, dust from the stamp mills, from the piles of ore and charcoal and litharge, dust whirling impotently, imprisoned within those imposing perimeter walls. The basalt columns of the gorge resonated with the cacophony from the daily pounding of the stamps, the whirring and scraping of the *arrastres*, the braying from the mule-trains, the neighing of the horses and the shouts of the workmen. In the background water gurgled continuously through channels, splashed from spouts, shoved against water-wheels, lubricated the ground ore, held together slurries and wetted the *tortas*, washed away mountains of unwanted waste, out of sight and out of mind, leaving the grounds of the *Hacienda* free from the eye-sore of hills of slag or

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[680] Buchan, *Report Real del Monte*, 19.

useless ore. It is no surprise that the first Conde de Regla chose the less intense *Hacienda* de San Miguel as his residence, instead of the fortress at Regla. Over this 'Babylonia' of back-breaking hard labour hung the mistrust and eternal vigilance of its management, overseeing the production of the small but heavy silver bars with the same obsessive attention to detail that a miser pays to his hoard. A cat and mouse game of accounting and production versus pilferage of ore, mercury, amalgam and silver, played every day of the year under the gaze of guards and overseers, regardless of barred gates and underground storage chambers.

'Reduction power' or '*hacienda* power' are two powerful phrases from the English business jargon of the mid-nineteenth century that explain the appetite of this industrial beast. To increase the reduction power of the company was to ramp up the capacity to refine the greatest quantity of the type of ore that could be produced by the mines. Since the ore came with so little lead the original intention to rely on smelting became impractical once the plan to dress the ores was discarded. The only remaining option was to increase the role of amalgamation, either by the traditional *patio* process or by importing the Freiberg barrel process to attempt to process the more difficult ores. The economy of scale behind '*hacienda* power' is the reason Regla was operated to its limits throughout the 1872 to 1888 period, with a brief hiatus in 1874. The environmental impact of this '*hacienda* power' at Regla can be quantified thanks to the detailed accounting records that span over ten years continuous production at the end of the nineteenth century.

The mercury legacy of silver refining at Regla lies dormant underground, as calomel entombed along river beds or as mercury impregnating the soil within the *hacienda*, but only a minor fraction as mercury dispersed long ago in the air. The air at Regla was the domain of dust from the *morteros* or the lead fume from the Satanic furnaces. The first would tend to be confined within the compound of the *hacienda*, the second would heavily contaminate the work areas adjacent to the furnaces, or come to ground after having been spewed from chimneys with no long flues or bag houses to protect their immediate surroundings. The English managers and workers had brought pasties and football from England to Pachuca, but there is no evidence of an attempt to collect the lead set free in the furnaces. The history of the English investment in the mining and refining of silver at Pachuca is marked by the omission of the techniques known at the time to control the loss of lead fumes to the environment.

In terms of sheer weight, it was the volume of solid waste that would have had a major impact on the environment had it not been washed downstream, away from Regla. The impact of large amounts of fine mineral silt, calomel and increased salt and copper levels in the water used by other communities far from the three refining *haciendas* polluting this stream of water remains to be studied and quantified. As to the impact on woodlands, all metallurgical activity created the need for firewood and charcoal. The data from the end of the nineteenth century show that improvements in furnace efficiency had brought down the consumption of charcoal for smelting to five times less than the level reported for Pachuca one hundred years earlier. Even then the forests around the *haciendas* were being cleared for wood, at a rate that would have become a major obstacle had more ores been destined for smelting.

How representative is Regla of the overall environmental impact of silver refining in Mexico? Regla produced a mix of silver from amalgamation and smelting that mirrors the nineteenth century more than the colonial period, when smelting was more prevalent in New Spain (Chapter 6). On average the quality of the ore amalgamated was 0.19% silver by weight, and 1.9% silver by weight for smelting, if anything within the higher range of silver ores in Mexico. The ores sent for *patio* amalgamation at Regla were mainly silver sulphide ores, as were most of the ores of Mexico, with the presence of native silver. There was no help from silver chlorides in these ores. The consumption of mercury, salt and copper sulphate at Regla lies on the lower range of the historical scale, but not outside the expected parameters. The total silver output from Regla during the period covered in this chapter reached a total of 350 t, which represents 0.7 % of all the silver refined in New Spain from the sixteenth to the end of the eighteenth century. The operations at Regla at the end of the nineteenth century were as chemically representative as any other from the end of the sixteenth century. Even iron, the additive that first appears in the Vice-Royalty of Peru in the late sixteenth century, continues to make its presence felt at Regla. Only the efficiency of the process could have improved during this whole period, as shown by the marked reduction in the use of charcoal for smelting, or the late switch to faster turn-around times for the *tortas* in the *patio* area, but not its chemical underpinning.

Regla is thus a microcosm that faithfully embodies the practices of historical silver refining in the New World. This whole thesis is predicated on ignoring the distracting multiplicity of what is undoubtedly a complex historical scenario, while trying to use basic chemistry and physics to focus on the metaphorical forest instead of so many trees. Wind patterns are site-specific, the architecture will change the relative height differential between chimneys and the perimeter walls, the efficiency of the processes will improve with experience and design, refining *haciendas* will be isolated units in the countryside or embedded within city limits, silver ores come in one hundred different flavours, but the picture that emerges from Regla transcends these inevitable accidents of time and location. Lead in the lead fume was the only heavy metal that was discharged to the air in great quantities as a consequence of the totality of historical silver refining activities in New Spain / Mexico, right up to the end of the nineteenth century. Calomel, the solid and insoluble chlorine salt of mercury (I), trapped nearly all the consumption of mercury and was washed downstream from all the amalgamation *haciendas*. The immediate danger of mercury lay in its constant contact with the skin, and in the accumulation of liquid mercury in the soil within the perimeter walls or entrained during the washing of the slurries.

The value of the account books kept for Regla and the other refining *haciendas* of the Compañia Real del Monte is not limited to the insights on the mass balance and environmental impact of the operations. By providing information on the economies of each refining process they also become the key to understanding the choices open to the refiners of silver in the New World, choices determined not only by the chemistry but also by the production cost of each process, the subject of the next chapter.

5 The economies of refining silver.

‘nor, unfortunately, is it possible to calculate the costs of amalgamation as against those of smelting. Even the price of labour is unknowable … costs of upkeep of plant, raw materials … are similarly an unknown quantity … it is at this point … that lack of knowledge of the costs of mining becomes a true hindrance to explanation’ Peter J. Bakewell, *Silver Mining and Society in Colonial Mexico: Zacatecas*, 1546-1700 (1971)

‘unfortunately at present we possess little information as to the price trends of such commodities as salt, lead, firewood and copper pyrites …in the last resort until long-term account books are discovered and studied, any explanation must remain at best, hypothetical’ D. A. Brading, *Miners and Merchants in Bourbon Mexico 1763-1810* (1971)

‘precise cost figures rarely show up in archival documents because producers did not keep accounts that showed all capital and operational costs’ Richard L. Garner and Spiro E. Stefanou, *Economic Growth and Change in Bourbon Mexico* (1990)

‘our degree of concrete knowledge on the costs of production is still very limited, since of all the necessary items required by mines and silver refining *haciendas*, only mercury has been the subject of detailed study … for the time being one can only tackle this topic from an eminently theoretical perspective, devoid of sufficient quantitative fundamentals and extract just a few provisional conclusions that may serve … as a guide to future research to be realized from sources that are still virtually unexplored’ Jaime J. Lacueva Muñoz, *La plata del Rey y de sus vasallos : minería y metalurgia en México* (Siglos XVI Y XVII) (2010)[681]

5.1 The most valuable jewel of the Crown

The environmental history of silver refining in New Spain was not only defined by the chemical nature of its ores, but also by the search for profits by the two groups of human actors that exercised a choice between amalgamation and smelting. At ground level lay the private sector involved in mining and refining, driven by the search for short-term substantial profits to offset the high level of risk of their business. On a higher supervisory and legislative plane

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681 *‘en cualquier caso, nuestro nivel de conocimientos concretos sobre los costos de explotación es todavía muy limitado, pues de todos los insumos necesarios para las minas y haciendas de beneficio, solo el mercurio ha sido objeto de estudio detallado ... por el momento solo es posible afrontar el tema desde una perspectiva eminentemente teórica, desprovista de los suficientes fundamentos cuantitativos y extraer tan solo algunas conclusiones provisionales que puedan ser ... guía para futuras investigaciones realizadas a partir de fuentes prácticamente inexploradas’*

lay the Crown officials, having to respond to the pressure of providing cash flows to the Royal Treasury by seeking to maximize the total fiscal rent from all activities related to silver refining in New Spain. As a result, macroeconomic fiscal imperatives and microeconomic refining production costs have to be analysed together with the chemical profile of the silver ores, so as to understand how the final balance between amalgamation and smelting was arrived at, which in turn determined the net environmental impact of silver refining in New Spain.

The role of the private sector in the production of silver in the New World is certainly worthy of note, and is a reflection of the agency they exercised in the final choice between the two refining options. When the first Conde de Regla died on the 27th November 1781, he left what has been termed as 'probably the largest estate of any noble in the colony [New Spain]', a sum that may have reached up to 5 million pesos. This included a hoard of 200,000 pesos in silver coins and bars, an order of magnitude more typically associated with the content of the royal treasury of New Spain.[682] Though the Spanish Crown was the owner of all the minerals to be found in its territories, it was private individuals who would retain around 80 percent of the value of all the silver extracted and refined within the Spanish Empire as of the sixteenth century, a very significant proportion by any standard.[683] For nearly 300 years Spain placed the whole financial risk of refining the silver ores of New Spain (and elsewhere in the New World) on the pockets of private individuals. This primary risk was not attenuated in a major way by any secondary support the Crown may have offered, as reflected in the survival rate within the

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[682] Couturier, *The Silver King*, 172.
[683] Humboldt estimated that 13 to 19% of the value of silver was retained by the Crown. Humboldt, *Essai politique*, Tome IV, 144-46.; 78.8% remained to the private silver refiner, according to Brown, *History of Mining*, 23.; 'silver taxes accounted for at least 12 percent and mintage fees for another 6 percent of silver's total value … transportation and miscellaneous expenses another 3 to 4 percent' in Garner and Stefanou, *Economic Growth Bourbon Mexico*, 115. This large share of revenues left in the private sector is cited as one of the characteristics of a 'pro-business institutional framework' in Rafael Dobado and Gustavo A. Marrero, "The Role of the Spanish Imperial State in the Mining-led Growth of Bourbon Mexico's Economy," *The Economic History Review* 64, no. 3 (2011): 862.

mining and refining business. The first Conde de Regla was part of the very small group of hugely successful investors and entrepreneurs who profited from this scheme. A far greater anonymous mass of Spanish *mineros* and *hacendados* participated in the silver lottery of the New World, where failure and bankruptcy was more common.[684] Whatever their size or success, the mining and refining operations created a novel and dangerous workplace context for the indigenous workers, their communities and their environment. The extent of this outstanding social and cultural debt on which the ultimate profitability of the Spanish silver extraction industry was built remains invisible in the accounts to be analyzed in this chapter.

The Spanish Crown made one significant exception to its policy of allowing the usufruct of its minerals in return for the payment of a royalty. The mercury mine in Spain at Almadén would be operated by private parties until the mid-seventeenth century under lease to the Crown, but throughout the colonial period the Crown retained a strict monopoly (*estanco*) on the distribution and sale of mercury in the New World.[685] No other raw material required by the refining processes was subject to this attempt by Spain at a rigid control of both supply and price, not even the silver ore itself. Why did mercury merit this singular attention? Mercury was never simply another reagent, on par with salt or lead. Even before it was used to amalgamate silver ores, the *Reyes Católicos* had considered the mines of Almadén to be the

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[684] In the Zacatecas of 1626, after 15 years of 'unprecedented amounts of silver', only 4 out of 95 owners of haciendas and mines were truly rich, according to Bakewell, *Silver Mining in Zacatecas*, 207. See also "Colonial Mining," 131. According to Brading, 8 out of 10 miners lost their money. Brading, *Miners Bourbon Mexico*, 169-70.

[685] The main reference work on Almadén are the two volumes by Antonio Matilla Tascón, *Historia de las minas de Almadén, 1 (desde la época romana hasta el año 1645)* (Madrid: Gráficas Osca, 1958).; *Historia de las minas de Almadén, 2 (desde 1646 a 1709)* (Madrid: Instituto de Estudios Fiscales, 1987). The other world-scale mercury mine that belonged to Spain during colonial times was Huancavelica, in the Vice-Royalty of Peru. Huancavelica would be operated directly by the Crown, but since it supplied a minor fraction of the mercury consumed in New Spain it will not be included in this chapter. One of the standard works on Huancavelica is by Guillermo Lohmann Villena, *Las minas de Huancavelica en los siglos XVI y XVII* (Sevilla: Impr. de la Escuela de Estudios Hispano-Americanos, 1949). The mine at Idria (see Chapter 1) would also supply mercury to New Spain, mainly in the eighteenth century. For studies on the mercury monopoly in New Spain see M.F. Lang, *El monopolio estatal del mercurio en el México colonial (1550-1710)* trans. R.C. Gómez (Mexico: Fondo de Cultura Económica, 1977).

jewel in their crown.[686] In 1609 the Viceroy of New Spain, Luis de Velasco, claimed that 'the most important business that exists today in the Indies is the trade in mercury, because it is its main pillar', evidence of its major role for the trade in silver.[687] The concern for mercury throughout the colonial period was twofold. It was evidently the technical lynchpin of the amalgamation process, but it was also in its own right a source of additional revenues to the Treasury, so that its role in the refining of silver had to be protected.

There is some evidence that the Spanish Crown consciously sought to obtain the highest possible price for mercury that the refiners in New Spain could bear, a kind of pragmatic sounding out of the elasticity of this novel market. Still, it is difficult to ascertain how the initial price levels were arrived at. There is an instruction from Joanna of Austria, the Princess Governess of Spain during the temporal absence of Philip II, who around 1559 issued a Royal Decree (*Real Cédula*) stating that 'we would benefit [on the sale of mercury in the New World] by earning double of what it costs over here [production cost at Almadén]'.[688] Whether this was simply a rule-of-thumb commercial advice of a timeless nature or an informed decision thanks to unknown advisors is not clear. The initial pricing levels per *quintal* in New Spain were certainly more than a doubling of the cost of production: 215 *pesos* in 1560, 310 *pesos* in 1565 and 1568, dropping to 180 *pesos* between 1572 and 1591, then to 165 *pesos* in 1591, 110 *pesos* in in 1597 until finally settling in for some 150 years at 82 *pesos* from 1617 onwards.[689]

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[686]'*los Reyes Católicos estimaban estas minas [Almadén] "como la joya mas apreciable de la monarquía"*'. Alfredo Menéndez Navarro, Un mundo sin sol, Biblioteca Chronica Nova de Estudios Historicos (Granada: Universidad de Granada / Universidad de Castilla - La Mancha, 1996), 158.

[687] '*el negocio mas importante que existe hoy en las Indias es el comercio del azogue, porque es su principal sustento*', as quoted in Castillo Martos and Lang, *Metales preciosos - union de dos mundos*, 139.

[688] '*Nos seriamos muy aprovechados y en dicho azogue se ganaría el doble de lo que acá costase*' in Castillo Martos, "Primeros beneficios amalgamacion," 378. It is not clear if she is referring to a sale price or net profit equal to double the production cost.

[689] There are many sources of mercury prices in New Spain during the colonial period in the historiography. I have chosen the values reported in Bakewell, *Silver Mining in Zacatecas*, 172.

The highest prices for mercury are registered during the initial years of the introduction of the amalgamation method to the New World. Comparing the level of New World prices to the known data sets of production costs incurred at Almadén (Figure 5-1), there is a comfortable margin between production costs (dots) and the price of mercury (solid black line) in New Spain until at least 1767, when the first decrease in price from 82 to 61 *pesos* is implemented, with the final decrease to 41 *pesos* decreed in 1776.[690] This conclusion remains valid even taking into account freight costs to the New World (2 to 3 *pesos* per quintal between 1568 and 1620s) and packing (under 3 *pesos* per quintal in 1619).[691] Prior to the second half of the eighteenth century, it was only around the 1660s that the margin had shrunk to levels that might reflect some financial sacrifice on the part of the supplier. Garner considers that the profit on mercury gained by the Spanish Crown ranged from 100 to 300 %.[692] Only in the last 30 years of this 300 year period could it be argued that mercury was by State design sold at or below its production cost at Almadén.[693]

[690] Production costs at Huancavelica were much higher, in the 58 to 73 pesos per quintal range. Brown, *History of Mining*, 32. However, mercury at Potosi was priced only slightly higher than in New Spain, as shown by the following values per quintal: 105 pesos in the sixteenth century, 97 pesos in 1645, 79 pesos in 1779, 71 pesos in 1787 and 50 pesos in 1809. Bakewell, "Colonial Mining," 122.

[691] Matilla Tascón, *Minas de Almadén (to 1645)*, 98, 221-222. Inland freight in New Spain was 3-4 pesos per quintal in the 1620s. Bakewell, *Silver Mining in Zacatecas*, 171. I have not found longer time series for these costs.

[692] Garner and Stefanou, *Economic Growth Bourbon Mexico*, 138.

[693] Matilla Tascón, *Minas de Almadén (to 1645)*, 37-183.; *Minas de Almadén (1646-1709)*, 97-113. Complimentary information from Bakewell, *Silver Mining in Zacatecas*, 172.; Lang, *Monopolio Estatal*, 50, 64. The end of the eighteenth century also saw the import of mercury from Idria, the 'German mercury' that appears in the accounts of the various *Cajas Reales* of New Spain, which was priced at the higher level of 62 pesos per quintal. Garner and Stefanou, *Economic Growth Bourbon Mexico*, 139. According to Humboldt, Idria mercury was priced at 52 *pesos* per *quintal* in 1784, but still provided a profit of 23% to the Spanish Crown. Humboldt, *Essai politique*, Tome IV, 87, 89. This change in Crown policy is one of the consequences of 'early Bourbon reformism' and signalled a decisive change from mercantilist policies on mercury to the proactive fostering of silver production, according to Dobado and Marrero, "The Role of the Spanish Imperial State in the Mining-led Growth of Bourbon Mexico's Economy," 869.

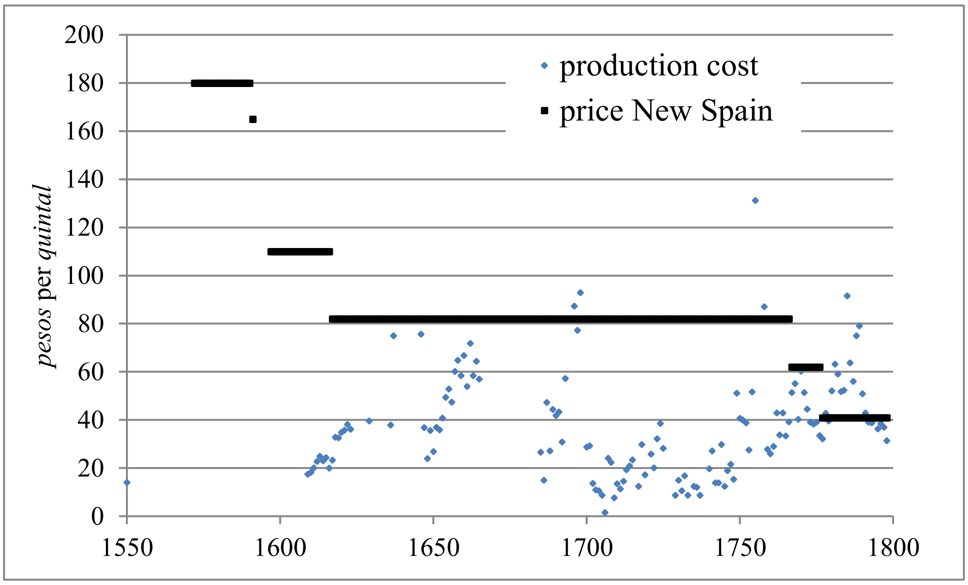

Figure 5-1. Production cost and price of mercury in New Spain, plotted from data in footnote 693.

Direct revenues from the sale of mercury were as prized by the Spanish Treasury as those from taxes on silver: According to Herbert Klein 'there is little doubt that mercury sales were the single largest generator of income [from monopoly taxes] in ... Mexico'.[694] The level of that net income, once production costs at Almadén or payments for mercury from Idria have been accounted for, has not been calculated, but the gross figures are impressive. From 1680 to 1809, the gross revenue from the mercury monopoly in New Spain was approximately 30% of the total revenues obtained by the Crown from mining activities.[695] A similar breakdown is

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[694] Herbert S. Klein, *The American Finances of the Spanish Empire : Royal Income and Expenditures in Colonial Mexico, Peru, and Bolivia, 1680-1809* (Albuquerque: University of New Mexico Press, 1998), 18.

[695] Based on the data in Table 5.2 (Estimated Average Annual Income from Mining Taxes, Vice-Royalty of New Spain, 1680-1809) and Table 5.3 (Estimated Average Annual Monopoly Tax Incomes, Vice-Royalty of New Spain, 1680-1809), assuming 30% of the average values in table 5.3 correspond to the sale of mercury (the percentage of total monopoly revenues corresponding to mercury related revenues is provided by Klein). Ibid., 19, 80, 86. It is not clear if Klein derives his estimate of 30% from primary sources. An estimate based on an average price of mercury at 72 pesos during this period, and government duties at 20% on silver indicates that mercury revenues should have been at least 40% of silver revenues. The difference with Klein's estimate may be due to a combination of incomplete records. It has been estimated that even at the peak periods of silver production, tax revenues from silver of the New World contributed one third of the revenues of the Spanish Treasury. Mauricio Drelichman and Hans-Joachim Voth, "Institutions and the Resource Curse in Early Modern Spain," in *Institutions and Economic Performance* ed. Elhanan Helpman (Cambridge, Mass.: Harvard University

observed in the data reported by Mendizábal for Pachuca in the early seventeenth century, with 50,000 *pesos* in revenues from silver taxes, and 30.000 *pesos* from the sale of mercury.[696] Even if adjusted by half to take into account production costs and freight to New Spain (inland freight was charged and accounted for separately within New Spain), the data confirm that mercury was an important source of revenue to the Crown in its own right.

In the light of the above, what can be deduced on the policy of the Spanish Crown in setting the prices for mercury in New Spain? The question is most pertinent since mercury is the economic parameter that has attracted the most attention in the historiography on production costs of amalgamation (see Section 5.2 below). As argued above, there is no evidence of mercury being sold consistently below its production cost before the third quarter of the eighteenth century. On pricing alone, the Crown was able to maintain a positive and substantial level of revenue thanks to its monopoly on mercury. This took place against two different operating models at Almadén. During the first century of amalgamation in New Spain the mercury mines of Almadén mines were leased to private concerns, with production targets and price set by the Crown in a public tender. After 1646 the mines would be run directly under the management of the Crown. The following two sections will explore how the Crown exploited its mercury from Almadén under each regime.

5.1.1 The Spanish Crown 'ganando indulgencias con escapulario ajeno'.[697]

Jakob Fugger, the founder of the banking dynasty, had managed to translate the very risky business of lending money to powerful, unpredictable and profligate royal debtors into a

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Press, 2008), 137. This would have made mercury sales the contributor of up to 10% of total revenues for the Treasury in Spain.

[696] Mendizábal, "Minerales de Pachuca," 274. His data are more in line with the expected ratio.

[697] 'earning indulgences with another's scapular'. A Spanish saying with strong Catholic overtones, it refers to gaining credit (religious indulgence) thanks to the sacrifices made by someone else (i.e. the symbolic commitment of having to wear a scapular under one's clothing).

huge personal fortune by claiming as collateral two valuable royal assets: land and minerals. Well before the first Conde de Regla bought his entry to Spanish nobility thanks to the refining of silver, Jakob Fugger had made a personal fortune from the mining and refining of silver and copper in *Mitteleuropa*. Columbus had not yet sailed to the New World when it was already an accepted practice of the Hapsburgs to raise loans by allowing the lender to take over the mining and refining of whatever commercial minerals happened to lie within their lands. Unpaid loans to the Crown came to be considered by the Fuggers as strategic sunk costs in return for net overall gains, whether as interest payments, minting rights or royal patronage in turbulent times of defaults by the Crown. As Charles V and then his son Phillip II managed to extract even greater sums from the heirs of Jakob Fugger, so was the Fugger family drawn into the sphere of royal assets in Spain, claiming as collateral the revenues from the *Maestrazgos* and ultimately the running of the silver mine at Guadalcanal. One of the prime assets of the *Maestrazgos* was the mercury mine of Almadén. The Fugger banking house would manage the mine in a series of periods that started in 1525 and would continue, with some lapses, until 1645, by which time the financially depleted banking family had ceded the production contract of Almadén back to the Crown.[698]

Matilla Tascón comments that the first contract to operate Almadén was offered as early as 1525 ‘in order to compensate him [Anton Fugger], according to what is said, for all that was owed to him by Charles V’.[699] The trail of debts owed by the Spanish sovereigns to the Fuggers up to mid seventeenth century as reported in the historiography does not differentiate what was owed due to mercury supplied from Almadén and what corresponded to unpaid capital and accrued interest. The following snapshots however provide enough information to suggest a

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[698] Matilla Tascón, *Minas de Almadén (to 1645)*, 37-326.
[699] *‘a fin de compensarle, según se afirma, de lo mucho que Carlos V le adeudaba*’ ibid., 37.

financial crash in slow motion. By 1560 the total debt owed to them by the Spanish Crown reached the sum of 2,975,797 ducats of 375 *maravedies* (over 4 million *pesos*).[700] In 1582 the Fuggers failed to produce mercury, and Matilla Tascón conjectures that this may have been linked to the fact that the Crown could not be trusted to pay them on time. By the end of 1633 the Spanish Crown's debts to the Fuggers reached over 4.7 million *pesos*. The representative of the Fuggers at Almadén complained to the Crown officials that no payments had been received for shipments of mercury from 1631 to 1633, and only partial ones had been made for 1630. In at least 1639 and 1645 remittances from New Spain derived from the sale of mercury were diverted to pay pressing obligations of the Crown, not to pay outstanding obligations on mercury to the Fuggers.[701] In the end, the Fuggers could not meet the delivery targets of the contract that run from 1636 to 1645.[702]

The leasing of Almadén to the Fuggers by the Crown took place well before silver changed the order of magnitude of the market for mercury, yet I suggest it would lead to a singular solution for its needs.[703] On the one hand Almadén would serve as a collateral whose value grew apace both with the need for mercury in the New World and with the increasing amount of debt owed to the Fuggers. At the same time, part or all of the debt outstanding to the Fuggers could be considered by the Crown as accounts receivable of the Fuggers, to be borne in increasing amounts by Almadén, repayable by the Crown at some point in the indeterminate future. By 1633 the total debt owed by the Crown to the Fuggers was equivalent to roughly 50,000 *quintales* of mercury at market price, capable of producing 5 million marks (1.2 million kg) of silver by amalgamation at a *correspondencia* of 100 marks per *quintal.* From 1560 to

[700] Ibid., 87.
[701] Lang, *Monopolio Estatal*, 79.
[702] Bakewell, *Silver Mining in Zacatecas*, 166-167.
[703] There is no similar reading in the historiography nor a reference to documents of the period stating an explicit policy of the Crown along the lines of my interpretation.

1639 a total of approximately 8 million kg of silver were refined by both amalgamation and smelting in New Spain.[704] Assuming that at least one quarter of this total was smelted in this period, this means that up to 20% of the total silver produced by amalgamation in New Spain by 1640 could have been due to mercury seemingly gifted by the Crown but ultimately paid for (as irrecoverable debt) by the Fuggers.[705] Since the values of mercury debt reported in the historiography for New Spain do not reach the level of 4 million *pesos*, it is probable the Crown did not even pass on the benefit of the total Fugger debt to the refiners in New Spain.[706]

The role of the Fuggers throughout this period raises at least two questions: why did they persevere until they went bankrupt, and why did they not reap the benefit from a textbook example of a new technology opening up a completely new market for a product only produced by them under licence from the Crown? To the first there is an article by the German historian of the Fuggers, Hermann Kellenbenz, which asks through its title whether the rent of the

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704 Based on a total of approximately 8 million kg of silver produced in New Spain from 1560 to 1639, according to Table 3-1 in TePaske and Brown, *Gold and Silver*, 112.

705 Almadén was the sole source of mercury in New Spain during most of the colonial period.

706 According to Lang, the debt run up on mercury by silver refiners in New Spain had already reached 1,080,000 *pesos* as early as 1580. Lang, *Monopolio Estatal*, 361. According to Bakewell the debt in New Spain by 1590 had increased to 1,828,787 *pesos*, and would still remain at 1.1 million *pesos* by 1597. To place these sums in perspective, new sales of mercury to the provinces of New Spain and Pachuca-Pánuco from 1590 to 1597 totaled some 2,500,000 *pesos*. Bakewell, "Notes Mexican Mining," 175-177. By the end of the sixteenth century a significant portion of the mercury that had been supplied had not been paid for. 'another of the correct appraisals by Calderon was to recognize that the [mercury] debt of the miners was irreversible' – '*otro de los aciertos de Calderon fue reparar que la deuda de los mineros era irreversible*', cited from a report from Alfonso Calderon to the *Concejo de Indias*, 15 April 1582 as quoted in Cubillo Moreno, "Dominios de la plata," 166. While there is no study of the average longevity of a mining-refining venture in New Spain during the last decades of the sixteenth century, it seems probable that not many of the original debtors were still in operation after seven years or more even if the Crown had decided to forcefully claim the sums owed on mercury: 'in Mexico, a mining success or bonanza rarely lasted more than a decade without the need arising for major capital investment'. Brading, "Mexican Silver Mining," 674. For mining/refining in the absence of bonanzas this period would be expected to be shortened. Bakewell and Lang report a persistent debt on mercury throughout New Spain during all the seventeenth century, with. Bakewell, *Silver Mining in Zacatecas*, 207.; Lang, *Monopolio Estatal*, 361. Castillo Martos states that the debt continued to be rolled over, never repaid, and a century later, in 1763, was approximately 1.12 million *pesos* for New Spain. Castillo Martos and Lang, *Metales preciosos - union de dos mundos*, 54, 145. A similar situation was also observed in the Vice-Royalty of Peru, with a mercury debt of 2.5 million pesos run up in Potosí as reported for the year 1608. Brading, "Mexican Silver Mining," 48. Nearly a century later the rolling debt remained high: 'some azogueros never paid for the mercury advanced to them, creating huge fiscal deficits. In the late seventeenth century, the Potosí refiners owed the treasury more than a million pesos in mercury debts, most of which the Crown never collected' in Brown, *History of Mining*, 23.

Maestrazgos was good business for the Fuggers in Spain after 1562. His short answer is yes, due to payments of interest rates that offered a way of slowly amortizing the outstanding debt and from collateral business opportunities, such as profits from arbitrage with Spanish silver minted at Hall (Tyrol) and Venice. Events not analyzed by Hellenbenz however indicate that ultimately by the mid-1640s the inclusion of Almadén had only aggravated their problem instead of solving it. The Fuggers had tried to extract themselves from the Spanish Monarchy's version of a Ponzi scheme as early as the 1550s. However the lure of fresh future cash flows offered as bait on each new demand for loans extended their line of credit to the breaking point.[707] As to the brave new world for mercury opened up by amalgamation, there is a certain irony in the fact that by inadvertently financing the introduction of amalgamation, the Fuggers became too weak to benefit from it.

5.1.2 The financing of Almadén and the price of mercury in New Spain.

The mercury debt owed by refiners to the Crown from the introduction of amalgamation in New Spain had been continually rolled over by successive Viceroys until Madrid issued instructions in 1634 to demand prompt payment from refiners for any new supplies of silver. This in turn has been interpreted as a watershed in the history of refining in New Spain, since the new and tougher attitude of the Crown with respect to mercury sales is claimed to have triggered a major switch from amalgamation to smelting after the 1650s.[708] This in turn introduced a major change in the profile of the environmental footprint left by the refining of silver. Lacueva places the context of this decision in 1634 to the new financial strategy of the Duque de Olivares, who since the ascension to the throne of the young King Philip IV in 1621

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[707] Hermann Kellenbenz, "Los Fugger en España en la época de Felipe II Fue un buen negocio el arrendamiento de los Maestrazgos después de 1562?," in *Dinero y crédito (Siglos XVI al XIX)*, ed. Alfonso Otazu(Madrid-Villalba-Segovia: Banco Urquijo 1977), 19-36.
[708] Lacueva Muñoz, *La plata del Rey*, 84.

had been implementing new ways to strengthen the collection of royal revenues.[709] However, the evidence presented in the previous section could also point to the realization by the Crown that the loans by the Fuggers, that had kept the mercury debt of New Spain rolling over for nearly one hundred years, were coming to an end.

The return of the mines to the direct control of the Crown did not offer any stability with regards their operational budget:

'[in the seventeenth century] the revenues from mercury sales to the Royal Treasuries … were diverted repeatedly to satisfying urgent needs of the Crown … deprived of a stable budget, Almadén and Huancavelica survived thanks to financial improvisations'.[710]

Matilla Tascon's detailed history of this period highlights persistent problems meeting the wages of its workforce or new capital investment in infrastructure, and a Royal Treasury using alternate regional taxes to fund Almadén. Even if the Crown had intended to manage the mines on the basis of their revenues from New Spain, this revenue never reached them in full or in a regular manner.[711] Variations in this eclectic manner of financing Almadén continue until 1708, when the oversight of the mine passes from the *Real Hacienda* to a *Junta de*

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[709] Ibid., 79-87.

[710] '[*en el siglo 17*] *los ingresos a las Cajas Reales por la venta de azogue ... se desviaron repetidamente hacia compromisos urgentes de la Corona ... privados de su dotación estable, Almadén y Huancavelica sobrevivían gracias a la improvisación financiera*' Castillo Martos and Lang, *Metales preciosos - union de dos mundos*, 146.

[711] In 1648 its workforce had not received their wages in nearly two years, the total labour debt at the time reaching 21.3 million *maravedises* (approximately 78,000 *pesos*). There was no money either to pay for the costs of new furnaces. The solution was to offer at least food to the workers (wheat, barley, oil) and to request the transfer of funds from revenues to the Crown (*servicio de millones*) due from surrounding towns (Alcázar, Villanueva de los Infantes, Ciudad Real). Ten years later the Kin g was still instructing the Viceroy in New Spain, the Conde de Alba de Aliste, to send to Spain as a separate remittance the revenues accrued from the sale of mercury in New Spain, the sum of 25 million *maravedies,* to cover investment in the mines. From 1650 to 1657, 3,165,814 *pesos* worth of mercury was delivered to Veracruz in New Spain, but only 678,887 *pesos* were remitted to Spain. It cannot be a surprise that from May 1658 to May 1659 production ceased at Almadén for lack of funds. By 1669 New Spain had still not sent to Spain the sum of 2,265,093 *pesos* still owed for mercury supplied in previous years. The consistent failure of this type of instructions, which according to Matilla Tascón were obeyed but never executed in the time honoured tradition of the authorities of the Hispanic New World, led the president of the *Real Hacienda* in Madrid in 1672 to assign specific amounts to be destined to the mines of Almadén from the revenues owed from the towns and regions of Córdoba, Villanueva de la Serena, Extremadura, Llerena and Trujillo. Matilla Tascón, *Minas de Almadén (1646-1709)*, 37-39, 117, 121.; Lang, *Monopolio Estatal*, 80-81.

Azogues, which is described by Matilla Tascón as giving '*palos de ciego*' ('swings by a blind man with a stick', a Spanish phrase that denotes any action taken in desperate ignorance of what is going on), as they tried to resolve the financing of operations at Almadén. The mine accounts had been inexistent for the past 5 years.[712]

The administrators of the operations at Almadén had no direct access to the sales revenues obtained from its ultimate customers in New Spain. In contrast, the monopoly sales from tobacco in New Spain were treated as a separate revenue channel that was sent directly back to Spain, bypassing the option for the local Vice-Royalty to spend it.[713] If the budget destined to maintain Almadén in operation was not sourced from the revenues obtained from its sales in New Spain, then the pricing of mercury was not determined by the normal sequence of production costs, capital investment, financing costs, expected return on capital and market reality (or elasticity). In such circumstances the application of any price level of mercury to its main market in the New World becomes more a question of maintaining traditional levels known to be acceptable, both as gross revenue streams to the Royal Treasury and by the needs of the refiners, to be adjusted only by the inspiration from the authority in place. The previous sections have underlined the discretionary nature of the price level of mercury for amalgamation, for which no historical evidence has been found that it was an informed decision based on the concatenated economies on the supply and production side of the silver refining chain.

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[712] Matilla Tascón, *Minas de Almadén (1646-1709)*, 125. Lang argues that the fortunes of Almadén prospered during the eighteenth century once the *Junta de Azogues* could follow the interests of the *Consejo de Indias* and not of the Royal Treasury. Lang, *Monopolio Estatal*, 63-96.
[713] Klein, *American Finances of the Spanish Empire*, 85, 94.

5.1.3 The environmental impact of the Crown monopoly on mercury.

A geological quirk of fate had placed the world's major source of mercury within the mainland of Spain, with enough capacity to supply nearly all the needs of New Spain. The Spanish Crown always regarded its Almadén mine as a special asset, and industrial scale amalgamation applied to the huge deposits of silver ore in New Spain raised its role as a revenue source to the Royal Treasury to unexpected levels. Since the mercury consumed in New Spain was to all practical purposes only sourced from Almadén, the strict control that resulted from the Crown monopoly of sales of mercury in New Spain also added the attraction of attenuating the production of contraband silver. Thanks to the *correspondencia* benchmark, the Crown officials could apportion mercury based on the production levels of silver, and not simply on the word of the refiner. The combination of a centralized source and an easy to apply operational benchmark made mercury a better option than lead or salt to keep track of the official production of silver and the corresponding payment of taxes.[714]

The question is therefore whether its obvious value as a revenue stream to the Treasury influenced the use of amalgamation in New Spain, and thus altered the course of its environmental history. Did the Crown take the conscious decision to manipulate the price of mercury so as to tilt the balance in favour of amalgamation versus smelting, thus guaranteeing an additional stream of revenues from its monopoly on mercury? The question recognizes that

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[714] Smelting was a refining operation on the household scale which for certain ores would not even have required a lead flux, so its control would be limited during colonial times. It could be argued that a rigid State control of salt would have been easier to implement, simply because its high bulk density would have made it much harder to traffic by contraband the large amounts required. The Spanish Crown only established a royalty on the production of salt from the major salt deposits in New Spain. The policy of the Crown in relation to salt in New Spain is similar to its policy on the usufruct of silver ores: 'it became obvious the Crown was avoiding all expenditure, even when, by so doing, some larger income was foregone'. The sources of salt in New Spain were multiple and 'on the periphery [where] it proved difficult to impose any strict control'. Local indigenous production was allowed in certain locations, as well as the farming out of production contracts to Spaniards. Ewald, *Mexican Salt Industry*, 19,21. As of the eighteenth century it established the Royal Monopoly of Salt Pans (Real Monopolio de Salinas). Mendizábal, *La mineria mexicana*, 79-81.

other important factors came into play in determining the balance between amalgamation and smelting, such as the chemical nature of the ore and the limits on the availability of all the resources required for each process.[715] Even so, the Crown could still have a deciding role, by actions such as withholding incentives in the search for lead deposits in New Spain, or guaranteeing the supply of cheaper mercury rather than cheaper charcoal. With no restrictions on raw materials and attractive pricing, smelting could have processed the widest range of silver ores in New Spain. The same could not be said of amalgamation.

Two parallel lines relevant to this question run through the primary sources of New Spain. One is the constant attempt throughout the colonial period in the New World to safeguard the level of mercury revenues to the Crown.[716] The other is the express intention of high officials to 'succour' the refiners, recognizing that without the production of silver there was no major source of mercury revenues for the Crown.[717] The tension between these two opposing drivers is evident: how far was the Crown willing to sacrifice its mercury revenues in order to assist refiners? The texts of the eighteenth century (Section 5.3) explicitly state the choice in mathematical terms, balancing the expected increase in silver taxes to the Crown against the expected loss of mercury revenues incurred by decreasing its price.

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[715] Chapter 6 will analyze the historical breakdown between smelting and amalgamation in New Spain and the influence of these factors.

[716] In Chapter 3, Section 3.5, reference was made to the zeal in prosecuting innovators in Potosí who in the late sixteenth century were searching for a more efficient use of mercury, which was feared to lower the volume of mercury revenues to the Crown. During the period of the Bourbon revision of mining and refining practices there was relief that smelting would never come to displace amalgamation, as examined in Francisco Pelayo López, "Las actividades mineras de J.C. Mutis y Juan José Elhuyar en Nueva Granada," *Revista de Indias* 50, no. 189 (1990): 462..

[717] '[it] succours the whole body of miners with the necessary mercury, taking note of those who need it and practising the due diligence to maintain the integrity of this activity' - '*se socorre el cuerpo todo de la minería con el azogue necesario, tomando cuenta a los que deben darla, y practicando las diligencias convenientes al seguro del ramo*'. This is a description of the role of the General Accountant for the Royal Mercury as quoted in Alejandro Espinosa Pitman, *José Antonio de Villaseñor y Sánchez, 1703-1759* (San Luis Potosí, S.L.P., México: Universidad Autónoma de San Luis Potosí, 2003), 56.

Modern historiography has interpreted the pricing policy on mercury by the Spanish Crown as a subsidy from the sixteenth century onwards. Herbert Klein is one of the several authors who insists in the importance of the Crown subsidy to mercury. As he phrases it: ‘on the question of subsidized mercury prices … the role of the crown [was] a major influence in mine production’.[718] Lacueva refers the decision by the Crown to demand prompt payment of mercury supplied to refiners in New Spain as a key event that ‘signalled the end … of the indiscriminate subsidy by the Crown … it became necessary to seek in the private sector the capital required to maintain afloat this sector’.[719]

It is not clear what is meant by the above use of the term subsidy, a word and concept that I have not come across in the documents of the period. The historical term subsidy in England in the seventeenth century meant ‘a tax levied at a given rate (specified in the statute) on the value of an individual’s movable goods or their income from land (whichever greater)’.[720] This is obviously not the case in New Spain, where the Crown ‘succoured’ the miners via the supply of mercury at a set price or through the pardoning of outstanding loans. In its modern economic sense, subsidy is an informed decision, based on a detailed knowledge of the impact on the production cost structure of the process to be favoured by the subsidy. In principle some greater national good (strategic, financial) must justify the channelling of resources to compensate what by itself would be a loss-making or non-competitive business. ‘A subsidy is a form of government support extended to an economic sector … with the aim of promoting an activity that the government considers beneficial to the economy overall and to

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[718] Klein, *American Finances of the Spanish Empire*, 82.
[719] ‘*supuso el fin … de la subvención indiscriminada de la Corona … fue necesario acudir a la iniciativa privada con el fin de allegar el capital necesario para mantener a flote el sector’*. Lacueva Muñoz, *La plata del Rey*, 84.
[720] http://www.nationalarchives.gov.uk/records/research-guides/taxation-before-1689.htm.

society at large'.[721] It is therefore not evident how the policy of the Spanish Crown with respect to mercury supplied to its colonial silver refiners meets the modern definition of a subsidy.

First of all, according to the history of mercury prices in New Spain (Figure 5-1), the highest values of all its market history are registered precisely in the first decades when the amalgamation process was being implemented in New Spain. This is the stage one expects a subsidy to be applied, to assist the new technology in gaining a foothold against the much more traditional process of smelting. Once amalgamation had taken hold, a major incentive to sacrifice revenues to the Crown from mercury sales disappeared.

Second, as a consequence of its policy of allowing the usufruct of its silver ores, the Spanish State had no first-hand experience during this period on the day-to-day running of a silver refining industry by amalgamation. It had not even been able to administer directly the Guadalcanal silver mine discovered in 1555, transferring its operation to the German financing family of the Fuggers. Even if it had, the ore produced was fit for smelting, not amalgamation. Amalgamation processes would only be implemented in Spain during the nineteenth century, at the silver mine of Hiendelaencina, and even then under the instance of English investors.[722] Its knowledge on the economic needs of the amalgamation process was at best second-hand, based on information supplied by the parties most interested in obtaining cheap consumables.[723] The empirical fact that even at the high end of mercury prices the volume of

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[721] Norman Kent Jennifer Myers, *Perverse Subsidies : How Tax Dollars Can Undercut the Environment and the Economy* (Washington, DC: Island Press, 2000), 5-8. Current definitions of a subsidy can be as varied and complex as a reader may wish, since modern international trade and tax systems have now made subsidies a complex legal battleground.

[722] In his obituary, a John Taylor born at Holwell, near Tavistock, Cornwall in 1808, son of a Mr. John Taylor, is mentioned as having been involved in the setting up of the Bella Raquel mining company that used the Freiberg barrel amalgamation process to process the silver ores from the Hiendelaencina mines. It is most probable the experience of John Taylor, father, at Real del Monte was being recycled now in Spain. Anonymous, "Memoirs of members deceased in 1881," *Proceedings - Institution of Mechanical Engineers* 36 (1882): 14.

[723] 'The Crown …did not intervene … in the day to day technical decisions of production, nor in their financing' -*'La Corona ... no intervino ... en las decisiones técnicas que marcaban el día a día de la explotación, ni en su financiación*'. Julio Sánchez Gómez and Guillermo Mira Delli-Zotti, "Minería americana y minería europea,

New World silver flooded over world markets, overwhelming at the beginning the European silver industry, gave the pragmatic answer to the Spanish officials that the mercury price being applied was enough to insure continued production of silver, an argument that would hold until the middle of the eighteenth century. The only quantitative production parameter that can be claimed on historical evidence to have been available from the sixteenth century to the Spanish authorities was the *correspondencia*. At a price of around 120 *pesos* per quintal of mercury in the late sixteenth century, the cost of mercury would correspond initially to approximately 15% of the value of silver produced by amalgamation.[724] Had a subsidy been intended, a much lower pricing range for mercury would have been adopted.

Third, accepting the premise that a flexible interpretation of subsidy would include not only a price drop but also the non-payment of outstanding loans on supply, up to 1646 events have revealed that if on the one hand the Crown in Spain was not receiving all the revenue from the sale of mercury, neither was the Crown paying the Fuggers for all the mercury that was being distributed in New Spain. German private capital had provided what Lacueva termed as the 'indiscriminate subsidy' up to 1646. A forced largesse of this nature cannot be interpreted as a subsidy to the refiners by the Spanish Crown, but rather the result of an opportunistic financial play that evolved in time, contingent on unfolding events on either side of the Atlantic.[725]

1750-1820: una perspectiva comparada," in *Mundialización de la ciencia y cultura nacional: Actas del Congreso Internacional "Ciencia, Descubrimiento y Mundo Colonial"*, ed. A. Lafuente, et al.(Aranjuez (Madrid): Doce Calles, 1993), 107.

[724] One kg of silver is equivalent to 4.4 marks, or approximately 35 *pesos* in value. Two kg of mercury are 0.043 *quintales*, which at 120 *pesos* per *quintal* represent 5 *pesos* in value. This represents some 15% of the total value of silver refined. As the price of mercury dropped to 82 pesos, the cost of mercury as a percentage of the value of silver refined would decrease to around 10%.

[725] The Spanish Crown did offer its indirect support to miners and refiners in the New World, though the local elites would have been expected to reap the most from this assistance (preferential supply of mercury to major refining concerns, dispensations from the payment of royalties, and other major tweaks to the system). The fact that the English investors in the region around Pachuca as late as the nineteenth century had to invest major capital simply building roads is an indication of the limited extent of the Crown's involvement in the general

Fourth, it is only after 1776 that the price of mercury in New Spain is seen to drop to the level of its production cost, or even below, the first clear sign that one of the conditions of a subsidy has been met. After 1776 the sacrifice of mercury revenues to the Crown had to be justified not only by a significant increase in silver production but also by an efficient use of the cheaper mercury, the latter a condition that will be further explored in Chapter 6.

Underlying the question as to whether a subsidy ever existed with regards to mercury pricing set by the Crown in New Spain are two more fundamental issues. First, a subsidy is applied by decreasing the cost to the producer of the input that has the greater impact in determining the final price of the product, in order to allow it to compete in the market. The price of silver in the period of interest was independent of the price of mercury, or of any of its manufacturing inputs by either process, since it had remained fixed over centuries by other economic conventions (Section 5.4). A decrease in the price of mercury by the Crown sought completely different objectives. It increased the incentives for private individuals to assume the business risk of producing silver, it increased the production of silver by increasing the amount of ores that could now be profitable to refine by amalgamation, and it affected the overall balance between amalgamation and smelting so as to keep the former in the

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infrastructure required by its silver industry. The extent to which the ordinary miner-refiner benefitted from the assistance of the Spanish Crown can be better judged in relation to what the German miners still received from their King in the region of the High Harz at the beginning of the nineteenth century. The King had the right to retain one tenth of the value of the minerals extracted (silver, lead, copper); to have a share in each mine, around 3%; to build all the common infrastructure required by mining and refining (water reservoirs, galleries to discharge water from mines, for crushing the ore, and smelters) and to operate the washing and smelting of ores exclusively, all for a fee payable by each mine. Finally, the Crown bought exclusively the lead and copper at a price lower than market prices, and profited from the difference (silver was coined at the official rate). On the other hand, the King had the obligation to provide all the wood required by mining and refining at no cost except that of cutting and freight; all other industrial consumables were sold at a regulated price, at times below market; the chief officials for mining, smelting and forests were paid by the Crown, all other wages by each mine; the Crown would provide a fixed amount of cereal (rye) at a low price to each worker; the Crown would partially compensate the mine for unexpected increases in certain materials if it could prove unable to meet the new prices; it would also compensate for certain increases in the price of oats required for the animals used in mining; injured or sick workers were cared for, and a fund established for widows. There is a major difference between the above and providing a legal framework for the claims of mines, selling mercury above its cost of production, and providing escorts for the shipments of silver. Héron de Villefosse, *De la richesse minérale du Royaume de Westphalie*, 89-94.

ascendancy.[726] Had the Crown decided to supply lead or charcoal below their production costs, the balance would have tilted towards smelting.[727] At the same time, the only reason that could convince the Crown to sacrifice its revenues on mercury was to compensate with an increase in the royalties it received from silver production and the concurrent increase in the monopoly sale of mercury.

It has been an implicit assumption in all the previous discussion in the historiography that the price of mercury was the defining economic factor that determined the competition between smelting and amalgamation, or even the final production levels of silver in New Spain. However, there is a dearth of hard economic data on production costs for amalgamation and smelting in the historiography to sustain this assumption, as will be made evident by the review presented in the following section.

5.2 The historiography on the economies of refining.

The historians of silver refining in the New World have been in the same quandary as the Spanish Crown. They know how much silver was registered, how much mercury was sold and at what price, but are quite in the dark as to the exact production costs involved in the amalgamation or smelting of silver ores in the New World. Even mercury, the most studied of all consumables of this period, was left at the end of the previous section with major questions pending regarding its exact economic impact on the production costs of amalgamation and its role in determining production levels of silver in New Spain. The quotations cited at the beginning of this chapter show how the foremost English and Spanish historians of colonial

[726] Dobado and Marrero argue that ‘it was in the interest of the Crown that amalgamation should be the preferred technique for silver refining’, in Dobado and Marrero, "The Role of the Spanish Imperial State in the Mining-led Growth of Bourbon Mexico's Economy," 866.

[727] The balance in refining processes will be treated in Chapter 6. See also the analysis of the shifting balance between amalgamation and smelting and the influence of mercury and lead costs and availability in Blanchard, *Russia's "Age of Silver". Precious-metal Production and Economic Growth in the Eighteenth Century* 3-31.

silver refining have found a landscape quite devoid of hard economic data on the production of silver from ores in the New World.[728]

The first historical attempt at an economic analysis of the production costs of amalgamation for New Spain was written in the mid-eighteenth century.[729] It is a discussion in print between the Accountant General of the Royal Mercury *(Contador General de los Reales Azogues*) José Antonio de Villaseñor y Sanchez and the Overseer of the Royal Mint (*Guardavista de la Casa de la Moneda*), Jose Antonio Fabry.[730] It takes place between 1741 and 1743, and contains as its central theme the two main arguments used at this time in favour and against a decrease in the rice of mercury, which had been held at 82 *pesos* per *quintal* for nearly 150 years. Villaseñor is defending the revenues to the Crown from the sale of mercury. He grounds his analysis on the fact that it costs the same to amalgamate an ore irrespective of its content of silver, except for the variable cost of mercury. On this basis he argues that even at the price of 82 *pesos* per *quintal,* the refiner could still make a profit with ores of 2 oz of silver per *quintal* (0.13% silver content by weight). Since the expense for mercury is

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[728] Bakewell, *Silver Mining in Zacatecas*, 187, 207.; Brading, *Miners Bourbon Mexico*, 154, 158.; Garner and Stefanou, *Economic Growth Bourbon Mexico*, 118.; Lacueva Muñoz, *La plata del Rey*, 58. Other historians have voiced similar concern over the dearth of hard economic data on refining by amalgamation or smelting in the New World: 'only minimal documentary evidence has been found' - *'no se han encontrado mas que minimas referencias documentales*' Cubillo Moreno, "Dominios de la plata," 30.; 'the documents on haciendas do not mention the workforce they employed … and it seems the account books of these production units have disappeared … no account books or other documents are known that registered specifically the levels of production' - '*los documentos sobre haciendas no hablan de la mano de obra empleada en las mismas ... y al parecer los libros de cuentas de estas unidades de producción han desaparecido ... no se conocen libros de cuenta u otros documentos que anoten específicamente los niveles de producción.*'. Lara Meza, *Haciendas de beneficio de Guanajuato*, 102, 105. I have not found in my own more modest searches within the archives of San Luis Potosí, Zacatecas or Guanajuato any account books that allow a reconstruction of production costs over time. The snippet of data available do not match the amount of detailed quantitative information on prices, consumption, costs, labour and ore quality as I have found for Regla in the second half of the nineteenth century.

[729] In Chapter Three I have made reference to the anonymous document that includes annual costs incurred for amalgamation in Potosí in 1601, but there is no comparable source at present for New Spain during the first two hundred years.

[730] Fabry, *Impugnacion a reflexiones de Villaseñor*. Jose Antonio de Villaseñor y Sanchez (1703-1759) is much better known as the author of a detailed description of the main cities and provinces of New Spain, published in two volumes as the *Teatro Americano*. For a biography see Espinosa Pitman, *Villaseñor y Sánchez*. He was the senior official in New Spain in charge of accounting for the distribution of mercury under the Crown monopoly.

proportional to the silver content, ores with lower silver content would only incur a small cost for mercury, and yet have to meet the much greater relative cost of all other expenses out of an increasingly smaller monetary value of silver content. He concludes it would not make sense to refine these ores even if mercury was given away for free. In case the cost of extraction could be circumvented by using ores found discarded in tailings, he calculates that even at 82 *pesos* for mercury the refiner could make a profit working with ores that had as low as 0.06% silver content (see Table 5-I). By placing the emphasis on the influence of the extraction cost of the ore on the final profit level of the refiner, he makes an extremely pertinent observation:

> 'what makes mines [and refining] unprofitable is the labour-intensive drainage, the tough nature of the ore wall, the timbering of the supports, the cutting and removal of the ores, the wages of the workers, the need of food, forage for the animals powering the drainage … even if they gave away lakes of mercury, these costs would never be met [for the low silver ores] … what limits silver mining is the lack of this ingredient [mercury] not its price'.[731]

What is impressive about Villaseñor's line of argument is not so much its mathematical conclusions, which as always depend on the validity of the starting values, but because he applies an elegant and concise method for analysing the sensitivity of refining production costs to the silver content of the ore. He freezes as a virtual fixed cost all the variable costs of production so they remain at the same level irrespective of the silver content of the ore. The only exception is the cost of mercury, which he varies as a function of silver content (see Table 5-I). He includes the extraction cost of the ore in order to calculate the level of profit for the refiner, an approach rarely seen in later exercises probably for lack of data. He applies the same extraction costs regardless of the richness of the ore, which is correct for the range of ores he includes in his working examples. He differentiates the ores from tailings by assuming the

[731] '*lo que hace incosteable las Minas son los laboriosos desagües, la dureza de sus frontones, el echado de sus respaldos, corta-saca de sus metales, carestía de operarios, necesidad de alimentos, y pastos para las bestias de los desagües ... aunque se diera en lagos el Azogue, nunca se costearían ... hace escasa la minería de plata la falta de ingrediente, no su precio*'. Fabry, *Impugnacion a reflexiones de Villaseñor*, 5.

extraction cost of the latter is by now a sunk cost, thus nil. He recognizes that the higher expense of mercury for ores with higher silver content is compensated by the increase in value of the silver refined. All that is missing from a perfect score is the fixed capital cost to the refiner and its impact on the break-even pricing for mercury.[732]

ore source		mine				tailings (terreros)
% silver (weight)	% (weight)	0.5%	0.25%	0.13%	0.06%	0.06%
silver content per *quintal*	oz / *quintal*	8	4	2	1	1
amount of silver in 100 *quintales*	marks	100	50	25	13	13
value of silver in 100 *quintales* @ 8 *pesos* 6 *tomines* per mark	*pesos*	873	437	218	109	109
mercury consumed	*pesos*	82	41	21	10	10
other production costs, including extraction, @ 1.5 pesos / quintal	*pesos*	150	150	150	150	
only other amalgamation costs @ 0.5 pesos per quintal	*pesos*					50
total variable production costs	*pesos*	232	191	171	160	60
profit	*pesos*	641	246	48	-51	49

Table 5-I. Interpretation of Villaseñor's working examples and method that sustained his argument against decreasing the price of mercury. Data adapted from footnote 730.

Fabry countered by arguing that in reality a greater portion of ores lie below the breakeven point calculated by Villaseñor at a mercury price of 82 pesos per quintal. By questioning the values adopted by Villaseñor he concludes that at 41 pesos per quintal it would be possible to make profitable to the refiners the amalgamation of the abundant ores with a low

[732] He also provides the historian with a guide as to an order of magnitude of extraction costs in mid eighteenth century (1 peso per quintal), as well as that of amalgamation costs net of mercury (0.5 pesos per quintal). Ibid., 1-5.

silver content. He then calculates that the increase in tax revenues from the additional production of silver would more than compensate the Crown for the decrease in the revenues from mercury. Fabry's line of reasoning highlights the distinction made at the end of Section 5.1.3 that the aim of reducing the price of mercury was not to reduce the price of silver but to increase its total output so as to compensate for the loss of mercury revenues.[733]

A very similar argument to that of Fabry is used in a 1774 report addressed to the Spanish King, Charles IV, by the Guanajuato medical doctor and miner Manuel Jose Dominguez de la Fuente. The reduction in the pricing of mercury from 82 to 62 *pesos* per *quintal* had not pacified the miners and refiners, who sensed that the Bourbon King was willing to decrease the price even further, since he was asking for their official view on what should be the ultimate lowest price of mercury. It is in this light that any economic breakdown provided by Dominguez de la Fuente should be read: it is an exercise in lobbying the Crown in favour of lower mercury prices, not an accounting book.[734] He argues for a lower price for mercury since this would allow miners to market the majority of the ore extracted, that at the time was being rejected as unprofitable by the refiners.[735] Villaseñor would have countered that

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[733] Fabry questions both the monetary value of one mark silver (8 *pesos* 6 *tomines* instead of 7 *pesos* 5 *tomines*) and the cost of extraction employed by Villaseñor. Ibid., 6-36.

[734] As a miner of modest means he faced the separation implemented in the mining/refining model by the eighteenth century, whereby those who only refined the ore by tolling (*maquila*) in haciendas took most of the profit and left the risk to those who only extracted the ore: 'the Miner is he who works; and the Refiner he who benefits' - 'el *Minero es el de el trabajo; y el Haziendero el beneficiado*',a pun on the refining (*beneficio*) of ores. He claimed that the owners of refining haciendas purchased the ores from miners 'under very questionable assumptions [as to deemed silver content, in the absence of assaying] … the Miner leaves with his doubt and mistrust and the Buyer keeps his reserve [the level of underestimation of the silver content] and his cautious [approach]'- '*bajo de mui falibles conjeturas … el Minero se va con su duda y desconfianza, y el Comprador queda con su Reserva y cautela*'. The value of silver extracted was paid after two and a half months in Guanajuato, and the cost of the maquila was considered 'very burdensome and because of that very disheartening' - '*mui gravosissima y por esso de grande desconzuelo*'. Since the refiners could only pass on to the miners the official cost of mercury as part of the toll charge, the benefits in the decrease in price would reach them in two ways, by increasing the amount of ore they could sell and by decreasing the cost of *maquila*. It is not known if it ever reached the Royal Court. The paleography of the original manuscript by Dominguez de la Fuente was carried out by its present owner, Salvador Covarrubias Alcocer, and published as Dominguez de la Fuente, *Leal Informe Politico-Legal*, 102, 104, 199.

[735] According to the author the most common ores had a silver content of 3 to 5 marks per *montón* of 32 *quintales* I have inferred he refers to marks per *monton*, since marks per *carga* would indicate too rich an ore not to be

the price of ore proposed by Dominguez de la Fuente at 4 pesos per *montón* does not reflect his real extraction cost estimated at 32 *pesos* per *montón*, in which case it still remained a question of throwing good money after bad. Dominguez de la Fuente could have replied that the lower quality ore was part of the normal output of a mine, so any price for his ore of 4 marks per *montón* silver content was better than throwing it away to the tailings heap, and the Crown would still compensate the drop in mercury price by selling more mercury to amalgamate the new quantities of ore coming to the refiners instead of being discarded.[736]

The next group of extracts from the historiography of the late eighteenth and early nineteenth century correspond to the period of the lowest historical prices for mercury in New Spain, thus the texts no longer discuss the issue of mercury revenues vs price. Production costs are reported but with no details on how they are calculated. I have summarized the main

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purchased. At the time refiners in Guanajuato were not buying ores for amalgamation with less than 5 marks of silver (0.083%) per *montón.* According to his data the custom of refiners was to purchase ore (*recibir de los Mineros a la Ley*) at a price of 11.6 *pesos* per kg of silver content. He proposes that refining centres (*Haziendas Refaccionarias*) be set up to work expressly with the large amounts of ore available with just 4 marks per Guanajuato *montón* (0.06 % silver), to be sold at a price from 3 to 8 *reales* per *carga*. The refiner would still obtain a profit, since the lower price of mercury would compensate for the purchase of the ore with a lower silver content His quantitative argument is not easy to follow, and the following interpretation is tentative: he uses virtually the same variable cost of amalgamation (without mercury) as Villaseñor, at 16 pesos 1 real per *monton*; he proposes that refiners can purchase ore at 3 *reales* per *carga* with a silver content of 4 marks per *monton*, or 4 pesos per *monton*. This adds up to 20 pesos for the cost of amalgamation of 1 *monton*, without mercury. He then arrives at a total cost of 22 *pesos* 2 *reales* per *monton*, from which I deduce he is using a cost of 2 *pesos* 2 *reales* for the cost of mercury consumed, which at a *correspondencia* (not given) of 100 marks per *quintal* of mercury, implies a new lower price for mercury of approximately 53 *pesos* per *quintal*. Ibid., 90-91.

736 The compensation in direct revenues to the Crown comes from the opportunity cost of both additional silver production and mercury sales that would not otherwise have been possible at the higher price for mercury, if Villaseñor's arguments are discounted for now. Thus assuming a *correspondencia* of 100 marks per *quintal*, a deemed value of 8 *pesos* per mark of silver and direct government revenues of 20% of the silver produced, a drop from 62 *pesos* to 41 *pesos* per *quintal* requires that total revenues of 222 *pesos* be maintained from a new level of (1+x) *quintales* of mercury at 41 *pesos* per *quintal* and 0.2*100(1+x) marks of silver at 8 *pesos* per mark, which gives a value of x of 0.1. This means that at least a 10% increase in mercury sales was required just for the Crown to breakeven in direct revenues. Based on an ore with 4 marks per *monton*, this would require amalgamating 2.5 new *montones* for every 10 *montones* of ore previously amalgamated (assuming an average of 10 marks of silver per *monton*, 0.16%), approximately a 25% increase in ore purchased by the refining haciendas, an obvious windfall for miners. Since the alternative was to increase the amount of value-less tailings, from the view-point of an opportunity cost Dominguez de la Fuente had a very valid point, finding the weakness in Villaseñor's arguments.

economic data that can be abstracted from all the texts included in this section in Table 5-II.[737] The background of each source is relevant. Garcés y Eguía is promoting his smelting recipe based on the claimed benefits of adding *tequesquite*, a naturally occurring sodium carbonate salt.[738] Humboldt provides one table on ore extraction cost, sundry information on mercury prices, and no details on production costs.[739] An unexpected ratio comes out of his figures on labour for these mines. On the basis of the number of workers employed underground in the mines, at Valenciana the ratio is 400 *quintales* of ore extracted, 200 marcs of silver produced per worker, while in Germany it is 25 *quintales* of ore extracted, 18 marcs of silver per worker. The German mine is less deep than the Valenciana mine (330 m to 514 m according to Humboldt) and its ore nearly twice as rich in silver, yet Humboldt does not comment on the disparity in the production output per underground worker between these two mines. It indicates a manpower efficiency an order of magnitude greater in Guanajuato than for a mine chosen from the most traditional mining area of the Erzgebirge in Europe.[740]

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[737] a) Fabry, *Impugnacion a reflexiones de Villaseñor*.b) Dominguez de la Fuente, *Leal Informe Politico-Legal*. c) de Sarria, *Ensayo de metalurgia*. d) Garcés y Eguía, *Nueva teórica del beneficio de plata*. e) Humboldt, *Essai politique*. f) Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*. g) Duport, *Métaux précieux au Mexique*. h) Laur, "De la metallurgie de l'argent au Mexique." i) Collins, *Metallurgy of Lead & Silver*.

[738] In his examples he works on the premise that it is possible to partition by washing on the *planillones* 100 *quintales* of an ore mixture with an average silver content of 0.25% into 90 *quintales* with a silver content of 0.14% (my calculation) that is treated by amalgamation, and 10 *quintales* with a silver content of 2.7% that is smelted. It is on this unexpected premise that he argues for the benefits of his smelting process in saving expenses on mercury, to the deemed benefit of the refiner. The higher the silver content prior to partition, the greater the saving on mercury, the higher the benefit to the refiner. Garcés y Eguía, *Nueva teórica del beneficio de plata*, 144-146. Sodium carbonate was a known agent of flux for smelting much prior to this publication, for example the use of soda as a flux in Agricola, *De re metallica*. Footnote pages 233, 558. His offhand reference to Sarria's earlier text which already mentions the use of *tequesquite* may be an effort to distract attention from the fact this additive was already known. Garcés y Eguía, *Nueva teórica del beneficio de plata*, 81. At Regla *tequesquite* would be tried for a few months and then discarded.

[739] Humboldt compared the extraction costs for the mines of Valenciana (Guanajuato) and Himmelfürst (near Freiberg, Germany) in an average year at the end of the eighteenth century. At Valenciana his data leads to an extraction cost of 6.9 *livres tournois* (1.3 *pesos*) per quintal, or 60.4 *livres tournois* (11.5 *pesos*) per kg of silver refined. For the European mine, it comes to an extraction cost of 17.1 *livres tournois* (3.3 *pesos*) per quintal of ore, 104.3 *livres tournois* (19.9 *pesos*) per kg of silver refined. Humboldt, *Essai politique*, Tome III, 413.

[740] For Valenciana he reports an ore that had on average 4 oz (0.5 marks) of silver per *quintal*, so that 720,000 *quintales* of ore from said mine produced 360,000 marks of silver by smelting or amalgamation; for Freiberg the ore has an average of 6 to 7 oz per *quintal* of silver, and from a production of 14,000 *quintales* a total of 10,000 marks of silver are refined. Ibid. The exchange rate of *pesos* (*piastres*) per *livre tournois* is calculated from Humboldt's assertion that 805 million *livre tournois* are equal to 153,333,000 *piastres*. Ibid., Tome IV, 255.

location	extraction cost	period	amalgamation costs		smelting costs	silver content	source
			excluding cost of mercury, cost of extraction of ore, capital cost	including mercury, excluding extraction cost of ore	excluding cost of extraction of ore, capital costs		
	peso/quintal ore		*pesos / quintal* ore	*pesos* / mark silver	*pesos / quintal* ore	%	
generic	1	mid 18c	0.5			0.125 to 0.5	a, 1-4
Guanajuato	?	end 18c	0.5			0.08 - 0.13	b, 90-91
generic	?		0.5 - 0.6		3 - 5	?	c, 131
generic	?		0.625			0.25	d, 144-146
generic	?				4	2.7	
Valenciana mine, Guanajuato	1.3					0.25	e, 255
generic	?		0.5 - 0.75			low to medium	f, 92
Zacatecas	?	mid 19c			5.3 - 6.7	'rich minerals'	g, 83-84
Sombrerete	?				2.7 - 3.3	'rich minerals'	g, 85
Nieves	?				1.3 - 2.7	?	g, 85
Zacualpan	?				5	?	g, 86
Guanajuato	?		*0.63*			?	g, 232
	?			2.15 (*maquila*)		*0.23*	g, 233
	?			*3.3* (*maquila*)		*0.19*	g, 233-234
	?			*4.8* (*maquila*)		*0.08*	g, 235
Zacatecas	*4.1*			2.55 (*maquila*)		0.46	g, 252
	?			*3.7* (*maquila*)		0.14	g, 275
Tasco	1.08			*3.3* (*maquila*)		0.15	g, 340-341
generic	*< 1.68*			*2.3* (*maquila*)		0.2	g, 370-374
Cerro San Pedro, San Luis Potosi	?				1	up to 0.3 (35% lead)	h, 246-248
Sombrerete	?				*2.4*	up to 1.75, medium to low lead	h, 248-250
Catorce	?				7	0.15 to 0.9; max 10% galena	h, 251-252
Regla	?				6.1	1.7; poor in lead	h, 253
Durango	?	end 19c	*0.90*	*1.15*		*0.18*	i, 60
Zacatecas	?		*0.32*	*0.39*		*0.07*	i, 60
Zacatecas	?		*0.33*	*0.39*		*0.05*	i, 61
Fresnillo	?		*0.46*	*0.51*		*0.06*	i, 61
Tasco	?		*0.41*	*0.72*		*0.32*	i, 61
Pachuca	?		*0.41*	*0.73*		*0.30*	i, 61

Table 5-II. Summary of amalgamation and smelting costs in New Spain/Mexico from the historiography up to the nineteenth century. Figures in italics are calculated from source data. Sources are indicated in footnote 737.

Sonneschmidt's monograph was published late, in 1825, though he should be assigned to the group of authors publishing around the turn of the century. He became an avowed disciple of the Mexican *patio* amalgamation method, but provides no support to his estimates:

'the amalgamation of New Spain … will subsist as long as the world subsists … the greatest advantage [to amalgamation] … is its low cost … ores with low or medium silver content, can be refined at the moderate cost of four to six *reales* per *quintal* … there is no cheaper refining cost even in Europe'.[741]

He considers production costs to be the major obstacle for smelting to compete with amalgamation, an important if qualitative conclusion from a first-hand observer and practitioner of refining in New Spain. He also recognizes the critical distinction between total mercury cost and the cost of mercury per unit of silver extracted: 'only in the refining [by amalgamation] of rich minerals does the cost rise, due to the greater consumption and loss of mercury, which is always proportional to the amount of silver extracted'.[742]

Finally, to complement the authors of the turn of the century, there is a primary document from 1802 that due to the scarcity of sources of this nature I have reproduced in full in Appendix D.[743] It is a narrative that throws further light into the world of Dominguez de la Fuente. Middlemen now appear who made a living without necessarily investing in fixed capital: the *rescatadores* who bought the ores at the mine mouth, refined it themselves and/or

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[741] '*la amalgamación de Nueva España subsistirá mientras que subsista el mundo ... la major ventaja ... es el poco costo ... minerales pobres y de mediana ley, se benefician con los moderados costos de cuatro o seis reales por cada un quintal ... beneficio más barato no lo hay ni en Europa'*. Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 92.
[742] '*solo en el beneficio de minerales ricos suben los costos, por motivo del mayor consumo y perdida de azogue, que esta siempre proporcionada con la ley de plata que se extrae'*, ibid.
[743] It is preceded in the archive by a letter dated 21 April 1802 from a delegation of Mining Deputies from Catorce (San Luis Potosí) informing that they have carried out the request by the Viceroy of New Spain dated 31 March 1802 to carry out a trial comparing the production costs of refining via the *cazo* process with smelting, using the same quality of ore for each process. Since the results reported in the letter do not correspond to the details in the report dated 21 April 1802 in Appendix D, with different signatories to each document, it would seem at least two trials were carried out, of which only one set of detailed results has survived in the archival records.

by *maquila*, and sold the refined silver at a discount to the *aviadores* (suppliers of goods on credit, also applies to the leasing of mines). The document is not an account book and its data are limited to single trial runs on small quantities. Even with these limitations it still reveals the nuances that apply to silver refining in New Spain. For example, even though amalgamated silver is said to achieve a higher price than smelted silver (Chapter 2), in this report it is the other way around. As to the processes involved, the document reveals the reality of the *cazo* process as practised in Catorce in the 1800s. Since the *cazo* process only extracted two-thirds of the silver content, in order to make it more profitable it was then necessary to treat the fine silt that came out of the vessels (*lamas cocidas*) by the conventional *patio* amalgamation to complete the extraction of the other third of silver.[744]

In this document the distribution of production costs for smelting is skewed by the very high cost of the ore at the plant gate and the need to lease the smelting facilities (Table 5-III). Both these factors would only apply to the case of middlemen involved in the refining of silver at Catorce. Smelting is shown to be unprofitable for these ores with 3 marks of silver per *carga* (0.5%) at a price of 12 *pesos* 4 *reales* per *carga* delivered to the refining unit. However, the authors point out that ores with 10 marks of silver per *carga* (1.7 %) can be smelted at a profit, subject to the pricing established by the mine owners.

From the mid-1820s to the end of the century much more information on refining comes out of the new independent Mexico, concurrent with the opening up of the silver mines to foreign investment and involvement. The most detailed economic data on amalgamation and smelting in Mexico during the nineteenth century come from three sources, St Clair Duport (1842), Buchan (1856) and Laur (1871). These authors provide an oasis of detailed information

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[744] I do not know if this two stage refining process applied to all the ores refined at Catorce.

	production variables	cost for 3 cargas, in pesos	summary	pesos		pesos/kg silver
	ore+freight	37.5		37.5	% of subtotal 1	
cazo	miller	0.4				
	tahonas workers	0.6				
	cazo workers	1.5				
	salaries	0.5	labour	2.9	33%	
	impure salt	1.0	impure salt	1.0	11%	
	mercury	1.0	mercury	1.0	11%	
	palma	1.5	others	3.9	44%	
	straw for mules	1.3				
	tahona	0.4				
	deposits	0.4				
	heating and refining	0.4				
	subtotal 1		for 6 marks silver	8.9		6.4
patio	mixing	1.5			% subtotal 2	
	washing vats and labour	0.3				
	amalgamator	0.4	labour	2.2	43%	
	impure salt	1.1	impure salt	1.1	22%	
	mercury	1.6	mercury	1.6	32%	
	magistral and lime	0.2	others	0.2	4%	
	subtotal 2		for 3 marks silver	5.1		7.4
	total exc. ore		for 9 marks silver	14.0		6.8
	total inc. ore		for 9 marks silver	51.5		24.9
			value of silver at 7 pesos per mark	63		
			profit (loss)	11.5		
smelting	miller	1.6			% total inc. ore	
	mixer	0.8				
	fluxing ore	1.9	labour	2.3	3%	
	litharge	22.5	litharge	24.4	30%	
	charcoal	7.3	fuel	7.3	9%	
	lease smelting furnace	9.0	others	10.8	13%	
	cupell	1.3				
	palma	0.5				
	total exc. ore			44.8		
	total inc. ore		for 7.5 marks silver	82.3		47.7
			value of silver at 7.5 pesos per mark	56.25		
			profit (loss)	-26.0		

Table 5-III. Production costs as reported in 1802 for the *cazo*, *patio* and smelting refining processes carried out at Catorce (San Luis Potosí), adapted from data in footnote 743 and Appendix D.

on production costs and practices based on a wide selection of Mexican refining operations, within an otherwise barren landscape on either side of the nineteenth century. Duport's monograph on Mexican silver production is a work that well merits the recognition given by his peers of the time.[745] Based on his extensive experience in Mexico he was another staunch European supporter of the patio amalgamation process. His breakdown of its production costs, excluding the cost of ore, before steam engines were installed at the amalgamation *hacienda* in Fresnillo is very perceptive. Instead of using the usual process stages such as milling, *patio* and washing, he apportions the cost according to the following headings: animal power 12%, labour 22%, fuel 1%, mercury 34%, salt 17%, *magistral* 9%, maintenance and others, 5%. He thus captures in a single set of numbers the essence of the colonial *patio* amalgamation process: pure animal and human energy mixed with chemical reagents, with no delicate machinery in-between.[746] In the case of amalgamation he considers the lack of power options to lower the cost of milling the ore a major challenge, since this stage absorbs more than half the total production cost and around 19% of the final value of silver.[747] Duport includes the variant of roasting the ores prior to *patio* amalgamation, as practised in Tasco, where the threshold for amalgamation to be profitable was a silver content of 0.125%.[748]

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[745] The treatise by St. Clair Duport was judged by Percy, himself a major figure in the nineteenth century on metallurgy, to be 'one of the best on the subject' Percy also mentions that he could not add the details on operations at Pachuca because a Mr. Buchan of the Real del Monte Company died suddenly a few days after promising to add to the text to be published on patio amalgamation. Percy, *Metallurgy*, I 576. Randall has pointed out that Duport did not include the major operations at Real del Monte and Regla, apparently due to conflicting commercial interests. Randall, *Real del Monte*, 236.

[746] His data from the Hacienda of Fresnillo (Zacatecas) is a very useful reference point for future sections of this chapter, due to the industrial magnitude of its operations and the fact it did not possess sources of hydraulic power or inexpensive sources of fuel. From 1st February 1838 to 31st January 1839, it processed 28,407 *montones* (of 920 kg) of an ore with an average 0.2% silver content, producing 229,035 marks of silver at a total cost of 645,370 *pesos.* Duport, *Métaux précieux au Mexique*, 279-80.

[747] Ibid., 400.

[748] Roasting according to Duport consumes 2% of the final refining cost of 2.08 *pesos* per *quintal* of an ore with 0.15% silver content. The extraction cost of ore accounts for 52%, at 1.08 *pesos* per *quintal*, 19% to mercury, 6% to salt and 4% to *magistral*. The cost translates to 30.1 *pesos* per kg of refined silver, which is getting close to the deemed silver value within the ore, but it already includes a 3.5% margin for the operator of the refining hacienda. According to Duport, under these conditions (mercury at 130 *pesos* per *quintal*, salt at 3 *pesos* per *quintal* and *magistral* at 3.5 *pesos* per *quintal*) the operator will not be able to refine at a profit ores with less than 0.125%

Based on his data set that covers most of the main mining districts of Mexico, Duport is the first to propose a detailed profile for the generic production costs of *patio* amalgamation in Mexico, based on an ore with 0.2% silver content [average], mercury at a price of 130 *pesos* per *quintal* [high], and a consumption of mercury of 13 oz per mark of refined silver [average]. He takes as a reference point the costs of placing one kg of silver on board a vessel for export from Mexico [free on board], expressing the costs in their equivalent in silver value, so as to drive home the point that costs have to be lower than the value of silver in the ore. Table 5-IV reproduces his estimates. The cash-in-hand margin available to the refiner to meet extraction costs and profit places a ceiling on extraction costs of 5.04 pesos per *carga* of ore of 0.2% silver content.[749]

He considered smelting as practised in Mexico up to the early 1840s to be inefficient as to fuel consumption, with no effort made to improve furnaces or the fluxes used, losing 15% of silver in the process. For Duport there was not sufficient incentive to improve current practices since he considered it was not an option to treat the majority of ores with a silver content between 0.15 and 0.2 % of silver.[750] He stated that it was 'impossible to establish the separate production cost items … for smelting' (Table 5-II).[751]

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silver content, since already at this level the cost of production rises to 8 pesos per mark of silver (35 pesos per kg of silver). Ibid., 340-41. The cut-off value corresponds to Villaseñor's limit for amalgamation at 2 oz of silver per quintal of ore.

749 Ibid., 370-374. The reasoning employed by Duport to treat export costs as discretionary implies the refiner could sell with equal opportunity to the domestic market if he manages to meet the cash costs of extraction, refining and government duties. It seems to ignore that since the majority of silver was exported as coin, these costs would ultimately have to be factored back in by any party purchasing silver in Mexico for export.

750 Ibid., 398.

751 *'impossible d'établir des prix séparés pour les parties de la production … de la fonte'*. Ibid., x, 83, 85, 351.

	g fine silver	
Government duties		145
export	*35*	
entry to port	*20*	
coinage	45	
casting bars	45	
Essay costs, smelting coinage costs		10
Freight to port		*25*
Mercury		112
Patio costs		342
rent	17.1	
general administration	20.52	
other reagents	61.56	
labour	47.88	
milling	171	
other costs	23.94	
total		634
margin to cover extraction cost and profit		366
margin without costs of export		446

Table 5-IV. Generic profile of *patio* amalgamation costs (excluding ore cost) in Mexico as practised around 1840, expressed in terms of g of fine silver. Specific export costs are highlighted in bold and italics. Data from footnote 749.

In 1855 John Buchan made public his report to the Directors of the Real del Monte Company on the workings of the mines and the refining of silver in their *haciendas*, including Regla. It is a source of generous information on the cost structure of a working commercial concern, rare for the degree of detail provided to the public.[752] Due to the relevance of its information to this chapter, I will address its content within the context of my own analysis of the accounting data from Regla in the following sections. There is an additional source of production economic data from the previous Adventurers Company of Real del Monte: 'John

[752] Buchan, *Report Real del Monte*. I am not clear what the intention was at the time to share with the public the production costs of the company in such detail.

Phillips found that for the year 1840 the cost of smelting was only 34 per cent of the value of silver produced, while that of *patio* amalgamation was 46.25 per cent'.[753]

The third author of note is Laur. He estimates that the range of silver content of the majority of ores in Mexico lies between 0.1 and 0.27%, which in his view are sufficient to cover the variable mining and amalgamation costs of the ore.[754] In the case of smelting, he reports that in general its costs are very high due to a lack of fuel, unless the ore is rich in lead (around 25 %). For lead-poor silver ores he states that the threshold silver content for smelting to be profitable in Mexico is 0.5 %. Of the partial variable cost, excluding the extraction cost of the ore, labour can make up from 19 to 55%, fuel 25 to 41%, and litharge when required up to 33%.[755]

By the end of the nineteenth century all major metallurgical texts included technical details on the Mexican *patio* amalgamation process. I will single out Collins who provides an interesting table of comparative costs for different amalgamation *haciendas* in Mexico that is not derived from the previous three authors. His values of production costs without including mercury are within the range of the other values in Table 5-II. Collins' data include the sourcing

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[753] Quoted from a report to the Directors dated 29 June 1841, Real del Monte Proceedings, in Randall, *Real del Monte*, 114. Burkart's lengthy essay on Real del Monte, translated by Miguel Velazquez de Leon and published in 1861, draws too much on Phillip's statement of 1840 and Buchan's report of 1855 to be considered a source of new data for Mexican refining operations. Burkart, "Memoria Real del Monte."

[754] By choosing a silver content of 100g per 100 kg of ore as the threshold value (0.1%), he is assuming that the value contained in around 70 g of silver per 100kg of ore is enough to cover all costs and leave sufficient profit for the refiner. In addition to the economic data on refining costs, Laur offers an interesting focus on the issue of the sourcing of power, since steam and animal sources incur costs, while water was nominally free. In the case of animal power it was subject to oscillations in the pricing of animal feed, and he cites the example of a major refining hacienda in Fresnillo that switched to steam engines around 1850 after the yearly expenditure on animal feed rose from 468,000 francs to 2,464,000 francs. He argues that silver production in Guanajuato decreased as the price of maize increased from 1862 to 1864. He employs two examples of what he terms average refining haciendas that use amalgamation to refine suitable ores, where the variable production cost (without including the cost of the ore or fixed capital costs) for ores between 0.09 and 0.2% silver content lies in the range of 30 to 42 g of fine silver per 100 kg of ore. Laur, "De la metallurgie de l'argent au Mexique," 51-62, 198-201.

[755] He mentions a range between 165 francs (15 *pesos*) per ton of ore to 800 francs per ton (72 *pesos*). The *peso* to franc conversion is based on Laur's equivalence of 13 *pesos* per *carga* to 50 francs per *quintal*, 0.09 *pesos* to 1 franc. For ores with more than 20% lead he provides data on the basis of an implicit value of 1 kg silver at 39.1 pesos. Ibid., 106, 243- 254.

of power for each *hacienda*, though it is the cost of the inputs that determines the major differences in his range of production costs.[756]

In the historiography since the 1970s I have only found three new examples of primary sources on production economics.[757] Brading in 1971 reproduces the data from one weekly account for an unnamed *hacienda* in the region of Zacatecas in 1801. My calculation of his breakdown of variable operational costs, net of the cost of ore, yields 17% for labour, 25% for raw materials, 26% for mercury and 33% for others, for an ore with an average of 0.19% of silver. The extraction cost of ore is 1.9 *pesos* per mark of silver.[758] He concurs with Villaseñor that 'refining profits depended upon what must remain, for the historian, an unknown factor – the price paid for the mineral in the auctions held at the pit-head'.[759] Where he differs from Villaseñor and Duport is in his view that with increasing silver content the expenditure on mercury was also higher, so that he concludes 'a point was then soon reached when it became more profitable to smelt than to amalgamate'.[760] He is not alone in the historiography in focusing on the total cost of mercury incurred instead of on the cost per kg of silver obtained.

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[756] Collins, *Metallurgy of Lead & Silver*, 60-61.
[757] The Mexican historian Rina Ortiz Peralta published two works on the Compañia Real del Monte. Rina Ortiz Peralta, "El beneficio de minerales en el siglo XIX: el caso de la Compañía Real del Monte y Pachuca," *Historias* 30(1993).;"Algunos aspectos del beneficio de minerales en el siglo XIX: el caso de la Compañia de Real del Monte y Pachuca," in *Hombres, Tecnica, Plata. Minería y Sociedad en Europa y América, Siglos XVI - XIX.*, ed. Julio Sánchez Gómez and Guillermo Mira Delli-Zotti (Sevilla: Aconcagua Libros, S.L., 2000). In the more recent work she includes a table with production costs for the barrel and patio amalgamation processes, but based on data from secondary sources already commented upon in this section (Burkart and Collins). Since she does not add new primary sources to the discussion I do not include her in my selection.
[758] His data includes a heading of a minor cost item under 'consumption of lead and litharge in *arrastre*', which may imply that smelting was carried out on a fraction of ore with higher silver content separated during milling. Brading, *Miners Bourbon Mexico*, 153-154. Table 10.
[759] Ibid., 155.
[760] Brading uses the following example: 1.875 pesos is the cost of mercury consumed in refining one *montón* (30 *cargas*) of an ore with 1 oz of silver, and 4.5 pesos for the mercury consumed refining the same amount of an ore with 2.5 oz of silver. Ibid. Table 11. The latter corresponds to 1.8 pesos of mercury per oz of silver, a 4% decrease in the mercury ratio for a 150% increase in silver amalgamated, in other words the mercury to silver ratio can be considered constant, and it is the margin of profit that is important, not the absolute amount spent on mercury per *montón*.

In 2008 Garcia Mendoza published his study of total mining and refining costs in two refining *haciendas* of Tasco, as registered in the period from the 2nd August 1562 to the 26th June 1564. This is an exciting time of innovation within the refining community of New Spain, barely eight years after the first use of mercury to process silver ores, when smelting had to be challenged successfully on costs and efficiency by this upstart technology if it was to be displaced. Unfortunately his attempt to determine how much silver was produced by either process is seriously flawed by his interpretation of the raw data.[761] The document provides useful information on the costs of consumables and labour in this early period, though not the amount of ore processed, the silver content of the same, or other important production parameters.[762] The analysis does not answer the question as to why amalgamation displaced smelting in New Spain.

In the same year Suarez Arguello and von Mentz published a compilation of correspondence and an extensive transcription of weekly summaries of partial production data of the mines and refining of silver carried out at Vetagrande on the outskirts of the city of Zacatecas, for two time series at the turn of the eighteenth century (1791-94, 1806-09). The quantitative information, such as the amount of ore treated and silver refined, debts, and other sundry cost items are not analyzed from an accounting point of view and by their limited nature

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[761] When any archival document of the period states that 'the yield for each *quintal* of lead was between two and three marks of silver'- '*el rendimiento por cada quintal de plomo era entre dos y tres marcos de plata*' it is referring to the yield from silver-rich lead ores, not to the amount of lead flux (*greta*) required to refine a quantity of silver. This misinterpretation invalidates his estimations of silver refined by smelting. In the case of mercury, he uses a mercury to silver weight ratio of 6.83, the number of significant figures belying the fundamental error of his value. This is an incorrect ratio, totally at odds with the chemistry and all the historical data on mercury to silver ratios reported in Chapter Three. His estimate for silver obtained by amalgamation is also wrong. The author then proceeds not to use his flawed breakdown between smelting and amalgamation, and analyzes costs (including labour) based on the combined activities of mining and total refining. García Mendoza, "Minas de plata en Taxco," 48-49. See also Table 2, p. 54.

[762] It is very significant that his primary sources do not include *magistral* or copper sulphate amongst the expenses incurred during amalgamation, which confirms the line of thought that the use of *magistral* originates first in Peru and then is incorporated in New Spain as of the early seventeenth century (Chapter Three).

cannot be used to establish production costs.[763] In one of the letters transcribed in their work there is an interesting comment regarding the guidelines applied at Vetagrande (Zacatecas) to decide on the refining option according to the content of silver in the ore:

‘in our smelting furnaces at Sauceda … we refine by fire … and as long as their silver content is 20 ounces per *carga* [0.42%], they offer profit to whoever has their own smelting facility, for the only other option is to throw them out together with the tailings, because using amalgamation would only mean wasting money on them’.[764]

The last sentence is intriguing, since one interpretation is that he has fallen into the trap of thinking that ores with a high silver content are more expensive to amalgamate since they consume more mercury. Otherwise his conclusion is a negation of all that has been reviewed so far.

The remainder of the historiography since the 1970s to the present is best grouped according to three strands of narrative since no new primary sources are added to what has been presented in the preceding paragraphs:

Amalgamation is the lowest cost option to refine ores with ‘low’ silver content. Subject to the price of mercury, the lower limit of profitability is set at 1.5 to 2.5 oz of silver per *quintal* of ore, 0.09 to 0.15% silver by weight.[765] Mercury is considered ‘the single most expensive item in the refining operations [by amalgamation]’.[766] It is proposed that mercury constituted 18 to 41% of the total cost of refining in minerals with 2 to 4 oz of silver per *quintal* (0.13 to

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763 Suarez Arguello and Von Mentz, *Epistolas y cuentas Vetagrande*.
764 ‘*en los hornos de fundición que tenemos en Sauceda … se les saca por fuego la que tienen, y como no baje su ley de 20 onzas por carga, ofrece utilidad a quien tiene fundición propia, pues de lo contrario sería necesario tirarlos al terrero, porque por el beneficio de azogue se perdería dinero en ellos'*. Extract from a letter sent to Don Antonio de Bassoco, on the 8th July 1808, as transcribed in ibid., 699.
765 Bakewell, *Silver Mining in Zacatecas*, 138.; Castillo Martos and Lang, *Metales preciosos - union de dos mundos*, 147.; Brading, *Miners Bourbon Mexico*, 120-121.; Garner, "Long-Term Silver Mining," 242.
766 "Long-Term Silver Mining," 249.; Lacueva Muñoz, *La plata del Rey*, 72.

0.26%).[767] It is also proposed that refining costs ranged from 18 to 24 percent of the value of silver produced.[768] No detailed breakdown of production costs is submitted to support these ranges.

Smelting is the lowest cost option to refine ores with 'high' silver content, which would otherwise incur a high cost of mercury. Lang does point out that this conclusion is only valid if the cost for both processes is compared based on a *montón* of ore.[769] The threshold cited to pass from amalgamation to smelting is given between 4 and 8 oz of silver per quintal of ore, 0.26 to 0.52%.[770] No detailed breakdown of production costs is submitted to support this range.

Smelting is the lowest cost option to refine silver ores in general. 'The smelting process was simpler, shorter and less costly than amalgamation'. This is certainly a minority opinion, but has been stated forcefully by Lacueva in one of the most recent books on colonial refining of silver in New Spain. In the absence of hard data on production costs, of which he is explicitly conscious, he bases his arguments on indirect indicators such as number of process stages.[771] It also seems to mirror John Phillips' assessment in his report to the Directors of the Adventurers Company of Real del Monte cited above.

Production choices over three centuries were made by a motley crew of refiners guided only by the amount of money in their pocket at the end of the day, and this in turn influenced the environmental history of silver refining in the New World. Amalgamation has

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[767] Brading, "Mexican Silver Mining," 668, 673.; Castillo Martos and Lang, *Metales preciosos - union de dos mundos*, 140.
[768] Brading, *Miners Bourbon Mexico*, 153.; Garner and Stefanou, *Economic Growth Bourbon Mexico*, 119.
[769] Lang, *Monopolio Estatal*, 50-51.
[770] 4 oz in Castillo Martos and Lang, *Metales preciosos - union de dos mundos*, 140.; 8 oz in Lang, *Monopolio Estatal*, 50-51.; 4 to 8 oz as a grey zone in Lang, "Silver Refining Technology in Spanish America (patio y fundición) " 141.
[771] '*el proceso de fundición era mucho más simple, más corto y menos costoso que el de amalgamación*' in Lacueva Muñoz, *La plata del Rey*, 89. It is the basis for his argument that amalgamation had been imposed by the sources of capital on the refiners, since thanks to its inherent drawbacks it provided a greater degree of subordination of the production factors to the owners of capital.

overshadowed much of the discussion, and it is common to find sweeping but unsupported statements such as 'mercury was essential to colonial silver mining because without it most of the silver ore could not be profitably refined'.[772] Dissenting voices have started to question the monothematic insistence on mercury:

'the frequent correlation that is proposed between the lack of mercury with the mining crises [in New Spain], underestimates how the miners could compensate using smelting according to the silver content of the ores being extracted … it is necessary to investigate the regional differences to establish the vulnerability of the economy to any restriction in the supply of mercury'.[773]

Back in 1943, the Mexican historian Mendizabal had already proposed factors totally unrelated to mercury to explain the unexpected increase in silver production registered in the district of Rosario at the end of the eighteenth century.[774] A necessary starting point, though not as interesting as repressed sexual drives, is the quantitative analysis of the cost of refining silver. Bakewell's common sense dictum that 'mining would obviously not have survived for long unless someone were making a profit from it' was correct in stating the obvious: if both amalgamation and smelting had prevailed over centuries, and made some people very rich, it

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772 Garner and Stefanou, *Economic Growth Bourbon Mexico*, 132.

773 *'la relación frecuente que se hace de la falta de azogue con las crisis mineras, menosprecia el complemento que los mineros podían tener con el proceso de fundición de acuerdo a la ley del mineral que se estaba extrayendo … hay que investigar las diferencias regionales para saber la vulnerabilidad de la economía ante la limitación en el abasto de azogue'* in Rosa Alicia Pérez Luque and Rafael Tovar Rangel, *La contabilidad de la Caja Real de Guanajuato. Una aproximacion a su historia economica 1665-1816* (Guanajuato, Mexico: Universidad de Guanajuato, 2006), 88-89.

774 The rich and various levels at which explanations can be found to account for variations in silver output in each mining region is well illustrated by the case of silver, Rosario and sex. In order to explain why the mining district of Rosario, in the period 1785 to 1789, contributed greater silver revenues than the more renowned Cajas of Guadalajara, Pachuca, Bolaños and Zimapan, Mendizabal proposed that this was due to the proletarianization of the indigenous workforce following the expulsion of the Jesuits from New Spain. As soon as the indigenous males of Rosario were freed from the Jesuit restrictions of working in mining, an occupation that was held to expose them to alcohol consumption, gambling and sexual relations, they flocked to the mines and haciendas of Rosario to make up for lost time, and thus created the peak in silver production. Mendizábal, *La mineria mexicana*, 62.

obviously made economic sense to have used them.[775] The rest of this chapter will attempt however to arrive at a more quantitative solution to the following questions:

Was mercury the major variable production cost in the amalgamation of silver or is the prominence of mercury costs in the historiography to a large extent the consequence of a lack of information on other cost items? Villaseñor and Duport have provided enough information in the historiography to render this narrative suspect. It is necessary to evaluate the influence of the total cost structure for amalgamation, such as salt, labour, the source of power for milling and the extraction cost of the ore in determining the final profit.

Under what conditions can the economies of smelting and amalgamation be compared in a meaningful way? The indications are already present in the historiography up to the nineteenth century that this comparison cannot be attempted by simply stating production costs divorced from the silver content of the ore they refer to. The sensitivity of such costs to the silver content of the ore was pointed out by Villaseñor over 250 years ago and yet remains to be fully reflected in the discussion. A more quantitative analysis is required on the boundary conditions as to silver content that would have determined the viability of one process over the other. In particular it is necessary to revise the long-repeated notion that a higher consumption of mercury made unprofitable the amalgamation of ores with a high silver content.

Why could smelting compete with amalgamation? As Chapter 6 will make evident, smelting accounted for around 40% of all the silver refined in New Spain, which implies it consistently provided profits to refiners throughout the colonial period. Could it be that, contrary to a narrative along Orwellian lines of ‘amalgamation good, smelting bad’, either process was profitable under certain conditions?

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[775] Bakewell, *Silver Mining in Zacatecas*, 187.

To reach an answer to these questions it is necessary to have access to a historical accounting data base that does not incorporate anachronistic elements such as steam or electricity, obtained from a commercially functioning industrial *patio* amalgamation and smelting operation, from which the cost structure of production can be calculated. There is no substitute for long time series of prices of consumables for each process, an operational accounting of their consumption, a detailed breakdown of labour costs and structure, and the amount and price of the product. The accounting books of Regla offer this resource to the historian.

5.3 The accounting records for Regla

The account books of Regla and other *haciendas* of the Compañia Real del Monte report in great detail the production costs for both amalgamation and smelting over the course of the second half of the nineteenth century, and their analysis will take up the rest of this chapter. [776] The value of the accounting records of production costs kept by the Compañia Real del Monte lies not only in their detail over decades, but also because this company was one of the very few mining and refining conglomerates in Mexico that ran three distinct refining methods concurrently on an industrial scale (*patio* amalgamation, barrel amalgamation and smelting). In the period 1853 to 1888, the Compañia de Real del Monte had spread its refining activity of silver ores from the mines of Real del Monte over five different refining *haciendas*, each with a specific remit as to the refining process it used to produce silver. Thus Regla applied *patio* amalgamation and was the only refining unit to smelt ores; Sanchez, Velasco and San Miguel only processed ores using amalgamation in *toneles* (barrels), along the lines of the

[776] Initially the new Mexican owners of the company decided that its accounting should be carried out by the Treasury of the Casa de la Moneda, and then by the Compañia de Tabaco, both enterprises that the owners also managed during this period. It is thanks to the insistence of one of the owners, Nicanor Beistegui, that the company was allowed to keep its own accounts as of 1852, which in turn made possible the contents that have served so well this chapter. Ruiz de la Barrera, "La Empresa de Minas del Real del Monte," 76, 81, 83.

Barba/Born/Freiburg process pointed out in Chapter 3; Loreto used mainly patio amalgamation though in at least one year it is listed as also applying amalgamation in *toneles*.[777] The production costs for each refining unit were also compared to each other, in the way modern business compares the profitability of discrete production units within an overall corporate cost structure.[778]

The analytical structure of the following sections is as follows. First I proceed to establish the macroeconomic scenario of the nineteenth century, its impact on operating costs and the viability of extrapolating economic data to the previous centuries. I then calculate the production cost of both processes as practised at Regla in the third quarter of the nineteenth century, averaged over at least a decade.[779] I determine for each process the input economic variables with greater impact on the final production cost, as well as a general breakdown of production costs by main areas. Finally, based on the cost structure for each process, I evaluate sensitivity scenarios to estimate how economic and technical conditions prevalent in the previous centuries would have impacted the relative production costs of both processes.

5.4 The macroeconomic context in the nineteenth century.

In the following sections I will be calculating and comparing costs across many decades without deflacting them. I will therefore briefly discuss the general economic context of these periods, both with regards to the pricing of silver and to inflation, and whether there was any impact from these factors on the time series of pricing for the main consumables at Regla.

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[777] The fame of Regla as a smelting centre transcended Real del Monte: 'the most important factory in Mexico for the refining of mineral ores by smelting is Regla' - '*L'usine la plus importante du Mexique, pour le traitement des minerais par la fonte, est celle de Regla*'. Laur, "De la metallurgie de l'argent au Mexique," 252.

[778] In Appendix B, I present the structure of the accounting books and explain how their information at times overlap or complement each other.

[779] According to Laur accounting records from Mexican refining *haciendas* may be subject to an under-accounting of received ores, so as to hide losses or pilfering or to compensate for inefficiencies of the refining processes. In the case of Regla I am analyzing the data at face value. Laur, "De la metallurgie de l'argent au Mexique," 91.

5.4.1 Silver

The difference in the valuation of silver with respect to gold in Europe and China, and the resulting effects of arbitrage on the world economy since the mid-sixteenth century have been amply commented upon in the historiography.[780] From a ratio of around 12 to 1 with respect to gold, the value of silver depreciated over the centuries in Europe to reach the 15 to 1 range by the mid nineteenth century, a devaluation of just 25% over 300 years.[781] When the Mexican investors stepped into the shoes of the Real del Monte Company they could have been

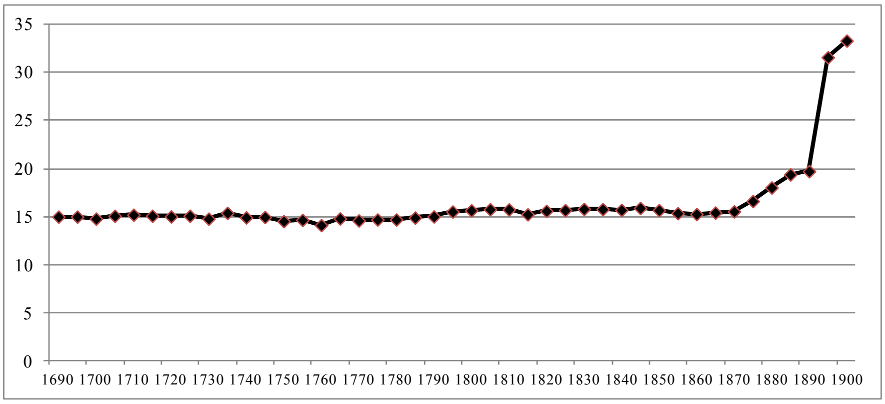

Figure 5-2. The evolution of the gold to silver ratio from 1690 to 1900. Data from footnote 781.

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[780] For example see Flynn and Giraldez, "Cycles of Silver: Global Economic Unity through the Mid-Eighteenth Century.";Dennis O. Flynn and Arturo Giraldez, "Arbitrage, China, and World Trade in the early modern period," *Journal of the Economic and Social History of the Orient* 38(1995).

[781] 'Average commercial ratio of silver to gold each calendar year since 1687' in the Report of the Director of the Mint contained within the Annual Report of the Secretary of the Treasury on the State of the Finances for the Fiscal Year ended June 30 1921, p. 654. http://fraser.stlouisfed.org/docs/publications/treasar/AR_TREASURY_1921.pdf

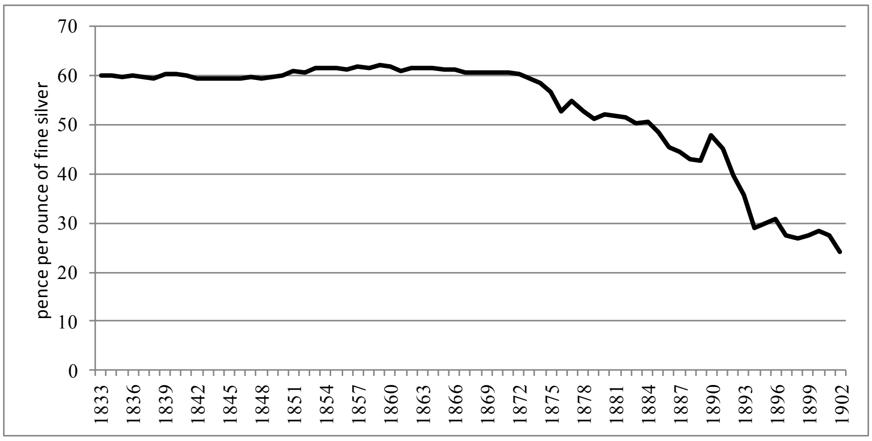

Figure 5-3. The evolution of the price of silver in the London market. Data from footnote 781.

forgiven for thinking that past performance of silver pricing was a very good guarantee to project future results. For nearly two hundred years the gold to silver ratio had been remarkably stable (Figure 5-2).[782] For any capital investor, the degree of confidence on future revenue streams is a major element in determining the expected economic viability of an industrial project. In the late 1840s the future price of silver was not a factor of concern to the silver refiners of Mexico, judging by the most recent stability of its international price at around 60 pence per ounce of fine silver in the London market (Figure 5-3). And yet Duport ends his extensive monograph on silver in Mexico published in 1846 with a phrase that captured both its technical longevity and an intimation of its mortality: 'a time will come, give or take a

[782] The same cannot be said of the silver content in the coinage minted by the Crown. The initial silver content was set at a value of 11 deniers 4 grains for 1 mark, which was made equal to 65 *reales* (8 pesos and 1 real). Then came a succession of devaluations via the reduction of deniers to a mark, or reales to a mark, reaching a cumulative 18% from colonial times to 1826. Joaquin D. Casasus, *La Question de l'argent au Mexique* (Paris: impr. de Chaix, 1892), 28-30.

century, when the only limit to the production of silver will be imposed by the accelerated decrease of its value'.[783]

As of the 1870s the floor shifted in a major way from under the silver market.[784] By 1902 the price of silver in London, the benchmark for silver sales in the world and the destination for much of the silver exported from Mexico in the nineteenth century, had plummeted to less than half its 1870 value, a near mirror-image of the devaluation of silver with respect to gold.[785] In 1873 H.R. Linderman, the Director of the U.S. Mint, included in his annual report an analysis of the developing weakness in the value of silver and its impact on the main Western economies. His commentary on the world-wide concatenation of events and on the self-fulfilling prophesy of the drop in the value of silver merits an extended quote:

'the steady value of the money-unit [national currency] can only be maintained by making one of the precious metals the standard or measure of value and assigning a subordinate position as to coinage for the other.. gold, being less variable than silver, and of superior value, has been adopted by ... Japan, Germany, the United States of America, Denmark, Sweden and Norway [Great Britain in 1816] ... this system [single standard]... enhances the value of the one, and depreciates that of the other ... large quantities of silver hitherto in circulation as standard money ... will... be thrown on the market as bullion, and aid in its further depreciation ...India has for many years past been the principal market for silver ... the decline [in demand is] due

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783 - '*le temps viendra, un siècle plutôt, un siècle plus tard, ou la production de l'argent n'aura d'autres limites que celles qui lui seront imposées par la baisse toujours croissante de sa valeur*'. Duport, *Métaux précieux au Mexique*, 426.

784 This is the period when the major silver mines of the United States of America came into the market. Viollet links the new production from the U.S.A. to the upheavals ('*bouleversements*') of the silver market. Eugène Viollet, "Le problème de l'Argent et l'Etalon d'Or au Mexique" (Université de Paris, 1907), 6. It leads to the question not analyzed in this thesis as to the comparative production costs of pan amalgamation, patio amalgamation, barrel amalgamation and smelting between the new North American works, the Mexican ones and the traditional European production sites, and the impact on silver pricing of new volumes coming to the market under a new set of production costs.

785 'Highest, lowest and average price of bar silver in London, per ounce British standard (0.925), since 1833; and the equivalent in United States gold coin, of an ounce 1.000 fine, taken at the average price and par of exchange' in the Report of the Director if the Mint contained within the Annual Report of the Secretary of the Treasury on the State of the Finances for the Fiscal Year ended June 30 1921, p. 653. http://fraser.stlouisfed.org/docs/publications/treasar/AR_TREASURY_1921.pdf. Part of this Mexican silver was re-exported to Asia. For data on the amounts of Mexican silver sent from London to China and the Federated Malay States Silver from 1864 to 1902 see Eduardo Flores Clair, Cuauhtémoc Velasco Avila, and Elia Ramírez Bautista, *Estadísticas mineras de México en el siglo XIX*, vol. II(México: Instituto Nacional de Antropología e Historia, 1985), 140-141.

principally to the fall in the price of cotton, soon after the close of the Civil War in this country'.[786]

In spite of these major changes in the international valuation of silver, Mexican silver production increased rather than decreased. The reasons that have been given state that most production costs were paid in local currency and local inflation did not react in proportion to the international decrease in the value of silver. In addition the Mexican State took specific actions to protect its most valued industry, such as keeping the dual standard until 1905, so refiners could exchange silver for gold at an attractive rate, and allowing the export of silver in bullion, foregoing the previous restriction of only allowing the export of coin after payment for coinage. Finally, the industry responded in the time honoured manner of compensating lower prices with a higher output that included the sale of other metals, such as lead.[787]

5.4.2 Maize

With regards to the data from the accounting books of Regla, for the period between 1853 and 1873 the macroeconomic scenario is stable with regards to the value of silver and the foreign exchange rate. The more critical period is from 1873 and 1888, when both the price of silver and the exchange rate of the Mexican peso to the U.S. dollar had continuously decreased by up to 25% with respect to their previous levels.[788] Is there an impact in this period on the

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[786] H.R. Linderman, 'Report of the Director of the Mint, November 1st 1873' in the Annual Report of the State of the Finances to the Forty-third Congress, First Session, December 1, 1873, Washington, Government Printing Office, 1873, pp. 476-477. http://fraser.stlouisfed.org/docs/publications/treasar/AR_TREASURY_1873.pdf

[787] Velasco Avila et al., *Estado y minería en México*, 271-275.

[788] Uribe Salas and Nuñez Altamirano have published a study focused on how the local small and medium mining enterprises of Real del Monte and Pachuca responded to the drastic decrease in the value of silver, and provides a detailed picture of how the Government of Mexico moved rapidly to shield its foremost industry. The authors argue that the smaller enterprises in fact profited after 1873 and that the overall increase in silver production was in fact due to this segment of the silver industry. Because the paper centres on the strategies of enterprises usually overshadowed by the Compañia Real del Monte (the authors note wryly that all local enterprises other than that company were by default medium to small), it does not include data on inflation or production costs. Uribe Salas and Nuñez Altamirano, "Depreciacion de la plata.."

microeconomics of the production process at Regla that needs to be identified and isolated from other factors that influence my comparative production cost analysis? The majority of production costs are for domestic expenses charged in Mexican *pesos*, as will be demonstrated in the following sections. An idea of the local inflation can be obtained from the long time series of maize prices at Regla for the period 1872 to 1888. Expenses on maize were not a major factor in determining the final production cost at Regla, since it was water and not animal power that drove the machinery, but they are useful as secondary indicators of local inflation around Regla. I will ignore the possibility that since maize at Regla was destined for animal feed, it responded to market pricing and dynamics different from those that acted on maize sold for human consumption.

The plot of monthly costs for maize purchased at Regla (in *pesos* per *cargas*) as calculated from the data in the *Contabilidad Mensual* is presented in Figure 5-4.[789] The overall profile corresponds to long trends of values between 4 and 5 *pesos* per *carga*, with no clear indication of any long-term increase in the same. Garner reports an average price of maize, for the valley of Mexico from 1700 to 1800 as 13.2 *reales* per *fanega,* 3.3 *pesos* per carga.[790] This average correlates with the first plateau of values in Figure 5-4. Overall there is no clear indication that the macroeconomic context influenced in a major way over this period the local inflation rate at Regla.[791]

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[789] The raw data indicate the total monthly expenditure on maize at Regla, expressed in *pesos*, and total amount in *cargas* of maize purchased. These data are then used to calculate the cost of maize in *pesos* per *carga.*
[790] Richard L Garner, "Price trends in eighteenth-century Mexico," *The Hispanic American Historical Review* 65, no. 2 (1985). p. 290. *Fanegas* have been used as units of volume, area and mass in nineteenth century Mexico. A *carga* is equal to 2 *fanegas.* Manuel Carrera Stampa, "The Evolution of Weights and Measures in New Spain," ibid.29, no. 1 (1949): 15.
[791] Garner's extensive study on maize prices does not indicate any regulation on maize prices that would condition any conclusion derived from their long term moverments.

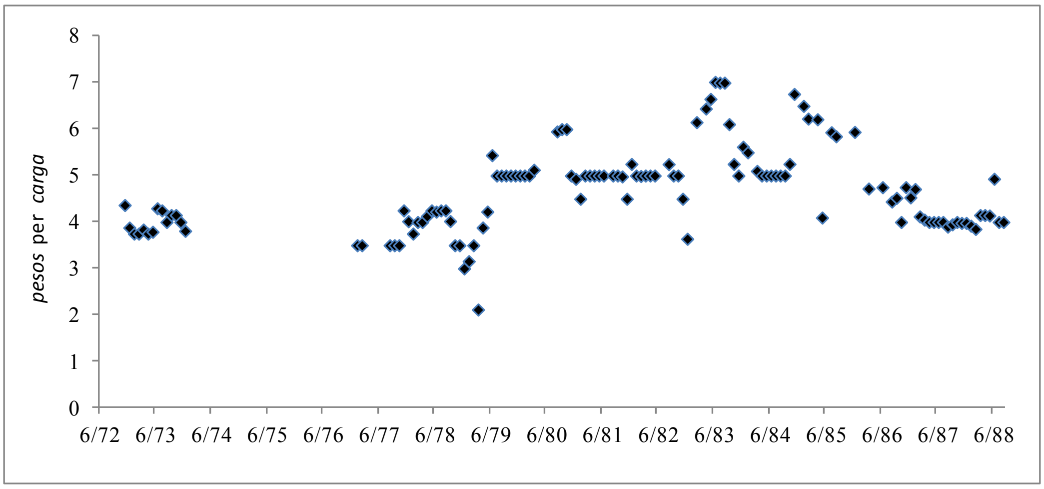

Figure 5-4. Time series for the expenditure on maize as fodder for animals at Regla (1872-1888). The source data used to calculate the values of monthly unit costs of maize in *pesos* per *carga* are from *Contabilidad Mensual*.

5.4.3 Salt

During the period of silver devaluation, salt prices show a step decrease between 1873 and 1875, then a very stable profile between 1875 and 1881, followed by a period of instability that combines an initial raise in prices followed by a long term decrease (Figure 5-5). The average over this period was 0.72 *pesos* per *arroba*.

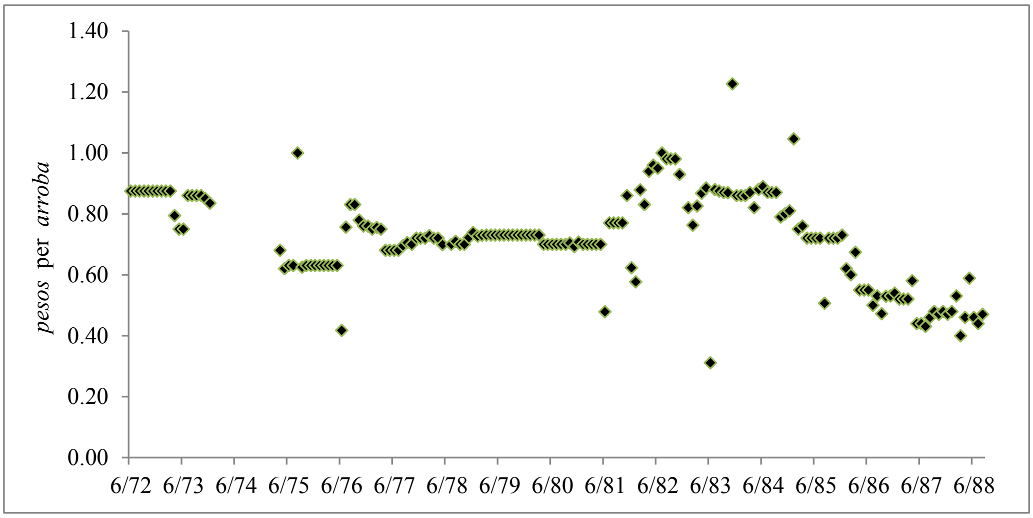

Figure 5-5. Monthly expenses of salt consumed at Regla (1872-1888), in *pesos* per *arroba*. Values calculated from data in *Contabilidad Mensual*.

The overall downward trend in prices is more evident on a much longer horizon, from 1852 to 1888 (Figure 5-6). The cost of freight played a major role in determining the cost of salt at the plant gate. In 1855 freight cost 42 dollars per ton to bring it 'from the State of San Luis, being a distance of some 300 miles'.[792] This would be equivalent to approximately 0.48 *pesos* per *arroba*, or around half the cost of salt at the plant gate. In the case of salt other factors more critical than the macro-economy were at play during the whole period.[793] In his report to the Directors of the Compañia de Real del Monte in 1855, Buchan explained:

'Amongst the materials required for the reduction of the ores, Salt is one of the most costly and difficult to obtain ... to secure the supply ... and also with the hope of reducing its cost, we have commenced .. the formation of large salt-works on the Lake of Tezcoco ... and we hope in time to render them adequate to all our needs'.[794]

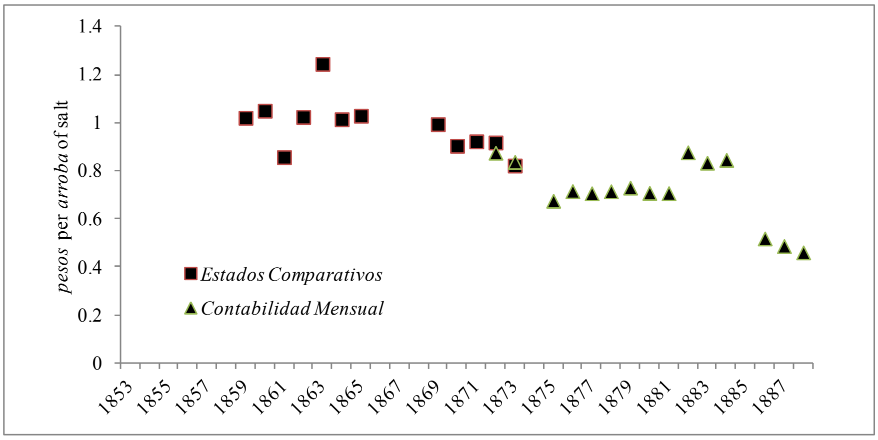

Figure 5-6. Yearly average expense on salt, in *pesos* per *arroba* (1853-1888). Values calculated from data in *Contabilidad Mensual* correspond to salt prices for Regla. Values calculated from data in *Estados Comparativos* correspond to the average price of salt registered for all the *haciendas* of the Compañia Real del Monte carrying out amalgamation in any given year.

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792 Salt was also brought in from salt pans in Campeche, using the ports of Tampico and Tuspan. Buchan, *Report Real del Monte*, 18-19.
793 In the absence of information on the sodium chloride content in the salt being purchased over these decades, I can only speculate that another factor to decrease cost is a worsening quality, since the consumption of salt per kg of silver amalgamated increases substantially for the last years of this period (Chapter Four).
794 Buchan, *Report Real del Monte*, 19. Lake Tezcoco was situated less than 100 km from Regla, so freight costs would have decreased substantially. It is not known if the project succeeded. At the present time all the lakes of this area have virtually dried up due to human agency.

5.4.4 Copper sulphate

Copper sulphate is reported as having been one of the items imported by the company, though it is not stated if all or part, and whether this was a regular practice or not.[795] If so, it shows a remarkable resiliency to macroeconomic events in the 1873 to 1888 timeline, as evidenced in the nearly flat array of data points in Figure 5-7, showing a large step decrease in 1875 and a minor one in 1878, and then a constant price to the end of the period.[796] The average cost over the period was 0.13 *pesos* per lb.

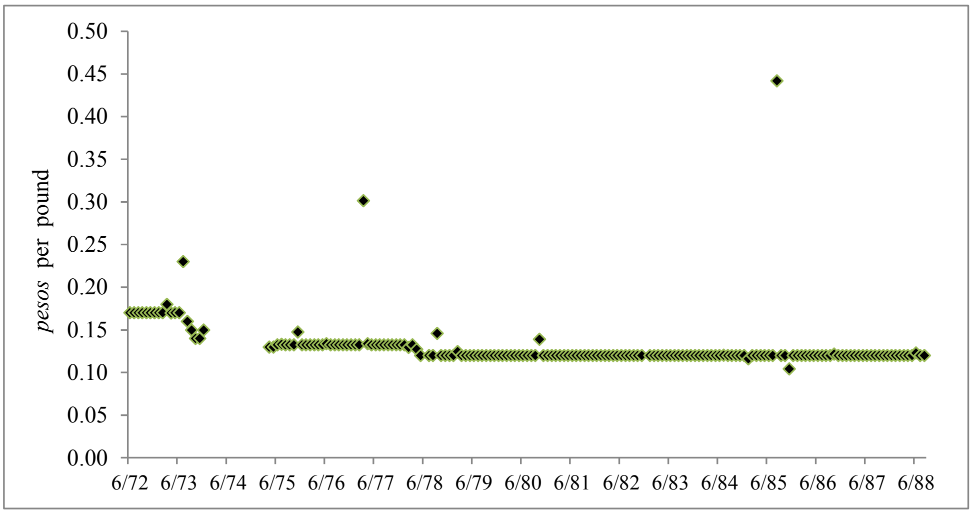

Figure 5-7. Monthly expenses of copper sulphate consumed at Regla, in *pesos* per pound. Values calculated from data in *Contabilidad Mensual*.

5.4.5 Mercury

The behaviour of mercury prices is also unexpected at first sight, being the one major reagent that had to be imported in its totality and thus most subject to the impact of the

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[795] Ruiz de la Barrera, "La Empresa de Minas del Real del Monte," 293.

[796] The *Estados Comparativos* report both the amount and expense of the purchases of copper sulphate and the cheaper *magistral*, but do not add to the present discussion except to indicate that copper sulphate was also added to amalgamation in barrels, not only to patio amalgamation. I have no information as to whether long-term contracts would be responsible for the profile in Figure 5-7.

devaluation of the *peso* that begins around 1873. Figure 5-8 shows a sudden eruption of prices around the year 1874, precisely the year during which refining operations at Regla became very erratic. Once the aftershocks of the explosion subside, mercury prices are unexpectedly stable, and in fact slowly decrease, from 1879 onwards, as the depreciation of the Mexican peso was gathering steam, only picking up again after 1887. The average price from 1878 to 1888 was 0.6 *pesos* per lb, 60 *pesos* per *quintal*.

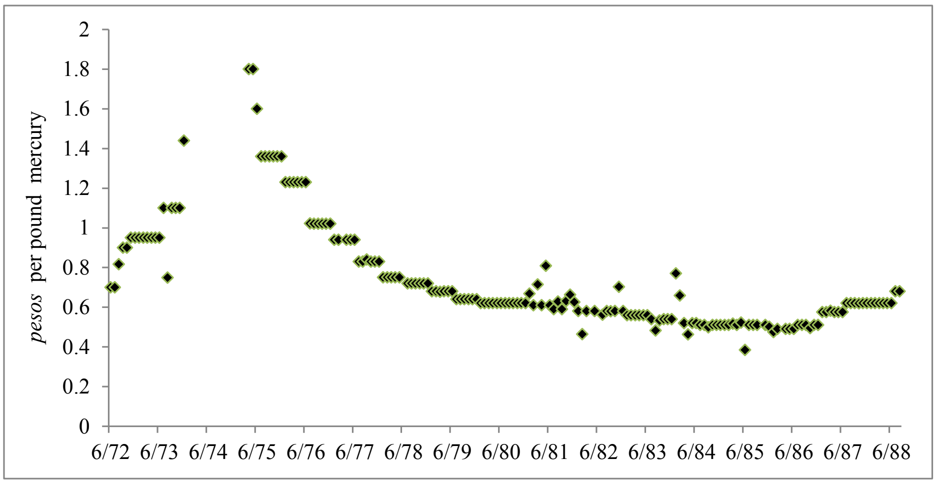

Figure 5-8. Monthly expenses of mercury consumed at Regla, in *pesos* per pound. Values calculated from data in *Contabilidad Mensual.*

The uniqueness of the peak in mercury pricing observed around 1874 becomes more evident when the average yearly cost for mercury per pound calculated from the *Estados Comparativos* completes the landscape of prices in the period prior to 1874, as observed in Figure 5-9. Not since the late sixteenth century had prices of mercury reached over 1.6 *pesos* per pound (160 *pesos* per *quintal*) in the New World. Contrary to salt, the control of mercury prices lay outside the scope of the management of the Compañia Real del Monte. In a scenario that seems very familiar, the Spanish authorities in the nineteenth century in their search for revenues, entered into negotiations with the Rothschild family that would lead the banking concern to provide a series of loans of increasing uncertainty regarding payback, in return for the concession of the mercury mine at Almadén. The Rothschilds then proceeded to profit from their near monopoly on mercury after 1832 by increasing the price of mercury to more than twice its previous level.[797]

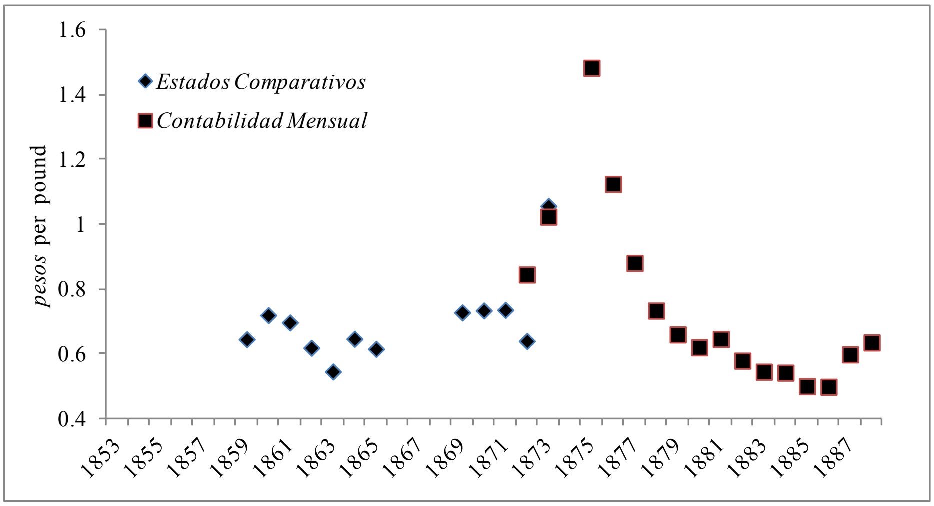

Figure 5-9. Yearly average expense on mercury, in *pesos* per pound. Values calculated from data in *Contabilidad Mensual* correspond to mercury cost at Regla. Values calculated from data in *Estados Comparativos* correspond to the average cost of mercury registered for all the *haciendas* of the Compañia Real del Monte carrying out amalgamation in any given year.

This would be followed from 1846 by the production of mercury from New Almaden and others in the western cordillera of the United States that would provide a new source of mercury in competition to Almadén and Idria (see Chapter 1). The demand for mercury created by the California Gold rush, the initial play for a monopoly position by the Rothschilds in the period 1830 to mid-1850s, and then the entry of unexpected new major sources in the Americas and the resulting glut of mercury in the market created the major pricing oscillations of the

[797] An analysis of the involvement of the Rothschilds in the mercury market of the nineteenth century is given in Miguel A. Lopez Morell and Jose M. O'Kean, "Seeking out and building monopolies, Rothschild strategies in non ferrous metals international markets (1830-1940)," in *14th Conference of the European Business History Association* (Glasgow2010).

nineteenth century that were reflected in all mercury markets. In its final paroxysm it would create the price spike that for a time must have contributed to derailing amalgamation operations at Regla in 1874. The resulting overproduction of mercury starting in 1874 and lasting to 1884 led to mercury prices from New Almaden dropping ‘from $126.22 per flask [of 76 lbs] in 1874 to $49.75 in 1875, and thereafter until 1883 the average price per flask was about $30.00 and, for a time, $25.00’.[798] The roller coaster pricing over the nineteenth century can be seen in Figure 5-10, where I have used the data reported by Schmitz on the historical pricing of mercury from three sources in the nineteenth century: Italy (Idria), London (mainly Almadén) and U.S. (mainly U.S. mines).[799]

Assuming that prior to 1850 the Idria prices remain a faithful reflection of world mercury market prices, the business fortunes of both the English Adventurers and their Mexican successors in the Compañia Real del Monte need to be judged within the context of the oscillations of this mercury market. The former were hit with a near tripling of mercury prices after 1836 that lasted to the end of their business venture in Mexico.

‘Phillips estimated that the increase in the price of mercury between 1827 and 1840 had been so drastic that the cost of amalgamation in the company’s mills was some $40,000 higher in 1840 than it would have been had the price of mercury remained at the 1827 level’.[800]

Herrera Canales has proposed that for Mexican silver refiners in the nineteenth century it was more critical to guarantee mercury supply than to worry about mercury pricing, since mercury ‘only had affected moderately their costs and profit’.[801] The scenario as described

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[798] Henry Winfred Splitter, "Quicksilver at New Almaden," *Pacific Historical Review* 26, no. 1 (1957). p. 36.
[799] Christopher Schmitz, *World Non-ferrous Metal Production and Prices, 1700-1976* (London; Totowa, N.J.: Cass ; Biblio Distribution Centre, 1979), 282-84.
[800] Randall, *Real del Monte*, 116-117.
[801] Inés Herrera Canales, "Mercurio para refinar la plata mexicana en el siglo XIX," *Historia Mexicana* 40, no. 1 (1990): 27-29.

above did affect major refiners such as Regla, and not only small producers. The new Mexican owners of Regla were blessed at the beginning of their venture when mercury prices dropped nearly to a level of the early 1820s. They would enjoy during the first critical years of production, when capital investment needs to be repaid as promptly as possible, a certain stability of mercury prices. When the new pricing hikes hit them in the early 1870s, it coincides with a period of financial crisis of the company. The drastic increase in the pricing of mercury alone could explain the fact that from May to July, and December 1874 no amalgamation was carried out at Regla, while from January to March 1875 the amounts amalgamated were close to nil or irrelevant. During these periods the only production of silver came from the smelting of slags (*grasas*), approximately 100 to 200 kg per month.[802] The combination of a low production of suitable ores and the spike in mercury prices knocked operations at Regla in 1874 and the first trimester of 1875 out of kilter.

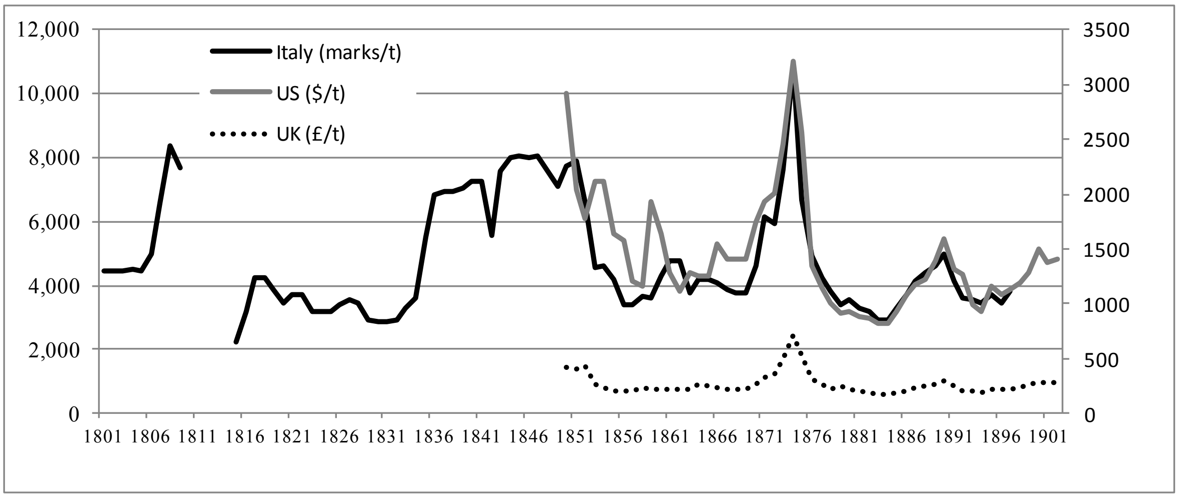

Figure 5-10. Nineteenth century mercury prices from footnote 799. The scale on the right applies to US and London prices, the scale on the left to prices from Italy.

[802] Data for 1874 and 1875 from *Informe Mensual Regla.*

The sole purpose of this chapter is to calculate the production costs at Regla for amalgamation and smelting, not the study of the finances of the whole Compañia Real del Monte or the effects of the macroeconomic context on its profitability to shareholders, but some background information is in order. The Company went through an initial very profitable period, when it was buoyed by a bonanza from the 1850s to 1860s, then suffered a financial crisis from 1873 to 1875 that began when it failed to report profits in 1872. The Company nearly went bankrupt and a cash injection of 1.5 million pesos was required by 1875. This was eventually repaid between 1877 and 1884. The explanation proposed for the origin of the crisis is the lack of investment to find new deposits leading to a drop in ore supply to its refining *haciendas*.[803] Other authors cite as the cause for the financial crisis the decrease of silver prices in the international market. It is also stated that the level of profits descended but remained steady in the period 1876 to 1892, which is the period whose operations are covered in this chapter. The Mexican Company was sold to United Smelting, Refining and Mining Company, a U.S. consortium, in 1906, by which time all the refining *haciendas* except Loreto had been closed down, and the cyanide process had displaced amalgamation with mercury.[804] No mention is made in either work of the spike in mercury prices precisely in the period of the greatest financial crisis of the Mexican-owned company, and its impact on production costs for amalgamation.

5.4.6 Charcoal

In the case of charcoal (Figure 5-11) the pricing profile shows very stable pricing until 1881, after which there is an approximate 40% increase in cost, which could be explained by

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[803] Ruiz de la Barrera, "La Empresa de Minas del Real del Monte," 110, 132-135.
[804] Ines Herrera Canales, Cuahtemoc Velasco Avila, and Eduardo Flores Clair, *Etnia y clase, los trabajadores ingleses de la Compañia del Monte y Pachuca, 1824-1906* (Mexico: INAH, 1981), 3-4.

fuel demands finally outstripping supply in this period of continuous smelting, coupled with the high demand for fuel from amalgamation in barrels, or by a change in sourcing.[805] The average over the whole period is 1.3 *pesos* per *carga* of charcoal.

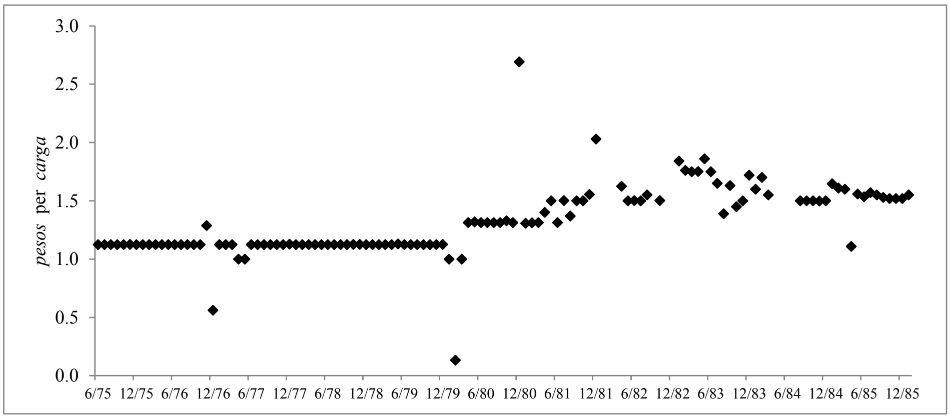

Figure 5-11. Monthly expenses on charcoal for smelting consumed at Regla (1875-1886), in *pesos* per *carga*. Values calculated from data in *Contabilidad Mensual.*

5.4.7 Litharge

In the opposite direction, the historic pricing of litharge (Figure 5-12) shows step decreases punctuating periods of stable pricing, with an average of 0.08 *pesos* per kg.[806] There is no evident influence of the macroeconomic scenarios on this profile.

[805] There is one reference in the literature to charcoal being imported from England and Germany in the nineteenth century, and brought to the Compañia Real del Monte by rail from the port of Veracruz. Saavedra Silva and Sánchez Salazar, "Espacio Pachuca-Real del Monte," 93. It does not specify either period, quantities or pricing, and I have no other source to confirm this. A switch to imported charcoal could explain the increase in price.
[806] As explained in Chapter 4, litharge accounts are reported both in pounds and arrobas, so to avoid confusion I have converted all to kg.

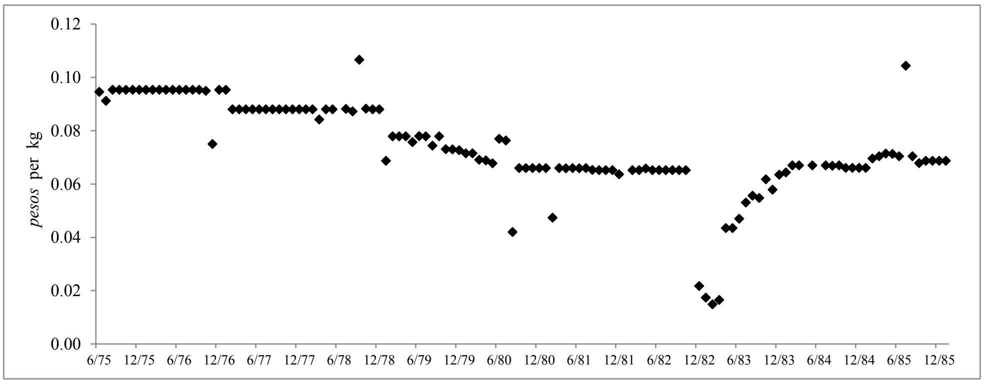

Figure 5-12. Monthly expenses on litharge consumed at Regla (1875-1886), in *pesos* per kg. Values calculated from data in *Contabilidad Mensual.*

In general it can be concluded that prices of consumables for Regla were not seriously affected by the macroeconomic scenario, a valid reflection of Mexico as a whole.[807] This lack of impact between the macroeconomic scenario and the input costs of production at Regla in the nineteenth century, and the stability of the silver to gold ratio from the 1870s to at least the 1700s, will provide a relatively stable context within which I can compare and project production costs without having to deflate my data. Prior to the eighteenth century a more exact exercise would require deflation, but for the purposes of comparative analysis set out in the following sections, the same margin of error for ignoring inflation applies to both sets of mixed data from various centuries, and the conclusions on relative behaviour are compromised, if at all, equally for both processes.

5.5 The partial variable production costs of amalgamation at Regla, 1872-1888.

In Figure 5-13 I have plotted the monthly variable amalgamation production costs as calculated for Regla, except for the cost of extracting the ore. From mid 1872 to early 1875 the variable amalgamation cost reflects the sudden increase and then decrease of mercury prices

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[807] Casasus, *La Question de l'argent*, 11.

around the 1874 peak (Figure 5-9). Because of the monthly interruptions of amalgamation observed in the monthly accounts for 1874 I prefer to work with the data from mid 1875 to mid 1888 as being much more representative of average operating conditions. The average variable cost for amalgamation, excluding the cost of ore, during this period is 7.8 *pesos* per kg of refined silver.

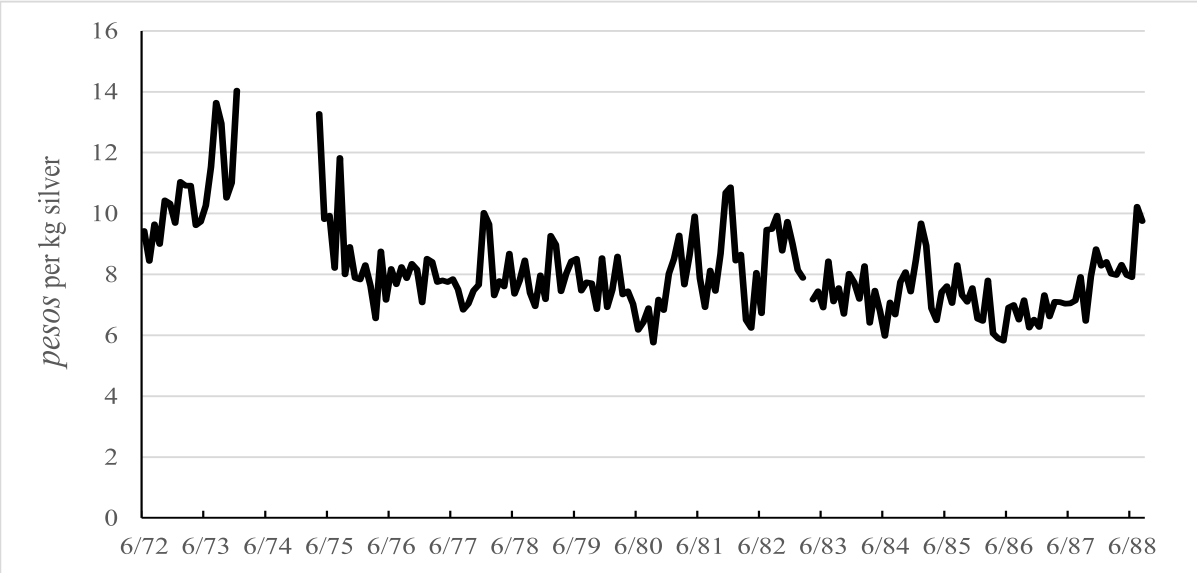

Figure 5-13. Monthly production costs of silver refined by amalgamation at Regla (1872-1888). Values calculated from data in *Contabilidad Mensual*.

The annual percentage breakdown of these amalgamation costs into their main components over the period is shown in Table 5-V. The details on how the accounting data are grouped into these headings is provided in Appendix B. The main reagents make up on average 56% of the partial variable amalgamation cost, of which the share of mercury costs (24%) is very similar to that of salt (23%). Labour contributes 17%, while the remaining 27% corresponds to other expenses, as detailed in Appendix B. The cost of fuel is hidden within the overall heading of 'other' since the *Contabilidad Mensual* does not provide a more detailed picture. It is however possible to arrive at an approximate estimation using the information both in the *Memorias* and in the *Estados Comparativos*. For the four weeks ending on May 29th

1877, this totalled 515.5 *cargas* of firewood, 634 *arrobas* of ocote and 89.5 *cargas* of charcoal from *ocote*. According to the same *Memorias No. 19 - 21* that served as the source for this information, the total cost of this fuel came to 373.24 *pesos*, which represents 2.5% of the total for that month. This order of magnitude for fuel required by amalgamation is confirmed by using the accounting data in the *Estados Comparativos* for the years 1872 and 1873, the only period during which there is an overlap in the available information. The fuel component in the total cost of amalgamation in this period is 2.4%, as obtained from the data summarized in Table 5-VI. The value as calculated errs on the high side, since it also includes fuel for cooking and domestic heating. As a working figure I assume this range also applies over the period 1875-1888.

Combining the data from Tables 5-V and 5-VI, I obtain the average percentage distribution of variable amalgamation costs at Regla in the period 1875 to 1888, set out in a pie chart in Figure 5-14. The only variable cost not present in this calculation is the cost assigned to the silver ore as delivered to the plant gate. The pie chart of Fig. 5-14 and the data in Table 5-V illustrate the major impact of salt on production costs. When consulting the source data I was struck by the fact that in many months more money was spent on salt at Regla than on mercury, and this can be observed at a yearly level in Table 5-V. It is understood that the period from 1876 to 1888 corresponds to low levels of mercury pricing, but a similar context would have arisen in colonial times after the price of mercury was lowered to 62 *pesos* a *quintal* in mid-eighteenth century. Much emphasis is rightly placed in the historiography on the influence of the cost of mercury within amalgamation, but the equivalent order of magnitude of the expenditure on salt needs also to be taken into account. Salt was a major consumable in the

amalgamation						
year	labour	mercury	salt	copper sulphate	other	total
mid 1872	24%	24%	24%	7%	21%	100%
1873	23%	27%	20%	7%	25%	100%
1874						
mid 1875	15%	43%	14%	7%	21%	100%
1876	15%	36%	23%	7%	19%	100%
1877	17%	28%	25%	11%	20%	100%
1878	16%	23%	24%	13%	23%	100%
1879	18%	19%	24%	16%	23%	100%
1880	19%	19%	22%	13%	27%	100%
1881	16%	21%	23%	11%	29%	100%
1882	16%	22%	24%	10%	28%	100%
1883	14%	22%	23%	11%	29%	100%
1884	15%	20%	27%	9%	29%	100%
1885	16%	22%	24%	7%	31%	100%
1886	18%	23%	23%	5%	32%	100%
1887	18%	24%	20%	5%	33%	100%
mid 1888	19%	21%	22%	4%	34%	100%
whole period	17%	25%	23%	9%	26%	100%
1875-1888	17%	24%	23%	9%	27%	100%

Table 5-V. The percentage breakdown of the main variable amalgamation costs at Regla, excluding the cost of ore at the plant gate. The percentage values were calculated from the individual headings within the monthly account data, and then averaged for the year. A total of 153 data sets are represented in the table. Source data from *Contabilidad Mensual.*

	June 1872 - December 1872	1873
	pesos	
firewood *(leña)*	1,615.04	939.97
charcoal and wood (from *ocote*)	2,224.52	3,758.13
total fuel costs	3,839.56	4,698.10
total amalgamation costs	159,410.60	196,719.61
% fuel costs	2.4%	2.4%

Table 5-VI. The percentage contribution to the total variable amalgamation refining cost of the total fuel required by the amalgamation process. Source data from *Estados Comparativos.*

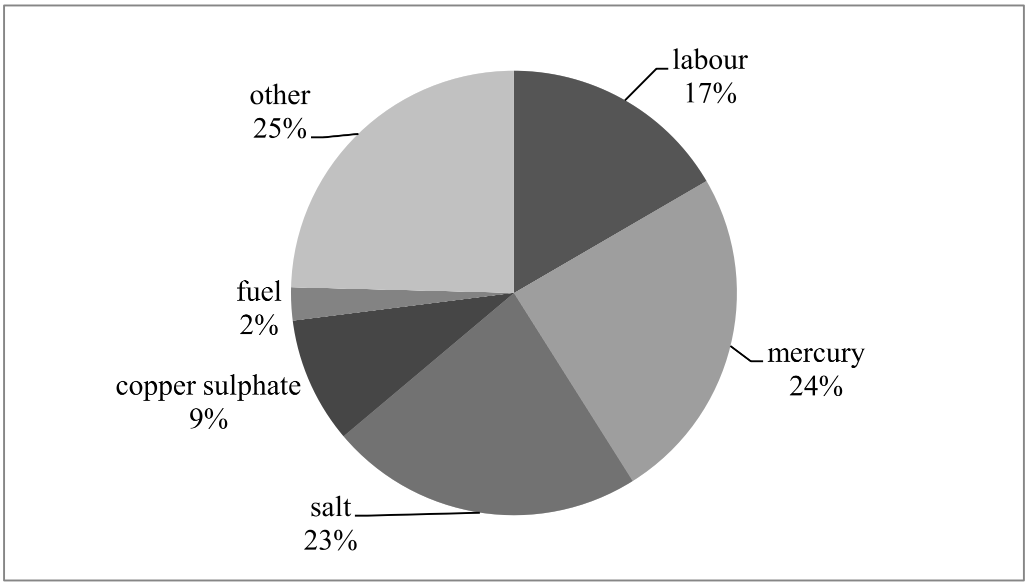

Figure 5-14. Percentage breakdown of the amalgamation cost of silver at Regla in the period 1872 to 1888, excluding the cost of silver ore at the plant gate.

process, and its impact on the economies of the process were as important as those of mercury.[808] Fortunately for amalgamation, salt was a domestic product, both in New Spain / Mexico and Peru, and as shown by the management at Regla, steps could be taken to minimize its cost.

5.6 The cost of ore: the missing link in variable costs at Regla

The accounting books do not include the cost of ore delivered to Regla. I have calculated an approximate value in Table 5-VII based on data published by Buchan on the costs for the ore produced in the period May 1849 to December 1852, and the years 1853 and 1854.[809]

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[808] 'the amount of salt needed for nutrition … and various other industries [in New Spain] appear to be of trifling significance compared with the demands of the silver industry … the price of salt was of considerable importance to the silver-ore processing plants'. Ewald, *Mexican Salt Industry*, 12, 211.; the fact that expenses on salt were greater than expenses on mercury at Real del Monte has already been commented upon by Ortiz Peralta, "Beneficio Minerales Real del Monte," 55.; "La Compañia de Real del Monte y Pachuca," 206. In the latter work she analyzes what she considers to be the novel incursion of a mining and refining concern into the business of salt production.

[809] Buchan, *Report Real del Monte*, 26-31.

The unit cost per *carga* of mined ore, including freight to the refining *haciendas*, shows a marked decrease over this short period. I use as a working figure the average of the years 1853 and 1854, at 2.6 *pesos* per *carga* of ore at the plant gate. I will assume as a working number that this average cost remained the same over the second half of the nineteenth century.[810] The average percentage of silver extracted from the ores processed by amalgamation at Regla was 0.17% by weight (Chapter 4), so the average extraction cost for the ore was 11.1 *pesos* per kg amalgamated silver.[811]

	May 1849 to December 1852	1853	1854
General expense [overheads]	92,456	30,152	36,410
Drainage of mines	215,541	69,334	83,707
Extraction cost	758,906	294,874	322,812
Freight to refining haciendas	105,283	63,768	82,640
total	1,172,186	458,128	525,569
cargas of ore	311,765	181,151	192,982
production cost per carga	3.76	2.53	2.72
	all costs in dollars (equivalent to *pesos*)		

Table 5-VII. Mining and other costs for Real del Monte mines in the period 1849 to 1854, raw data adapted from footnote 809.

[810] This is a major assumption, induced by the need to have a working figure on ore costs at Regla. Though labour was responsible for a major part of mining costs, other factors such as flooding, depletion of the ore deposit, cost of wood for timbers, investment in machinery could have created major variations in this cost in the second half of the nineteenth century. On the other hand the strategy of this Company was to lease many mine holdings so as to switch from one source of ore rapidly to another. This would have kept mining costs down if an alternative deposit to a deeper or depleting mine could be found. Mendizabal pointed out that it was economic, not technical causes that led to mines being abandoned. Mendizábal, *La mineria mexicana*, 26.

[811] At a silver extraction rate of 0.17%, 0.23 kg of silver are refined from 138 kg (1 carga) of ore, so that at 2.6 pesos per carga it is equivalent to 11.1 pesos per kg refined silver.

This introduces a major new component in the breakdown of variable costs, a single input greater in cost than the sum of mercury, salt and copper sulphate. The total average amalgamation variable cost is now 18.9 *pesos* per 1 kg of refined silver. The pie chart of variable production costs now changes to the breakdown shown in Figure 5-15. The cost of extracting ores was the major influence on the total variable cost of amalgamating silver ores, and not mercury, as pointed out by Villaseñor in 1741.

The pie chart of Figure 5-15 mirrors well the distribution of silver production costs between mining and amalgamation for the Compañia de Real del Monte, which assigned to refining 40% of the total costs of the company.[812] The chart as presented in a standard breakdown of major production cost headings camouflages however a very significant statistic. It has been estimated that labour costs made up 85% of the total extraction cost of mining ores in Mexico in the nineteenth century.[813] If this estimate is correct, then 55% of the cost of amalgamating silver at Regla was due to the cost of labour in mining and refining, with up to an additional 10% in cost of local labour hidden under the headings of salt, fuel and others.

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[812] Ortiz Peralta, "La Compañia de Real del Monte y Pachuca," 202.
[813] Viollet, "Le problème de l'Argent," 121.

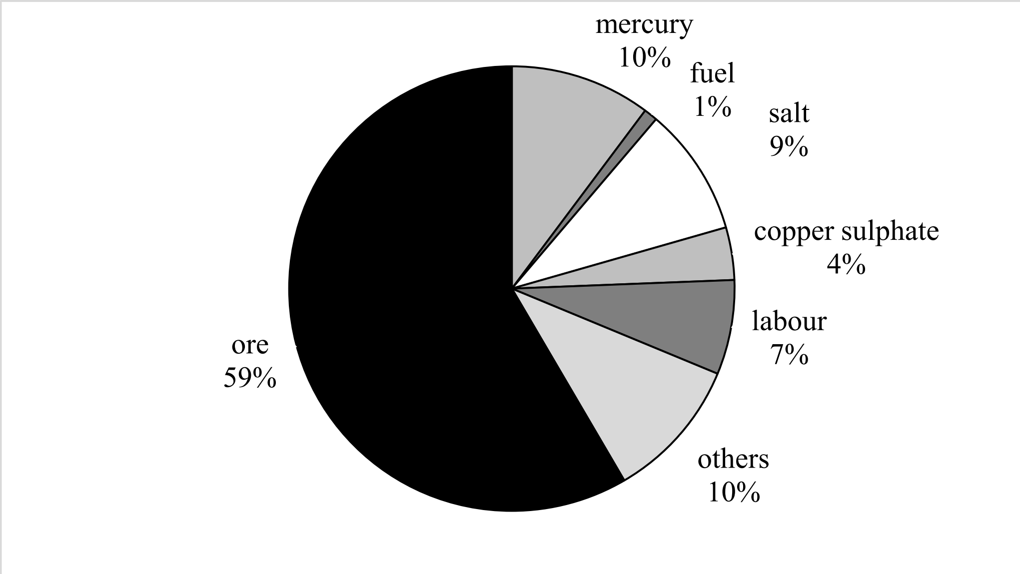

Figure 5-15. Percentage breakdown of the total variable cost of production by amalgamation at Regla, based on the production cost of ore from the mines of Real del Monte in 1853-1854. Other data as in Figure 5-14.

5.7 The capital cost of amalgamation at Regla.

The total cost of production by amalgamation at Regla would need to incorporate as well the fixed capital cost due to the investment in infrastructure. Since in 1846 most of the infrastructure at Regla was bought at a pittance from its previous English owners, from an accounting point of view the servicing of this fixed capital cost is not representative of an amalgamation *hacienda* built from scratch. The report by John Buchan includes a listing for 'reforming and enlarging reduction works at Regla' of $20,000, compared to the capital cost of 'erecting the new reduction work of Velasco' at $209,750, based on the barrel process.[814] The original cost of construction of Regla in the late eighteenth century has been reported at

[814] Buchan, *Report Real del Monte*, 26. Another reference point is the cost of construction of the major amalgamation facility of Proaño in Fresnillos, Zacatecas, with a larger amalgamation processing capacity than Regla (see Chapter Three). It is reported as having cost 300,000 *pesos* in the first half of the nineteenth century, before steam engines were installed. The fixed annual cost of servicing that investment is set at 5%. Since depreciation for tax purposes was probably not an established accounting practice at this time, its fixed capital cost is probably treated as a nominal interest rate on a loan. Duport, *Métaux précieux au Mexique*, 262-63, 278.

levels over $500,000, but there are strong reasons not to take even the original investment as a guide.[815]

Visitors to Regla wondered 'why his walls were built so thick, or why so many massive arches should have been constructed, is an enigma to the present generation, as they could by no means have been intended for a fortress down in a *barranca*'.[816] As Humboldt pointed out, one of the advantages of the amalgamation process was precisely its low capital expenditure in plant infrastructure.[817] Regla was overdesigned for the needs of both processes, so its capital cost is not a guide to an average cost in the silver refining business.

According to Duport the rental in Guanajuato of an amalgamation *hacienda* would amount to 50 *pesos* per year per *arrastre*.[818] If this benchmark were applied to Regla, with 24 *arrastres*, it would have induced a rent of 1,200 *pesos* per year. With an average production of nearly 20,000 kg of silver by amalgamation during this period at Regla, even a ten-fold increase in this level of rent would only correspond to half a *peso* for every kg of silver produced. In the light of all these considerations, I will therefore ignore the fixed cost of capital for amalgamation at Regla and focus only on the total variable cost. Since I will require an estimate on a generic fixed capital cost of amalgamation for my sensitivity runs later on in this chapter, I will use Duport's information that the rental cost of an amalgamation *hacienda* in the State

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[815] According to Terrero 2 million *pesos* were spent to construct the *haciendas* of Regla, San Francisco Javier, San Miguel and San Antonio. Manuel Romero de Terreros, *Antiguas haciendas de México* (Editorial Patria, 1956), 300. Other figures are 425,708 *pesos* in Ladd, *The Making of a Strike*, 144.; £1 million in H. G. Ward, *Mexico*, Second ed.(London: H. Colburn, 1829), 140., and £500,000 in Lyon, *Tour of Mexico*, 153.
[816] Wilson, *Mexico and Its Religion*, 366.
[817] Humboldt, *Essai politique*, 84.
[818] 'The rent of an hacienda de beneficio is fixed according to the number of arrastras, at a rate of 50 piastres per year' - '*Le loyer d'un hacienda de beneficio se règle d'après le nombre d'arrastras, a raison de 50 piastres par an*'. Duport, *Métaux précieux au Mexique*, 237. The wording is ambiguous, but a rental of just 50 pesos per year for the hacienda would be trivial and it does not correlate with his breakdown of costs in page 232 of his book, where rental came out to nearly 60 pesos for each arrastre.

of Guanajuato capable of processing 2,565 *montones* of ore a year represents 4 - 5% of the variable refining cost of silver.[819]

5.8 The partial variable production cost of amalgamation as a function of silver content of the ore.

The cost of refining is a function of the silver content of an ore, and without a knowledge of this function it is not possible to compare the economies of amalgamation with smelting. Table 5-VIII summarizes the method I have applied that allows me to calculate the total variable production cost as a function of the silver content in the ore, and to establish the breakeven point between silver value and amalgamation costs.[820] The key column that functions as the fixed axis of the matrix is shaded in grey. It corresponds to an ore with an average silver content of 0.19% by weight, to which all costs reported so far refer to. From top to bottom the first two values indicate the amount of silver in a *montón* (assuming a total extraction rate of silver of 90%), then the deemed value of the refined silver in *pesos* (adopting an equivalence of 38 *pesos* per kg of silver).[821] The second tranche of values correspond to the average variable costs calculated in Sections 5.5 and 5.6 adjusted to the total amount of silver in a *montón*. The matrix is then assembled from this column, by choosing different silver contents and adjusting the cost of mercury (at a mercury to silver weight ratio of 1.3) and fuel, maintaining constant all the other values. The fuel costs vary as they reflect the amount of amalgam fired in a *capellina* and the bars cast. The cost of salt and copper sulphate do not vary with silver content since they were added proportional to the size of the *montón*, not to its silver content. Labour and other costs are deemed constant throughout the range.

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[819] Ibid., 232.
[820] A similar result would be obtained applying Villaseñor's matrix based only on costs per montón. I developed my method before coming across the work by Villaseñor, which helped me to understand his approach.
[821] The value of 38 pesos per kg of silver is calculated from the data from 1849 to 1854 in Buchan, *Report Real del Monte*, 26-31.

Before I plot the function I draw attention to the fact that the cost of mercury consumed during *patio* amalgamation at Regla increases with the silver content of the ore only when calculated on the basis of a *montón*. On the basis of variable production costs the whole operation decreases in cost at higher silver content when calculated on the basis of one kg of silver refined. The data point to the fallacy of judging the viability of amalgamating ores with high silver content only on the increase in cost of the total amount of mercury consumed.

Based on the matrix in Table 5-VIII, the function of variable costs versus silver content in Figure 5-16 indicates that it would not have been profitable to amalgamate ores at Regla with a gross (unextracted) silver content below 0.09%. This correlates well with the histogram in Figure 4.32, where the lowest tranche registered in the accounts of Regla corresponds to ores with 0.7 to 0.10% silver content. Obviously a greater refinement is possible, since this simple calculation does not include the fixed costs, yet it still remains a valid indicator of the limits to amalgamation at Regla based on the quality of the ore. By processing ores of an average 0.19% silver content, the total variable costs corresponded to approximately 50% of the silver value in the ore, thus providing a healthy margin for the operators of Regla from which to retain a profit from the operation.

With respect to the second parameter, the cost of amalgamation per kg of silver as a function of silver content in the ore, Figure 5-17 shows the expected decrease in unit cost as the silver content increases. I have chosen as a cut-off point all production costs over 50 pesos, since by this time the cost of production will have exceeded the value of the silver being produced. To emphasize that only one point of the curve has been calculated from the actual

Amalgamation	% silver in ore	0.00%	0.02%	0.04%	0.06%	0.08%	0.12%	0.19%	0.60%	1.00%	1.90%	3.00%
	kg of silver in *monton*	0.00	0.25	0.50	0.75	0.99	1.49	2.36	7.45	12.42	23.60	37.26
	value silver *pesos*	0	9	19	28	38	57	90	283	472	897	1416
	variable production cost *pesos* per kg silver	variable production costs in *pesos* per *monton*										
Fuel	0.19	0.00	0.05	0.09	0.14	0.19	0.28	0.44	1.40	2.33	4.43	7.00
Mercury	1.91	0.00	0.48	0.95	1.43	1.90	2.85	4.52	14.27	23.78	45.18	71.33
Salt	1.78	4.21	4.21	4.21	4.21	4.21	4.21	4.21	4.21	4.21	4.21	4.21
Copper Sulphate	0.72	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
Labour	1.30	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07	3.07
others	1.93	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54
ore	*11.1*	*26.2*	*26.2*	*26.2*	*26.2*	*26.2*	*26.2*	*26.2*	*26.2*	*26.2*	*26.2*	*26.2*
total	18.93	39.71	40.23	40.75	41.27	41.80	42.84	44.67	55.37	65.82	89.32	118.04
	variable production cost *pesos* per kg silver		161.96	82.03	55.39	42.07	28.74	18.93	7.43	5.30	3.78	3.17

Table 5-VIII. Matrix to determine the variation of total production cost by *patio* amalgamation at Regla as a function of silver content in the ore. All data derived from the accounting books of Regla, except for the cost of ore which has been derived from Section 5.6.

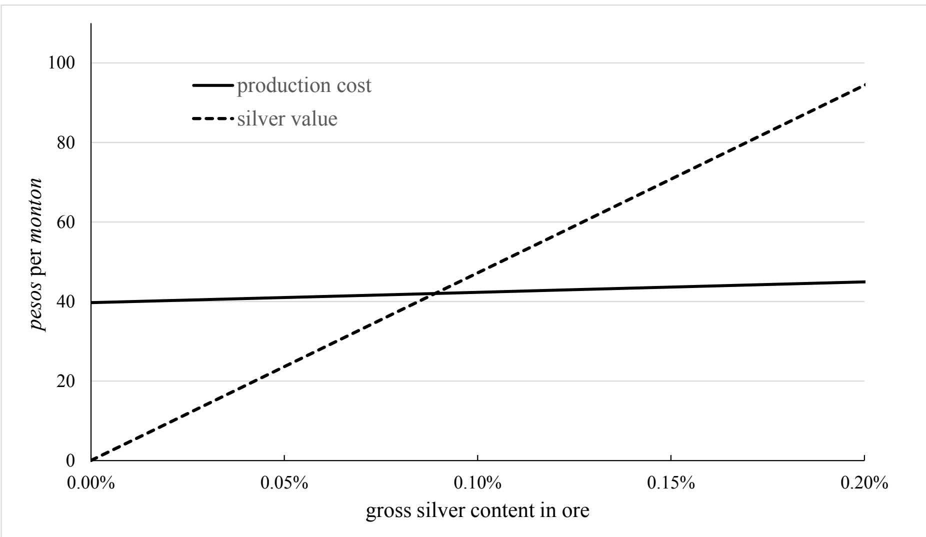

Figure 5-16. Cross-over point between the average variable cost of processing one *montón* by *patio* amalgamation at Regla, and a deemed maximum value for the silver extracted from the ore. Data sourced from Table 5-VIII.

accounting records of the period, I have used a large circular marker for the sole accounting value, with all the other points in the curve projected according to the methodology set out in Table 5-VIII. The profile of the curve begs the question why *patio* amalgamation is never indicated as being suitable for refining ores with a high silver content since after all, the richer the ore, the lower the production cost. I have already commented in Chapter 4 that the accounting records show amalgamation *tortas* being prepared with mixtures that included ores of a silver content usually associated with smelting, though they never represented the majority content of a *torta*. Three practical issues may have constrained the use of amalgamation for ores with a high content of silver. First is the possibility that ores with a higher content of silver also contained lead, which would make them unsuitable on chemical grounds for amalgamation. Second, a greater use of mercury would have required purchasing and maintaining an increased inventory. Over the whole historical period of amalgamation market availability of mercury and cash flow constraints on working capital may have limited this option. Third, there could be operational problems in the milling to a very fine powder the ores with a high content of native silver. Native silver is not easy to amalgamate when present in large sizes within an ore.[822] What is important to point out is that on the basis of these graphs there is nothing *per se* in the economies of amalgamation that would limit the application of the process to ores with a high silver content.

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[822] Sarria and Sonneschmidt comment on the operational problems encountered milling and amalgamating ores with a high content of native silver. de Sarria, Ensayo de metalurgia, 146.; Sonneschmidt and de Fagoaga, Tratado de la amalgamación de Nueva España, 54, 56. In Peru in the sixteenth and seventeenth century they employed the *tintin* method for very rich silver ores, which required pounding the rich silver mass in an ore immersed in mercury repeatedly with an iron bar. 'the ore in which pure Silver can be observed, mixed with stone … cannot be ground well, nor is Mercury able to embrace such large [pieces of] Silver' – *'el metal en que se ven en su forma [la] Plata puros, mezclados con la piedra ... ni puede molerse bien, ni el Azogue abrazar [la] Plata tan gruessa*'. For a description of the tintin process see Barba, *Arte de los metales*, 127-29.

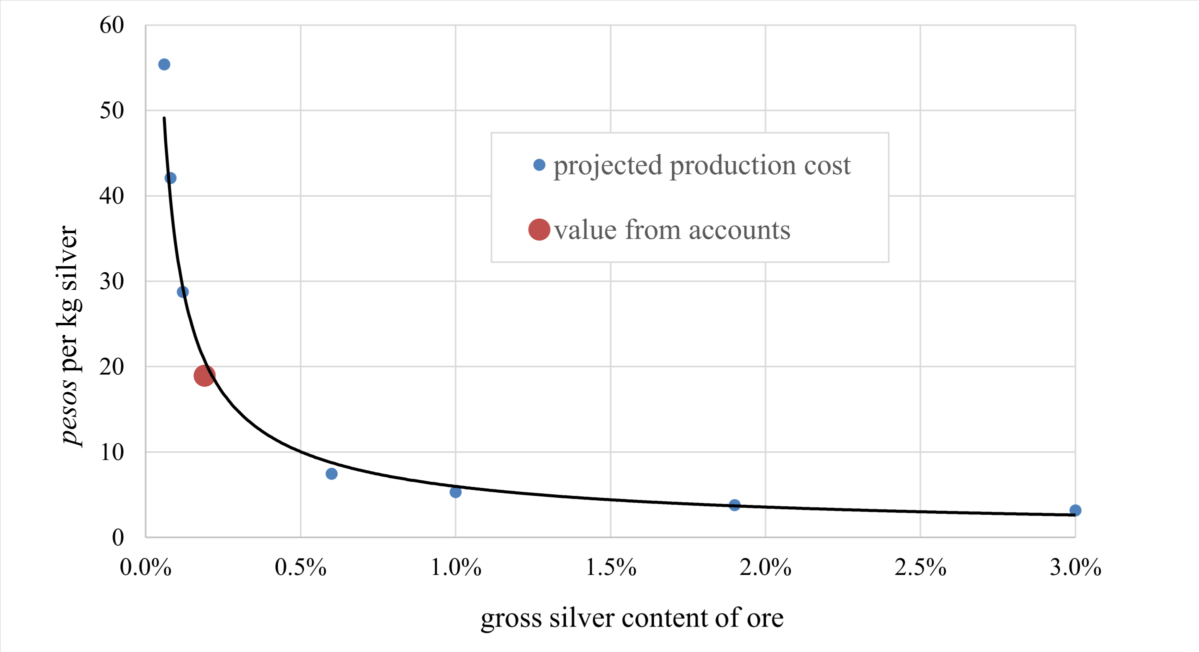

Figure 5-17. The projected cost of production using *patio* amalgamation at Regla (1875-1888) as a function of the gross silver content of the ore. Data from Table 5-VIII.

5.9 The partial variable production costs of smelting at Regla, 1872-1888

The variable production cost per kg of refined silver obtained via smelting at Regla averaged 5.2 *pesos* in the period June 1875 to January 1886, excluding the extraction cost of the ore (Figure 5-18). To better illustrate the grouping of values in spite of outlying data points I have opted to represent the scatter of the data. The percentage breakdown of the variable refining costs of smelting, without the variable cost of the ore, is shown in Table 5-IX. The deemed production cost of ore for smelting has been assumed to be exactly the same as that for amalgamation, 2.6 *pesos* per *carga* or 1.04 *pesos* per kg of silver.[823]

[823] At 2.6 *pesos* per *carga* production cost (1853-1854), for an ore with 1.9% silver this is equivalent to a cost of ore of 1 *peso* per kg of silver refined by smelting. From another context Duport states : 'one would need to be able to separate the costs of extracting the ore for smelting from those of the ore for amalgamation, and this is impossible; since, in all mines the selection is made on the mass of mineral that comes out of the mine, from where the richest ore is selected for smelting' - '*il faudrait pouvoir séparer les frais d'extraction du minéral fondu de celui destiné à l'amalgamation, et c'est une chose impossible ; car, dans toutes les exploitations on choisit sur*

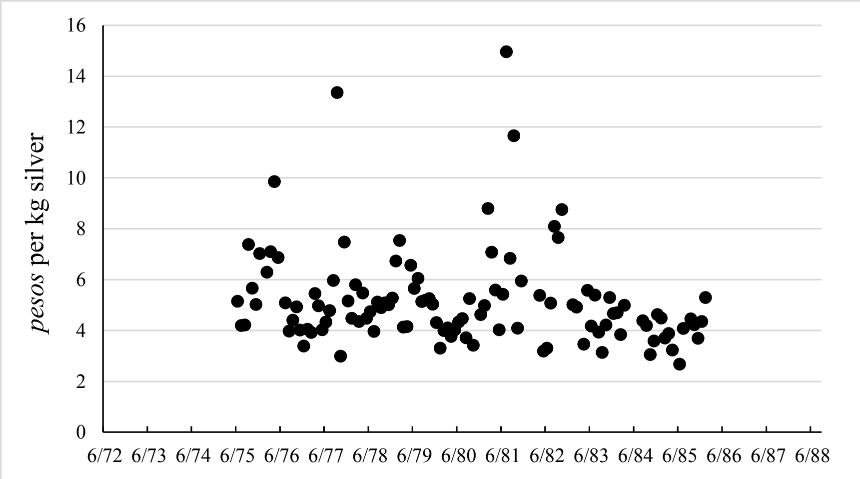

Figure 5-18. Monthly production costs of silver refined by smelting at Regla (1875-1886). Values calculated from data in *Contabilidad Mensual.*

smelting					
year	labour	litharge	charcoal	others	total
mid 1875	27%	26%	35%	12%	100%
1876	33%	20%	34%	14%	100%
1877	26%	24%	34%	16%	100%
1878	27%	26%	32%	15%	100%
1879	21%	21%	32%	25%	100%
1880	21%	21%	34%	25%	100%
1881	26%	14%	37%	23%	100%
1882	25%	19%	34%	22%	100%
1883	26%	12%	50%	12%	100%
1884	29%	20%	45%	6%	100%
1885	23%	21%	46%	10%	100%
average	26%	20%	38%	16%	100%

Table 5-IX. The percentage contribution to the partial variable refining cost of the main cost elements of the process. The percentage values were calculated on a monthly basis, and then averaged for the year. A total of 103 data sets are represented in the table. Source data from *Contabilidad Mensual.*

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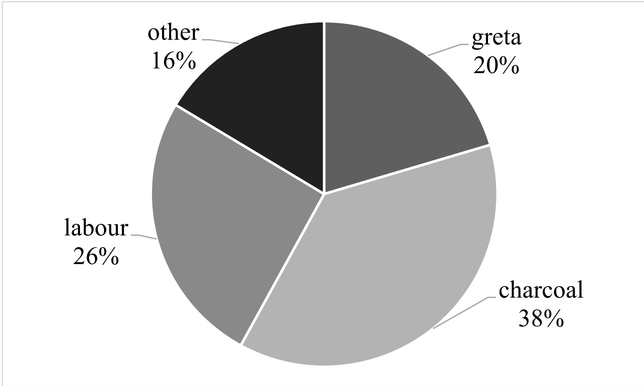
la masse du minerai, tel qu'il sort de la mine les parties riches qu'on destine a la fonte'. Duport, *Métaux précieux au Mexique*, 369. It could also be assumed to be zero, since the proportion of ores for smelting to ores for amalgamation at Regla was 2:100 (Chapter 4), and it could be argued that the mining business was structured around amalgamation, with rich ores being only a windfall profit. I do not adopt a zero value because I wish to extrapolate my projections to cases where the ore for smelting was mined for its own sake.

Figure 5-19 shows how the inclusion of the deemed variable cost of the ore changes the percentage profile, though to a much lesser extent than was observed for the case of amalgamation. Fuel (31%), then labour (21%), are the main cost components of the process. The influence of the cost of ore and litharge on the final production cost of smelting are equal (17%). The cost of labour in mining and refining would amount to around 35% of the final production cost by smelting, but the local labour fraction of fuel costs and others would probably add another 15%. Though less than the 65% contribution of labour costs to the total estimated for amalgamation, it still represents half the total variable cost for smelting at Regla in this period.

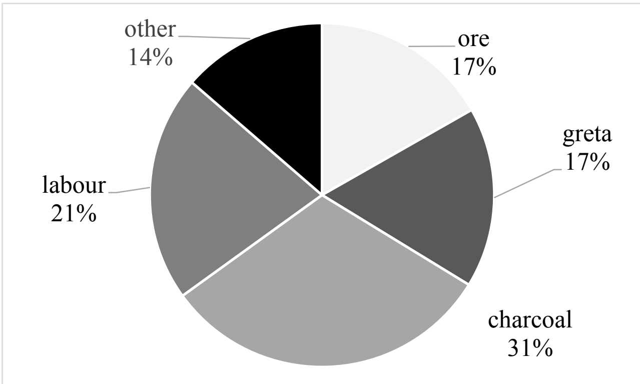
5.10 The variable production cost of smelting as a function of the silver content of the ore.

As in the case of amalgamation I will construe a matrix that will allow the calculation of the function of the variable cost of smelting function with respect to the silver content present in the ore. The column in grey in Table 5-X is the reference column for the subsequent calculations. This column represents the average costs registered at Regla to smelt ores with an average silver content of 1.9% (Chapter 4), plus the deemed extraction cost at 1.04 *pesos* per kg of silver refined, for a total of 6.2 *pesos* per kg of silver refined, or 14.65 *pesos* per *carga* of ore smelted.[824] The account books list side by side costs in *pesos* per *monton* for amalgamation runs and *pesos* per *carga* for smelting runs, so care must be taken in comparing values. Table 5-X shows this set of values derived from the accounting registers as my reference point in the column highlighted in grey. I then generate in the rest of Table 5-X the

[824] In contrast to ores for amalgamation, I pointed out in Section 4.5.1 that the gross silver content calculated from the accounts in ores for smelting is found to be equal to the silver extracted by smelting, within the error of the data.



(a)



(b)

Figure 5-19. Percentage breakdown of variable smelting costs at Regla (1875-1886), (a) without and (b) with the deemed variable cost of the ore.

variation in production cost per *carga* of ore and per kg of silver as a function of the silver content. I assume that the only cost that varies in a manner directly proportional to the silver content of the ore is the cost of litharge, and that all the other costs remain at the level that corresponds to the smelting of the 1.9% ore. Since the whole mass of ore is heated, the cost of charcoal will not vary with silver content; if it had, then results would have been more favourable to smelting. Figure 5-20 shows that smelting at Regla during this period was not an economic option for ores that had a silver content lower than 0.3%. According to the histogram in Figure 4.41, the lowest tranche of silver ores refined by smelting had a silver content of 1%.

With regards to the cost of production as a function of silver content, Figure 5-21 shows both the single value derived directly from the accounting registers (large circular marker) and the other data points projected according to the method set out in Table 5-X. Even at a silver content of around 2% the costs of amalgamation at Regla (3.7 *pesos* per kg silver) are significantly lower than those for smelting (5.9 *pesos* per kg silver). Even if the cost of ore for smelting was set at zero, assuming that it was a windfall product from the normal extraction of ores for amalgamation, the same advantage for amalgamation applies. This reinforces my assumption that it was operational reasons, and not economic ones, that limited the use of amalgamation at high silver contents at Regla.

Smelting	% silver in ore	0.0%	0.04%	0.06%	0.08%	0.10%	0.12%	0.16%	0.19%	0.40%	0.60%	1.00%	1.90%	3.00%
	kg of silver in a *carga*	0.00	0.0497	0.075	0.099	0.124	0.149	0.199	0.236	0.497	0.745	1.242	2.360	3.726
	value of silver, *pesos*	0	2	3	4	5	6	7.6	9	19	28	47	90	142
	variable production cost *pesos* per kg silver	variable production cost in *pesos* per *carga*												
Fuel	1.94	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58	4.58
Litharge	1.05	0.00	0.05	0.08	0.10	0.13	0.16	0.21	0.25	0.52	0.79	1.31	2.49	3.93
Labour	1.32	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13
others	0.85	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
ore	1.04	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45	2.45
total	6.21	12.16	12.21	12.24	12.26	12.29	12.32	12.37	12.41	12.68	12.94	13.47	14.65	16.09
	variable production cost *pesos* per kg silver	n/a	245.78	164.20	123.42	98.94	82.63	62.24	52.58	25.53	17.37	10.84	6.21	4.32

Table 5-X. The derivation of the total cost of smelting per *carga* and of the variable production cost per kg of silver as a function of silver content in the ore. For source of data see text.

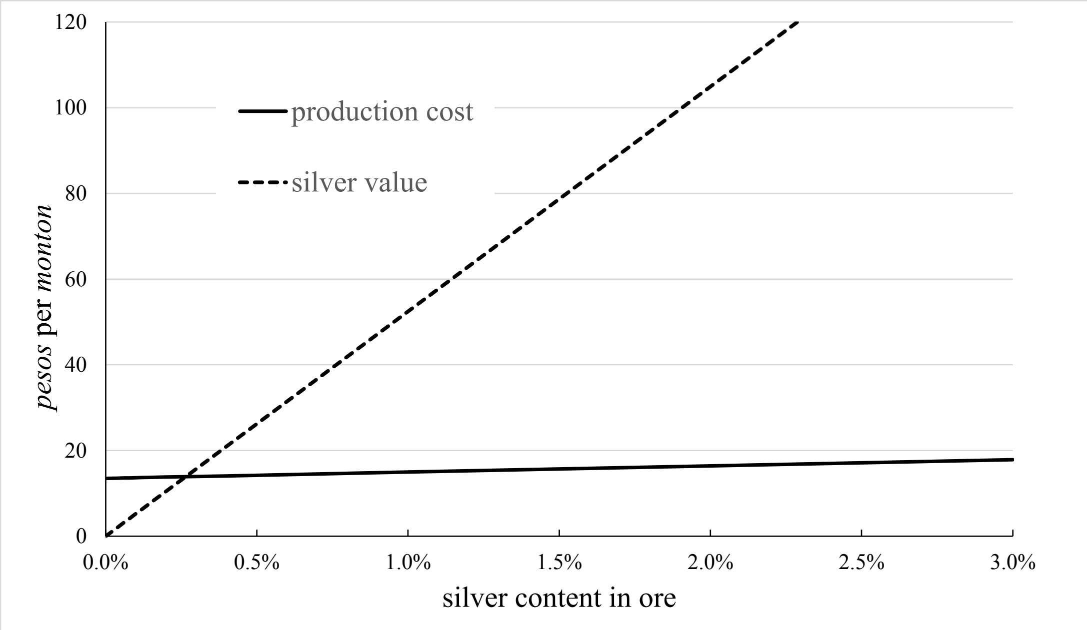


Figure 5-20. Cross-over point between the average variable cost of processing one *carga* by smelting and the value of silver extracted from the ore. Data from Table 5-X.

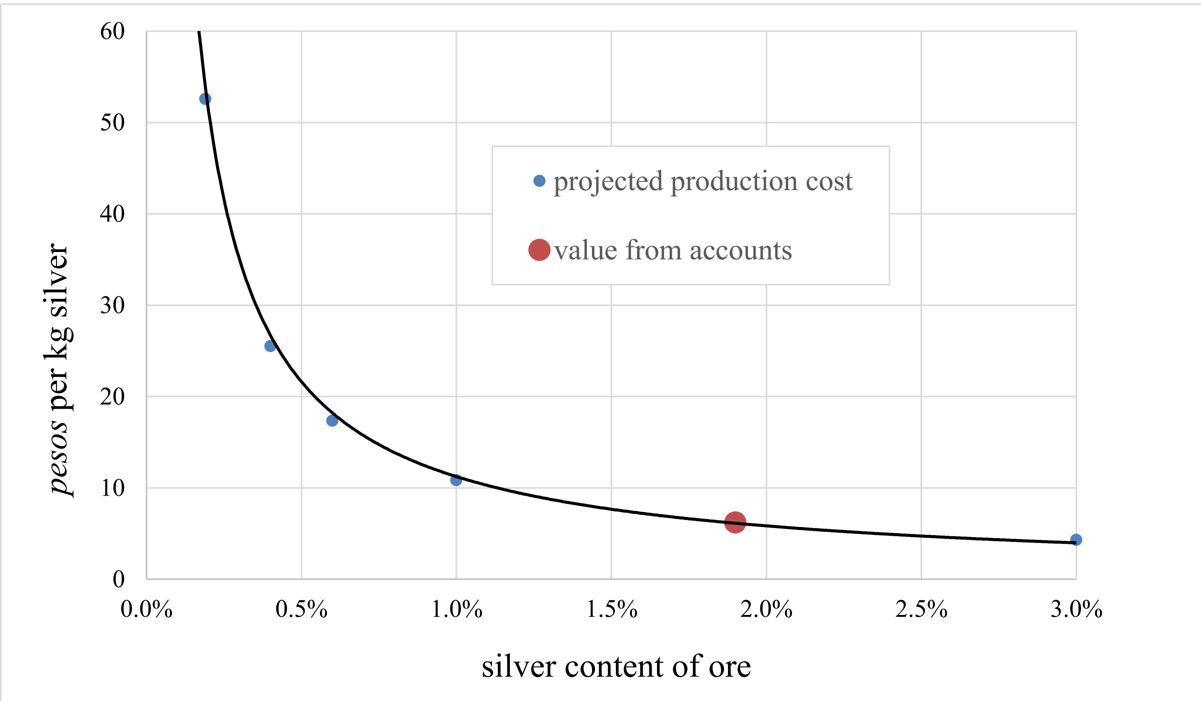


Figure 5-21. The variable production cost by smelting at Regla as a function of the silver content of the ore. Data from Table 5-X.

5.11 *Patio* amalgamation vs smelting at Regla

The results of the exercise shown in Tables 5-VIII and 5-X highlight the care that must be taken in comparing the production cost of amalgamation versus smelting. At first sight the results seem to correlate with the report that 'John Phillips found that for the year 1840 the cost of smelting was only 34% of the value of silver produced, while that of *patio* amalgamation was 46.25 percent'.[825] According to my calculations the corresponding values for the third quarter of the nineteenth century are 16% and 49% respectively, but in any case both sets of values as reported by Phillips give the impression that smelting is a better option than amalgamation. However my set of figures (and I strongly suspect the same applies to those stated by Phillips) have to be provided with the caveat that they are comparing apples and pears, since they apply to an ore with 1.9 % silver in the case of smelting and to an ore with 0.19% silver in the case of amalgamation.[826]

There is little point in stating a refining cost for a silver ore without indicating the silver content it applies to. A meaningful comparison between the refining costs of amalgamation and smelting can only be carried out at the same level of silver content of the ore being refined. This is the academic equivalent of what a refiner in the field holding a piece of ore in his hand will ask himself, which of the two processes shall I apply to this rock? Smelting could not have been applied at Regla in the third quarter of the nineteenth century for an ore with just 0.19% of silver content, since the variable costs for smelting exceeded the value of silver that could be extracted from it. In contrast, amalgamation could have been applied in theory at a

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[825] Quoted from a report to the Directors dated 29 June 1841, Real del Monte Proceedings, in Randall, *Real del Monte*, 114.

[826] Phillips, as many of the English managers of the company of the period, was strongly in favour of replacing the Mexican patio amalgamation process with the English tradition of smelting, and offered his data as support to his argument. Whether he was being disingenuous at the time or believed he was comparing costs on the same basis is open to question.

lower production cost to ores with 1.9 % silver. The fact it wasn't applied means that other constraints (technical, supply) came into play, but not the theoretical margin of profit. It is worthwhile at this point of the analysis to bear in mind the following advice from a nineteenth century textbook on the metallurgy of silver ores:

'the question as to the most economical treatment of an ore will be determined .. [by] all conditions … the cost of the same … being only one of many … and it may happen that a wasteful process is the best, or that a costly process is the cheapest … the proper treatment [is that] which, however wasteful, costly, or even unscientific, enables the owner to make the most money out of his ore'[827]

The results for Regla in the second half of the nineteenth century are unequivocal: amalgamation was a more cost effective refining process than smelting for ores with a silver content of 0.19%, and could break-even on ores with 0.09% silver. None of these ranges of ore could be smelted at a profit, under the set of conditions prevalent at Regla in this period. Smelting would be used until 1882 on ores that averaged 1.9% silver, and the minimum silver content in the ore needed to be above 0.3%. Nevertheless the economic data point to a production cost above that of amalgamation even for the ores with a higher content of silver. It does not come as a surprise that as of the late nineteenth century the Company decided to export the ores with a higher silver content to be smelted in England.[828]

One other important caveat applies to the comparison of production costs. In 1855 Buchan reported that: 'As far, however, as I have been able to judge by a constant attention to all these circumstances, the silver left unextracted by the several processes employed is nearly as follows: by smelting 6 per cent; by *patio* amalgamation 15 percent.'[829] In Section 4.5.3 the data for Regla after 1874 do not show any major difference in the percentage of unextracted

[827] Eissler, *The Metallurgy of Argentiferous Lead*, 349.
[828] Ruiz de la Barrera, "La Empresa de Minas del Real del Monte," 285, 298.
[829] Buchan, *Report Real del Monte*, 18.

silver between the two processes, admittedly within a range of limited values showing a very high average deviation. I have therefore preferred to apply in my calculations a correction of 10% between the gross and the extracted silver content in ores for amalgamation, while no correction was applied for the ores destined for smelting.

How do the data from Regla compare with the conclusions stated in the historiography (Section 5.2)? On the minimum content of silver required by each process to compensate extraction cost with the value of silver in the ore the correlation is good. Only 3 out of 17 examples in Table 5-II show ores below 0.09% silver content being amalgamated, and only one example of smelting applied to ores below 0.3% silver. On generic statements the divergence is notable. Smelting is not automatically the best choice on economic grounds for ores with higher silver content, unless lead content or restrictions on working capital and supply are at play. Mercury does not represent the highest production cost fraction in amalgamation, it is the cost of ore (only Villaseñor and Brading have pointed this out). Salt could be as important a cost factor as mercury. At Regla in the third quarter of the nineteenth century, smelting was not a process with a lower cost than amalgamation. The next section will address the question whether during the whole course of silver refining in New Spain / Mexico, smelting ever came to be able to compete with *patio* amalgamation on production costs.

5.12 Extrapolating the results from Regla to other historical scenarios

Production costs are location and time specific. The former because the costs of extracting ore, labour, fuel, other consumables, inland freight, availability of hydraulic power, the degree of ingratiation with local authorities to obtain exemptions of duties, mercury at cost or even a sufficient mercury quota at the official price in colonial times, all varied according to the region. The latter because the pricing and availability of mercury and charcoal, the nature and demands of the labour force, the fuel efficiency of the smelting furnaces, the degree of skill of the smelters and the depth of the mines depend to a high degree on the period being studied.

Therefore instead of trying to cover all these eventualities, I will reproduce conditions that would have been found during two important historical periods that can complement the picture provided by Regla: the pioneering stage of the sixteenth century and the shifting sands of the seventeenth to eighteenth centuries. In order to reconstruct the production costs for the historical periods I first establish the spread of historical values of the main cost factors of refining silver in Table 5-XI as can be found in the historiography.[830] Table 5-XII then indicates that the values registered at Regla do not all correspond to the same position in all the historical ranges. This gives a strong indication that the relation between production costs of amalgamation and smelting was not fixed but could show significant variations in different historical periods from the results observed in the previous section.

Of the two periods that served as bookends to the history of silver refining with mercury in the New World, Regla is the example that helps to explain the success of amalgamation in Mexico towards the end of the nineteenth century. Figure 5-22 is a powerful advertisement for the *patio* process, showing that at Regla it could even undercut the economies of smelting of ores with a high silver content. These results confirm that Regla was well configured for amalgamation. Its ore shows low to medium extraction costs, the *hacienda* had an extremely low fixed capital cost, it enjoyed free and constant hydraulic power, medium to low cost for mercury after 1875, employed one of the lowest ratios of mercury to silver for *patio* amalgamation, and during the period 1876 to 1888 its *patio* reactor operated at full capacity, thus optimizing labour costs. The same cannot be said of smelting, where the smelting capacity

[830] a) García Mendoza, "Minas de plata en Taxco."; b) Menegus Borneman, "Las comunidades productoras de sal y los mercados mineros: los casos de Taxco y Temascaltepec."; c) Fabry, *Impugnacion a reflexiones de Villaseñor*.; d) Dominguez de la Fuente, *Leal Informe Politico-Legal*.; e) Brading, *Miners Bourbon Mexico*.; f) Duport, *Métaux précieux au Mexique*.; g) Laur, "De la metallurgie de l'argent au Mexique." ; h) West, *The Parral Mining District*.

	location	period	cost	unit reported	notes	calculated to a common unit		source, page
Mercury	generic	16c to 19c	30 - 190	*pesos/quintal*				this chapter; a, 54
Salt	Tasco	16c	1.16	*pesos/fanega*		0.1	*pesos/arroba*	a, 54
	New Spain	1717	18 to 20	*real/fanega*	plus freight	>0.3		b, 82
	Pachuca	1743	20-22	*pesos/carga*		1.7-1.8		c
	Guanajuato	1763	3	*pesos/fanega*		0.4		d, 207-212
	New Spain	late 18c	1	*pesos/fanega*		0.1		e, 153-154
	Regla	1801	3.75	*pesos/* 75 lbs		1.3		e, 155
	Mexico	mid 19c	2 to 12	*pesos/carga*		0.2 to 1		f, 87
	Fresnillo	mid 19c	11 to 26	*real/fanega*	*fanega* of 200 lbs	0.2 to 0.4		f, 278
	Mexico	1860s	5	*pesos/carga*		0.40		g, 63
	Mexico	second half 19c	4 to 12	*pesos/carga*		0.3 to 1		g, 65-66
Copper sulphate	Zacatecas	late 18c	1.66	*pesos/arroba*		0.07	*pesos*/pound	e, 153-154
	Mexico	mid 19c	3 to 5	*pesos/carga*		0.12 to 0.2		f, 98
	Fresnillo	mid 19c	3.5 to 5.75	*pesos/carga*		0.14 to 0.23		f, 278
Litharge (*greta*)	Tasco	16c	2.70	*pesos/quintal*		0.06	*pesos*/kg	a, 54
	Guanajuato	1760s to 1774	1.25	*pesos*/2 *quintales*		0.01		d,270
	Mexico	mid 19c	2.5 to 4	*pesos/quintal*		0.05 to 0.09		f, 75
	Mexico	second half 19c	0.07	*pesos/arroba*		0.01		g, 83
	Catorce	1870	12	*pesos/carga*		0.09		g, 251-252
Charcoal	Tasco	16c	0.3	*pesos/carga*		0.3	*pesos/carga*	a, 54
	Fresnillo	mid 19c	1.5	*reales/arroba*		2.3		f, 278
	Fresnillo	second half 19c	0.19	*pesos/arroba*		2.3		g, 83
	Zacatecas	second half 19c	0.19	*pesos/arroba*		2.3		g, 83
	Guanajuato	second half 19c	0.21	*pesos/arroba*		2.5		g, 83
ores	generic	all	nil		tailings	0	*pesos/carga*	f, 375
	Parral	1649	0.25 to 0.3	*pesos/quintal*	check	0.7 to 0.9		h, 96
	Regla	1801	0.3	*pesos/quintal*	1 oz/qtal silver	0.9		e, 155
	Regla	1801	0.8	*pesos/quintal*	2.5 oz/qtal silver	2.4		e, 155
	Zacatecas	1839-1840	8.33	*pesos*/14 *arrobas*	0.20%	7.1		f, 223
	buscones	1840s	8.1	*pesos*/14 *arrobas*	?	6.9		f, 223
	Zacatecas	mid 19c	5.5	*pesos/carga*	0.17 to 0.25%	5.5		f, 246
	Zacatecas	mid 19c	4.39	*pesos*/mark silver	0.46%			f, 252
	Fresnillo	mid 19c	3.43 to 3.75	*pesos/carga*	0.20%	3.4 to 3.8		f, 259
	Guadalupe y Calvo	mid 19c	5.25	*pesos/carga*	0.25 to 0.3%	5.3		f, 308
Furnace efficiency	generic	16c to 18c	1000	kg/kg silver				this chapter
		second half 19c	200					
Fixed capital cost	generic	all	nil	small scale smelting works				
			5% of variable cost	large amalgamation works				f, 279-280
Source of power	generic	all	nil	water power				
			12% of variable cost	animal power				f, 279-280

Table 5-XI. Selection of historical costs from the sixteenth to nineteenth century of the main factors that determine the production cost of amalgamation and smelting. Sources in footnote 830.

		Regla	historical values	% variable costs at Regla	
				amalgamation	smelting
cost of ore	*pesos* /*carga*	2.6	0 to 7.1	58	16
cost of power for mills, furnaces		free	approx. 12% of variable costs	0	
fixed capital cost		very low	approx. 5% of variable costs	assumed negligible	assumed negligible
mercury to silver ratio		1.3	1.3 to 2.1	10	
mercury	*pesos* /*quintal*	60	30 to 190		
salt	*pesos* /*arroba*	0.7	0.1 to 1.8	9	
copper sulphate	*pesos* /pound	0.13	0.07 to 0.23	4	
efficiency furnaces		200 kg fuel/ kg silver	1000 kg fuel/kg silver		32
charcoal	*pesos* /*carga*	1.3	0.3 to 2.5		
litharge	*pesos* /kg	0.08	0 to 0.9		17
labour		high	indirect; low to high	7	22

Table 5-XII. The profile of costs registered at Regla in the third quarter of the nineteenth century within the historical context of New Spain / Mexico. For sources see Table 5-XI and Sections 5.8 and 5.11.

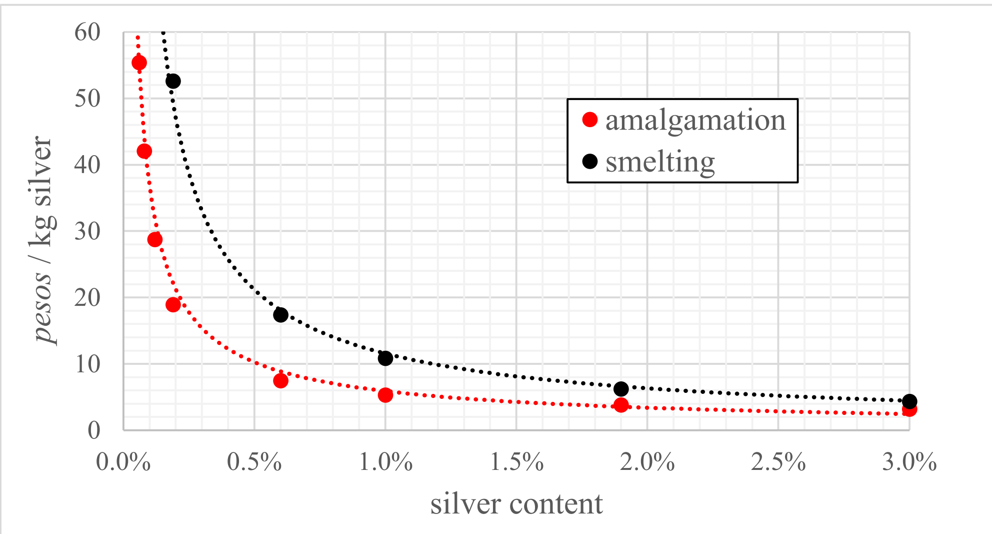

Figure 5-22. Total variable refining cost at Regla (1875-1888), as a function of the silver content of the ore. Data from Tables 5-VIII and 5-X.

had been over-designed (six blast furnaces had been built, exceeding by far the amount of available ore for smelting), labour for smelting had therefore become a fixed cost as it was underutilized yet had to be retained due to its specialist skills, and the ore was poor in lead, requiring the purchase of litharge. The one redeeming feature for smelting at Regla was the very high fuel efficiency of its blast furnaces.

At the other bookend to this history, the second half of the sixteenth century, when refiners were still grappling with smelting and amalgamation was beginning to offer some of them solace, the context was completely different. For smelting it was characterized by inexpensive infrastructure, negligible extraction costs for the initial rich surface deposits, abundant and nearby fuel sources, inefficient furnaces and ores rich in lead in some locations. As to amalgamation, it was initially applied to ores obtained from tailings, thus with zero extraction cost, mercury was sold at the highest levels of historical prices, the novelty of the process resulted in some very high mercury to silver ratios, investment in new stamp mills was the major capital cost involved, and water was not always available to drive them. This new context can be translated into numbers that will allow me to calculate a new set of comparative refining costs for both processes. The aim is not to arrive at absolute production economic data but to estimate changes in the relative efficiency of both processes to refine at a profit ores with different levels of silver content. The method is analogous to that applied in Tables 5-VIII and 5-X, except that now I will change certain key values as set out in Table 5-XIII. Once the new values are substituted in a calculation matrix (reproduced in Appendix E), a new plot of comparative production costs as a function of silver content is generated (Figure 5-23). Smelting is now the clear choice, on the basis of cost, for ores with a silver content above 0.5%, while amalgamation remains the process of choice for ores with a silver content below this threshold.

	original Regla data	projected value for 16c context	explanation
	pesos per kg of silver		
amalgamation			
mercury	1.94	9.93	a factor of 5.12 = (180/60)*(2.1/1.3)
labour	1.31	0.13	10% of 19c value
ore	11.1	0	tailings
fuel	0.19	0.04	(0.3/1.3)
power	0	1.2	approx. 12% variable cost
fixed capital	0	0.5	approx. 5% variable cost
smelting			
fuel	1.94	2.23	a factor of 1.15 =(1000/200)*(0.3/1.3)
litharge	1.02	0	lead rich ores
labour	1.33	0.13	10% of 19c value
ore	1.00	0	rich surface deposits
power	0	0	low cost
fixed capital	0	0	inexpensive infrastructure

Table 5-XIII. Sensitivity values for a cost approximation to the context of refining of silver in the second half of the sixteenth century.

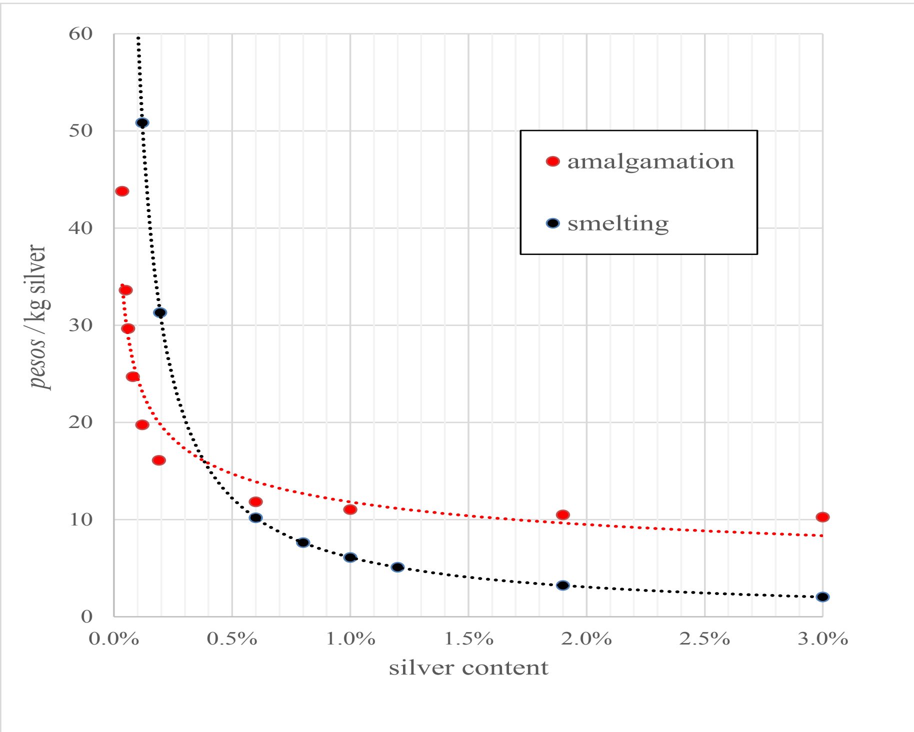

Figure 5-23. Comparative production costs of amalgamation and smelting in the context of the second half of the sixteenth century as a function of the silver content of the ore. See Appendix E for source data.

The period between the bookends is too complex to reduce to a single graph. The decades from mid seventeenth century to the end of the eighteenth century were a period of alternating fortunes for amalgamation and smelting. Infrastructure costs become important as major industrial concerns develop that cover mining and refining of their own ores as well as the ores from smaller miners via the lucrative *maquila*, the toll charged for refining ores.[831] In contrast, smelting continued to require a much lower capital fixed cost, and could always be carried out at a much smaller scale. Mercury prices would drop to their lowest historical levels at the end of this period, though mercury to silver ratios would remain high except where iron was used as an additive or the nature of the ore dictated otherwise. Furnace efficiency remained low.

Two comments in the historiography point to a fine economic balancing act during this period between amalgamation and smelting. The appraisal by Humboldt that 'usually it is only the abundance of mercury and the ease of procuring it that determine the choice of the miner [refiner] on the [refining] method he will choose', by its silence on refining costs is pregnant with the implicit assumption that smelting was only displaced by an opportunistic supply of mercury, not by an inherent economic shackling of its feet.[832] Garner comments that in the years between 1798 and 1803 in Zacatecas, cutting the *diezmo* to one half triggered an increase

[831] The view from the other side was quite stark. Small miners bore all the risk of mining and had to sell their ores at the mercy of big refining haciendas who never informed the miner of the real silver content of their product, but simply returned to him an amount of silver corresponding to its deemed content on which the tolling charge was calculated, with the refiner doing all the deeming. An extensive litany of complaints can be found in Dominguez de la Fuente, *Leal Informe Politico-Legal*. The potential for fraud was ever present, regardless of the legal context that developed around the *maquila*. The law recognized that refining was a legitimate activity separate from mining. Haciendas by law had to publish their toll charges, such that the cost of mercury was at the same price it was sold to refiners, while a 12% premium could be applied to other consumables. Mining judges could revise the charges applied by the tolling haciendas. In principle the owner of ore could assist and intervene during process. Federico Kunz, "Evolucion historica del regimen legal del beneficio de minerales en Mexico " in *Mineria Regional Mexicana. Primera reunion de historiadores de la mineria latinoamericana*, ed. Dolores Avila Herrera and Rina Ortiz (Mexico: Instituto Nacional de Antropologia e Historia, 1994), 65-77.

[832] '*souvent ce n'est que l'abondance du mercure et la facilite de s'en procurer qui decident le mineur dans le choix de la methode qu'il emploie*'. Humboldt, *Essai politique*, Tome IV, 56.

of 2.5 times the previous amount of silver smelted, which again is mostly (but not all) lost in 1803 when on re-establishing the previous *diezmo* production of silver decreases by one third.[833] The decrease in the *diezmo* is equivalent to approximately 2 pesos in the value of one kg of silver, just 5% of the value of the silver being refined. It was a very fine line that at times kept smelting and refiners apart.

The method applied to the sixteenth century can be used to determine whether conditions could have existed in parts of New Spain in the seventeenth and eighteenth centuries that would cause the two functions of production costs versus silver content to overlap substantially onto a single curve. This would have the practical consequence that a refiner could apply either amalgamation to smelting, subject to the nature of the ore, without unduly sacrificing his profit margin. Table 5-XIV and Figure 5-24 have been drawn up in this light. They do not attempt to represent specific locations or years within this very complex period, they only represent a context that is feasible in the light of what is known at the present time. The plots that correspond to this new data set prove that it is possible to find a historical context where the curves of production cost versus silver content in the ore for amalgamation and smelting are superimposed on each other, as seen in Figure 5-25. It provides the first quantitative explanation to the empirical observation in the historiography that after mid seventeenth century major shifts are observed within silver refining in New Spain, with smelting increasing its presence with respect to amalgamation (see Chapter 6). It proves that under a certain set of conditions, refiners of this period could have been able to choose amalgamation or smelting without having to sacrifice their profit levels.

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[833] Garner and Stefanou, *Economic Growth Bourbon Mexico*, 135. The *diezmo* was the royalty of 10% imposed by the Crown on silver produced.

	original Regla data	projected value for 17-18c context	explanation
	pesos per kg of silver		
amalgamation			
mercury	1.94	2.7	a factor of 1.4 = (60/60)*(1.8/1.3)
labour	1.31	0.7	50% of 19c value
ore	11.1	16.7	a factor of 1.5, less efficient deep mining
fuel	0.19	0.04	(0.3/1.3)
salt	1.83	3.7	a factor of 2, salt sources not optimized
power	0	2.8	12% variable cost
fixed capital	0	1.3	5% variable cost
smelting			
fuel	1.94	2.2	a factor of 1.15 =(1000/200)*(0.3/1.3)
litharge	1.02	0	lead rich ores
labour	1.33	0.7	50% of 19c value
ore	1.00	0	cost borne by ore for amalgamation
power	0	0	low cost
fixed capital	0	0	inexpensive infrastructure

Table 5-XIV. A theoretical context of production costs viable for the period 17c to 18c, and within the limits of data provided in Table 5-XII.

Charcoal would have been needed at low prices to offset the inefficient furnaces, and lead fluxes not required or available at a very low price. The extraction cost of ores for smelting would have had to be low, either in practice or at an accounting level.[834] Salt needs to be expensive, water power absent from the amalgamation *hacienda*, capital cost of infrastructure

[834] ores with as little as 0.0125% (4 oz per ton) silver broke even on production costs if the ore was priced at zero value at the smelting work in Konigsberg, Norway, in the nineteenth century. Percy, *Metallurgy*, I 513. However see Appendix F for the context to European production costs and threshold silver values in the ores.

and inefficient mining costs high.[835] None of these conditions can be described as unrealistic for the period.

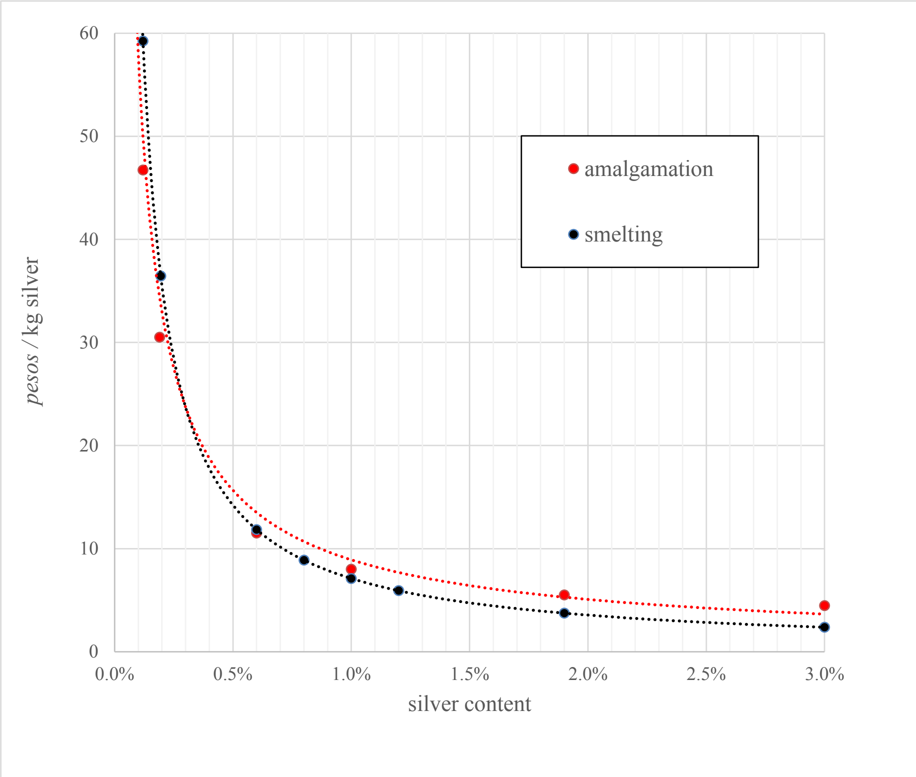

Figure 5-24. Total production cost as a function of the silver content of the ore, within the context of the period from the mid-seventeenth to mid-eighteenth century. See text for details on the generation of the values plotted.

There are still too many gaps in the historiography on economic data of refining for this period to take this analysis any further, but it has demonstrated that the production costs of smelting could have been equivalent to those of amalgamation for some refiners in New Spain.

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[835] ‘already by the late eighteenth century …. mining had reached very deep levels’ - *‘ya desde las postrimerías del siglo XVIII ... las explotaciones habían alcanzado gran profundidad’*. Ortiz Peralta, "La Compañia de Real del Monte y Pachuca," 201.

This is very important since it means that refiners could choose between amalgamation and smelting, subject to the nature of the ores, without sacrificing the margin of profit.[836]

5.13 The structure of labour costs at Regla.

Smelting has been reported in the historiography as requiring major amounts of labour. Medina promoted the amalgamation process by drawing attention to the many stages of labour required by the smelting process as being applied in his time.[837] The deemed intensive need for labour in New Spain during the initial period when only smelting was used has been set against the ravages caused by epidemics within the indigenous labour pool to indicate a deficiency of manpower that contributed to the introduction of amalgamation.[838] On the other hand, a recent compilation of the various classes of labour required in an amalgamation *hacienda* has concluded that amalgamation required more labour than smelting.[839] There is no equivalent work on the structure of the labour force of a refining *hacienda* comparable to the study of the Zacatecas mining community of the nineteenth century.[840] In the case of Regla two studies appear in the historiography, one related to the English component of the workforce, and the

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[836] In Chapter 6 I will come back to the problem of explaining the changes observed in the balance between amalgamation and smelting in most of the *Cajas* (Regional Treasuries) throughout the colonial period.

[837] '*Y así he visto como se benefician los dichos metales en muchas partes con greta y cendrada y la muy grande costa de los dueños de las minas … de indios como de negros, porque un ingenio de caballos que trae un horno andando bueno … así que … ha menester cuatro fundidores y cuatro cargadores y dos españoles que se muden por sus cuartos, y por personas que anden con los caballos del ingenio por sus cuartos, y más dos afinadores, y para moler la greta y cendrada otras dos personas, y para hacer los hornos y labrar las piedras otras dos, y para hollar las cendradas cada una que afinan, son menester seis personas, porque al final de dos días a la semana que vendrán a ser dos personas cada día y de noche doce negros, y más para cubrir y sacar dicho carbón*' in Castillo Martos, *Bartolomé de Medina*, 112.

[838] Berthe, "Le mercure et l'industrie mexicaine au XVIéme siècle," 145-46.

[839] Lara Meza, *Haciendas de beneficio de Guanajuato*, 101.

[840] Guadalupe Navas, "Zacatecas a fin del siglo XIX," in *Mineria Regional Mexicana. Primera reunion de historiadores de la mineria latinoamericana.* , ed. Dolores Avila Herrera and Rina Ortiz (Mexico: Instituto Nacional de Antropologia e Historia, 1994). It should be pointed out that prisoners housed in a *Presidio* (jail) were part of the general labour used by the Compañia Real del Monte until the end of 1874, but only worked in the mines. The *Presidio* was built in 1850. Inés Herrera Canales and Rina Ortiz Peralta, "Mexican Mining Heritage-The Real Del Monte Site," *CRM (Washington)* 21, no. 7 (1998): 20.

other states there were eighteen different labour functions within Regla but does not include any economic data.[841]

The degree of detail on labour included in some of the Regla account books shed further light into the structure of labour costs in both processes. The *Memorias Semanales* provide a very detailed breakdown of the labour structure and costs at Regla. Table 5-XV summarizes one such example using the *Memorias* Number 18 to 21, accounting records that cover the four weeks beginning the 5th May 1877 to the week starting the 26th May 1877, that spell out the itemized labour costs incurred by both *patio* amalgamation and smelting at Regla.[842] An initial overview brings to light some interesting facets on the labour structure at Regla in the later part of the nineteenth century.

a. Not all the workforce is on the payroll as full time employees of Regla. Those on part-time wages are mostly craftsmen involved in the ongoing repairs and maintenance required by the *hacienda*. Unskilled manual workers (*peones*) are paid according to different wage scales on a per diem basis, but there is no guide to determine the reason for the pay differentials. Part of the work is outsourced: the stamp mill is run by two work teams, which are paid on the basis of *cargas* of ore processed per week; the cupellation of silver and its casting into silver bars is also carried out by work teams and the cost charged per bars cast.

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[841] Herrera Canales, Velasco Avila and Flores Clair have focused their detailed analysis on the fortunes of the English workforce at the Compañia de Real del Monte under its new Mexican ownership. They detect that Englishmen were kept in key management posts (‘*puestos de confianza*’) for some twenty years after the Company was bought from its original English owners. Part of their duties were those of supervision over manual labourers. The post of Director from 1848 to 1868 was held by just one extended English family: John Buchan (1848 to 1856), followed by his brother-in-law Thomas R. Auld (until 1862) and then by his brother-in-law’s brother, Edward Auld (until 1868). Cornish miners emigrated to Real del Monte and other parts of Mexico during the nineteenth century, leaving evidence of their Cornish culture transplanted to Real del Monte. Two Mexicans were responsible as Directors during the period of interest in this chapter, Jose Maria Camargo from 1872 to 1873, and Jose de Landero, until 1899. Herrera Canales, Velasco Avila, and Flores Clair, *Etnia y clase*, 2, 7, 9-27, 47-64. On the different labour functions within Regla see Ladd, *The Making of a Strike*, 7.

[842] The wages at Regla were slightly below those reported by Laur for Fresnillo, which had a larger workforce (415) and throughput (48,000 tons) than Regla. Laur, "De la metallurgie de l'argent au Mexique," 85-86.

		by day or week	by task	wage *pesos*	total man-days		cost of labour *pesos*
Stamp mill							
Epitacio Flores & team			unknown	per *cargas* of ore	623	*a*	
Geronimo Marquez & team			unknown				
	subtotal 1				623		324
Arrastres							
Vicente Osorio	Captain (*Capitan*)	1		7 / wk	24	*b*	
Ysidro Rios	Captain	1		7 / wk	24	*b*	
Jesus Osorio	Overseer (*Velador*)	1		4 / wk	24	*b*	
	Workers (*Peones*)	20		0.38, 0.44 / d	551	*c*	
	subtotal 2	23			623		274
Patio Amalgamation							
Cayetano Ortiz	Captain	1		9 / wk	24	*b*	
Rafael Perez	Captain	1		7 / wk	24	*b*	
Luz Acevedo	Assistant (*Ayudante*)	1		6 / wk	24	*b*	
Nestor Hernandez	Assistant	1		6 / wk	24	*b*	
	Workers (*Peones*)	44		0.19;0.38;0.5 / d	978	*c*	
	subtotal 3	48			1074		688
Capellina & casting of silver bars							
Mauro Vargas	for minding *capellinas*		1	1 per *capellina*	unknown		
Jesus Hernandez & team	for casting 26 silver bars		unknown	0.25 per bar cast	unknown		
	subtotal 4						28
General Administration							
Juan Cuataparo	Administrator	1		40 / wk	24	*b*	
Jose Adrian Palomo	Paymaster ore (Rayador)	1		18 / wk	24	*b*	
Jesus Guerrero	Stock person (Recibidor)	1		12 / wk	24	*b*	
Eduardo Fuentes	Assistant	1		7 / wk	24	*b*	
Jorge Castro	Assistant	1		7 / wk	24	*b*	
Jose Salazar	Overseer	1		7 / wk	24	*b*	
Ramon Hurtado	Gatekeeper	1		7 / wk	24	*b*	
Lauro Perez	Gatekeeper	1		7 / wk	24	*b*	
Justo Yslas	Gatekeeper	1		4 / wk	24	*b*	
	subtotal 4	9			216		436
Repairs							
	Bricklayer	4		0.75 / d	90	*c*	
	Workers (*Peones*)	21		0.38 / d	474	*c*	
	Master Carpenter	1		10 / wk	24	*b*	
	Carpenters	6		1;0.75;0.63 /d	135	*c*	
	Carpenters	3		1.5 / wk	72	*b*	
	Master Smith	1		8 / wk	24	*b*	
	Smiths	4		0.75;0.5;0,38/d	93.3	*c*	
	Sonadores?	2		0.19/d	46	*c*	
	Roofers	2		0.75;0.38/d	34	*c*	
	Leathersmith	1		0.75/d	14	*c*	
	subtotal 5	45			1007		625
Recovering amalgam from fine ore residue							
Rafael Romero	Captain	1		7 / wk	24	*b*	
Ignacio Castillo	Assistant	1		4 / wk	24	*b*	
		33		0.25;0.19;0.12 / d	695	*c*	
	subtotal 6	35			743		161
Stables							
Joaquin Perez	Head of stable	1		7 / wk	24	*b*	
	Workers (*Peones*)	4		0.38 / d	112	*c*	
	subtotal 7	5			136		70
Smelting							
Antioco Perez	Captain	1		14 / wk	24	*b*	
Panfilo Perez	Captain	1		7 / wk	24	*b*	
Lucas Guzman	Assistant	1		5 / wk	24	*b*	
Jose Mugica	Assistant	1		5 / wk	24	*b*	
	Furnacemen	8		0.62 / d	222	*c*	
	Carriers	8		0.5 / d	221	*c*	
	Charcoal-loaders	8		0.25 / d	221	*c*	
	Workers (*Peones*)	24		0.38;0.25;0.12 / d	356	*c*	
Jesus Hernandez & team	refining		unknown	per cupellation	unknown		
Pasenal Palacios	various		1	per shift	unknown		
Eduardo Lopez	Assistant		1	per task	unknown		
	Ventilation team		1	per task	unknown		
	subtotal 8	52	3		1116		550
Extraordinary expenses							
Andres Yenteno	Medical doctor	1		8 / wk	24	*d*	
	help with *capellinas*				unknown		
	subtotal 9	1			24		40

notes: a. deemed equivalent to *arrastres* b. based on 6 day week c. as reported in days in *Memorias*. Miscellaneous work paid by unit or *varas* such as horseshoe fitting, stone laying and wood sawing has not been included since no information is provided except total cost of labour, and it represents a minor fraction of the total wage cost..

Table 5-XV. Breakdown of labour man-days and costs for the various refining stages carried out at at Regla based on data for the four week period ending on May 29th 1877 (*Memorias Numero* 18 - 22).

b. There is no designation of an *azoguero* by such name in the accounts. Most probably the captains that are accounted for under *patio* amalgamation are the equivalent of an *azoguero*.[843]

c. As expected, the work of minding the separation of mercury from silver in a *capellina* is so simple that the minder of the *capellina* was paid just 1 peso per *capellina* run. The actual man-handling of the *capellina* is done as a side activity by *peones* who are given a tip (*gratificacion*) between that is registered under Various Expenses. The tip is equivalent in value to the payment for minding a *capellina*.

d. The group of skilled workers (bricklayers, carpenters, etc) in charge of repairs and maintenance are not named, not even the master carpenter or the master smith, both of which had weekly wages equivalent to those of named captains or assistants. The *peones* are not listed by individual names either. Thus it is not possible to confirm the large presence of women expected within the *planillero* squads. On the other hand the junior gatekeeper merits being identified as Justo Yslas earning 4 *pesos* a week, less than what a *peon* made.

e. The senior captain in charge of smelting earns double the wage of the captains in charge of amalgamation, an indication of the greater skill required for the smelting process. The wage structure of the smelting section indicates that the group of very skilled workers and their assistants was kept on the weekly payroll irrespective of whether smelting was carried out during the week.

f. There is no job description that can be readily identified for custodians of the integrity of the refined silver or of the mercury inventory. This would place primary responsibility on

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843 According to Duport the *azogueros* in the main haciendas of Guanajuato in the 1840s were earning 25 pesos per week. This is considerably more than the 7 to 9 pesos being paid to the captains in charge of amalgamation at Regla. Duport, *Métaux précieux au Mexique*, 237.

avoiding pilfering of materials or of silver on the captains of each work team, with central staff completing the oversight. Just three gatekeepers covering a weekly 24 hour supervision of the gate traffic seems a bare minimum for an *hacienda* the size of Regla. In general it seems a very lean operation for providing oversight over each stage of the process.

There is sufficient information in Table 5-XV to carry out a quantitative analysis of the manpower requirements of each process, though the following assumptions are still required:

i) Data on total man-days and man-weeks, and the cost of wages and labour by day or task, while ample are not complete. Man-days spent on the stamp mills are not specified, though the total cost is accounted for. Since this cost is higher than the total cost of labour for the *arrastres*, I have assumed that the man-days spent on the stamp-mills are at least as high as those spent on the *arrastres*.

ii) The length of a shift in a working day is unknown. According to Duport, commenting upon labour in the *haciendas* of Guanajuato in the 1840s:

'The wages of the workers are 0.50 *piastres* [*pesos*] per day. They come to work on Sunday evening, and do not leave until the next Sunday in the morning, or at the earliest on the Saturday evening. There is no shift of workers for the day and night [work]'.[844]

His report coincides with the continuity in the monthly and weekly accounts that indicate that Regla functioned year round. According to Mendizabal, the work-day of a peon earning 0.5 pesos a day was 12 hours.[845] The accounting figures in the Memorias are provided as either man-weeks or man-days. I have decided to convert where necessary the figures to

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[844] '*Le salaire des ouvriers est de piastres 0.5 par jour. Ils entrent le dimanche á la nuit, et ne sortent plus jusqu'au dimanche matin, ou au plus tôt le samedi soir. Il n'y a pas de relais d'ouvriers pour le jour et la nuit'*. Ibid.
[845] Mendizábal, "Minerales de Pachuca," 295. See also Brading, Miners Bourbon Mexico, 153-154.

man-days by assuming a six day week. I did not use man-hours since I have no information on the length of the working day for manual and non-manual labour at Regla.

I partition the known costs and man-days according to the nature of each refining process. In those cases where both processes would have shared the same activity, I apply a factor based on the percentage of silver refined by each process during the month of May 1877 (see Chapter 4). Common units such as General Administration would have had a higher wage bill if Regla had functioned solely as either a smelting or a *patio* amalgamation *hacienda*, than that shown by the breakdown method I have adopted. The approximation is however sufficient for the purpose of the exercise.

Tables 5-XVI to 5-XVIII show the labour structure (cost, man-days and total number of workers, respectively) for Regla as a whole and then for each refining process according to the method detailed above.

	Regla as a whole		patio amalgamation (77% of silver refined)		smelting (23% of silver refined)	
	pesos		pesos		pesos	
Stamp mill	324	10%	249	11%	75	8%
Arrastres	274	9%	274	12%		
Patio Amalgamation	688	22%	688	30%		
Capellina & casting of silver bars	28	1%	28	1%		
General Administration	436	14%	335	15%	101	11%
Maintenance	625	20%	480	21%	145	16%
Planilleros / recovery amalgam	161	5%	161	7%		
Stables	70	2%	54	2%	16	2%
Smelting	550	17%			550	61%
Extraordinary expenses	40	1%	30	1%	9	1%
total	3,195	100%	2,298	100%	898	100%

Table 5-XVI. Labour costs at Regla, according to the *Memorias* 18 – 22, and the deemed distribution of labour costs between *patio* amalgamation and smelting.

	Regla as a whole		patio amalgamation (77% of silver refined)		smelting (23% of silver refined)	
	man-days		man-days		man-days	
Stamp mill	623	11%	478	12%	145	9%
Arrastres	623	11%	623	16%		
Patio Amalgamation	1074	19%	1074	27%		
Capellina & casting of silver bars	unknown		unknown			
General Administration	216	4%	166	4%	50	3%
Maintenance	1007	18%	773	19%	234	15%
Planilleros / recovery amalgam	743	13%	743	19%		
Stables	136	2%	104	3%	32	2%
Smelting	1116	20%			1116	71%
Extraordinary expenses	24	0%	18	0%	6	0%
total	5561	100%	3980	100%	1582	100%

Table 5-XVII. Labour man-days at Regla, based on data from the *Memorias* 18 – 22, and the deemed distribution of man-days (manual and non-manual labour) between *patio* amalgamation and smelting.

	Regla as a whole		patio amalgamation (77% of silver refined)		smelting (23% of silver refined)	
	total workers		total workers		total workers	
Stamp mill	unknown		unknown		unknown	
Arrastres	23	11%	18	12%	5	8%
Patio Amalgamation	48	22%	48	33%		
Capellina & casting of silver bars	unknown		unknown			
General Administration	9	4%	7	5%	2	3%
Maintenance	45	21%	35	24%	10	15%
Planilleros / recovery amalgam	34	16%	34	23%		
Stables	5	2%	4	3%	1	2%
Smelting	52	24%	0	0%	52	73%
Extraordinary expenses	1	0%	1	1%		
total	217	100%	146	100%	71	100%

Table 5-XVIII. Labour force at Regla, based on the Memorias 18 – 22, and the deemed distribution of the workforce (manual and non-manual labour) between *patio* amalgamation and smelting.

The main conclusions derived from these tables are:

1. Repairs make up 20% of total labour costs, an important amount second only to *patio* amalgamation, and above the combined cost of milling and *arrastres*, or the labour cost for the

smelting section. Though the machinery at Regla was not complex, it involved many moving parts, which explains the high labour cost of maintenance.

2. The labour cost of the *planilleros* belies the amount of man-days and personnel expended in the search for amalgam and mercury that was entrained in the slurry from the washing of the *tortas*. Nearly one fifth of the total man-days required for the *patio* amalgamation was used in this recovery process. In number of workers it matched the workforce on maintenance duties and visually it would have represented a group of people three-quarters the size of the whole *patio* amalgamation work-force. This underlines the thoroughness applied to the recovery cycle of amalgam and mercury lost into the water streams.

3. In the smelting process, the labour related to the furnace smelting of the ores represent 60% of costs, and around 70% of man-days and workforce. There is no equivalent stage in the *patio* amalgamation that absorbs so much labour power. Regla may be an anomaly in this respect, since it possessed six blast furnaces at one time, and was clearly overdesigned for the amount of ore it received for smelting. In addition, the need to maintain a trained group of smelting craftsmen and support workers regardless of the actual amount of ore being delivered converted their wages into a virtual fixed cost.[846] For this reason the value of 2.7 man-days per kg of smelted silver at Regla (1,582 man-days / 590 kg silver) is higher than the value of 2 .0 man-days per kg of amalgamated silver (3980 man-days / 1947 kg silver).[847] These values must be treated as applicable only to Regla during the late 1870s.

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[846] Since during the late 1870s Regla was operating its patio amalgamation process to its fullest extent, the same consideration did not apply to the workforce assigned to amalgamation.
[847] Laur states that an average of 4.5 man-days per ton of ore (average silver content of 0.11%) are required for the amalgamation process practised in Mexico by the second half of the nineteenth century, based on his analysis of two one-year accounts for two refining haciendas (Zacatecas and Guanajuato). Laur, "De la metallurgie de l'argent au Mexique," 202. This is approximately twice the value I have estimated to apply at Regla, and the average days of the amalgamation runs may account for this.

4. Labour constituted a higher percentage of variable costs in smelting (22 to 26%) than in amalgamation (7 to 17%). The difference in labour cost per kg of silver produced is a reflection of the fact that the skills of a smelting crew converted it into a fixed cost, so that in scenarios of irregular or limited smelting runs it would have been a drawback compared to amalgamation. Can the introduction of amalgamation be in part explained as a result of labour shortages? The results from Regla do not reflect a smelting operation run at the optimal level, so do not provide a clear-cut answer to this hypothesis.

5.14 *Patio* vs Barrel Amalgamation

Barrel amalgamation was the adaptation of Barba's *cazo* process carried out by Baron Borg in Europe at the end of the eighteenth century. At the time it was implemented it led to strong but very contrasting opinions on the utility of the process in New Spain. Humboldt was one of the earliest supporters of this 'Freiberg' process, but pointed out that the sheer scale of the ores waiting to be refined in New Spain dwarfed the extent of its application in Europe.[848] Sonneschmidt on the other hand concluded that after ten years of trials in New Spain it had failed to convince its users since it was more costly, extracted less silver than the *patio* process, consumed more mercury [in contrast to the original *cazo* process on which it was based] and produced impure silver.[849] It was firmly in the mind of the English managers of the Adventurers Company of Real del Monte from the very beginning of their project implementation stage, as evidenced in the following extract from a letter dated 23rd August 1825 to Roger Morgan, Esq., at Regla from James Vetch at Mineral del Monte (Real del Monte): 'proceed to state the plan we have agreed upon for applying the Freyberg method to existing circumstances'.[850] Not all

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[848] According to Humboldt 60 thousand *quintales* were refined using barrel amalgamation in Europe, while in New Spain 10 million *quintales* would have been the required quantity. Humboldt, *Essai politique*, Tome IV, 85.
[849] Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, iii, x.
[850] AHCRMyP, Fondo Siglo XIX, Sección: Correspondencia, Serie: Compañía a Varios, Subserie: Correspondencia General, 8-1: 20 Abril 1825 – 1 Noviembre 1825. According to Duport, the barrel process had

the English managers would feel it represented a better process. In a letter from Rule to London in 1842 he admits that none of the attempts to improve on the traditional *patio* process had worked better than the original process itself when properly executed.[851] Nevertheless John Buchan proceeded to convince the new Mexican owners to implement it on a much greater scale.[852] The results reported were not positive. In the initial years the barrel process only extracted 80% of silver in the ores.[853] Prior roasting of the ore had to be applied, at least until the 1860s.[854]

Though it never threatened to displace the *patio* process, its appearance at the time of the Bourbon initiatives adopted to increase the production of silver, and then during the phase of foreign capital investment in Mexico, has made it an obligatory reference in discussions on the technical relevance of both historical events.[855] The historiography does not include a

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been tried out in Oaxaca and Bolaños prior to the 1840s. Duport, Métaux précieux au Mexique, 51. According to Laur the Real del Monte Company was the first to apply in any major scale the barrel process in Mexico. Laur, "De la metallurgie de l'argent au Mexique," 225. It was only applied in Oaxaca, Bolaños and Real del Monte, according to John Phillips, *Descriptive Notice of the Silver Mines and Amalgamation Process of Mexico. Extracted from the Railway Register* (London: Pelham Richardson, 1846), 16.

[851] Randall, Real del Monte, 115-118.

[852] Ruiz de la Barrera, "La Empresa de Minas del Real del Monte," 113.

[853] Buchan, *Report Real del Monte*, 18.

[854] Ruiz de la Barrera, "La Empresa de Minas del Real del Monte," 309.

[855] From 1877 to 1892 barrel amalgamation contributed just 4% of total silver refined in Mexico. Flores Clair, Velasco Avila, and Ramírez Bautista, *Estadísticas mineras*, II, 161-62. For a positive review of the Freiberg process as a more modern alternative to the patio process see Sempat Assadourian, "Base técnica y relaciones de producción," 429. For the view that the more effective Bourbon reforms were administrative rather than technical, see Castillo Martos and Lang, *Metales preciosos - union de dos mundos*, 157, 183. In the case of foreign capital investment in the nineteenth century, Velasco et al conclude that: [as a consequence of English investment] there was no fundamental change … the introduction of the steam engine to pump water from the mines and many attempts to substitute the patio amalgamation process that resulted in minor modifications in the methods to reduce ores'. They add: 'in the relations of production very few fundamental modifications took place … in the refining processes … no notable change was implemented in the form of organization of the labour process' - *'no hubo un cambio fundamental ... la introducción de la maquina de vapor para el desague y muchos intentos por sustituir el beneficio de amalgamación en patio que redundaron en modificaciones menores de los métodos de reducción de minerales*' and '*en las relaciones de producción, hubo muy pocas modificaciones fundamentales ... en los procesos de beneficio ... no hubo un cambio notable en la forma de organización del proceso de trabajo'*. Velasco Avila et al., *Estado y minería en México*, 106-107, 250-251.

detailed economic comparison between the production costs of barrel amalgamation and the traditional *patio* process, so the reasons for the failure of the barrel method to displace *patio* amalgamation have not been quantified from an economic point of view.

An understanding of the economic basis to the permanence of the *patio* process against the forces of change is needed to understand the course taken by the environmental history of Mexico in the nineteenth century. I will quote at length from Randall, though at times it is difficult to untangle views reported from views endorsed by this historian of the Adventurers Company of Real del Monte:

‘those of them who knew anything at all about silver reduction methods, and in particular John Taylor, were aware that the traditional patio amalgamation process of Mexico **was woefully inefficient and should be improved** … they continued to believe that they could devise a method of reducing silver ore better than the one employed for centuries at Real del Monte and throughout colonial Mexico. **They were right in both instances**, but the company went under …those company officials who had to cope with the larger problem of extracting silver from ore in an economical manner were never comfortable with the patio process. They found it to be slow and increasingly expensive (owing largely to the rising cost of quicksilver) when dealing with common types of low-grade ore – and almost entirely useless when dealing with those types that were called “rebellious” ... in a sense the English expended huge amounts of time, energy and money in a fruitless effort **to learn a Mexican trick** they did not even like [emphasis added]’[856]

It is difficult to know how much on silver refining was really known by these English managers. John Taylor never set foot in Mexico, and England by 1854 was producing a paltry 70,000 pounds troy of smelted silver compared to Mexico’s output of 1,750,000 pounds troy coming mainly from *patio* amalgamation.[857]. He became the editor of a journal that lasted all of one volume, in which he published his new design for retorts to separate more efficiently mercury from the silver amalgam at the *haciendas* of the company in Mexico, so as to replace

[856] Randall, *Real del Monte*, 86-87, 115.
[857] Production data from J. D. Whitney, *The metallic wealth of the United States, described and compared with that of other countries* (Philadelphia: Lippincott, Grambo & Co., 1854), 506.

the *capellinas* then in use. The phrasing of the results of trials of the retort at Regla encapsulates the stubborn bias against all local skills: 'although … the loss of mercury was rather greater than by the usual method of the country, yet … they may be rendered perfect'.[858] The *capellinas* were never replaced at Regla, or anywhere else in Mexico, for the retorts designed by Taylor. A Mexican viewpoint on the level of English expertise is given in the following extract: 'the recently arrived English miners … in general do not know any other minerals than copper, tin, iron and coal , and they are completely ignorant of the *patio* refining process which is so important [in Mexico]'.[859]

Randall does not back up with facts his modern assessment that 'they were right' in branding the *patio* process as 'woefully inefficient' and that the new English technicians were predestined to devise a better refining alternative to the *patio* process. It is fortunate therefore that the *Estados Comparativos* kept by the Compañia Real del Monte compare over a period that spans twenty years, though with significant gaps in the currently available time series, the variable production cost profile for the two types of amalgamation process with which the silver ores from the Real del Monte mines were refined. The *patio* amalgamation process was

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858 John Taylor, "Description of Retorts for the Distillation of the Mercury from Amalgamated Metals " *Records of mining* I(1829): 142.

859 '*los mineros ingleses recién llegados ... por lo regular no conocen otros minerales que los de cobre, estaño, fierro y carbón, y que ignoran por completo el beneficio de patio que es tan importante*' in Viajero, "Las Minas de Mexico," 182. An anonymous Englishman returning from Mexico published in England in 1856, under the pseudonym 'Traveller' (*Viajero*), a scathing criticism of the way English capital had been extravagantly wasted on Mexican mining ventures. In a footnote, the Mexican translator appended his opinion on the skills of English miners. A modern Mexican historian writes: 'the arrogant English investors and administrators … believed they possessed a vast knowledge …. much greater than the aggregate practical experience of the Spanish and Criollo owners [of refining haciendas] in Mexico. The economic failure of the English company can be explained to a large degree on the blind faith placed on that assumption.' - '*los altivos inversionistas y administradores ingleses ... creían poseer un vasto conocimiento ... mucho mayor del que habían acumulado en la práctica los propietarios españoles y criollos en México. El fracaso económico de la sociedad inglesa se explica en gran parte por la fe ciega en tales principios'*. Herrera Canales, Velasco Avila, and Flores Clair, *Etnia y clase*, 7.

applied at Regla and Loreto, and Sanchez, Velasco and San Miguel were based exclusively on the barrel (*toneles*) process.

The relative importance of each *hacienda* in the whole scheme of production for the company during the period can be judged from Figure 5-25. Velasco is the main refining unit for the silver ores of Real del Monte in the first years of operation of the newly revived company under Mexican ownership. Velasco came to process using barrel amalgamation over twice the amount of ore than any other of the refining *haciendas*. However, by the early 1870s it suffers a marked decrease in the amount of ore processed. As seen in the previous chapter, Regla would maintain an average of around 84,000 cargas per year until 1888.[860]

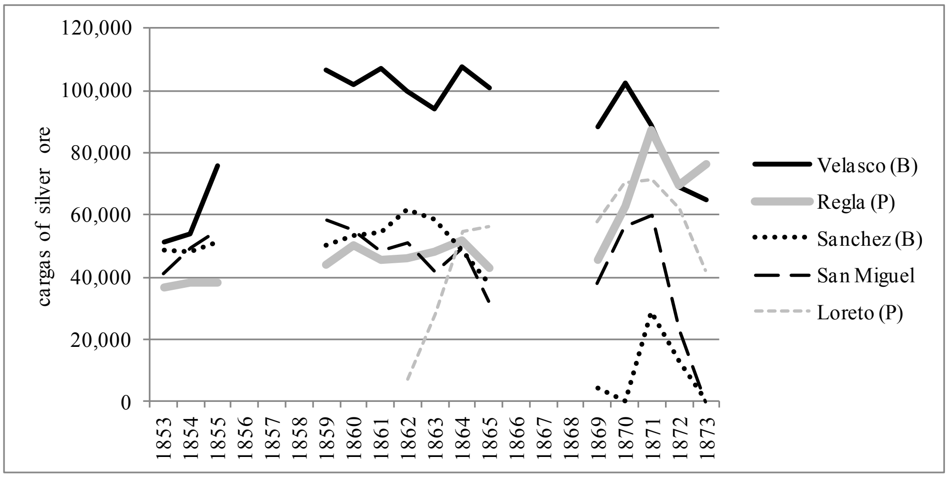

Figure 5-25. Annual average of *cargas* of silver ore processed at the refining *haciendas* of the Compañia Real del Monte in the period 1853 to 1873. Source data from *Estados Comparativos*.

[860] It has been reported that 80% of all ores at Real del Monte were processed using barrel amalgamation between 1849 and 1862, but by 1877 this fraction had decreased to just 24%. It is claimed to increase again to around half by the end of the century, mainly on the back of tolling of third party ores. In her first article Ortiz Peralta includes a table that assigns quantities to the different refining *haciendas*, but it incorrectly classifies the production at Regla as under *toneles*, barrels. This places some doubt on her percentages. Rina Ortiz Peralta, "El beneficio de minerales en el siglo XIX: El caso de la Compañia Real del Monte," *Tzintzun : Revista de Estudios Historicos* 14, no. Julio-Diciembre (1991): 77-79. In a second article that is basically a slightly edited version of the first, she omits the suspect table but maintains the percentages. "Beneficio Minerales Real del Monte," 54.

What made both Velasco and the barrel process the main refining venue for the company? The variable production cost for the barrel process averages from 10 to 13 *pesos* per kg of refined silver during this period, as shown in Table 5-XIX. Velasco is the leaner of the barrel operations, while San Miguel shows the highest unit costs. All require more *pesos* to refine silver than the average registered at Regla using the traditional *patio* method. The lower values observed for smelting correspond to ores with a higher silver content than those refined by amalgamation, so they are not directly comparable to the others in the table. Otherwise, in the case of *patio* and barrel amalgamation the comparison is being made on the basis of very similar ranges of silver content in the raw ore during this period, as shown in Table 5- XX.

	Sanchez (B)	Velasco (B)	San Miguel (B)	Regla (P)	Regla (S)	Loreto (B)	Loreto (P)
1853	11.53	11.34	15.75	12.52	8.03		
1854	10.84	9.36	12.73	9.91	9.60		
1855	11.34	9.36	11.93	8.20			
1856							
1857							
1858							
1859	11.51	9.27	11.92	9.56	5.91		
1860	7.58	8.25	10.76	9.06	8.50		
1861	8.16	9.04	7.93	9.41	7.96		
1862	6.82	9.56	11.34	8.56	9.34	10.90	6.99
1863	9.20	11.53	14.02	8.91	8.91		15.25
1864	10.81	10.57	12.43	8.70	8.97		11.29
1865	10.76	10.81	15.28	9.25	11.15		11.85
1866							
1867							
1868							
1869	9.40	8.86	14.59	10.76			14.48
1870		6.97	10.75	9.23			8.42
1871	12.41	7.81	14.19	9.35			7.77
1872	12.84	11.73	19.14	10.12			11.84
1873		17.10		11.25			15.26
average	10.25	10.10	13.06	9.65	8.71	10.90	11.46

Table 5-XIX. Variable production costs in *pesos* per kg of refined silver for the various refining *haciendas* of the Compañia Real del Monte, in the period 1853 to 1873. The gaps in grey indicate the *haciendas* were not in use at the time. The gaps in white indicate a lack of primary sources for the period. Source data from *Estados Comparativos*.

	Sanchez (B)	Velasco (B)	San Miguel (B)	Regla (P)	Loreto (P)
1853	0.20%	0.16%	0.15%	0.14%	
1854	0.26%	0.24%	0.17%	0.15%	
1855	0.27%	0.24%	0.19%	0.21%	
1859	0.29%	0.28%	0.19%	0.22%	
1860	0.36%	0.32%	0.19%	0.24%	
1861	0.34%	0.26%	0.27%	0.23%	
1862	0.28%	0.24%	0.22%	0.24%	0.38%
1863	0.25%	0.22%	0.17%	0.22%	0.19%
1864	0.22%	0.21%	0.21%	0.23%	0.26%
1865	0.23%	0.21%	0.18%	0.25%	0.26%
1869	0.13%	0.25%	0.14%	0.16%	0.17%
1870		0.34%	0.19%	0.19%	0.28%
1871	0.17%	0.33%	0.16%	0.29%	0.36%
1872	0.17%	0.21%	0.09%	0.24%	0.24%
1873		0.13%		0.18%	0.18%
average	0.24%	0.24%	0.18%	0.21%	0.26%

Table 5-XX. Silver content of ore before processing. Raw data from *Estados Comparativos*.

If we now compare the losses of silver incurred by each *hacienda*, the amount of silver left unextracted in the processed ore, they confirm the initial judgment made in 1854 by John Buchan that barrel amalgamation was the least efficient of the refining processes in extracting silver from the ore. As the data in Table 5-XX indicate, during the first three years of operation, on average up to one quarter of the silver could be left unextracted in the ores processed at Sanchez and San Miguel, and only slightly lower at Velasco. Velasco, the more efficient of the barrel process *haciendas*, still lost 40% more silver than at Regla using the *patio* process, and double the silver losses via smelting at Regla.

Where did the advantage of the barrel amalgamation process lie with respect to the traditional *patio* method? First of all, it is the claimed lower consumption of mercury, due to the fact other reagents (copper, iron) reduce the silver chloride in the ore to silver. The operational data from the *haciendas* both confirm and question this assumption. The average values of the Hg to Ag weight ratio reported in Table 5-XXI show that barrel amalgamation on the whole consumed about half the amount of mercury with respect to the traditional *patio* process. However, the yearly data for the latter part of this period, when Velasco loses its predominance as the refining flagship of the company, show mercury to silver ratios commensurate with those registered for the *patio* process. Ortiz assigns this fact to the elimination of the prior roasting of the ore implemented between 1868 and 1872.[861] But this begs the question whether in monetary terms the magic had ever existed, since we have seen that variable unit production costs for barrel amalgamation were always higher than for *patio* amalgamation. In principle there was a saving to be made in mercury in certain years (though evidently not in all), but the saving had been lost through additional costs incurred by the process.

A more detailed breakdown of the variable production costs for each *hacienda* during this period shows what happened. In the case of the barrel process, the savings on mercury were overshadowed by the greater spending on the fuel required to roast the silver ores with salt, and then to heat the barrels. Thus the column in Table 5-XXII indicating the total *pesos* spent on both mercury and fuel to produce 1 kg of silver is higher for the barrel process than for the traditional *patio* process. Since the cost of salt is roughly equivalent for both processes, it turns out that the barrel process offered no net advantages on cost even when it has saved at times on mercury consumption. Why then was the barrel process ever implemented by the Compañia de Real del Monte?

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[861] "Beneficio Minerales Real del Monte," 55.

	Sanchez (B)	Velasco (B)	San Miguel (B)	Regla (P)	Regla (S)	Loreto (B)	Loreto (P)
1853	19.3	18.6	23.3	11.8	9.9		
1854	24.8	17.0	25.2	11.3	7.0		
1855	24.8	19.1	26.5	10.8			
1856							
1857							
1858							
1859	20.4	15.3	19.4	12.9	6.5		
1860	19.6	16.0	16.8	13.9	8.0		
1861	19.5	15.6	13.1	12.2	5.8		
1862	20.8	12.1	19.4	11.4	5.6	5.8	3.1
1863	19.9	10.7	14.4	3.7	6.8		10.2
1864	12.1	13.7	24.4	4.7	4.9	0.0	8.1
1865	12.5	9.6	21.9	7.6	2.6	0.0	1.4
1866							
1867							
1868							
1869	9.1	9.1	12.6				6.0
1870	11.5	13.7	6.2			11.5	
1871	12.4	12.8	12.0	10.0			7.2
1872	7.2		11.3	12.0	11.9	8.9	
1873		13.4		7.0			6.5
average	16.7	14.0	17.6	9.9	6.9	5.2	6.1

Table 5-XXI. Losses of silver, expressed as weight percentage, registered at the refining *haciendas* of the Compania Real del Monte, in the period 1853 to 1873. The gaps in grey indicate the *haciendas* were not in use at the time. The gaps in white indicate a lack of primary sources for the period. Source data from *Estados Comparativos*.

	Sanchez (B)	Velasco (B)	San Miguel (B)	Regla (P)	Loreto (P)
1853	0.71	0.72	0.59	1.89	
1854	0.61	0.63	0.67	1.61	
1855	0.88	0.70	0.95	1.57	
1856					
1857					
1858					
1859	0.83	0.66	0.37	1.69	
1860	0.51	0.57	0.56	1.65	
1861	0.58	0.62	1.01	1.83	
1862	0.61	0.62	0.40	1.74	1.16
1863	0.58	0.62	0.73	1.72	1.56
1864	0.71	0.62	0.63	1.42	1.53
1865	0.63	0.88	0.45	1.44	1.42
1866					
1867					
1868					
1869	0.26	1.21	1.15	1.50	1.81
1870		1.48	0.83	1.40	1.33
1871	1.52	1.47	1.46	1.61	1.83
1872	1.52	1.52	1.26	1.49	1.79
1873		0.67		1.38	1.63
average	0.77	0.87	0.79	1.59	1.56

Table 5-XXII. Mercury to silver weight ratio registered at the refining *haciendas* of the Compania Real del Monte, in the period 1853 to 1873. The gaps in grey indicate the *haciendas* were not in use at the time. The gaps in white indicate a lack of primary sources for the period. Source data from *Estados Comparativos*.

pesos spent to produce 1 kg silver by amalgamation							
	mercury	salt	copper sulphate	fuel	others+labour	total	mercury+ fuel
Sanchez	1.0	2.0	0.0	2.7	4.5	10.25	3.7
Velasco	1.4	2.2	0.0	2.4	4.1	10.10	3.9
San Miguel	1.2	3.2	0.0	2.7	6.0	13.06	3.9
Regla	2.5	2.2	0.9	0.2	3.8	9.65	2.7
Loreto	2.8	2.3	0.8	0.2	5.3	11.46	3.0

Table 5-XXIII. The average amount of *pesos* required to refine 1 kg of silver using the two amalgamation processes. The *haciendas* in italics used the barrel process, and the *haciendas* in normal script used the traditional *patio* amalgamation. The data has been calculated for the period 1853 to 1873 using as source the *Estados Comparativos*.

Buchan justified the choice not on economic grounds but by assuming it was the only way to treat major amounts of the recalcitrant silver ores being produced by the mines at Real del Monte, in spite of the evident economic drawbacks that are clearly spelt out in his report of 1854.[862] This is a more realistic appraisal of a necessary evil than an endorsement of the barrel process. In addition, by cutting down on the amalgamation period it could compensate its low rate of extraction with a higher output of silver. It may be significant that Velasco retained its pre-eminence when it was able to process 2.5 times the amount of ore compared to Regla. Once their throughput became very similar, for example towards the end of the 1853-1873 period, Regla would have been a much better economic choice to process ores, under equal chemical conditions.

[862] Buchan, *Report Real del Monte*, 16-18.pp. The table with the comparative costs of production appears on page 17 of his report. Prior roasting followed by patio amalgamation may have been another option. According to Duport, the silver ores that did not respond well to patio amalgamation in Zacatecas were the black or red sulphides of antimony and silver, which could retain up to 40% of their silver after amalgamation. Duport, *Métaux précieux au Mexique*, 246.

I would seriously question that it was 'the most important innovation left by the English who exploited the mines of Pachuca and Real del Monte'.[863] I would argue that the reduction of fuel requirements by a factor of five in the smelting furnaces merits that distinction. I question even more strongly Randall's conclusion that 'the firm succeeded in making lasting technical advances … in the treatment of low-grade silver ore' and that 'it definitely improved on Mexico's traditional ore-reduction method … to supplant altogether the traditional Mexican method of treating silver ore ... from the patio ... to barrels, where it was quick and less destructive of that costly commodity [mercury]', when the accounts of Regla offer such a clear refutation.[864]

The barrel process as practised at Regla did not always reduce the consumption of mercury, it never decreased the amount of unextracted silver left in the ore after treatment (quite the contrary) and did not provide an ample margin of profit based on its variable production cost, as has been claimed.[865] Its capacity to treat difficult ores owed more to the prior roasting with salt than to the barrel amalgamation itself. [866] It definitely never displaced *patio* amalgamation as the most cost-effective option to refine the majority of Mexico's silver ores.[867] The irony remains that even some who have recognized its failure still appeal to the 'timelessness' of the Mexican scenario. 'In Europe where speed was important and labour

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[863] '*fue la innovación mas importante legada por los ingleses que explotaron los distritos mineros de Pachuca y Real del Monte*' Ortiz Peralta, "Beneficio Minerales Real del Monte," 52-53.
[864] Randall, *Real del Monte*, 87, 109, 118.
[865] Ortiz Peralta, "Beneficio Minerales Real del Monte," 53.
[866] Barba had recognized nearly three centuries before that the *Cazo* process (on which the barrel process is based) worked better with ores high in silver content, either elemental silver or silver halides, as was the case in Catorce at the end of the eighteenth century. Barba, *Arte de los metales*, 111-12. Roasting with salt converts silver compounds in the ore to silver chloride (a silver halide), as indicated in Chapter 3.
[867] It never achieved a major penetration of the refining market in Europe. In Spain 'the most extensive amalgamation (60 barrels) at La Bella Raquel, span ores from Hiendelaencina [Guadalajara]'.Kerl, Crookes, and Röhrig, *Prof. Kerl's Metallurgy*, 331.

expensive, the much faster … more wasteful Born process was preferable' while in Mexico 'time was not important and labour cheap … [so that] it was more profitable to use the slower, less wasteful *patio* process'.[868] The barrel process did not fail because 'time was not important' in Mexico. It failed for the simple reason the *patio* amalgamation process was never a 'Mexican trick' but an industrial process whose production costs per kg of silver refined from the typical ores of Mexico were lower than those of the European barrel process. It is fitting that John Phillips in 1846 acknowledged that 'with respect to the loss sustained by English Companies in the prosecution of mining undertakings in Mexico, that much of it has arisen from the circumstance of their not having given due credit to the Mexicans for skill in the application of the means they possessed'.[869] In general the comparison of production costs on both sides of the Atlantic needs to take into account that the refining processes in New Spain / Mexico had to overcome the challenge that only the value of silver could cover the production costs, without the additional revenues from lead or copper as in Europe (see Appendix F). The important exception was in those cases where additional revenues from gold found together with the silver aided substantially the refiner in covering his costs (see example in Section 2.5).

5.15 Concluding remarks

This chapter has been a search for a long overdue quantitative answer to the question as to whether economic drivers determined a clear choice between amalgamation and smelting in the New World. The environmental impact from each is so different that one would expect that the answer can explain to a great extent the direction taken by the environmental history of silver refining in the Americas. Thanks to the detailed accounting records kept at Regla it is

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[868] Clement G. Motten, *Mexican silver and the enlightenment* (Philadelphia: University of Pennsylvania Press, 1950), 53. The stereotype on time and Mexico is repeated by other authors: '[amalgamation] costs little … can be worked on a larger scale as well as a small one… cheapness of plant compensates for the time … in Mexico … time has no value'. Egleston, *The Metallurgy of Silver*, 311.
[869] Phillips, *Descriptive Notice*, 20.

now possible for the first time to base an answer on a very long time series of operational data corresponding both to *patio* amalgamation and smelting, as practised in one of the largest refining *haciendas* in Mexico of the second half of the nineteenth century. I had no choice on the span of years covered by the extant documentation, but was fortunate to find it included not only a sudden break in operations that forced a smelting of discarded slags, but also a span of more than ten years of the *hacienda* operating at full capacity as far as amalgamation was concerned. In addition, from 1872 to 1888 the mercury market seemed to parody the whole span of Spain's pricing during the *estanco*, in a manner showing that in colonial New Spain prices were not so different from what market drivers could determine in the nineteenth century. With regards to smelting, Regla was the *pièce de résistance* of the whole stable of refining *haciendas*, the only one designated to receive ores fit for smelting. The most important technological innovation of the English investment and know-how in refining was the installation of blast furnaces run with such efficiency they cut the consumption of charcoal by a factor of five.

In the previous chapter I argued that in its operating essence, the nineteenth century *hacienda* at Regla is a twin sister to any other *hacienda* of the previous 300 years, and not a distant and unrecognizable relative. Thus the diagnostic carried out on its profile of production costs could be used to recreate the competition over the centuries of amalgamation and smelting. Thanks to the initial stability over two centuries of the silver to gold ratio, and the immutability up to 1888 of production costs to the collapse of silver prices, I was able to ignore deflaction over three centuries without jeopardizing the comparisons. During this extended period amalgamation and smelting jostled to win not the hearts but the pockets of the mixed patchwork of miners and refiners of New Spain, a technical jousting unique in its longevity to the history of technology. For some 350 years neither technology (the traditional smelting and the newcomer amalgamation) changed in a substantive manner, and neither managed to displace the other. The balance observed between the two refining processes up to the nineteenth century (Chapter 6) was a clear indication that many times these hard-headed, self-made but very pragmatic individuals had found little to choose between them, at least on economic terms.

The answer that the accounts from Regla have provided will bolster the argument to be rounded off in the next chapter that the relation between amalgamation and smelting was not a one-dimensional, zero-sum game. In other words, increases in production by amalgamation did not come necessarily at the expense of smelting, or vice versa. For much of the time and in many locations, amalgamation did offer the best cost alternative to extract silver from ores with a minimum silver content in the range of 0.1 to 0.2%. The only period mercury was the major influence on the costs of amalgamation in New Spain was in the second half of the sixteenth century, when tailings were being raided and the Crown sold mercury for the highest price it could get, without even having to pay for part of it. For the next three hundred years it was the extraction cost of the ore that determined the profit margin of a refiner, as had been pointed out by Villaseñor. This remains a valid statement even if the implementation of the tolling business allowed refiners to divorce part of their profits from the mining cost involved. Reducing the price of mercury increased the impact of salt prices on the total cost structure until they became equal in importance, around 10% of total cost each at Regla, and yet salt was never the intense focus of the lobby by refiners as was mercury. The cost of power for amalgamation *haciendas* completes the trilogy of production costs that most influenced the margin of profit, yet it is even more absent than the cost of salt from many a modern analysis. Copper sulphate, or its less refined variety by the name of *magistral*, was the most cost effective of all ingredients for the process. Fuel was a very minor contributor to the cost of amalgamation, thus isolating the process from the vicissitudes of searching for sufficient woodland resources, as well as making its impact on wood resources negligible. As to the fixed cost of capital, it would seem that once the major hurdle of raising capital was cleared, its service was not a major burden on production costs. As always, regardless of the breakdown of production costs, the need to continuously provide working capital can make or break a business, thus the importance given in the historiography to the allocation and sources of capital in the history of silver refining in the New World.

Smelting remained throughout a viable option, first of all for the obvious reason that for some ores rich in lead it was the only effective way to refine them. The minimum silver content that made smelting profitable lay in the range of 0.3 to 0.5%, though in practice at Regla no ores below 1% silver were smelted. The next chapter will underline the important role played by smelting in New Spain, a fact that gives credibility to the proximity of production costs for both processes proposed in the calculations of this chapter. Thanks to the data from Regla I have been able to show quantitatively that the amalgamation and smelting cost curves, as a function of silver content of the ore, virtually merge into each other under certain conditions approximating those likely to have occurred in the period between the seventeenth to eighteenth centuries. The capacity to scale down smelting operations and labour requirements, compared to the more ponderous nature of amalgamation, made smelting a very versatile option, subject mostly to the ability to access cheap and sufficient fuel.

More data on other *haciendas* are necessary to establish whether Regla was an isolated case of a very efficient *patio* amalgamation operation, or whether *patio* amalgamation was a more potent refining process than has been credited. Taylor had identified back in the 1820s the two major challenges the English faced at Regla in order to implant smelting as the preferred option: dressing the ore to increase its silver content, and finding enough fuel to feed the blast furnaces. Smelting of silver ores made sense in the England of the Cornishmen and the Erzgebirge of the Germans because the sale of lead and copper made profitable their economies of production. In New Spain / Mexico the whole weight of meeting the costs of smelting fell only on silver and whatever gold was present in the ore. This was the challenge faced by smelting, not the scale of available ore that loomed so large an obstacle in the imagination of Humboldt. Argentiferous copper was never a major component of Mexico's silver ore deposits, in contrast to the European scenario, so the production of copper was not an option to defray the costs of refining silver in New Spain or Mexico. The production of lead for the market would only become important in the twentieth century.

I cannot find any other example of a commodity that from the sixteenth century was produced both in Europe and the New World, under an industrial context where the market price was fixed at basically the same level for all producers on both sides of the Atlantic during three hundred years. During this time refiners had to fit their local variations in wages, fuel, reagents, infrastructure costs and government duties into a box of just one size, the valuation of silver that had remained nearly unchanged for over twelve generations of refiners. Under these conditions it makes no sense to analyse the historical scenario of the cost of production from the point of view of the price elasticity of silver in the market, and this reality certainly tied the hands of producers on both sides of the Atlantic. It would take the appearance of a huge wave of silver suddenly coming to the market from the refining mills of Nevada in the 1870s to shake the whole silver price structure to its roots.

At any given time the volume of silver in the market depends on what percentage in known deposits can be profitably mined and refined given the production costs and efficiency of the available technology. The production cost of smelted silver prior to the sixteenth century, the technical limits to the smelting process applied, and the market for lead and copper played a major role in fixing the volume of silver historically available to Europe, and thus of the final silver to gold ratio. Amalgamation was not the process that historically set the price of silver. It never progressed beyond a fringe operation in Europe as of the end of the eighteenth century, and smelting was always the preferred choice.

It would be logical to argue that a lower wage scale in the New World compared to Europe would have been a significant help to keep competitive the variable costs of amalgamation, of which around two thirds are direct labour costs, or of smelting, at one half. This fact should not overshadow recognition of the efficiency of the mining workforce in the New World, clearly quantified in Humboldt's data at being some ten times more efficient than their German counterparts, though this factor was silenced in his commentary. It turns out that time was just as important in Mexico as in Europe. To their efficiency must be added their attrition, and those of their communities, in human lives, occupational diseases and environmental damage from mining and refining, a hidden but very real contribution to maintaining a competitive production cost of silver.

By the nineteenth century European silver production had recovered, and now even offered better smelting economies for ores imported from the Mexican mines. In the tradition of the hare and the tortoise, smelting would outlive the amalgamation of silver in New Spain. Looking back, it is tempting to conclude that the environmental history of the New World veered in a totally new direction as soon as some of the first miners of New Spain found they were left with more coin at the end of the day if they used cold mercury instead of a hot and fussy furnace. In this case, however, chemistry trumps economics. Lead would continue to be the main environmental hazard for silver refiners, a heavy metal issued to the air in New Spain in greater quantities than any volatile emissions of mercury. How much, when and where is the subject of the next and final chapter.

6 The environmental impact of silver refining: a shift of paradigm.

'There's the story, then there's the real story, then there's the story of how the story came to be told. Then there's what you leave out of the story. Which is part of the story too'. Margaret Atwood, *MaddAddam* (2013)

6.1 The magnitude of the impact: the method employed

Of all the chemical substances that shape the environmental history of silver refining in in New Spain, only the production of silver and the consumption of mercury constitute a fairly continuous data set in the official tax records. Both data sets can be used to reconstruct the quantities of other chemicals and matter voided into the environment, using the ratios built up in the preceding chapters and the theoretical base of the *correspondencia*. The more fundamental problem lies in that the whole framework within which silver production and mercury sales were registered was tinged with corruption:

'The Royal Treasury in New Spain was a very efficient organization, carefully controlled and with very precise working guidelines, but at the same time it was a centre of corruption and traffic of influences. Then as now, these two aspects coexisted without interfering with each other, so that as long as the accounting figures matched precisely, other parallel practices were accepted so as to privilege certain miners in the distribution of mercury or in the evasion of taxes'.[870]

Rampant corruption and contraband have been pointed out in the historiography as distorting the historical production data, so that up to an estimated two thirds of the total silver

[870] '*La Real Hacienda en Nueva España era una organización eficiente, controlada cuidadosamente y con normas de trabajo muy precisas, pero al mismo tiempo era foco de corrupción y tráfico de influencias. Entonces como ahora, estos dos aspectos coexistían sin estorbar el uno al otro, así que mientras los datos contables cuadraban en forma precisa, por otro lado se aceptaban cohechos para privilegios a algunos mineros en el reparto de azogues o para evadir impuestos*' in Pérez Luque and Tovar Rangel, *Caja Real Guanajuato*, 13. The phrase 'then as now' is a warning that accounting coherence on paper does not have the same implications even at present in different parts of the world.

registered has been deemed to have been excluded from the official record of New Spain.[871] I have proposed in a separate paper that any major disparity between the installed refining capacity and official registered silver production can be used to estimate a probable degree of contraband silver, since private capital, contrary to State finances, cannot sustain a fixed capital investment frozen into an unproductive facility. In the case of Potosí, I estimated the installed production capacity could have produced twice the official registered figure in the period 1576 to 1650.[872] I have no such option to cover the whole period of silver refining in New Spain / Mexico. I have therefore relied on the official registers for silver production available in the historiography. These values should be interpreted as the base line, with real levels expected to have been higher, so that the absolute magnitude of the environmental impact vectors could have been substantially greater than any estimates to be calculated in this chapter. The relative magnitudes of these vectors to one another however remain a valid guide to their relative impact on the environment.

TePaske authored one of the most complete reviews of published data sets and provided a compilation of the production of silver in New Spain by *Caja* (regional Treasury, usually but not always a mining district), from the sixteenth century up to independence.[873] Refining *haciendas* sent their silver to be taxed and stamped at the *Cajas.* Between 1521 and 1810 the *Cajas* of interest are, in descending order, Zacatecas (20.6% of total colonial silver production), Guanajuato and Mexico (17.3% each), Durango (12.1%), San Luis Potosí (8.8%), Guadalajara

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[871] Flynn and Giraldez, "Cycles of Silver: Global Economic Unity through the Mid-Eighteenth Century," 435.; Hausberger, *Metales preciosos*, 41-44.; Bakewell, "Registered Silver Production in the Potosi District 1550-1735," 80.

[872] Guerrero, "Contraband of Silver from Potosí and Oruro," 76-77.

[873] TePaske and Brown, *Gold and Silver*, 82, 115-16. Care must be taken with the pie chart of Figure 3.5 in TePaske's work that breaks down the total silver production expressed in kg for all the main *Cajas* of New Spain, since for the *Caja* of Mexico the figure used is 3,703 thousand kg, which does not correspond to the total silver production according to Table 3-4 (8,703 thousand kg). It is most probable the 8 became a 3 at some point of the posthumous editing process. This skews all the percentages values reported in the pie chart. The data in his Table 3-4 should be used instead.

(7.8%), Pachuca (5.4%), Sombrerete (3.7%), Bolaños and Rosario (2.3 and 2.2 % respectively), Zimapán (1.7%) and Chihuahua (0.5%). The *Cajas* however were not fiscal districts set in stone. Their hierarchy and the extent of the regional spheres of each *Caja* changed over time, as the *Reales de Minas* even within a region.

The environmental history of silver refining in New Spain / Mexico is thus a fluid mosaic, where the content and nature of each element constantly change over time, reflecting the temporal idiosyncrasy of each mining district reporting to the *Cajas*. Hausberger, from whose work I have adapted the map shown in Figure 6-1, anchored his analysis of the silver industry in New Spain using a comparative regional analysis of the data, an approach that will also be adapted in this chapter.[874] Figure 6-1 shows very clearly the disparate nature of these regional environmental pressure points. For example, the magnitude of the impact vectors to be calculated from the data in the *Cajas* of Guanajuato and Pachuca impacted a much more reduced geographical area than the case of Durango and Guadalajara. Furthermore, while the *haciendas* reporting to the *Caja* of Guanajuato were within or close to the city of Guanajuato, in the case of Pachuca only the *Hacienda* de Loreto was within the city limits, and all the other refining activity was well away from the main urban centres. To this geographical diversity must be added a technical diversity, since amalgamation and smelting were not applied uniformly across all the regional *Cajas*, or even within the historical period of interest for a single *Caja.* This temporal diversity will become evident in the following sections.

The data on silver production in the nineteenth century are not as detailed as the data for the colonial period. Its records suffered on par with the political situation in Mexico, and the most detailed statistics are found only for the latter part of the century. I have set out in

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[874] Hausberger, *Metales preciosos*, 64, 82-87.

Table 6-I the main sources in the historiography on the production of silver in this period. The figures calculated by Soetbeer up to 1875 are the source quoted for other estimates published up to this year.[875] For 1876 up to 1899 I include the data from Gonzalez Reyna and from Flores Clair, Velasco Avila and Ramirez Bautista.[876] I have not found an equivalent breakdown of data by region as is available for New Spain, so only a gross national approximation can be attempted on the basis of the total silver production from 1820 to 1899.

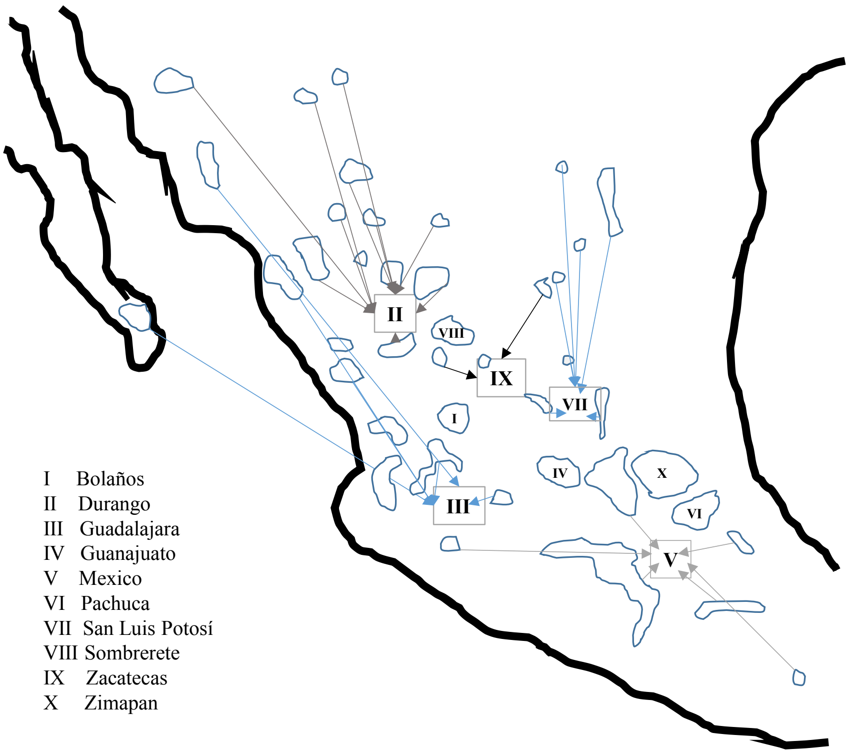

Figure 6-1. Map of regional *Cajas* of main mining districts in New Spain, snapshot of the 1760s, adapted from original map in footnote 874.

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[875] Adolf Soetbeer, *Edelmetall-produktion und werthverhältniss zwischen gold und silber seit der entdeckung Amerika's bis zur gegenwart* (Gotha J. Perthes, 1879), 49-60. The other works that rely on Soetbeer's data are Merrill, *Summarized Data of Silver Production* ; Jenaro González Reyna, *Minería y Riqueza de México*, Monografías Industriales (México: Banco de México, 1944).; Flores Clair, Velasco Avila, and Ramírez Bautista, *Estadísticas mineras*, II.

[876] González Reyna, *Minería y Riqueza de México*.; Flores Clair, Velasco Avila, and Ramírez Bautista, *Estadísticas mineras*, II.. The data from the latter are presented also in Velasco Avila et al., *Estado y minería en México*.

Period	silver production (kg)		
	Soetbeer	González Reyna	Flores Clair et al
1801 - 1810	5,538,000		
1811 - 1820	3,120,000		
1821 - 1830	2,648,400		
1831 - 1840	3,309,900		
1841 - 1850	4,203,100		
1851 - 1855	2,330,500		
1856 - 1860	2,239,000		
1861 - 1865	2,365,000		
1866 - 1870	2,604,500		
1871 - 1875	3,009,000		
1821-1875	22,709,400		
1876		546,410	570,000
1877		588,518	635,572
1878		610,683	641,502
1879		643,907	704,783
1880		694,000	756,505
1881		714,573	743,372
1882		718,658	756,345
1883		748,681	810,448
1884		793,377	849,579
1885		824,079	873,996
1886		876,724	959,215
1887		939,779	1,005,080
1888		986,382	1,051,995
1889		983,799	998,742
1890		990,237	1,068,088
1891-1899		13,250,485	13,796,861
1876 - 1899		24,910,292	26,222,083
1821-1899			48,931,483

Table 6-I. Silver production in Mexico, nineteenth century. Sources from footnotes 875 and 876. The data after 1875 corresponds to fiscal years beginning in the year indicated.

Partial breakdowns are available in the historiography that separate production as a function of amalgamation or smelting, but none that spans the whole colonial period and all the *Cajas*. The following sections present an estimate of the silver produced by each refining process based on the raw primary tax and mercury sale data of each *Caja* as has been gathered and transcribed by Tepaske, Klein and other collaborators in Mexico and Spain.[877] Their data set (to which I will refer henceforth as the TK set) includes the duties and *senoreaje* (duty on coinage) identified as coming from silver refined by amalgamation (*plata de azogue*) and those coming from smelted silver (*plata de fuego*). It does not distinguish between *patio* amalgamation and amalgamation using the *cazo* process (as in Catorce, *Caja* of San Luis Potosí). In addition, the records also show the amount of revenues from the sale of mercury by each *Caja*. These can be converted into an approximate weight of mercury using the reported price ranges for mercury for each period in question.[878] Freight does not have to be subtracted from these values since this was a separate cost and included as such in the accounts of the *Caja*.[879] The fact that silver taxes and mercury sales are registered for a same period does not guarantee these amounts are correlated, due to credits, late payments by refiners, inventory build-ups, or even contraband of mercury. By aggregating the mercury data into a decade whenever possible, the potential for mismatches will tend to be minimized but not eliminated. With this limitation in mind I report approximate mercury to silver ratios in the following sections.

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[877] Prof. Herbert S. Klein of Columbia University very kindly sent me his Excel files with the raw information collated from primary sources on tax revenues and mercury revenues during the colonial period for the provincial *Cajas*. Any error in the sorting and calculations based on the raw data transcribed in his files is solely this author's responsibility.
[878] For the calculation of the total weight of mercury I have used the Almadén price even for the small amounts of mercury brought from Idria and Peru.
[879] 'when selling to miners mercury and freight were charged separately' – '*al vender a mineros se cobra aparte azogue y fletes*' in Pérez Luque and Tovar Rangel, *Caja Real Guanajuato*, 37.

The separation of silver royalties based on refining process starts to be reported in the late seventeenth century. For the earlier periods where no such distinction was made in the *Cajas*, I project where necessary a probable split using the information available on sales of mercury or extrapolating from known ranges of the mercury to silver ratio. Once I have estimated the periodic regional production of silver by amalgamation and smelting, I proceed to estimate the magnitude of the main environmental impact vectors based on the ratios per kg of refined silver calculated in the previous chapters.

The interpretation given to the historical split between amalgamation and smelting observed for each *Caja* will first take into account the nature of the silver ores (rich in lead or dry). Changes over time in the nature of the ore, or the introduction of lead fluxes from another region, can be a leading cause for a change in the balance between refining processes.[880] The change of registry of the output of mines from one *Caja* to another will also impact the amalgamation/smelting split by changing the nature of the ores being processed.

The impact of the pricing of mercury is easier to determine as the main cause of the observed refining split in those *Cajas* where amalgamation historically predominated, since the nature of the ores is seen historically to be amenable to amalgamation and the infrastructure was already in place to immediately take advantage of the lower prices. [881] In general mercury pricing was not the only factor nor was smelting the second-best option for refiners of the silver

[880] For example, refiners in Zacatecas used lead flux sourced from Zimapán, as cited in Mendizábal, *La mineria mexicana*, 72.
[881] More aggresive aid than a simple general price decrease could keep amalgamation as the refining option over smelting. In the late 1760s Jose de la Borda in Zacatecas was granted mercury at 30 *pesos* / *quintal*, no silver tax was levied during renovation work on his mines, and the silver tax on his production was decreased by 50% for 20 years. Brading, "Mexican Silver Mining," 671. Even as the price of mercury was being decreased policy makers were still debating whether to implement a complete switch from amalgamation to smelting in New Spain, though problems in the supply of mercury may have been the real issue. Arthur P. Whitaker, "The Elhuyar Mining Missions and the Enlightenment," ibid.31(1951): 573-576.

ores of New Spain or Mexico.[882] The production cost curves derived in Chapter 5 show a sufficiently fine line between amalgamation and smelting to allow them to compete on profit-margins subject to location and time-specific costs, availability of ores and reagents. Major capital requirements would not be required if there was no actual switch from one refining process to the other, if only the quantities being processed by each type of *hacienda* varied with time.

6.1.1 *Caja* of Zacatecas

The tax revenues on silver produced are reported in *pesos* in the TK set for the *Caja* of Zacatecas under '*1% y Diezmos de Plata de Azogue*' and '*1% y Diezmos de Plata de Fuego*'. The fraction of silver refined by amalgamation and smelting is thus calculated directly from the *peso* amounts registered under each heading in the same time period. These appear in Figure 6-2 and all subsequent plots of the following *Cajas* as the data points under the heading 'duties'. In addition, in certain periods a tax on the minting of coins (*señoreage or señoreaje*) is included under the same rubric, as '*1% Diezmos Señoreage Plata de Azogue*' or '*1% Diezmos Señoreage Plata de Fuego*'.[883] On the assumption that these amounts have not distorted the original split of production between amalgamation and smelting, these data points are plotted under 'duties & coin' in Figure 6-2 and subsequent plots of this nature. The smooth merging observed between both sources of data confirms empirically my assumption. For the case of Zacatecas I have also included the data reported by Lacueva, who has recently published annual data sets of silver production in Zacatecas, since it covers a period prior to 1700 when the time periods

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[882] As an example, at the end of the nineteenth century the switch to smelting with coal as of 1893 increased in a few years silver production from 39 to 74 million kg, according to Mendizábal, *La mineria mexicana*, 106.
[883] '*señoreage* : a tax on the minting of coins by private individuals' - '*señoreage : impuesto sobre la acuñación de monedas por particulares*' in Pérez Luque and Tovar Rangel, *Caja Real Guanajuato*, 61. Also defined as a mintage tax in Bakewell, *Silver Mining in Zacatecas*, 245.

for the TK set do not always correspond exactly to twelve month intervals.[884] There is no evident misfit between all sources of data for this period.[885]

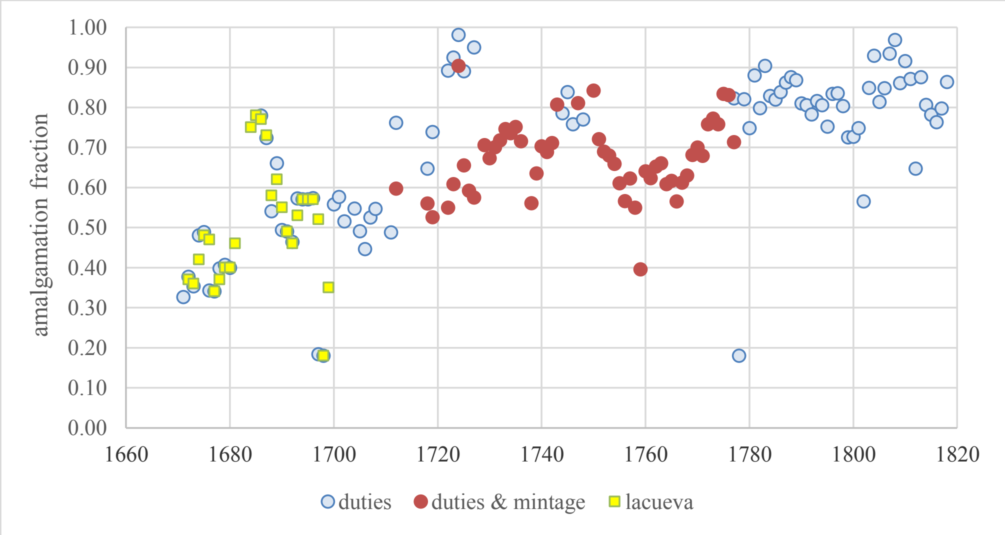

Figure 6-2. The fraction of total silver refined by amalgamation in Zacatecas in the period 1670 to 1820. Prior to 1700 the time intervals are exactly one year only for the Lacueva data. Fractions calculated by the author on the basis of the raw data from TK set and footnote 894.

The profile of Figure 6-2 indicates a predominance of smelting in the second half of the seventeenth century shifting to a complete reversal between smelting and amalgamation by the end of the eighteenth century. The interpretation of the alternations between amalgamation and smelting in Zacatecas based on mercury alone has been questioned already.[886] The reason for

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[884] Lacueva Muñoz, *La plata del Rey*, 391.

[885] Bakewell published a table with percentage values of silver produced by smelting for some of the main *Cajas*. He does not provide the source of the two values he provides for each *Caja*, for the 1720s or 1730s and for the 1760s of 1770s. I will be citing his values in the footnotes of the following sections, and overall they confirm my own findings. The data presented in these sections span a much wider period than Bakewell's data, which allows a more general picture to emerge. For Zacatecas he states that smelting produced around 30% of its silver both in the 1720s and 1760s. Bakewell, "Colonial Mining," 145.

[886] Lacueva has argued that Bakewell, the leading proponent of the mercury argument, ignored the contribution of smelting per se in Zacatecas irrespective of the supply of mercury. See Lacueva Muñoz, La plata del Rey, 187-210. For other proponents of the mercury argument see Brading and Cross, "Colonial Silver Mining: Mexico and Peru," 573-78. 'It is not a surprise then that in the eighteenth century, when production in New Spain reached its highest ever historical levels, the two processes had been working side by side, and the switch between one and the other subject mostly to the price of mercury.' In Blanchard, *Russia's "Age of Silver". Precious-metal Production and Economic Growth in the Eighteenth Century* 3-31.

the change in refining process is quite straightforward. As of the 1680s the lead rich ores of Sombrerete were no longer registered at the Zacatecas *Caja*, and the effect of this reaasignment after 1680 of ores that had until then been smelted and registered at Zacatecas is evident in Figure 6.3. Amalgamation is seen to peak in the 1730s and then responds to the price decrease of mercury in the 1780s. There is no evidence to suggest a zero sum game, where refiners switched from smelting to amalgamation when mercury prices dropped, at the expense of the amount of ore smelted. The nature of the ore prevailed: ores that could be smelted continued to be smelted, and a lower mercury price made it profitable to process more of the ore that could be amalgamated. On average over this period amalgamation accounted for two thirds and smelting for one third of total silver produced, but during the time the ores from Sombrerete were included in this *Caja*, the fraction of smelted silver registered in the *Caja* represented over half the total of silver produced.

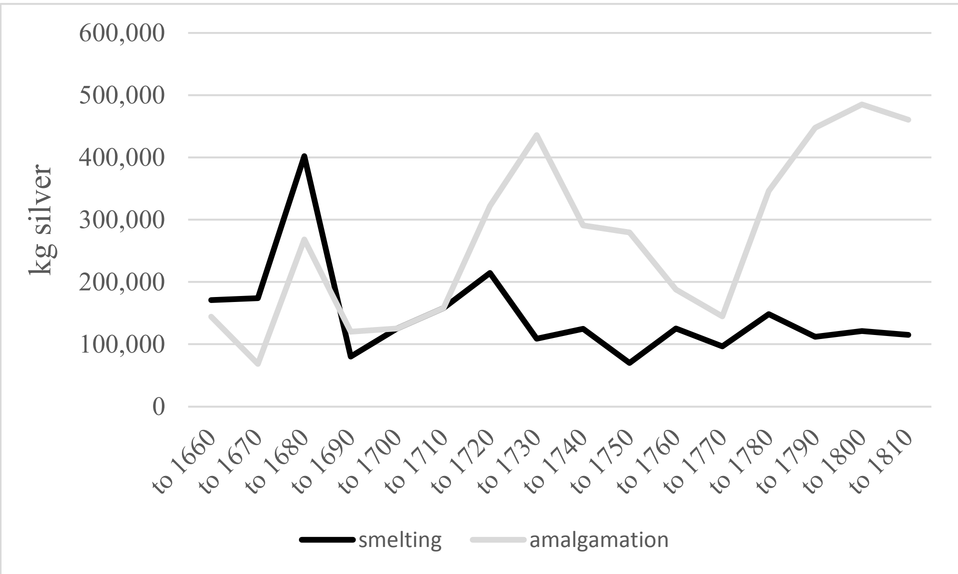

Figure 6-3. Registry of silver at the *Caja* of Zacatecas according to refining process. Data from Table 6-II.

In order to correlate the production of silver with the available data on mercury sales broken down by period, I have repeated with the TK set one of the classical calculations carried out in the historiography of silver refining, the conversion of silver tax revenues into a weight of silver production.[887] In parallel I have estimated the weight of mercury (in kg) consumed in the amalgamation of silver ores by dividing each registered sale revenue by the price of a *quintal* of mercury.

Table 6-II is the first example of how all these projections are combined. The data plotted in Figure 6-2 are used to generate average values of the mercury to silver weight according to each time period. The average of this ratio for the period 1670 to 1810 is 2.05, and this value is extrapolated for the period prior to 1670.[888] The weight of silver produced by amalgamation is calculated using this ratio and the amount of mercury calculated from the sale figures. The balance from the total silver produced according to the tax registries provides the weight of silver obtained by smelting. Prior to 1651, the TK set does not segregate data on silver according to refining process. For the period 1611 to 1650, I make use of two sets of data in the historiography: total silver produced as reported by TePaske, and the amount of mercury distributed to Zacatecas from late 1608 to 1649, as reported by Bakewell (these figures are in bold in Table 6-II).[889] For the first period from 1590 to 1610, for which I have no information on mercury sales or distribution, I assume the same amalgamation fraction of 0.7 applies, and

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[887] I have followed Bakewell's path in applying factors of 10.9 and 20.8 to reverse calculate from the tax data under 1% and *diezmos* and *quintos* the value of silver produced in *pesos* (of 272 *maravedies*). I have used his value of 8 *pesos* 1 *real* for a mark of silver up to the year 1700, and 8 *pesos* 6 *reales* after that date. Bakewell, *Silver Mining in Zacatecas*, 245.

[888] Brading assumed that prior to 1632 an average *correspondencia* value was 100, equivalent to a weight ratio of 2. Brading, *Miners Bourbon Mexico*, 11.

[889] At least three sets of silver production data for this period have been published for the *Caja* of Zacatecas. Bakewell published his production data in marks, TePaske in *pesos* (of 272 *maravedies*) and kg of fine silver and Lacueva likewise in *pesos*. Their totals for this period differ slightly, according to my calculations based on their data: 3,218,152 kg for Bakewell, 3,153,180 kg for TePaske and 3,336,221 kg for Lacueva, a spread of not more than 6% over the lowest value. Bakewell, *Silver Mining in Zacatecas*, 242-46.; TePaske and Brown, *Gold and Silver*, 115-16.; Lacueva Muñoz, *La plata del Rey*, 388-90. For the data on mercury see Bakewell, *Silver Mining in Zacatecas*, 251.

from TePaske’s figure on silver production (in bold in Table 6-II) I work back to calculate the deemed amount of mercury consumed.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	breakdown (kg)			mercury to silver ratio
						as calomel	as liquid mercury	as volatilized mercury	
1591-1610	**1,500,000**	0.7	A	1,050,000	2,152,500	1,829,625	301,350	21,525	2.05
			S	450,000					
1611-1650	**1,650,000**	0.7	A	1,185,402	**2,430,075**	2,065,564	340,211	24,301	2.05
			S	464,598					
2/1651 - 4/1661	315,388	0.5	A	144,558	296,345	251,893	41,488	2,963	2.05
			S	170,829					
5/1661 - 4/1663, 5/1664 - 6/1670	242,674	0.3	A	68,658	140,750	119,637	19,705	1,407	2.05
			S	174,015					
7/1670 to 6/1681	670,575	0.4	A	268,230	468,508	398,232	65,591	4,685	1.7
			S	402,345					
1/1686 to 2/1692	200,432	0.6	A	120,259	218,731	185,921	30,622	2,187	1.8
			S	80,173					
3/1692 to 12/1700	250,211	0.5	A	125,105	281,986	239,688	39,478	2,820	2.3
			S	125,105					
1/1701 to 12/1710	316,089	0.5	A	158,044	310,918	264,280	43,529	3,109	2.0
			S	158,044					
1/1711 to 12/1720	536,709	0.6	A	322,025	649,013	551,661	90,862	6,490	2.0
			S	214,683					
1/1721 to 12/1730	544,886	0.8	A	435,909	742,401	631,041	103,936	7,424	1.7
			S	108,977					
1/1731 to 12/1740	415,326	0.7	A	290,728	616,362	523,908	86,291	6,164	2.1
			S	124,598					
1/1741 to 12/1750, exc 1749	349,798	0.8	A	279,839	620,106	527,090	86,815	6,201	2.2
			S	69,960					
1/1751 to 12/1760	313,580	0.6	A	188,148	490,145	**349,955**	135,288	4,901	2.6
			S	125,432					
1/1761 to 12/1770	241,316	0.6	A	144,790	290,293	246,749	40,641	2,903	2.0
			S	96,526					
1/1771 to 12/1780	494,484	0.7	A	346,139	587,454	499,336	82,244	5,875	1.7
			S	148,345					
1/1781 to 12/1790	559,775	0.8	A	447,820	1,185,986	**832,945**	341,182	11,860	2.6
			S	111,955					
1/1791 to 12/1800	606,623	0.8	A	485,298	790,299	671,754	110,642	7,903	1.6
			S	121,325					
1/1801 to 12/1810 ex 1802	575,722	0.8	A	460,578	1,287,572	**856,675**	418,021	12,876	2.8
			S	115,144					
total	9,783,589				13,559,445	11,045,956	2,377,895	135,594	

Table 6-II. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the *Caja* of Zacatecas. In this and following tables A: Amalgamation, S: Smelting, For the method and sources see text.

The estimated breakdown in production by refining process is then used to project a base-line scenario of the magnitude of the main environmental impact vectors that correspond to the refined silver registered at the *Caja* of Zacatecas from 1590 to 1820. For amalgamation the main vectors are calomel washed away in water streams, liquid mercury in the soil or in the water, and volatilized mercury during the casting of the silver bars, as shown in Table 6-II, using the breakdown established in Chapter 3 (85%, 14% and 1%, respectively, of the total amount of mercury consumed). The amount of calomel cannot be greater than 1.86 times the amount of silver refined, so when the mercury to silver ratio is above 2.3 for any period, the ceiling value of calomel loss is applied and the liquid mercury loss is adjusted accordingly (values in bold italics). The magnitudes for salt and copper sulphate consumed and washed away from the treated ore, of solid waste washed away in waterways and woodland required for firewood as a result of amalgamation are reported in Table 6-III, according to the ratios per kg of silver calculated in Chapter 4 at Regla.

For smelting the vectors correspond to lead and lead compounds lost in flue gases, woodland required to produce charcoal and solid waste as slag, and their magnitude established according to the ratios reported in Chapters 2 and 4 per kg of silver smelted. I have chosen to report for lead and lead in compounds issued to the atmosphere a range of 5 to 10 kg per kg of smelted silver, rather than a single ratio. The values for woodland consumed in both Tables are overestimated, since I have not factored in the natural cycle of regeneration, which would reduce the projections by at least 50%. The results are reported in Table 6-IV. All figures in Tables 6-III and 6-IV have been rounded off to the nearest significant number, to reflect the

1591 to 1810	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
	thousand t						thousand ha
	10	7	200	17	50	4,000	20

Table 6-III. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of Zacatecas.

1591 to 1810	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	10	3	15 to 30	160	3,300	1,300

Table 6-IV. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of Zacatecas.

limitations of the exercise. Finally, to check on my calculations on silver production, I compare my results with the totals reported by Tepaske.[890]

6.1.2 *Caja* of Guanajuato

Prior to 1650 refiners of the Guanajuato area registered their silver in the *Caja* of Mexico (Ciudad de México). After that date the level of silver ore extracted in the mines around the city of Guanajuato made it necessary to set up a separate *Caja*. According to TePaske the majority of the silver registered at the *Caja* of Guanajuato came from the ore extracted from the mines in its near vicinity, in other words from refining *haciendas* close to Guanajuato.[891] Figure 6-4 shows how the fraction of amalgamated silver varied over the period 1679 to 1816. The impact of lower mercury pricing as of the 1780s is reflected in the steady increase of the fraction of amalgamation that already dominated production of silver in this area, starting from a market share of approximately 0.65.[892] Again, the decrease in mercury pricing altered the

[890] In Table 6-II the total is 9.8 million kg, compared to 10.1 million kg reported in TePaske and Brown, *Gold and Silver*, 121-23.
[891] Ibid., 95.
[892] Bakewell reported 35% for smelting in the 1730s and 27% in the 1770s. Bakewell, "Colonial Mining," 145.

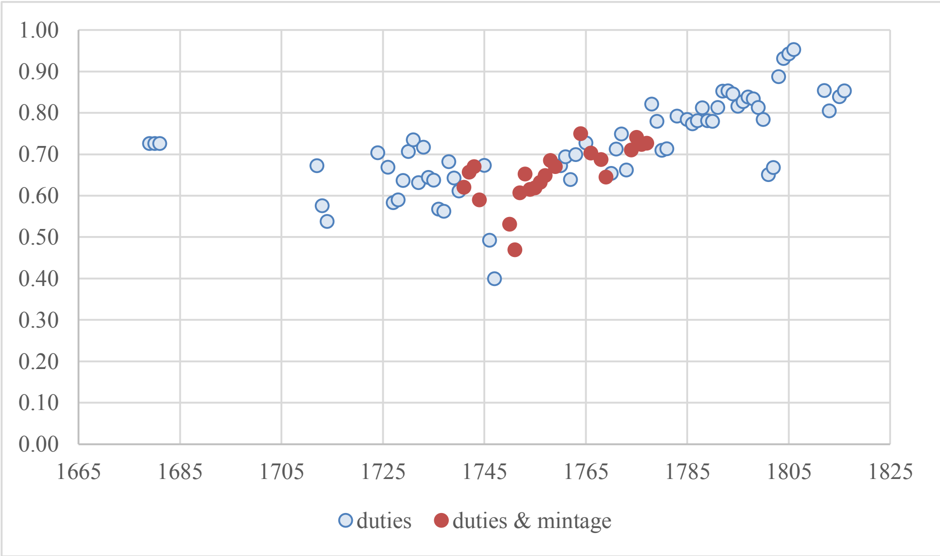

Figure 6-4. The fraction of total silver refined by amalgamation as registered in the *Caja* of Guanajuato in the period 1679 to 1816. Prior to 1720 the time intervals of the raw data in the TK data have been approximated to the calendar years.

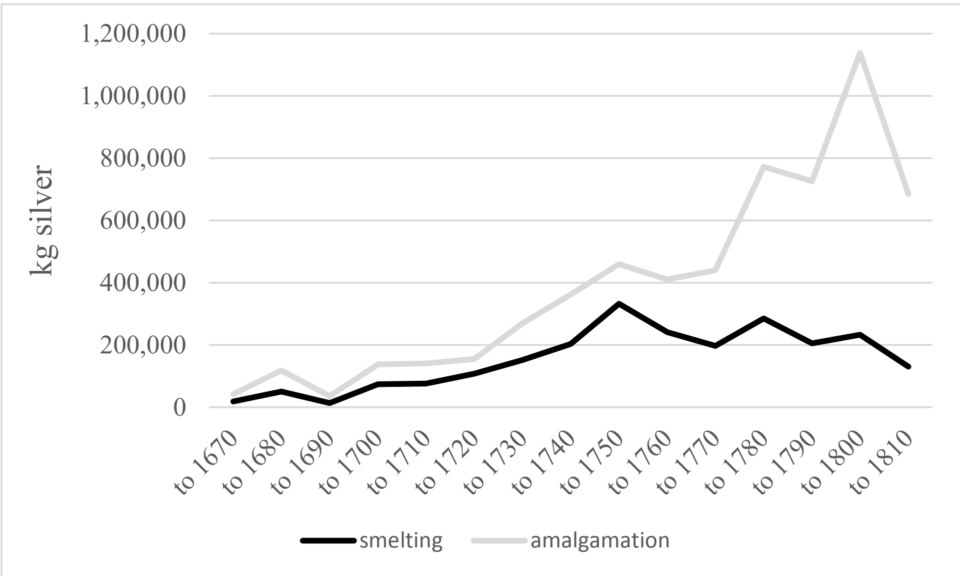

Figure 6-5. Registry of silver at the *Caja* of Guanajuato according to refining process. Data from Table 6-V.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	breakdown (kg)			mercury to silver ratio
						as calomel	as liquid mercury	as volatilized mercury	
5/1665 to 2/1671	60,870	0.70	A	42,609	96,080	81,668	13,451	961	2.3
			S	18,261					
3/1671 to 3/1681	168,370	0.70	A	117,859	191,991	163,192	26,879	1,920	1.6
			S	50,511					
4/1681 to 7/1684	49,969	0.73	A	36,477	44,231	37,596	6,192	442	1.2
			S	13,492					
6/1690 to 1/1701	212,323	0.65	A	138,010	171,413	145,701	23,998	1,714	1.2
			S	74,313					
2/1701 to 2/1710	217,069	0.65	A	141,095	177,727	151,068	24,882	1,777	1.3
			S	75,974					
3/1711 to 12/1720	263,708	0.59	A	155,588	270,894	230,260	37,925	2,709	1.7
			S	108,120					
1/1721 to 12/1730	422,272	0.64	A	270,254	448,296	381,051	62,761	4,483	1.7
			S	152,018					
1/1731 to 12/1740	565,316	0.64	A	361,802	530,439	450,873	74,261	5,304	1.5
			S	203,514					
1/1741 to 12/1750	792,108	0.58	A	459,422	830,679	706,077	116,295	8,307	1.8
			S	332,685					
1/1751 to 12/1760	650,639	0.63	A	409,902	647,787	550,619	90,690	6,478	1.6
			S	240,736					
1/1761 to 12/1770	637,455	0.69	A	439,844	828,293	704,049	115,961	8,283	1.9
			S	197,611					
1/1771 to 12/1780	1,058,474	0.73	A	772,686	1,414,740	1,202,529	198,064	14,147	1.8
			S	285,788					
1/1781 to 12/1790	931,462	0.78	A	726,541	1,610,538	1,368,957	225,475	16,105	2.2
			S	204,922					
1/1791 to 12/1800	1,371,119	0.83	A	1,138,029	1,588,932	1,350,592	222,450	15,889	1.4
			S	233,090					
1/1801 to 12/1806	815,637	0.84	A	685,135	1,493,699	1,269,644	209,118	14,937	2.2
			S	130,502					
total	8,216,791				10,345,738	8,793,877	1,448,403	103,457	

Table 6-V. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the *Caja* of Guanajuato.

balance between amalgamation and smelting, but the baseline of smelting had been reached before the first of the decreases in mercury pricing, as shown in Figure 6-5, so the increase in amalgamation after the 1770s cannot be due from a poaching of ores that would otherwise have been smelted. Though Guanajuato is a *Caja* where amalgamation always dominated, with an average over the whole period based on total silver produced of 71%, the two refining processes were more evenly balanced for nearly a century, before the price of mercury was cut by 50%.

Between 1690 and 1710 no distinction was made between amalgamated and smelted silver. For lack of sufficient data I have extrapolated the value of the amalgamation fraction for the period 1665 to 1681, and interpolated it for the period 1690 to 1710.[893] Tables 6-V, 6-VI and 6-VII provide the projections on the magnitude of the main environmental impact vectors from 1665 to 1806.

1665 to 1806	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
	thousand t						thousand ha
	8	6	170	15	40	3,600	17

Table 6-VI. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of Guanajuato.

[893] The total of 8.2 million kg of silver I have calculated as produced in this period corresponds well with TePaske's figure of 8.5 million kg in TePaske and Brown, *Gold and Silver*, 130-31. The information in the TK data set for Guanajuato has also been published in detail in Pérez Luque and Tovar Rangel, *Caja Real Guanajuato*, 99-246.

	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
1665 to 1806	thousand t					thousand ha
	8	2	12 to 24	140	2,300	900

Table 6-VII. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of Guanajuato.

6.1.3 *Caja* of Mexico

The *Caja* at México was the first established by Spain to channel the silver product refined in New Spain. As production grew other regional *Cajas* sprung up, which means that the tax and revenue records in the Mexico *Caja* not only reflect the refining activity in the vicinity of Ciudad de México (58 *Reales de Minas* by mid 1760s, including the major production centre at Taxco) but at different times have also included the silver and mercury that were later reported by the new *Cajas* of Guanajuato, San Luis Potosí, Zimapán and Pachuca.[894] This creates major problems for the analysis of the TK set for this *Caja*. First of all, the distinction between amalgamated and smelted silver only appears very late in the records, as can be seen in the very limited results reported in Figure 6-6. Second, even though the silver tax records are identified for other regions, which helps to avoid double accounting of their totals, mercury revenues are reported as an aggregate, with no such distinction. I have therefore opted to use Tepaske's data on silver production for the *Caja* during the period 1521 to 1810, and have assumed an amalgamation fraction of 0.8, based on Figure 6-4, and a mercury to silver ratio of 1.8 to apply over the whole period.

[894] TePaske and Brown, *Gold and Silver*, 84-87. Mexicans refer to Ciudad de México simply as México, so the *Caja* de México does not refer to the whole country, but to the *Caja* situated in its capital, Ciudad de México.

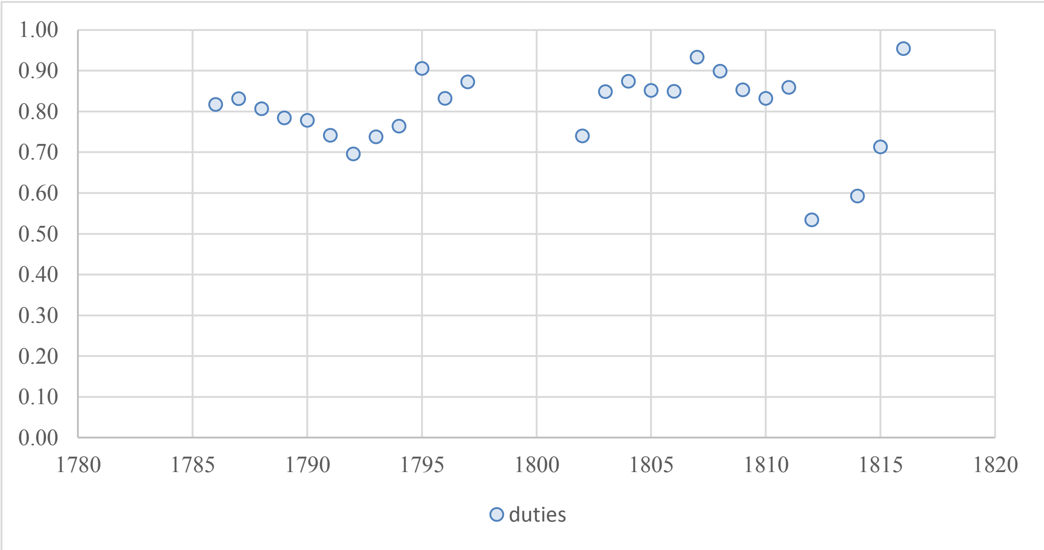

Figure 6-6. The fraction of total silver refined by amalgamation as registered in the *Caja* of México in the period 1786 to 1816. The raw data are from the TK data set.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	breakdown (kg)		
						as calomel	as liquid mercury	as volatilized mercury
1521 to 1560	**770,410**	*0.00*	A	*0*	*0*	*0*	*0*	*0*
			S	*770,410*				
1561 to 1600	**2,251,290**	*0.80*	A	*1,801,032*	*3,241,858*	*2,755,579*	*453,860*	*32,419*
			S	*450,258*				
1601 to 1700	**2,783,840**	*0.80*	A	*2,227,072*	*4,008,730*	*3,407,420*	*561,222*	*40,087*
			S	*556,768*				
1701 to 1810	**2,897,520**	*0.80*	A	*2,318,016*	*4,172,429*	*3,546,564*	*584,140*	*41,724*
			S	*579,504*				
total	**8,703,060**				*11,423,016*	*9,709,564*	*1,599,222*	*114,230*

Table 6-VIII. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the Caja of México. Values in bold from footnote 894.

The analysis for the *Caja* of Mexico is therefore less detailed and subject to a much greater uncertainty than for all the other Cajas. It is also biased in favour of amalgamation. Tables 6-VIII, 6-IX and 6-X present the projections of the relevant magnitudes of the main environmental impact vectors.

1521 to 1810	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
	thousand t						thousand ha
	9	6	190	16	40	3,900	19

Table 6-IX. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of México.

1521 to 1810	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	9	2	12 to 24	140	2,400	950

Table 6-X. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of México.

6.1.4 *Caja* of Durango

Established in 1599, the *Caja* of Durango represents the production of refining sites (42 *Reales de Minas* in 1761-1767) around the capital of the colonial province of Nueva Vizcaya, some two hundred miles to the northwest of Zacatecas. Among the contributors were Parral and Chihuahua, the latter becoming a *Caja* in its own right as of 1785.[895] Figure 6-7 shows how the fraction of amalgamated silver varied over the period 1679 to 1816. The registries of tax for the two decades between 1740 and 1760 do not discriminate revenues according to refining process. but the data on mercury sales in the TK set for this hidden period indicate an increasing use of amalgamation.

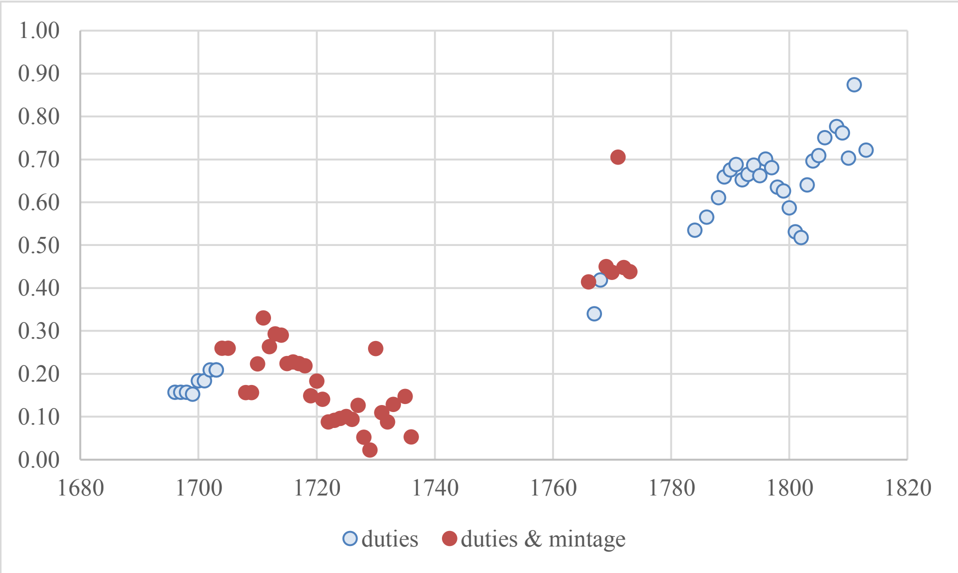

Figure 6-7. The fraction of total silver refined by amalgamation as registered in the *Caja* of Durango in the period 1696 to 1813. Between 1737 and 1765 no distinction was made between amalgamated and smelted silver in the tax register. Prior to 1713 I have approximated the irregular time series of the raw data in the TK data to their nearest calendar years.

The price decrease of mercury coincides with a tilt towards amalgamation after the 1780s, together with a concurrent drop in the amount of ore being smelted, as seen in Figure 6-8. . This profile is an exception to that which was observed for the previous *Cajas*. It can reflect either a poaching of ores by cheaper mercury from smelting to amalgamation or simply the exhaustion of lead rich silver ores in the mines of the region. A historic import of lead flux from other regions to smelt dry ores prior to the 1770s would favour rhe former explanation,

[895] Ibid., 91-93, 119.

otherwise the technical difficulties of amalgamating lead rich ores would discount it. On average smelting accounted for 61% of the total silver registered at the *Caja* of Durango.

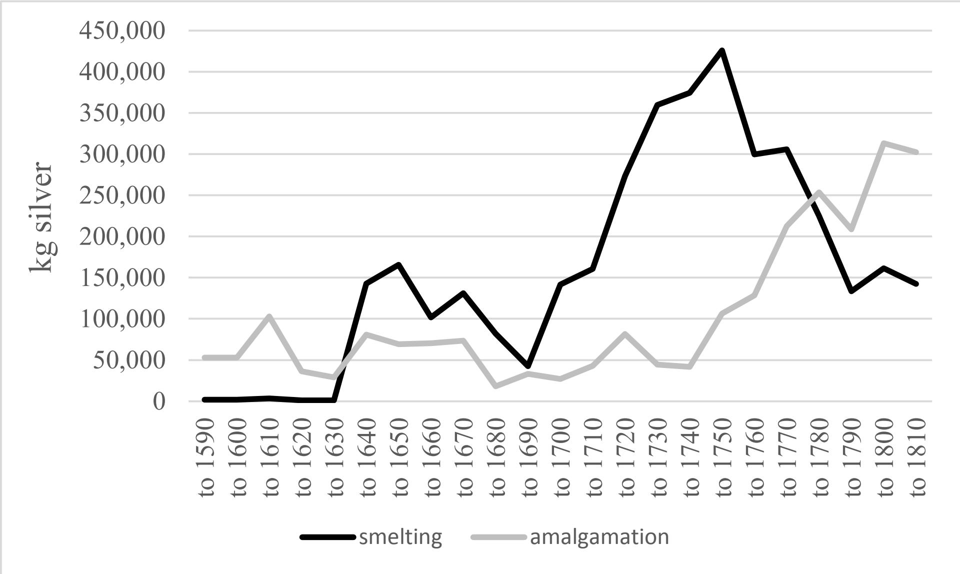

Figure 6-8. Registry of silver at the *Caja* of Durango according to refining process. Data from Table 6-XI.

In Table 6-XI, from 1622 to 1696 the average historical mercury to silver ratio calculated for Durango (2.1) is applied to the TK data on mercury so as to project how much silver would have been refined by amalgamation during this period, and from that projected value I calculate the fraction of amalgamated silver. For the period prior to 1622, I complement the data on silver production from the TK set with Lacueva's data for the years 1578 to 1598.[896] I then apply the amalgamation ratio projected for 1622 (0.97) to all this period, at the risk of overestimating the use of amalgamation. The deemed amounts of silver obtained by amalgamation allow me to estimate the amount of mercury consumed, again based on a ratio of 2.1. The results are given in Tables 6-XI, 6-XII and 6-XIII.[897]

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[896] Lacueva Muñoz, *La plata del Rey*, 397.
[897] The total for silver produced and registered at Durango in the table from 1599 onwards corresponds nearly exactly with the figure of 5.9 million kg in TePaske and Brown, *Gold and Silver*, 125-27.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	breakdown (kg)			mercury to silver ratio
						as calomel	as liquid mercury	as volatilized mercury	
1578-1598	**109,516**	0.97	A	106,231	223,085	189,622	31,232	2,231	2.1
			S	3,285					
1/1599 to 6/1611	105,916	0.97	A	102,739	215,752	183,389	30,205	2,158	2.1
			S	3,177					
7/1611 to 4/1615	37,422	0.97	A	36,299	76,228	64,794	10,672	762	2.1
			S	1,123					
5/1622 to 4/1625	29,828	0.97	A	28,845	60,574	51,488	8,480	606	2.1
			S	984					
6/1632 to 6/1641	223,591	0.36	A	80,938	169,969	144,474	23,796	1,700	2.1
			S	142,653					
7/1641 to 12/1650	234,813	0.30	A	69,274	145,476	123,655	20,367	1,455	2.1
			S	165,539					
1/1651 to 12/1659 exc 1654	171,920	0.41	A	70,368	147,773	125,607	20,688	1,478	2.1
			S	101,552					
1/1664 to 5/1673	204,639	0.36	A	73,541	154,437	131,272	21,621	1,544	2.1
			S	131,097					
6/1673 to 7/1677	100,278	0.18	A	18,221	38,265	32,525	5,357	383	2.1
			S	82,056					
1/1685 to 12/1688	75,456	0.44	A	33,010	69,321	58,923	9,705	693	2.1
			S	42,445					
1/1689 to 6/1700	168,564	0.16	A	26,970	91,629	**50,165**	40,548	916	3.4
			S	141,593					
7/1700 to 6/1711	203,352	0.21	A	42,704	97,567	82,932	13,659	976	2.3
			S	160,648					
7/1711 to 12/1720	355,211	0.23	A	81,699	107,857	91,679	15,100	1,079	1.3
			S	273,513					
1/1721 to 12/1730	404,195	0.11	A	44,461	51,731	43,972	7,242	517	1.2
			S	359,734					
1/1731 to 12/1740 exc. 1734	415,980	0.1	A	41,598	44,639	37,943	6,249	446	1.1
			S	374,382					
1/1741 to 12/1750	532,680	0.2	A	106,536	85,549	72,717	11,977	855	0.8
			S	426,144					
1/1752 to 12/1760	428,258	0.3	A	128,477	159,861	135,882	22,381	1,599	1.2
			S	299,780					
1/1761 to 12/1770	518,147	0.41	A	212,440	410,587	348,999	57,482	4,106	1.9
			S	305,707					
1/1771 to 12/1780	478,270	0.53	A	253,483	677,749	**471,478**	199,493	6,777	2.7
			S	224,787					
1/1781 to 12/1790 exc 1787	342,124	0.61	A	208,696	509,953	**388,174**	116,680	5,100	2.4
			S	133,428					
1/1791 to 12/1800	474,878	0.66	A	313,419	735,234	624,949	102,933	7,352	2.3
			S	161,458					
1/1801 to 12/1810 exc 1806	444,626	0.68	A	302,346	705,805	599,934	98,813	7,058	2.3
			S	142,280					
total	6,059,664				4,979,042	4,054,571	874,681	49,790	

Table 6-XI. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the *Caja* of Durango. Silver production figure in bold from footnote 896, ceiling for calomel estimates indicated in bold italic figures.

1578 to 1810	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
	thousand t						thousand ha
	6	2	70	6	17	1,500	7

Table 6-XII. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of Durango.

1578 to 1810	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	6	4	18 to 36	220	3,700	1,500

Table 6-XIII. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of Durango.

6.1.5 *Caja* of San Luis Potosí

The split between smelting and amalgamation reflected in the tax records of the *Caja* of San Luis Potosí is the best example why these curves must be interpreted first of all based on the nature of the ore being processed. At a first reading of Figure 6.9 the change from smelting to amalgamation coincides so well with the decrease in the price of mercury in the 1770s that a causal link seems the explanation. However it is the change of the type of ore, and not the price of mercury, that determines the profile in Figure 6.9. The initial period corresponds predominantly to the smelting of lead rich ores, first found in the mines of the Cerro San Pedro on the hills that surround the town, and then from other locations such as Charcas and Guadalcazar. In the early eighteenth century when mention of amalgamation

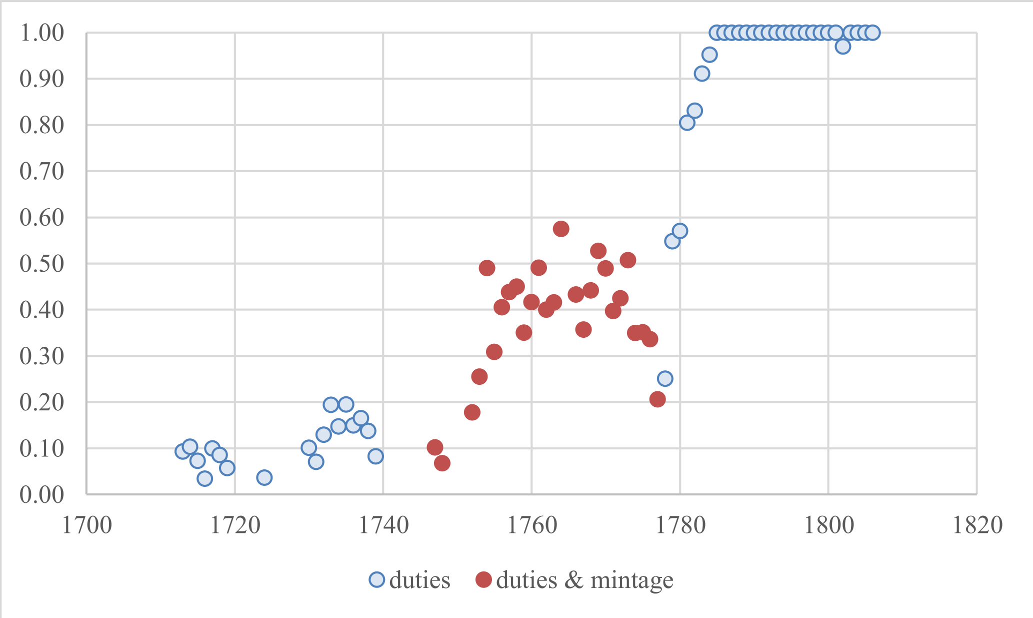

Figure 6-9. The fraction of total silver refined by amalgamation as registered in the *Caja* of San Luis Potosí in the period 1713 to 1806. Source of raw data is the TK set.

haciendas start to appear in archival records.[898] In the 1770s silver was discovered at Catorce, 250 km to the north of the town of San Luis Potosí.[899] The ore, rich in native silver and silver halides, was refined using Barba's *cazo* amalgamation process and complemented by an extraction using the *patio* process (Chapter 5).[900] It is the production from Catorce that explains the predominance of amalgamation in the production of silver registered at San Luis Potosí as of the 1780s observed in Figure 6-9, not the decrease in the price of mercury. The impact of

[898] During this period Bakewell reports 86% of silver produced by smelting in the 1730s dropping to 54% by the 1760s. Bakewell, "Colonial Mining," 145. Smelting is reported as accounting for 92% of production in 1718, and then decreasing to 48.6% in 1761-1767 and then virtually disappearing at 1.6% by 1785-89 and later years, in Inés Herrera Canales, "El método de refinación con azogue en la minería potosina colonial: del fuego al cazo " in *La plata en Iberoamérica: Siglos XVI al XIX*, ed. Jesus Paniagua Pérez and Nuria Salazar Simarro (Leon: Universidad de León, 2008), 68.

[899] Ines Herrera Canales, "El auge de la plateria potosina en la segunda mitad del siglo XVIII, al argento vivo," in *Ophir en las Indias. Estudios sobre la plata americana. Siglos XVI-XIX*, ed. Jesus Paniagua Perez and Nuria Salazar Simarro (Leon: Universidad de Leon, 2010), 115-21.

[900] The average mercury to silver weight ratio calculated from the TK data set for San Luis Potosí averages 1.7 between 1710 and 1780, and 0.9 from 1781 to 1806. The use of the *cazo* method cut average mercury consumption by half, though this decrease is very dependent on the nature of the ore.

the mines of Catorce is reflected in the profile of the register of silver for this *Caja* (Figure 6-10). It is interesting to observe that the baseline of smelting remained fairly constant over the whole period covered in Figure 6-10, only decreasing substantially as of the 1790s.

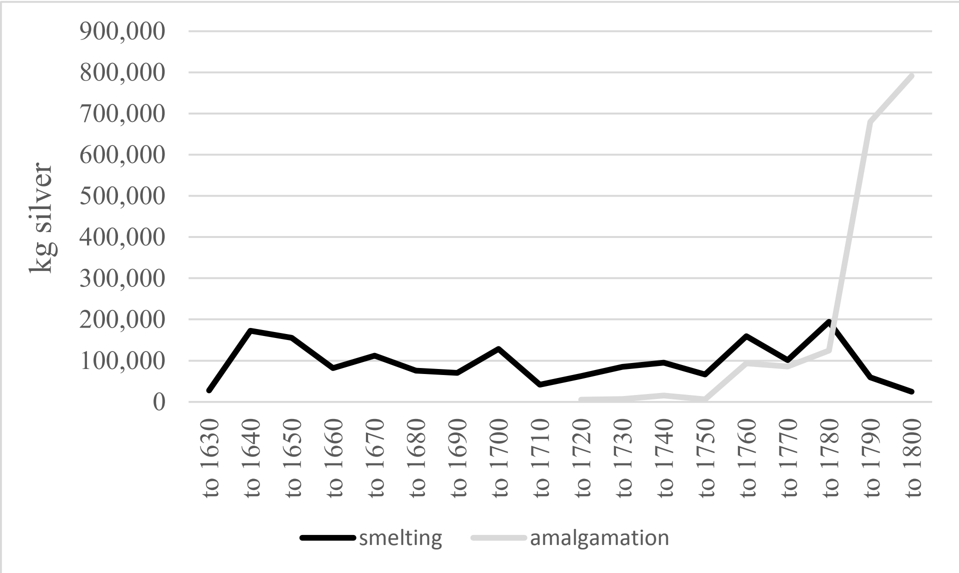

Figure 6-10. Registry of silver at the *Caja* of San Luis Potosí according to refining process. Data from Table 6-XIV.

The hard data on the ratio of amalgamation to smelting begin to be recorded in the TK set as of 1712. Prior to that date, the TK set for San Luis Potosí contains data on taxes paid on silver, beginning with a figure said to correspond with the taxes paid from March 1528 to March 1629. Since mining and refining only started in earnest at the end of the sixteenth century, I have preferred to report that initial value converted into kg in Table 6-XIV as 'up to March 1629'. Revenues from mercury sales only appear from 1672 onwards, and I am assuming smelting completely dominated production in the early years (see Chapter 3). From 1672 to 1710 I divide the weight of mercury sold by 1.7 (the average mercury to silver ratio from 1710 to 1770 according to the TK data that does not involve the *cazo* process) so as to arrive at a deemed weight of silver obtained by amalgamation, and from there I project an amalgamation fraction for each period.[901]

Because of the geographical split between Catorce and the rest of the *haciendas* registering their silver at the *Caja* of San Luis Potosí, it is prudent to divide the percentage of silver refined by each process into two historical periods. The first, from the early 1600s to 1780, assigns 82% of all silver produced to smelting. The second, as of 1780, assigns 96% of the silver produced to amalgamation, most of which was produced at the mines of Catorce. The environmental impact of silver refining for this *Caja* is thus also divided along geographical lines. Smelting would impact the region around and within the town of San Luis Potosí for some 160 years, while the more isolated area around the mines of Catorce would be spared the consequences of smelting. The results in Tables 6-XIV to 6-XVI must be interpreted bearing this division in mind.

The area of Catorce would see in just 30 years most of the impact from amalgamation: 1,400,000 t of mineral waste, subject to the silver content of the Catorce ores, while a level of 2,000 t of calomel is consistent with the level of mercury consumed. No copper sulphate consumption is reported because the *cazo* process did not use this reagent. The estimate of woodland consumed for amalgamation is below the level expected to have occurred, since the *cazo* process requires more fuel than the *patio* process.

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[901] The total amount of silver registered at the *Caja* according to Table 6-XIV is 3.9 million kg. The total reported byTepaske up to the end of 1806 is just over 4 million kg. TePaske and Brown, *Gold and Silver*, 127-29.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	breakdown (kg) as calomel	as liquid mercury	as volatilized mercury	mercury to silver ratio
up to 3/1629	27,519	*0*	A	*0*	*0*	*0*	*0*	*0*	
			S	*27,519*					
2/1630 to 4/1640	172,664	*0*	A	*0*	*0*	*0*	*0*	*0*	
			S	*172,664*					
12/1640 to 2/1651	155,489	*0*	A	*0*	*0*	*0*	*0*	*0*	
			S	*155,489*					
12/1653 to 6/1661	82,141	*0*	A	*0*	*0*	*0*	*0*	*0*	
			S	*82,141*					
7/1661 to 10/1671	112,388	*0*	A	*0*	*0*	*0*	*0*	*0*	
			S	*112,388*					
12/1672 to 2/1675, 11/1677 to 4/1681	75,525	*0.04*	A	*3,396*	5,774	*4,908*	*808*	*58*	*1.7*
			S	*72,129*					
5/1681 to 7/1684, 3/1686 to 3/1688	70,374	*0.10*	A	*6,844*	11,635	*9,890*	*1,629*	*116*	*1.7*
			S	*63,529*					
1/1690 to 4/1701	128,682	*0.04*	A	*4,800*	8,159	*6,935*	*1,142*	*82*	*1.7*
			S	*123,882*					
1/1706 to 12/1710	41,832	*0.03*	A	*1,235*	2,099	*1,784*	*294*	*21*	*1.7*
			S	*40,597*					
1/1712 to 12/1720	68,138	0.08	A	*5,451*	8,165	*6,940*	*1,143*	*82*	1.5
			S	*62,687*					
1/1721 to 12/1730	91,046	0.07	A	*6,373*	7,250	*6,163*	*1,015*	*73*	1.1
			S	*84,673*					
1/1731 to 12/1740	110,512	0.14	A	*15,472*	34,540	*29,359*	*4,836*	*345*	2.2
			S	*95,040*					
1/1741 to 12/1748	71,885	0.08	A	*5,751*	11,788	*10,020*	*1,650*	*118*	2.0
			S	*66,134*					
1/1752 to 12/1760	252,907	0.37	A	*93,576*	188,859	*160,530*	*26,440*	*1,889*	2.0
			S	*159,332*					
1/1761 to 12/1770 exc 1765	186,820	0.46	A	*85,937*	133,103	*113,138*	*18,634*	*1,331*	1.5
			S	*100,883*					
1/1771 to 12/1780	318,643	0.39	A	*124,271*	138,863	*118,033*	*19,441*	*1,389*	1.1
			S	*194,372*					
1/1781 to 12/1790	738,851	0.92	A	*679,743*	659,313	*560,416*	*92,304*	*6,593*	1.0
			S	*59,108*					
1/1791 to 12/1800	815,894	0.97	A	*791,417*	571,467	*485,747*	*80,005*	*5,715*	0.7
			S	*24,477*					
1/1801 to 12/1806	424,969	1	A	*424,969*	406,692	*345,688*	*56,937*	*4,067*	1.0
			S	*0*					
total	3,946,278				*2,187,709*	*1,859,553*	*306,279*	*21,877*	

Table 6-XIV. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the *Caja* of San Luis Potosí.

1600s to 1806	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
	thousand t						thousand ha
	4	2	70	-	16	1,400	7

Table 6-XV. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of San Luis Potosí.

1600s to 1806	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	4	2	8 to 16	100	1,700	700

Table 6-XVI. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of San Luis Potosí.

6.1.6 *Caja* of Guadalajara

The silver registered at the *Caja* of Guadalajara came from multiple small and medium refiners, with 46 *Reales de Minas* operating in the mid-1760s.[902] Figure 6-11 shows how the fraction of amalgamated silver varied over the period 1679 to 1816. Amalgamation was the main refining process used, and the tendency to increase its share from approximately 60 % until it became the predominant route to silver is observed even before the price reduction of

[902] Ibid., 90-91.

mercury in the 1770s.[903] The evidence that the price of mercury was not the only factor that influenced the split between amalgamation and smelting also comes from Figure 6-12.

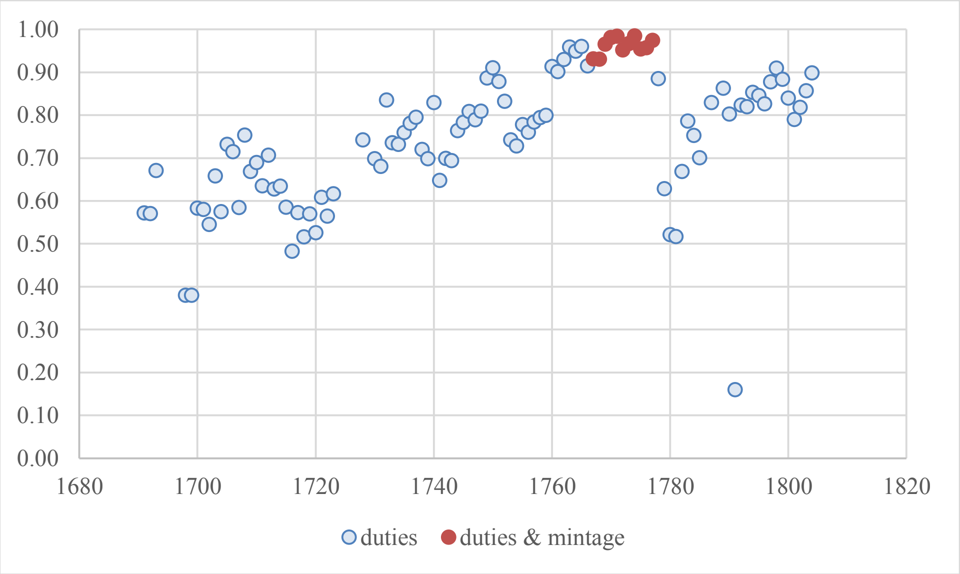

Figure 6-11. The fraction of total silver refined by amalgamation as registered in the *Caja* of Guadalajara in the period 1691 to 1804. Prior to 1699 I have approximated the irregular time series of the raw data in the TK set to their nearest calendar years.

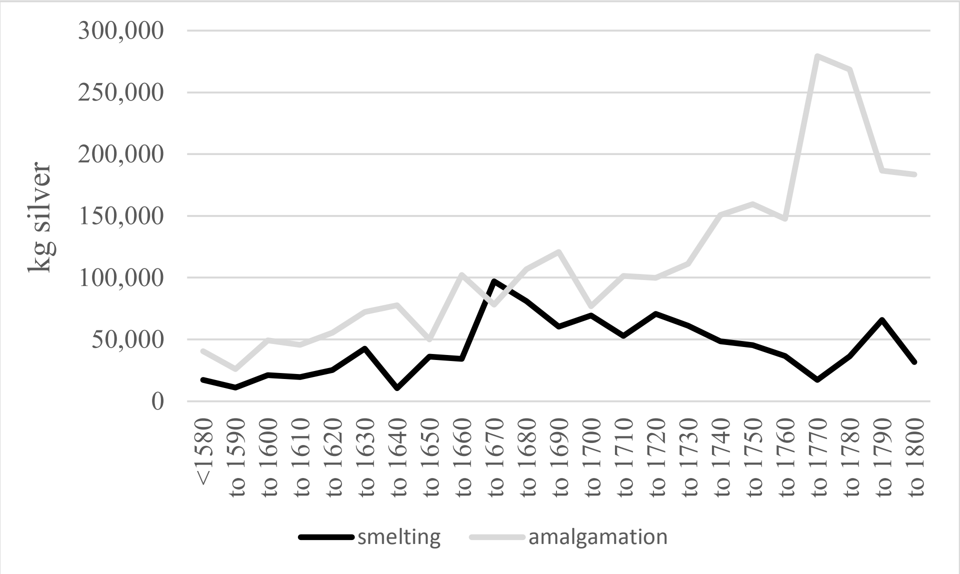

Figure 6-12. Registry of silver at the *Caja* of Guadalajara according to refining process. Data from Table 6-XVII.

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[903] Bakewell reported 26% smelting in the 1730s dropping to 8% by the 1770s. Bakewell, "Colonial Mining," 145.

Prior to the 1760s the balance between the processes had shifted from a close pairing to an evident dominace of amalgamation. This shift was accentuated once inexpensive mercury became available, but as Villaseñor had pointed out, not even free mercury could work miracles. Amalgamation returned to the level it would have reached even without the decrease in the price of mercury. The *Caja* of Guadalajara registered in total 73% of amalgamated silver and 27% of smelted silver.[904]

The amalgamation fraction is calculated directly from the TK data set from 1690 onwards. The average ratio of mercury to silver calculated for this period is 2.1, as shown in Table 6-XVII. To estimate the amalgamation fraction for the earlier periods I apply this ratio to the data from the TK set on sales of mercury from 1611 to 1690. The average projected amalgamation fraction for this period is 0.7. I then apply this fraction to the period where I have no data on mercury sales, 1568 to 1611, to estimate a total amount of silver refined by amalgamation, from where I obtain the deemed quantities of mercury consumed using the average mercury to silver ratio of 2.1.

[904] The total for silver produced and registered at the *Caja* of Guadalajara according to Table 6-XVI is 3.7 million kg, similar to the total of 3.8 million kg in TePaske and Brown, *Gold and Silver*, 116.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	breakdown (kg)			mercury to silver ratio
						as calomel	as liquid mercury	as volatilized mercury	
1568, 1578,1579	57,647	0.7	A	40,353	84,390	71,731	11,815	844	2.1
			S	17,294					
1/1581 to 12/1590, exc. 1585, 1588, 1589	37,100	0.7	A	25,970	54,311	46,165	7,604	543	2.1
			S	11,130					
1/1591 to 3/1601	70,457	0.7	A	49,320	103,143	87,671	14,440	1,031	2.1
			S	21,137					
4/1601 to 3/1611, exc. 1605	65,012	0.7	A	45,508	95,171	80,895	13,324	952	2.1
			S	19,504					
4/1611 to 3/1621	80,698	0.7	A	55,468	115,999	98,599	16,240	1,160	2.1
			S	25,231					
4/1621 to 4/1631	114,861	0.6	A	72,329	151,261	128,572	21,177	1,513	2.1
			S	42,532					
5/1631 to 4/1641	88,119	0.9	A	77,670	162,430	138,066	22,740	1,624	2.1
			S	10,450					
5/1641 to 5/1651	85,969	0.6	A	49,962	104,486	88,813	14,628	1,045	2.1
			S	36,006					
6/1651 to 12/1660	136,504	0.7	A	102,294	213,927	181,838	29,950	2,139	2.1
			S	34,209					
1/1661 to 2/1671	175,092	0.4	A	78,208	163,555	139,022	22,898	1,636	2.1
			S	96,885					
3/1671 to 3/1681	187,842	0.6	A	106,923	223,607	190,066	31,305	2,236	2.1
			S	80,919					
4/1681 to 6/1690	181,195	0.7	A	120,816	252,662	214,762	35,373	2,527	2.1
			S	60,379					
7/1690 to 6/1701 ex mid 1693 to mid 1696	146,283	0.53	A	76,919	144,062	122,453	20,169	1,441	1.9
			S	69,364					
1/1701 to 12/1710	154,299	0.66	A	101,471	177,326	150,727	24,826	1,773	1.7
			S	52,828					
1/1711 to 12/1720	170,740	0.59	A	99,955	195,663	166,313	27,393	1,957	2.0
			S	70,785					
1/1721 to 12/1730	172,303	0.65	A	111,278	249,515	212,087	34,932	2,495	2.2
			S	61,025					
1/1731 to 12/1740	199,184	0.76	A	150,680	298,825	254,001	41,835	2,988	2.0
			S	48,504					
1/1741 to 12/1750	204,671	0.78	A	159,427	307,543	261,412	43,056	3,075	1.9
			S	45,244					
1/1751 to 12/1760	184,246	0.80	A	147,564	356,895	**274,469**	78,857	3,569	2.4
			S	36,682					
1/1761 to 12/1770	296,484	0.94	A	279,318	572,694	486,790	80,177	5,727	2.1
			S	17,166					
1/1771 to 12/1780	304,919	0.88	A	268,537	527,232	448,147	73,812	5,272	2.0
			S	36,382					
1/1781 to 12/1790	252,230	0.74	A	186,589	483,742	**347,055**	131,850	4,837	2.6
			S	65,641					
1/1791 to 12/1800	215,008	0.85	A	183,414	330,124	280,606	46,217	3,301	1.8
			S	31,594					
1801 to 1804	78,527	0.84	A	66,009	167,555	**122,777**	43,103	1,676	2.5
			S	12,518					
total	3,659,392				5,536,120	4,593,040	887,719	55,361	

Table 6-XVII. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the *Caja* of Guadalajara.

1568 to 1804	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
	thousand t						thousand ha
	4	3	80	7	20	1,600	8

Table 6-XVIII. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of Guadalajara.

1568 to 1804	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	4	1	5 to 10	60	1,000	400

Table 6-XIX. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of Guadalajara.

6.1.7 *Caja* of Pachuca

From the start of mining in the region of Pachuca in 1552 until 1667, all its silver production was registered at the nearby *Caja* de Mexico. Its registry corresponds to refining activities concentrated around two main sites, Pachuca and Real del Monte.[905] Figure 6-13

[905] Ibid., 96-98.

shows the evolution in the fraction of amalgamated silver over the period 1679 to 1816. At first sight it indicates an unexpected change to smelting after the price of mercury had decreased.[906]

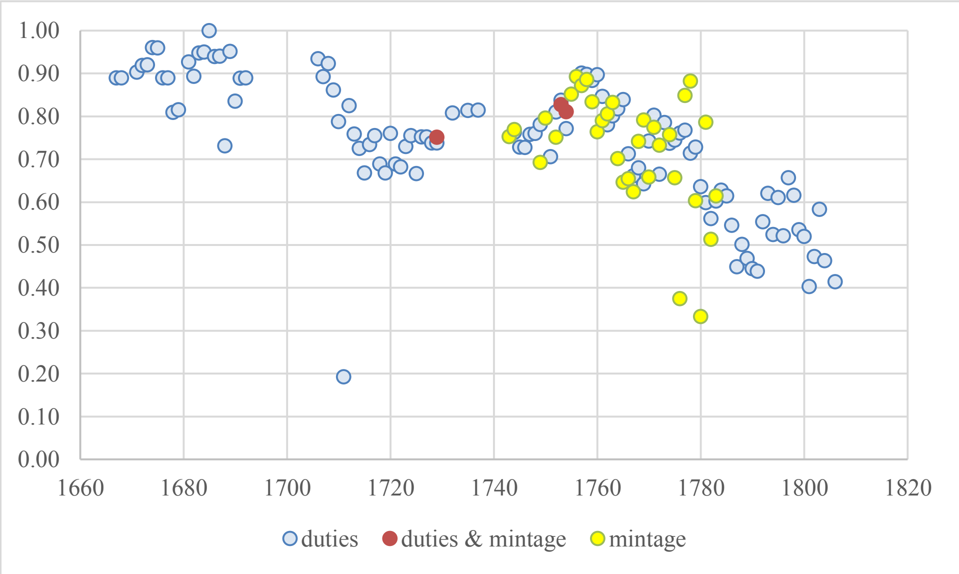

Figure 6-13. The fraction of total silver refined by amalgamation as registered in the *Caja* of Pachuca in the period 1667 to 1820. Prior to 1706 I have approximated the irregular time series of the raw data in the TK set to their nearest calendar years.

The interpretation however is not quite straightforward. As the fraction of amalgamated silver decreases towards the end of the eighteenth century, so did the level of silver production overall (Figure 6-14). In Chapter 4 I mentioned that lead-rich ores were supplied to the first Count of Regla from the mines of Zimapán. One interpretation for Figure 6-13 is that the smelting fraction increased as the availability of the ores for amalgamation decreased, while the overall production of silver declined. This is another example of how the nature of the available ore is more important than the price of mercury. In spite of the impression given by Figure 6-13, the *haciendas* that registered their silver at the *Caja* of Pachuca were mainly

[906] Bakewell reports 27% by of silver produced by smelting in the 1720s, decreasing slightly to 23% by the 1760s. Bakewell, "Colonial Mining," 145. The migration of lead rich ores to the new *Caja* of Zimapan as of the 1730s (see below) may have contributed to the low spike in the amalgamation fraction observed around the 1760s.

amalgamation *haciendas*, supplying 73% of the total silver produced. Smelting would contribute with 27% of the production.

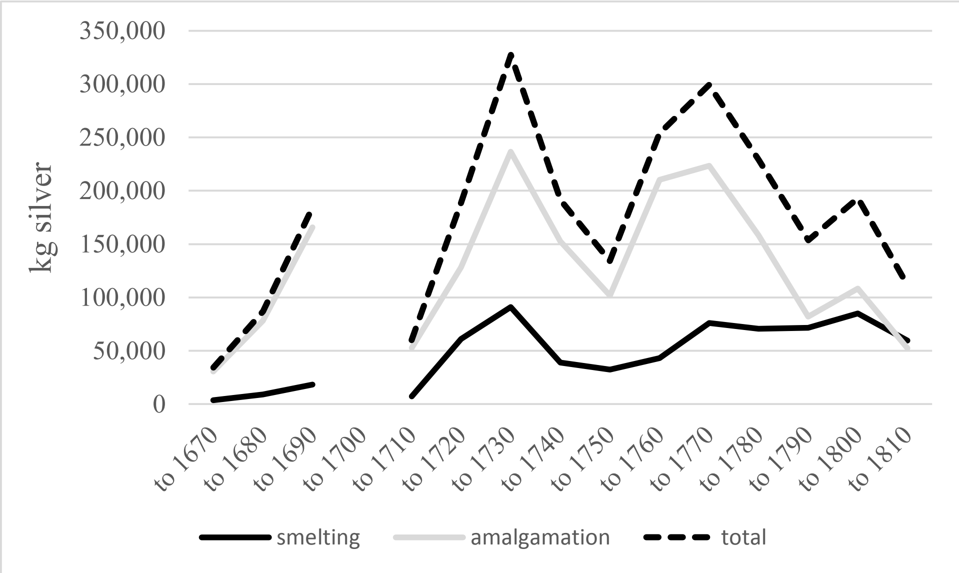

Figure 6-14. Silver registered at the *Caja* of Pachuca. Data from Table 6-XX.

Tables 6-XX to 6-XXII summarize the data and results for the *Caja* of Pachuca. The mercury to silver ratio for the period 1667 to 1806 is 2.[907]

[907] The total of 2.5 million kg of silver produced from 1667 to 1806 corresponds well with the figure of 2.6 million kg in TePaske and Brown, *Gold and Silver*, 132-33.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	breakdown (kg)			mercury to silver ratio
						as calomel	as liquid mercury	as volatilized mercury	
9/1667 to 2/1671	34,341	0.89	A	*30,553*	52,305	*44,460*	*7,323*	*523*	1.7
			S	*3,788*					
3/1671 to 1/1680	87,016	0.90	A	*77,996*	154,706	*131,500*	*21,659*	*1,547*	2.0
			S	*9,020*					
11/1680 to 5/1693	184,106	0.90	A	*165,695*	376,266	*319,826*	*52,677*	*3,763*	2.3
			S	*18,411*					
1/1706 to 12/1710	60,077	0.88	A	*52,859*	85,314	*72,517*	*11,944*	*853*	1.6
			S	*7,218*					
1/1711 to 12/1720	189,289	0.68	A	*128,283*	255,624	*217,281*	*35,787*	*2,556*	2.0
			S	*61,007*					
1/1721 to 12/1730	327,528	0.72	A	*236,640*	479,629	*407,685*	*67,148*	*4,796*	2.0
			S	*90,888*					
1/1731 to 12/1740	191,368	0.80	A	*152,517*	295,395	*251,086*	*41,355*	*2,954*	1.9
			S	*38,851*					
1/1741 to 12/1749	134,187	0.76	A	*101,799*	209,256	*177,868*	*29,296*	*2,093*	2.1
			S	*32,388*					
1/1751 to 12/1760	253,687	0.83	A	*210,418*	341,768	*290,503*	*47,847*	*3,418*	1.6
			S	*43,269*					
1/1761 to 12/1770	299,372	0.75	A	*223,331*	341,426	*290,212*	*47,800*	*3,414*	1.5
			S	*76,040*					
1/1771 to 12/1780	228,999	0.69	A	*158,277*	299,692	*254,738*	*41,957*	*2,997*	1.9
			S	*70,722*					
1/1781 to 12/1790	153,629	0.53	A	*82,008*	279,349	*152,535*	*124,021*	*2,793*	3.4
			S	*71,621*					
1/1791 to 12/1800	193,246	0.56	A	*108,221*	246,137	*209,217*	*34,459*	*2,461*	2.3
			S	*85,025*					
1801 to 1804, 1806	111,808	0.47	A	*52,269*	171,709	*97,221*	*72,771*	*1,717*	3.3
			S	*59,539*					
total	2,448,652				*3,588,578*	*2,916,647*	*636,045*	*35,886*	

Table 6-XX. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the *Caja* of Pachuca.

	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
1667 to 1806	thousand t						thousand ha
	2	2	50	5	12	1,100	5

Table 6-XXI. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of Pachuca.

1667 to 1806	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	2	1	3 to 6	40	700	270

Table 6-XXII. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of Pachuca.

6.1.8 *Caja* of Sombrerete

The *Caja* at Sombrerete was established in 1683, and the silver from its ores had been registered until then at the *Caja* of Zacatecas. The bell-shaped profile of the plot in Figure 6-11 of the fraction of silver amalgamated shows an impressive back and forth between smelting and amalgamation.[908] It is reported that from the 1760s more than 90 % of the registered silver came from local mines of Sombrerete, and most from 'the rich vein of El Pabellón … [which had] a high lead content'.[909] A high lead content in ores rules out amalgamation as the refining method of choice, so it explains the return of smelting after the 1760s irrespective of the price of mercury.

[908] Bakewell reported 68% for silver by smelting in the 1720s, decreasing to 33% by the 1760s, but he did not extend his data to the end of the century and so could not remark on the increase again in smelting fraction. Bakewell, "Colonial Mining," 145. Lacueva indicates that at the end of the seventeenth century smelting was used in the new mines of Sombrerete, where in the period from 1688 to 1699 up to 88% of silver would be produced by smelting of ores. Lacueva Muñoz, *La plata del Rey*, 401.
[909] TePaske and Brown, *Gold and Silver*, 98-99.

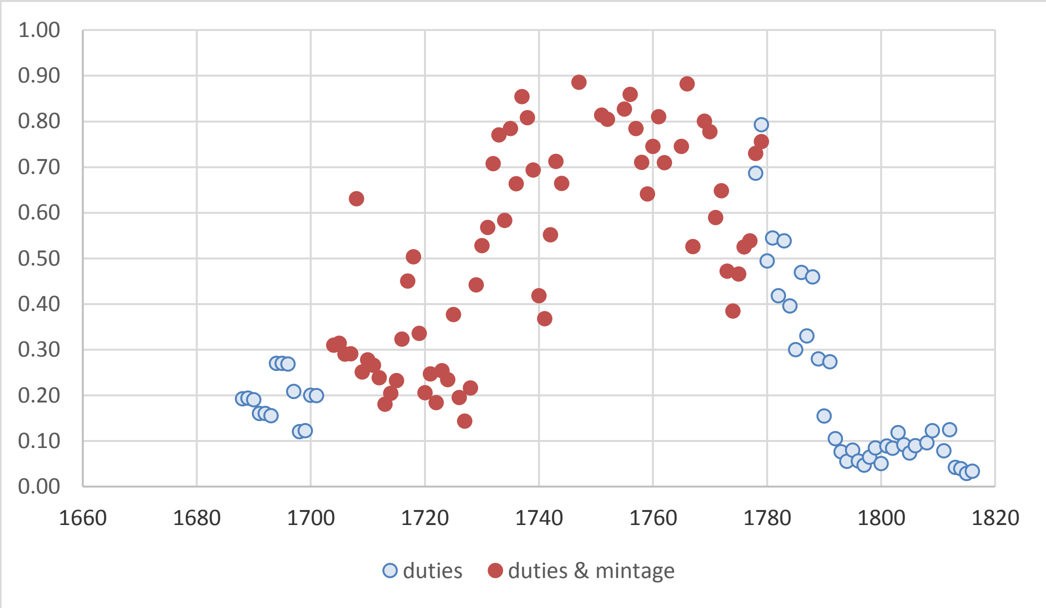

Figure 6-15. The fraction of total silver refined by amalgamation as registered in the *Caja* of Sombrerete in the period 1680 to 1820. Prior to 1760 I have approximated the irregular time series of the raw data in the TK set to their nearest calendar years.

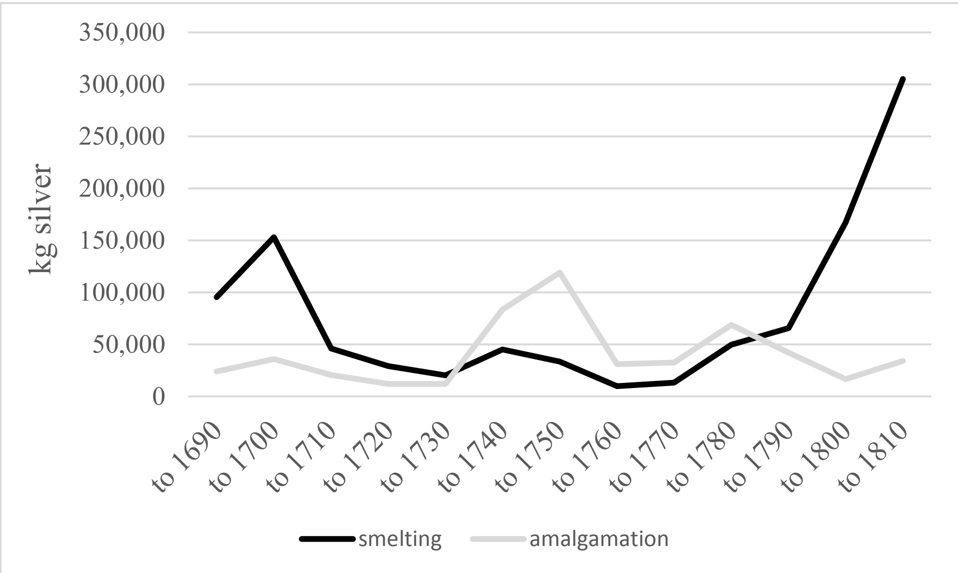

Figure 6-16. Silver registered at the *Caja* of Sombrerete. Data from Table 6-XXIII.

The peak in the amalgamation fraction is observed before the decrease in mercury prices is implemented. The level of smelting on either side is fairly constant (Figure 6-16), so no poaching of ores is taking place. It coincides with a peak in production as well so new ores fit for amalgamation were being fed to the *haciendas*. Existing amalgamation *haciendas* would have profited the most, since no new capital expenditures would have been required. By the end of the eighteenth century production peaked again, but this time on the back of lead-rich ores. TePaske proposed that refiners at Sombrerete switched from amalgamation to smelting when mercury became scarce 'due to disruptions in trans-Atlantic shipping'.[910] It would not have been profitable to attempt to amalgamate ores with a high lead content, even less before the decrease in mercury prices, so I prefer to argue that the bell-shaped profile in Figure 6-11 is caused by major changes in the nature of the ore being refined.

The breakdown of my calculations based on the data in the TK set is presented in Table 6-XXIII.[911] The mercury to silver ratio during this period shows an interesting behaviour. On average it has a value of 2.1, which falls within the expected historical range. However, when calculated by decade it shows an abnormal range after 1780, reaching the value of 9.2 from 1791 to 1800. The average from 1683 to 1780 is 1.6, but from 1781 to 1816 it increases to 4.8, at the same time the amount of silver produced by amalgamation reaches a minimum. This can be interpreted as very inexpensive mercury being used in an inefficient manner to amalgamate lead-rich ores, thus leading to its waste in a non-productive manner from 1780 to 1810. By requiring on average twice the amount of mercury at half the traditional price to produce the same amount of silver, it undercuts the argument that the decrease in mercury prices was beneficial to the Crown revenues as a whole, at least for the *Caja* of Sombrerete during this period.[912] In addition came a concurrent environmental impact, with more liquid mercury being lost while calomel amounts reach their chemical ceiling value (figures in bold).

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[910] Ibid., 99.
[911] The aggregate total of silver produced (1.8 million kg) corresponds well to the total of 1.6 million kg in ibid., 133-34.
[912] It could also be argued that an abnormally high mercury to silver ratio indicates a combination of bad practice and contraband of mercury. Why refiners would suddenly become bad operators after the experience shown in

The *Caja* of Sombrerete was in smelting territory. 68% of the total silver registered at the *Caja* came from smelting *haciendas*, 32% from amalgamation. The magnitudes of the main environmental impact vectors are estimated in Tables XXIII to XXV.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	breakdown (kg)			mercury to silver ratio
						as calomel	as liquid mercury	as volatilized mercury	
5/1683 to 5/1690, exc mid 1684 -mid 1688	119,115	0.2	A	23,823	32,071	27,261	4,490	321	1.3
			S	95,292					
5/1690 to 5/1701	189,032	0.19	A	35,916	74,296	63,151	10,401	743	2.1
			S	153,116					
6/1701 to 3/1711	66,583	0.31	A	20,641	26,411	22,450	3,698	264	1.3
			S	45,942					
4/1711 to 12/1720	40,832	0.29	A	11,841	23,069	19,609	3,230	231	1.9
			S	28,991					
1/1721 to 12/1730	32,122	0.37	A	11,885	21,349	18,147	2,989	213	1.8
			S	20,237					
1/1731 to 12/1740	128,583	0.65	A	83,579	130,547	110,965	18,277	1,305	1.6
			S	45,004					
1/1741 to 12/1750 exc 1747,1748	152,455	0.78	A	118,915	184,837	157,111	25,877	1,848	1.6
			S	33,540					
1/1753 to 12/1760	40,616	0.76	A	30,868	65,535	55,705	9,175	655	2.1
			S	9,748					
1/1761 to 12/1770	45,723	0.71	A	32,464	33,103	28,137	4,634	331	1.0
			S	13,260					
1/1771 to 12/1780	118,356	0.58	A	68,647	61,405	52,194	8,597	614	0.9
			S	49,710					
1/1781 to 12/1790	107,826	0.39	A	42,052	158,534	**78,217**	78,731	1,585	3.8
			S	65,774					
1/1791 to 12/1800	183,605	0.09	A	16,524	151,716	**30,735**	119,463	1,517	9.2
			S	167,081					
1/1801 to 12/1809 exc 1807	339,262	0.10	A	33,926	133,794	**63,103**	69,354	1,338	3.9
			S	305,336					
1/1811 to 12/1816	87,100	0.06	A	5,226	12,567	**10,682**	1,759	126	2.4
			S	81,874					
total	1,651,212				1,109,234	737,467	360,675	11,092	

Table 6-XXIII. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the *Caja* of Sombrerete.

the 1760s with mercury to silver ratios well below 2, or why the least expensive mercury in the history of New Spain would make sense to contraband weaken these alternative explanations.

1683 to 1816	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
	thousand t						thousand ha
	2	1	16	1	4	330	2

Table 6-XXIV. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of Sombrerete.

1683 to 1816	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	2	1	6 to 12	70	1,100	450

Table 6-XXV. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of Sombrerete.

6.1.9 *Caja* of Bolaños

Major mining in the region around Bolaños started in 1747, and the *Caja* was established some six years later. Records are affected by a fifteen year tax exemption on the *diezmo* granted to one of the principal miners of this region as of 1789.[913] The data from the TK sets as plotted in Figure 6-18 show that Bolaños was amalgamation territory even before the price decrease of mercury in the 1760s. Over 94% of all the silver registered in this *Caja* came from amalgamation (Table 6-XXVI). The mercury to silver ratio again shows a step increase that coincides with the decrease in the price of mercury, from 1.9 prior to 1760 to an average of 3.2 from 1761 to 1804, reaching a value of 5.2 in the following decade. A non-

[913] TePaske and Brown, *Gold and Silver*, 101.

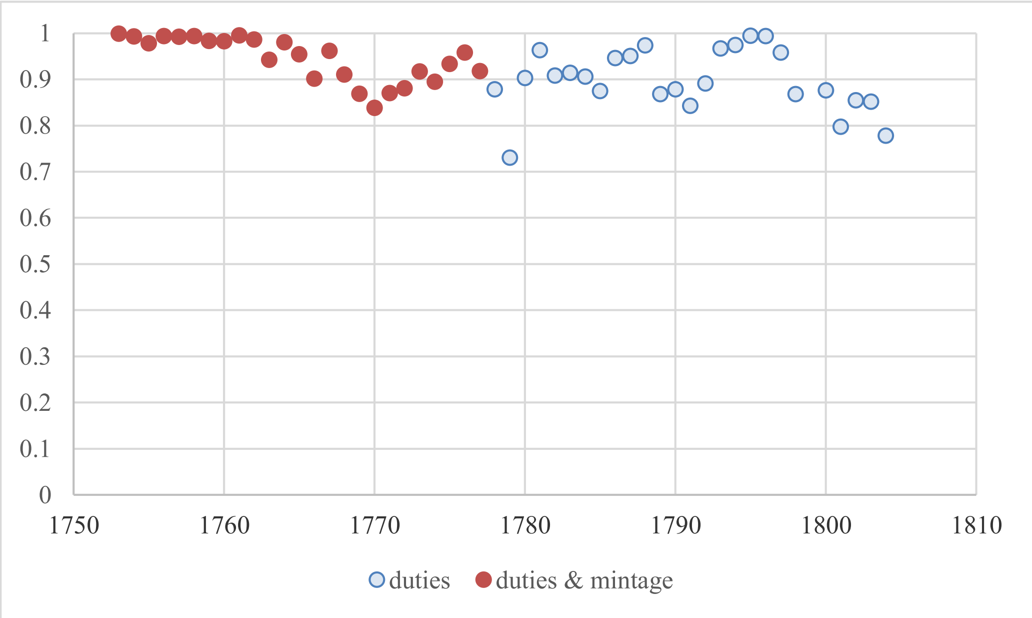

Figure 6-17. The fraction of total silver refined by amalgamation as registered in the *Caja* of Bolaños in the period 1753 to 1804. Raw data from TK set.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	breakdown (kg) as calomel	breakdown (kg) as liquid mercury	breakdown (kg) as volatilized mercury	mercury to silver ratio
1/1753 to 12/1760	460,551	0.99	A	455,770	864,622	*734,929*	*121,047*	*8,646*	1.9
			S	4,781					
1/1761 to 12/1770	166,019	0.93	A	155,080	376,216	***288,449***	*84,005*	*3,762*	2.4
			S	10,939					
1/1771 to 12/1780	214,718	0.89	A	190,762	478,827	***354,817***	*119,222*	*4,788*	2.5
			S	23,957					
1/1781 to 12/1790	218,996	0.92	A	201,123	637,264	***374,089***	*256,802*	*6,373*	3.2
			S	17,873					
1/1791 to 12/1800	108,061	0.93	A	100,453	519,384	***186,843***	*327,347*	*5,194*	5.2
			S	7,607					
1/1801 to 12/1804	10,479	0.82	A	8,598	23,103	***15,993***	*6,879*	*231*	2.7
			S	1,880					
total	1,178,824				2,899,416	*1,955,120*	*915,302*	*28,994*	

Table 6-XXVI. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the *Caja* of Bolaños.

efficient use of inexpensive mercury again implicates a change in the environmental impact of amalgamation (figures in bold).[914]

1753 to 1804	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
	thousand t						thousand ha
	1	1	30	3	8	700	3

Table 6-XXVII. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of Bolaños.

1753 to 1804	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	1	0.1	0.5 to 1	4	70	30

Table 6-XXVIII. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of Bolaños.

6.1.10 *Caja* of Rosario

According to Tepaske the *Caja* of Rosario was set up in 1770, moved to Alamos in 1783 and then to Cosalá around 1807.[915] The records of the TK set are simply identified as Rosario. Figure 6-19 shows smelting maintaining a relatively constant fraction under one third even after the decrease in mercury pricing. Of the total silver registered in this *Caja*, 71% corresponds to amalgamation and 29% to smelting (Table 6-XXIX).[916] Again the mercury to

[914] The total of 1.2 million kg of silver produced from 1753 to 1804, corresponds well with the figure of 1.1 million kg in ibid., 135-36.
[915] Ibid., 103.
[916] The total of 1.1 million kg of silver registered from 1770 to 1809, is virtually the same as the total reported in ibid., 135-36.

silver ratio is higher than the historical range for New Spain in the first two decades just after the price decrease of mercury, but not to the extent of potential waste observed in the previous two *Cajas*. The calomel projection is fixed at its ceiling value (figures in bold) during these decades.

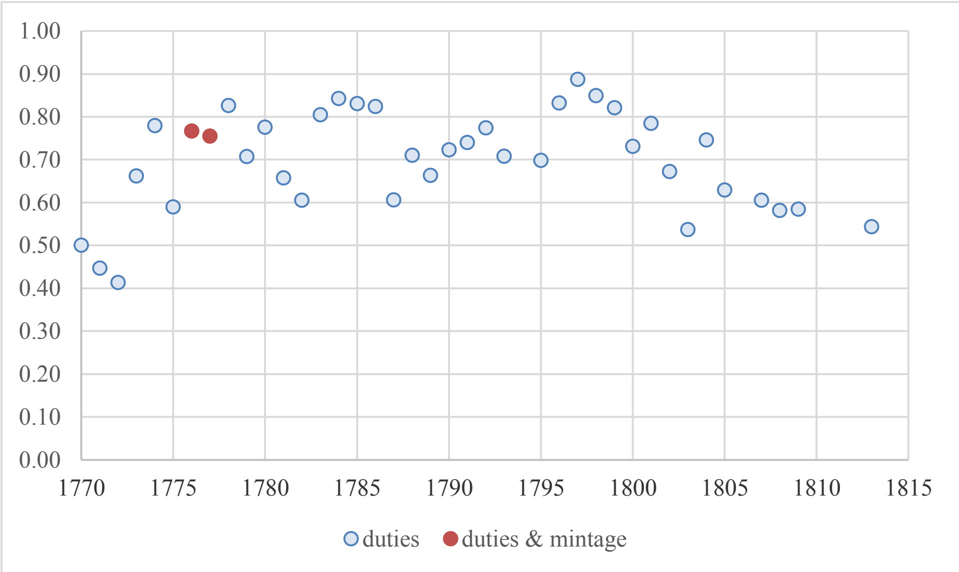

Figure 6-18. The fraction of total silver refined by amalgamation as registered in the *Caja* of Rosario in the period 1770 to 1813. Raw data from TK set.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	mercury losses			mercury to silver weight ratio
						as calomel	as liquid mercury	as volatilized mercury	
1/1770 to 12/1780	87,354	0.66	A	57,654	149,415	***107,236***	*40,685*	*1,494*	2.6
			S	29,700					
1/1781 to 12/1790	268,810	0.73	A	196,231	559,577	***364,990***	*188,991*	*5,596*	2.9
			S	72,579					
1/1791 to 12/1800 exc 1794	373,230	0.78	A	291,119	585,950	*498,057*	*82,033*	*5,859*	2.0
			S	82,111					
1/1801 to 12/1809 exc 1806	360,896	0.64	A	231,756	490,704	*417,099*	*68,699*	*4,907*	2.1
			S	129,141					
total	1,090,290				1,785,646	*1,387,382*	*380,408*	*17,856*	

Table 6-XXIX. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the *Caja* of Rosario.

1770 to 1809	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
	thousand t						thousand ha
	1	1	25	2	5	500	2

Table 6-XXX. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of Rosario.

1770 to 1809	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	1	0.3	2 to 4	20	300	130

Table 6-XXXI. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of Bolaños.

Tables 6-XXX and 6-XXXI provide the ranges of magnitude of the remaining environmental vectors for this *Caja*, reflecting the joint importance of both amalgamation and smelting.

6.1.11 *Caja* of Zimapán.

The silver from Zimapán was initially registered as of the sixteenth century first in the *Caja* of México and then after 1667 in the *Caja* of Pachuca, but in 1729 it was awarded its own *Caja*. Though various mines produced its registered silver, by the 1760 Zimapán contributed

86% of the total with an ore rich in lead.[917] It is the nature of the ore that determines the profile seen in Figure 6-20, a near total absence of amalgamation in the refining of silver at Zimapán.[918]

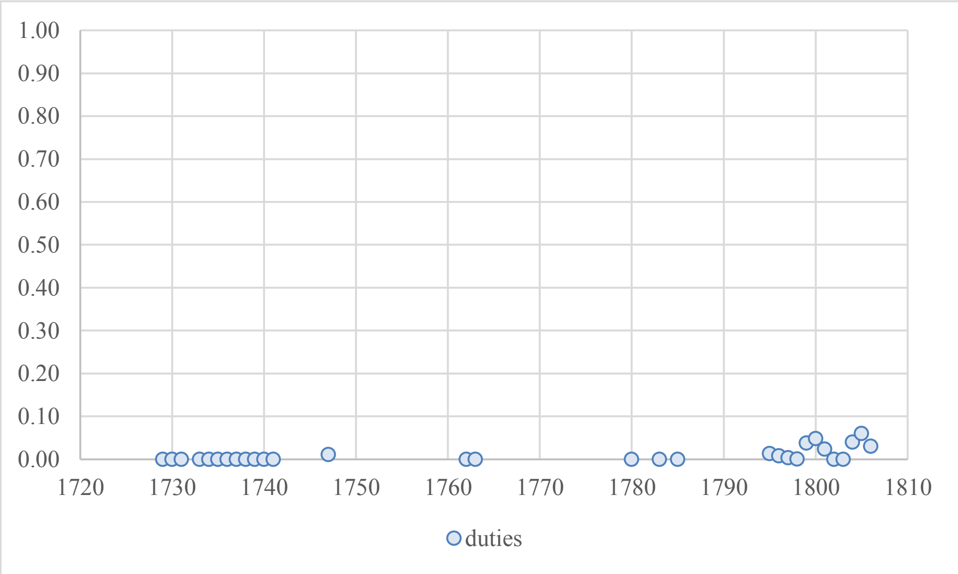

Figure 6-19. The fraction of total silver refined by amalgamation as registered in the *Caja* of Zimapán in the period 1729 to 1806. Raw data from TK set.

For all practical purposes the total production of silver came from smelting (Table 6-XXXII).[919] The only environmental impact vectors correspond to smelting, and their magnitudes are projected in Table 6-XXXIII.

[917] Ibid., 100. There were more than 100 smelting furnaces in Zimapán in 1795 according to Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 62.
[918] Bakewell reported that smelting reached 90+% in the 1720s and 94% in the 1760s. Bakewell, "Colonial Mining," 145.
[919] The total of 0.8 million kg of silver produced from 1729 to 1806, corresponds well with TePaske's figure of 0.9 million kg. TePaske and Brown, *Gold and Silver*, 134-35.

period	total silver kg	fraction amalgamated silver	process	silver produced kg
1/1729 to 12/1740	67,661	0	A	0
			S	67,661
1/1741 to 12/1748	60,545	0	A	0
			S	60,545
1/1752 to 12/1759	71,005	0	A	0
			S	71,005
1/1761 to 12/1770	106,210	0	A	0
			S	106,210
1/1771 to 12/1780	150,355	0	A	0
			S	150,355
1/1781 to 12/1790	125,489	0	A	0
			S	125,489
1/1791 to 12/1800	143,017	0	A	0
			S	143,017
1/1801 to 12/1806	74,912	0.02	A	1,498
			S	73,413
total	799,194			

Table 6-XXXII. Production of silver by smelting as registered in the *Caja* of Zimapán.

1729 to 1806	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	0.8	0.8	4 to 8	50	800	320

Table 6-XXXIII. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of Zimapán.

6.1.12 *Caja* of Chihuahua.

According to TePaske this was the 'last *mining Caja* created in New Spain'.[920] The split between smelting and amalgamation seems impervious to the decrease in mercury prices, most probably due to the lead content of the ores. Santa Eulalia and Santa Barbara, the principal mines feeding the refining *haciendas* that reported to the *Caja* in Chihuahua, are linked to the few known lead bearing deposits of New Spain.[921] It was only in the nineteenth century that the amalgamation fraction increased (Figure 6-21). Overall smelting provide 60% of the silver registered at this *Caja*, and amalgamation the remaining 40% (Table 6-XXXIV).[922] The abnormal range of mercury to silver ratios up to the end of the eighteenth century would indicate a waste of inexpensive mercury due to amalgamating lead-rich ores.[923] As commented for other *Cajas* showing similar ranges, this would have an environmental impact, increasing the amount of mercury physically lost to the environment (numbers in bold).

Tables 6-XXXV and 6-XXXVI complete the estimate of the magnitudes of the main environmental impact vectors derived from the colonial refining activities of silver ores.

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[920] Ibid., 104.
[921] Rice, "Silver-Lead Mines Santa Barbara," 208-209.
[922] There is a gap in the TK set on silver production from 1791 to 1796 which I fill in Table 6-XXXIIV with TePaske's figure of 55,029 kg (figure in italic bold). Including this number, the total for silver in the table is virtually the same as TePaske's total for Chihuahua of 0.24 million kg. TePaske and Brown, *Gold and Silver*, 137.
[923] The data in the TK set have an entry for the calendar year 1790 that indicates the purchase of 114,000 pesos of mercury, approximately 128,000 kg of mercury. This amount of mercury does not correlate with the production level of silver in the previous years, so I have placed it as mercury consumed in the following period.

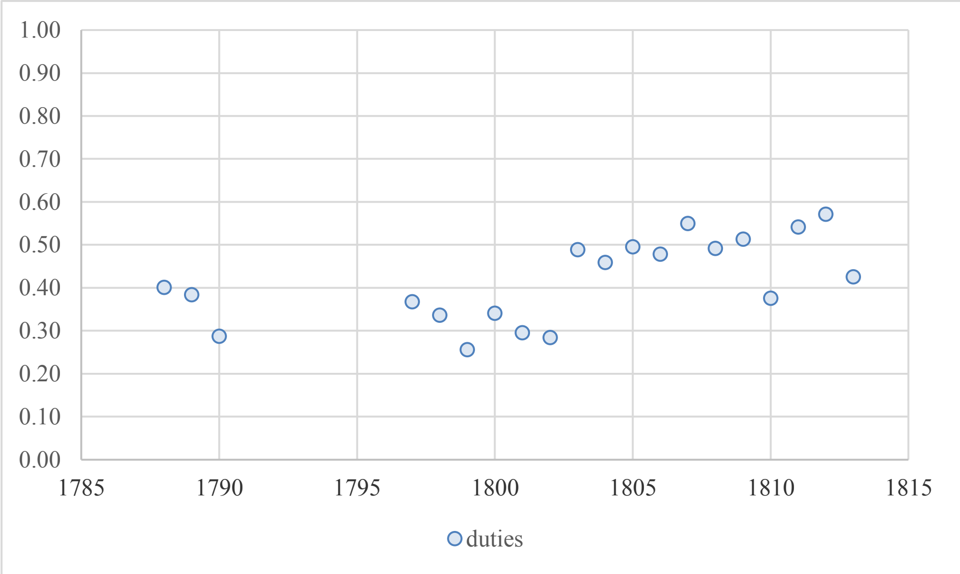

Figure 6-20. The fraction of total silver refined by amalgamation as registered in the *Caja* of Chihuahua in the period 1788 to 1813. Raw data from TK set.

period	total silver kg	fraction amalgamated silver	process	silver produced kg	mercury consumed kg	breakdown (kg)			mercury to silver ratio
						as calomel	as liquid mercury	as volatilized mercury	
1/1785 to 12/1790 exc 1787	32,882	0.36	A	*11,837*	76,709	***22,018***	*53,925*	*767*	*6.5*
			S	*21,044*					
1/1791 to 12/1796	***55,029***	*0.34*	A	*18,710*	*114,000*	***34,800***	*78,060*	*1,140*	*6.1*
			S	*36,319*					
1/1797 to 12/1800	39,496	0.32	A	*12,639*	34,084	***23,508***	*10,235*	*341*	*2.7*
			S	*26,857*					
1/1801 to 12/1810	93,014	0.44	A	*40,926*	129,563	***76,122***	*52,145*	*1,296*	*3.2*
			S	*52,088*					
1/1811 to 12/1814	25,023	0.51	A	*12,762*	20,599	*17,509*	*2,884*	*206*	*1.6*
			S	*12,261*					
total	245,443				374,955	*173,957*	*197,248*	*3,750*	

Table 6-XXXIV. Magnitude of the environmental impact vectors for calomel, liquid mercury and volatile mercury, corresponding to the silver obtained by amalgamation and registered in the *Caja* of Chihuaha.

1785 to 1814	total silver produced	by amalgamation	salt consumed	copper sulphate consumed	equivalent charcoal consumed	mineral waste	woodland consumed
	thousand t						thousand ha
	0.2	0.10	3	0	1	60	0

Table 6-XXXV. Projected magnitude of other main environmental impact vectors corresponding to the silver obtained by amalgamation and registered in the *Caja* of Chihuahua.

1785 to 1814	total silver produced	by smelting	volatile lead loss	slag waste	charcoal consumed	woodland consumed
	thousand t					thousand ha
	0.2	0.15	1 to 2	10	150	60

Table 6-XXXVI. Projected magnitude of the main environmental impact vectors corresponding to the silver obtained by smelting and registered in the *Caja* of Chihuahua.

6.1.13 Aggregate totals for New Spain

Table 6-XXXVII gives a summary of all the magnitudes calculated for the *Cajas* of New Spain analyzed in the previous sections. The first important conclusion is that amalgamation accounted for approximately 64% of the silver produced in New Spain, and smelting 36%. It coincides with the report in the historiography that in 1777 the *Administrador General de Minas* reported that 40% of all production was by smelting.[924] It also shows a much

[924] As quoted in Mervyn F. Lang, "Amalgamacion y fundicion en la mineria americana.," in *Estudios de historia de las técnicas, la arqueología industrial y las Ciencias*, ed. Juan Luis García Hourcade, Juan M. Moreno Yuste, and Gloria Ruiz Hernández(Salamanca: Juanta de Castilla y Leon, 1998), 674. Up to the eighteenth century at least half of the silver ores mined in Honduras were smelted. Newson, "Silver Mining Honduras," 52.

more balanced distribution between amalgamation and smelting output than what at times has been reported in the

	total silver amalgamation	total calomel	total liquid mercury	total volatile mercury	total salt	total copper sulphate	total woodland	total mineral waste	total silver smelted	total volatile lead	total slag waste	total woodland
Zacatecas	7	11	2	0.1	200	17	20	4,000	3	15 to 30	160	1,300
Guanajuato	6	9	1	0.1	170	15	17	3,600	2	12 to 24	140	900
Mexico	6	10	2	0.1	190	16	19	3,900	2	12 to 24	140	950
Durango	2	4	1	0.05	70	6	7	1,500	4	18 to 36	220	1,500
San Luis Potosí	2	2	0.3	0.02	70	-	7	1,400	2	8 to 16	100	700
Guadalajara	3	5	1	0.06	80	7	8	1,600	1	5 to 10	60	400
Pachuca	2	3	1	0.04	50	5	5	1,100	1	3 to 6	40	270
Sombrerete	0.5	1	0.4	0.01	16	1	2	330	1	6 to 12	70	450
Bolaños	1	2	1	0.03	30	3	3	700	0.1	0.5 to 1	4	30
Rosario	1	1	0.4	0.02	25	2	2	500	0.3	2 to 4	20	130
Zimapán	0	0	0	0	0	0	0	0	0.8	4 to 8	50	320
Chihuahua	0.1	0.2	0.2	0	3	0	0	60	0.1	1 to 2	10	60
total New Spain	31	47	10	1	904	72	90	18,690	17	90 to 180	1,014	7,010

Table 6-XXXVII. Summary of main magnitudes projected for each of the main mining Cajas of New Spain. Woodland figures expressed in units of a thousand ha, all the others in units of a thousand t.

historiography.[925] Three stages can be discerned in Figure 6-21. The data for the initial period up to the 1640s are the one most subject to extrapolations of all, and probably overestimates the importance of amalgamation (see discussion for each *Caja* above). In any case it was

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[925] An extreme case is the claim that 95% of all silver was produced by amalgamation. Castillo Martos, "Alquimia en la metalurgia de plata y oro en Europa y America " xxiv. Humboldt estimated that the overall ratio of amalgamated silver to smelted silver was 3.5 to 1. In the period around the beginning of the nineteenth century, he estimated that smelting produced 10% of the total silver, and amalgamation (patio, *cazo* and barrel) the remaining 90%. Humboldt, *Essai politique*, Tome IV, 49-50, 106. Modern historians have based their estimate of the split between amalgamation and smelting on calculations using a deemed *correspondencia* value and the total amount of mercury imported into New Spain. Brading and Cross used a *correspondencia* value of 110 marks per *quintal* to arrive at a range between 70% and 87% for amalgamation. Brading and Cross, "Colonial Silver Mining: Mexico and Peru," 570, 579. Garner estimated a range between 80% to 90 % amalgamation, based on a *correspondencia* of 100 marks per *quintal*. Garner, "Long-Term Silver Mining," 918. Mendizabal proposed that amalgamation accounted for 75% of all the silver produced in New Spain, without specifying his source. Mendizábal, *La mineria mexicana*, 71-73.

characterized by a very lenient policy on the payment of mercury supplied to the refiners, together with a source of tailings with a sunken cost that could be amalgamated. Both factors can explain the peak in the amalgamated fraction of total silver production. From mid seventeenth to mid eighteenth century the stricter policy on the supply of mercury levels the playing field between amalgamation and smelting to the point both share equally the production of silver in New Spain. It reflects the more natural balance between the two refining processes based on the nature of ores available, with the bias on the part of the Crown towards amalgamation somewhat muted. During this period ores with a silver content below 0.08% continue to be discarded but make up an important part of the ore extracted from the mines (see discussion in section 5.2, above). Starting in the 1740s according to Dobado and Marrero the supply of mercury from Almadén increases, which would allow refiners to process an increase in the ore being extracted.[926]

Amalgamation now shows a tendency to account for more than half of silver production, a divergence of curves that becomes more significant once the step decreases in the price of mercury are implemented in 1767 and 1776. The steep rise in silver production by amalgamation in the latter part of the eighteenth century brings to mind the same drastic increase seen in Potosí in the 1570s, and one possible cause is not only a sudden increase in ore extraction but also the incorporation of tailings that could now be refined at a profit, due to the low price of mercury and because their sunken cost of extraction was now nil, cutting their amalgamation cost by more than half. Under these conditions it would have been impossible for smelting to compete for the refining of these ores.

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[926] Dobado and Marrero, "The Role of the Spanish Imperial State in the Mining-led Growth of Bourbon Mexico's Economy," 867. There is an element of chicken and egg in the arguments presented. Supply volume of mercury by itself without a decrease in price does not induce an increase in silver production unless an increase has also taken place in the amount of ore suitable for amalgamation at the prevalent pricing of mercury.

The downward price movements of mercury influenced the slope of the amalgamation profile but not that of smelting. This reinforces the argument that it was the nature of the ore, and not the price of mercury, that determined the choice of refining method. The reduction in price of mercury did increase the amount of ore that could be processed at a profit in an amalgamation *hacienda*, thus the increase observed after the 1760s. Thus each refining process continued to be profitable with the ores available, and only the quantity available to each process varied. No switching of ores or infrastructure is involved in a major way. There are signs though that cheaper mercury was wasted in refining lead-rich ores in some *Cajas*.

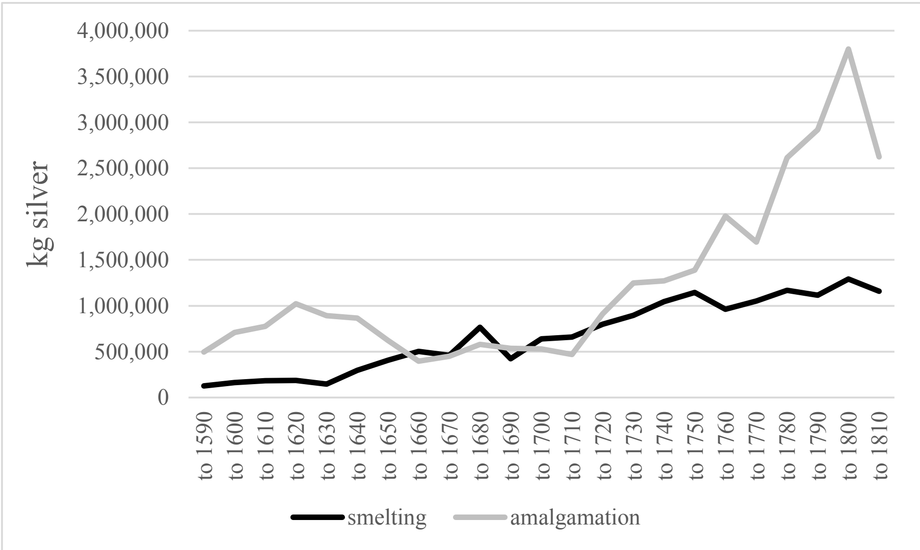

Figure 6-21. Registry of silver by process, as projected for New Spain.

With regard to the magnitude of the main environmental impact vectors, I will report total amounts over the colonial period rather than a single yearly average, since as seen for each *Caja*, silver production is irregular and weighed towards the last 100 years of the colonial period. Because the amalgamation/smelting split also varied with time the total amount cannot be pro-rated according to the silver production by century. The total mineral waste voided into waterways is the dominant value, with nearly 19 million t. In terms of weight, the major chemical that was washed into waterways was salt, with an order of magnitude of 1 million t. The remaining environmental impact vectors on water basins are an order of magnitude smaller. The copper sulphate consumed, which would be washed away as copper ions or copper salts, is projected as being greater (72 thousand t) than the water-insoluble calomel (47 thousand t). Liquid mercury, whether in the soil or washed away, is projected at 10 thousand t.

In the air it is lead as metallic lead or in lead compounds that dominates, with a range between 90 and 180 thousand t. Volatile mercury would have accounted for around one thousand tons over this whole period. Finally the impact on woodland is greatest for smelting, with a maximum of 7 million ha of woodland consumed if no natural regeneration is factored in, some 80 times greater than the requirements for amalgamation during the same period.

In Table 6-XXXVIII I present the amalgamation / smelting breakdown based on silver produced for each *Caja.*[927] Since the *haciendas* reporting to each *Caja* varied with time this is only a snapshot of the average over the whole period, with overlap of regions over the whole colonial period as new *Cajas* were hived off from existing ones. In order to visualize the geographical distribution of the two refining processes I adopt Figure 6-1 as an approximation to the whole colonial period and have shaded in Figure 6-22 the different territories of the *Cajas* according to which refining process dominated their production: black for smelting (San Luis Potosí (except for Catorce), Durango, Sombrerete and Zimapán, and Chihuahua is not shown in the map), and grey where amalgamation predominated (Zacatecas, Guanjuato, Mexico, Pachuca, Guadalajara, Bolaños and the district of Catorce in San Luis Potosi). The magnitude of the environmental impact vectors due to smelting could however be greater even in regions

[927] As a crosscheck, the total in Table XXXVII is rounded off to 48 thousand t, compared to 49.1 thousand t reported in TePaske and Brown, *Gold and Silver*, 116.

nominally dominated by amalgamation, subject to the total amount of silver being produced by both methods.

Caja	silver by amalgamation t	silver by smelting t	% amalgamation	% smelting
Zacatecas	6,522	3,262	67%	33%
Guanajuato	5,895	2,322	72%	28%
Mexico	6,346	2,357	73%	27%
Durango	2,382	3,677	39%	61%
San Luis Potosí	2,249	1,697	57%	43%
Guadalajara	2,656	1,003	73%	27%
Pachuca	1,781	668	73%	27%
Sombrerete	536	1,115	32%	68%
Bolaños	1,112	67	94%	6%
Rosario	777	314	71%	29%
Zimapán	0	799	0%	100%
Chihuahua	97	149	39%	61%
total New Spain	30,353	17,429	64%	36%

Table 6-XXXVIII. Amalgamation and smelting by *Caja* over the whole colonial period in New Spain. Source data from Table 6-XXXVII.

This is clear in the series shown in Figures 6-23 and 6-24 where I plot the magnitude of the environmental impact vectors corresponding to smelting. While Durango remains the area that would have been most affected by the environmental impact of smelting, it is closely followed by areas where amalgamation predominated, such as Zacatecas, Mexico and Guanajuato. With regard to the impact of amalgamation by region, it follows more closely the ranking of *Cajas* where amalgamation dominated, as illustrated in Figures 6-25 to 6-28. All these are average representations over the whole period, and according to the *Caja* could have changed substantially during smaller historical spans.

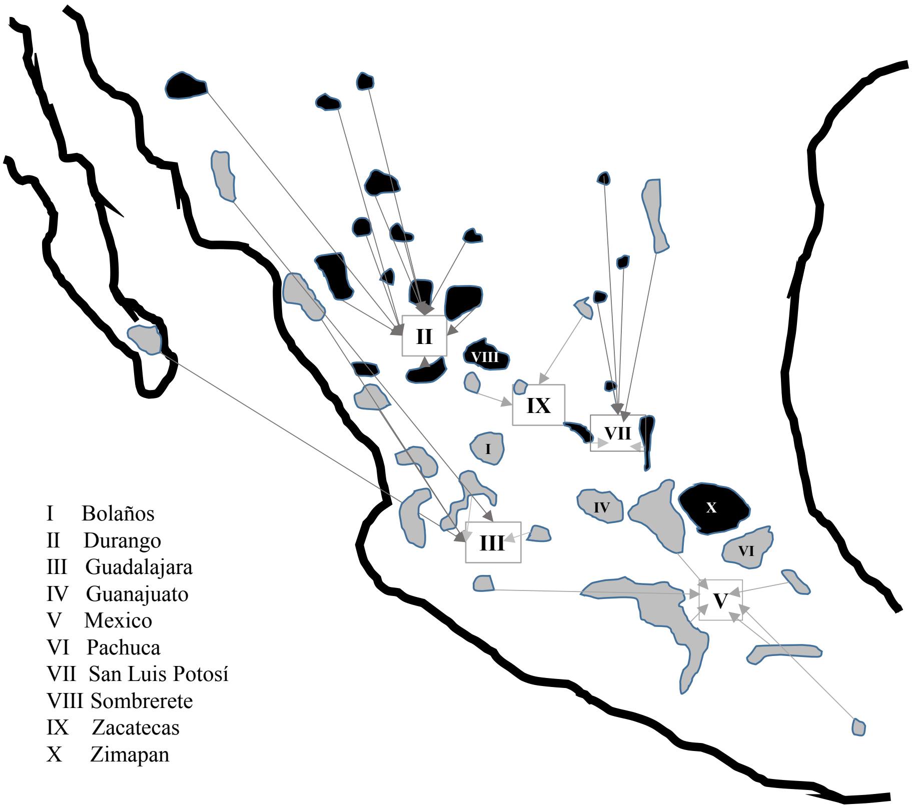

Figure 6-22. Approximate geographical distribution of main refining processes applied in the *Cajas* of New Spain. Black: smelting, Grey: amalgamation. Adapted from Figure 6.1.

To carry the regional environmental analysis forward on a more detailed basis will require incorporating data on waterways and water basins, historical landfills, wind roses and geographical contours, relative distribution of refining *haciendas* by location, size and refining process, population centres, agricultural centres and cattle rearing, woodlands used to source fuel, regeneration rates for the local woodland, transit routes to and within each region. In addition a detailed knowledge on the changes in the architectural details of the refining *haciendas* of each region over time is required, so as to be able to model the deposition of lead around each establishment.[928]

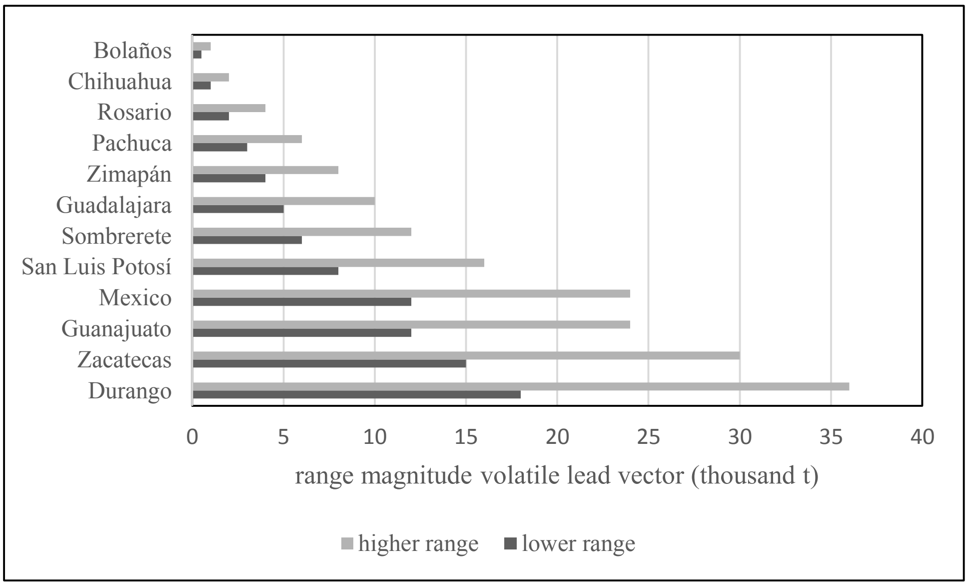

Figure 6-23. Listing of *Cajas* by the magnitude of the vector corresponding to lead and lead compounds. Data from table 6-XXXVIII

[928] In chapter 2 I made reference to the regional studies identifying primary economic functions carried out by Prof. Salazar in the region around the town of San Luis Potosí. Another study has centred on determining the role of 'mining as a creator of economic spaces due to its great organizing power' - '*mineria como creador de espacios económicos por su gran poder organizador*'. The authors draw up maps of geographical networks that grew around the mining and refining activities in Pachuca and Real del Monte in the nineteenth century. Saavedra Silva and Sánchez Salazar, "Espacio Pachuca-Real del Monte," 83-97. Each cluster of refining *haciendas* creates by their sole presence a source of an economic force field, attracting by its needs the other economic activities that grew out of refining. Overlaid on this economic 'gravitational' contour map would lie the vectors of environmental impact due initially to the original refining of silver and then to the growth of other economic activity.

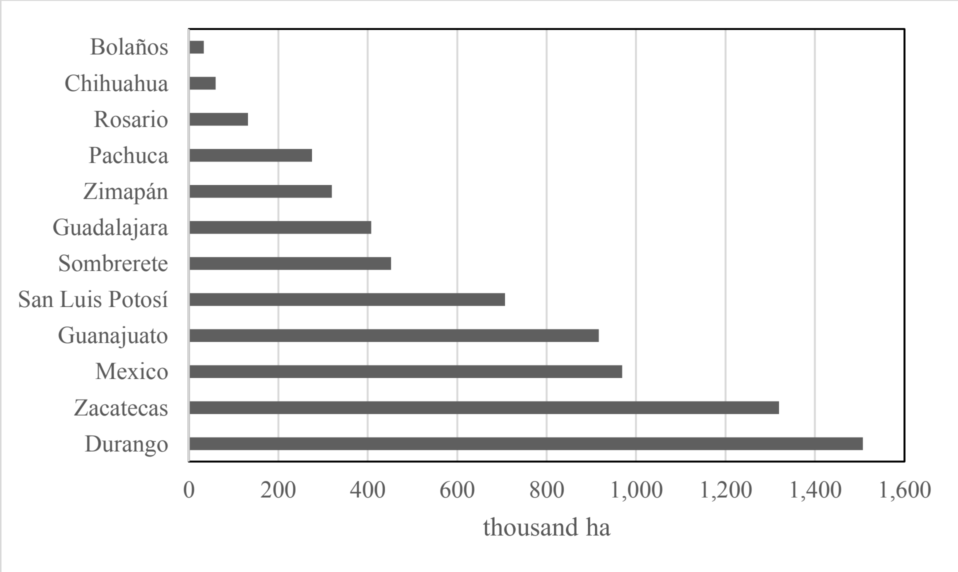

Figure 6-24. Woodland consumed by smelting and amalgamation according to *Caja*. Data from Table 6- XXXVIII.

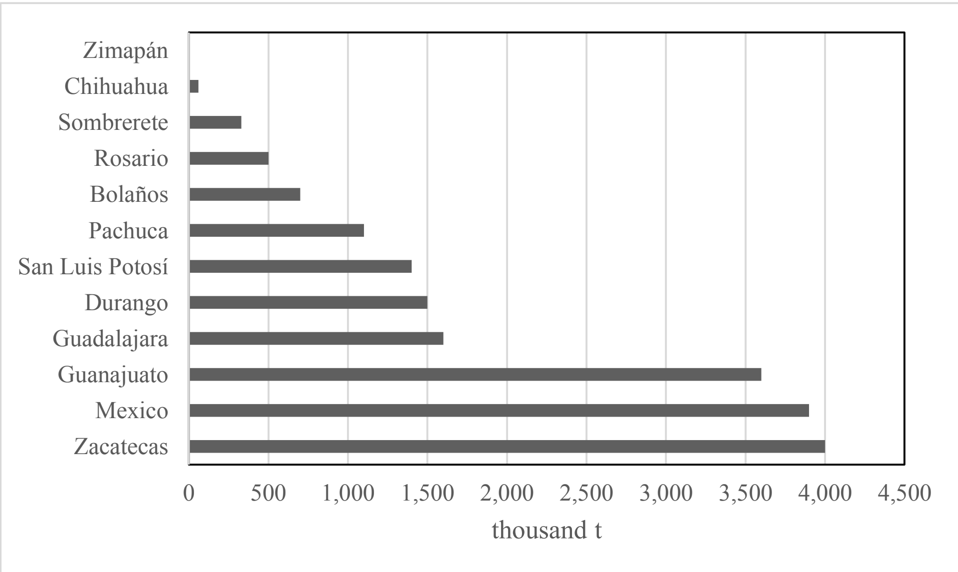

Figure 6-25. Ranking of *Cajas* according to the magnitude of the environmental impact vector of mineral waste voided into waterways. Data from Table 6-XXXVIII.

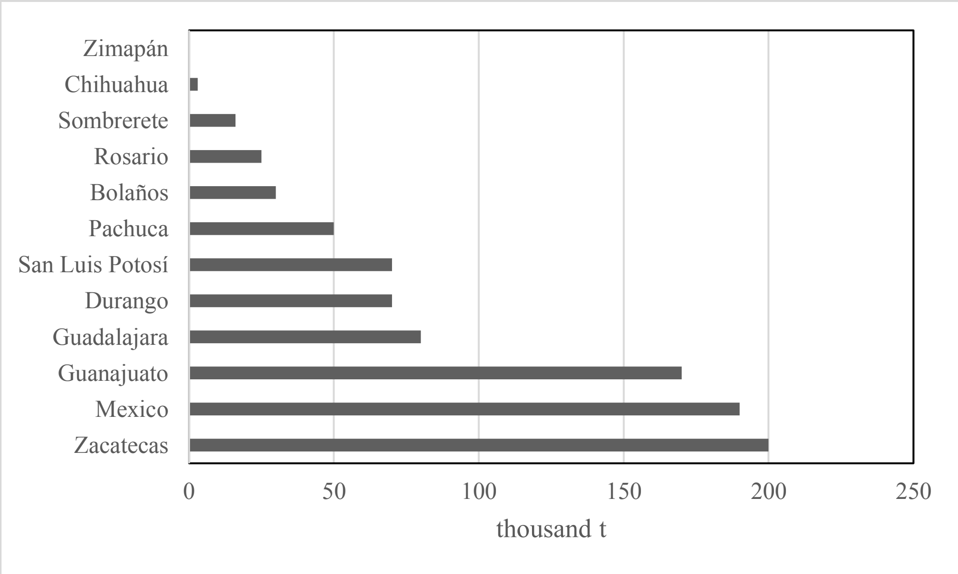

Figure 6-26. Ranking of *Cajas* according to the magnitude of the environmental impact vector of salt voided into waterways. Data from Table 6-XXXVIII.

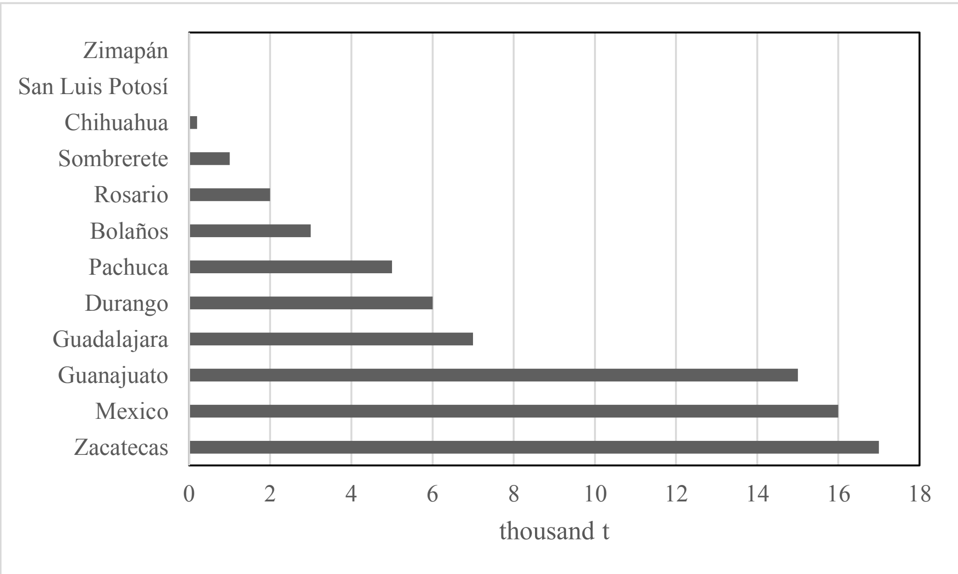

Figure 6-27. Ranking of *Cajas* according to the magnitude of the environmental impact vector of copper sulphate consumed and voided into waterways. Data from Table 6-XXXVIII.

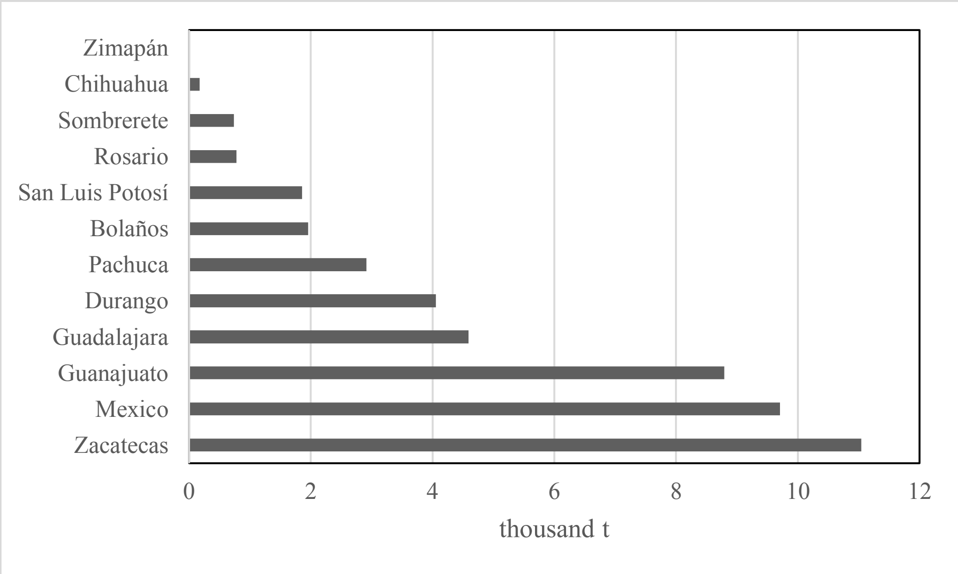

Figure 6-28. Ranking of *Cajas* according to the magnitude of the environmental impact vector of calomel voided into waterways. Data from Table 6-XXXVIII.

6.1.14 Aggregate totals for Mexico, 1820 to 1900

Unfortunately the data that quantify silver production according to refining process is limited in the period it covers (fiscal years beginning 1877 to 1896), contains evident errors in its figures for smelting as of 1893, and the yearly totals calculated from its data are between 20% to 40% less than the yearly data in Table 6-XXXIX. Bearing this in mind, Figure 6-29 plots the percentage of amalgamation and smelting registered for a period when barrel amalgamation and leaching (*lixiviación*) were also being applied.[929] The latter reaches a peak fraction of 0.18 in the fiscal years 1891 and 1892, but by 1896 the total silver registered has decreased to 36,995 kg from its peak at 203,932 kg. The average fraction of silver produced by barrel amalgamation in this period is 0.04.[930]

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[929] The leaching process mentioned in the statistics does not refer to cyanide leaching but to the earlier processes, such as the hyposulphite process included in Collins, *Metallurgy of Lead & Silver*, 186-241.

[930] Flores Clair, Velasco Avila, and Ramírez Bautista, Estadísticas mineras, II, 161-62. Laur and Duport estimated that smelting produced 10% of silver in Mexico, though Laur cautioned that 'it is however not possible to establish

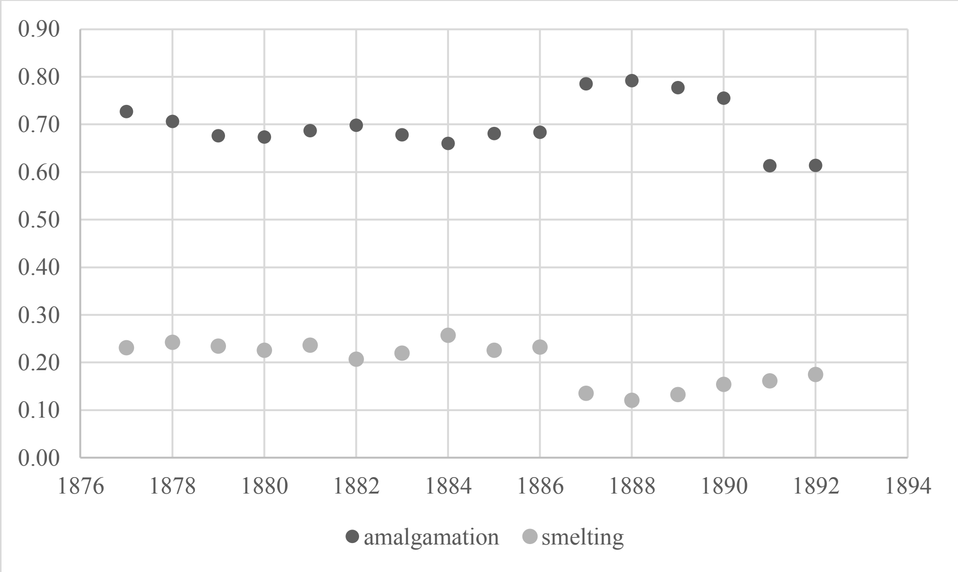

Figure 6-29. Amalgamation and smelting fraction of silver presented at the Mexican mints, 1876 to 1892. Raw data from footnote 900.

In Table XXXIV I present a projection of the magnitudes of the main environmental impact vectors for the whole of Mexico during the nineteenth century, subject to the limitations in each of the data sets signalled in the previous paragraphs. In the absence of mercury consumption data I have assumed an average mercury to silver ratio of 1.8. The other ratios per kg of silver are the same as applied to colonial New Spain. I present the data in such a manner the projected breakdown of the magnitudes of the environmental impact vectors can be adjusted in the future as better figures comes to light on a regional basis.

with certitude their relative importance' - '*il n'est cependant pas possible d'établir, avec certitude, leur importance relative*'.Laur, "De la metallurgie de l'argent au Mexique," 106. ; Duport, *Métaux précieux au Mexique*, 86.

period	total silver produced	amalgamation		mercury consumed	calomel	liquid mercury	volatile mercury	salt	copper sulphate	mineral waste	woodland
		fraction	kg	thousand t							thousand ha
1821 - 1830	2,648,400	*0.75*	*1,986,300*								
1831 - 1840	3,309,900	*0.75*	*2,482,425*								
1841 - 1850	4,203,100	*0.75*	*3,152,325*								
1851 - 1860	4,569,500	*0.75*	*3,427,125*								
1861 - 1870	4,969,500	*0.75*	*3,727,125*								
1871 - 1880	6,317,362	*0.75*	*4,738,022*								
1881 - 1890	9,116,860	0.7	6,381,802								
1891 - 1899	13,796,861	*0.7*	*9,657,803*								
1821-1899			*35,552,926*	*64*	*30*	*5*	*0.4*	*1,100*	*90*	*22,000*	*100*

period	total silver produced	smelting		volatile lead	slag	woodland
		fraction	kg	thousand t		thousand ha
1821 - 1830	2,648,400	*0.25*	*662,100*			
1831 - 1840	3,309,900	*0.25*	*827,475*			
1841 - 1850	4,203,100	*0.25*	*1,050,775*			
1851 - 1860	4,569,500	*0.25*	*1,142,375*			
1861 - 1870	4,969,500	*0.25*	*1,242,375*			
1871 - 1880	6,317,362	*0.2*	*1,263,472*			
1881 - 1890	9,116,860	0.2	1,823,372			
1891 - 1899	13,796,861	*0.2*	*2,759,372*			
1821 - 1899			*10,771,317*	*50 to 100*	*700*	*4,300*

Table 6-XXXIX. Projected magnitudes of main environmental impact vectors for amalgamation and smelting in Mexico, 1821 to 1899.

6.1.15 Environmental impact vectors, sixteenth to nineteenth century: conclusions.

Since at present there is no regional breakdown for the data corresponding to republican Mexico in the nineteenth century I will limit the following discussion to a comparison of the projected aggregate totals for this period compared to those for New Spain (Table 6-XL). The amount of silver produced in Mexico during the nineteenth century was approximately equal to all the silver produced in the colonial period, and most of this production took place between 1850 and 1900. Thus the yearly environmental impact imposed upon the refining regions in Mexico from amalgamation and smelting processes was mostly compressed into a period of

	total silver amalgamation	total mercury in calomel	total liquid mercury	total volatile mercury	total salt	total copper sulphate	total woodland	total mineral waste	total silver smelted	total volatile lead	total slag waste	total woodland
New Spain	31	47	10	1	900	70	90	19,000	20	90 to 180	1,000	7,000
Mexico	36	54	9	1	1,000	90	100	22,000	11	50 to 100	700	4,300

Table 6-XL. Total magnitude of environmental impact vectors from amalgamation and smelting as projected for New Spain and Mexico. All numbers have been rounded off, and expressed in thousand t except for woodland which is in thousand ha.

approximately 50 years. In the case of New Spain the span is greater on average but can vary substantially with each *Caja* since production was never homogeneous over time nor, as discussed, limited to one major process during the whole period. Bearing these conditions in mind, the following observations can be made:

a, Due to the lower incidence of smelting and an increased efficiency of the furnaces, 60% less woodland was consumed as a result of smelting and about half the levels of emissions of lead and lead compounds are projected to have been reached in the nineteenth century compared to the whole colonial period, even though the total silver production levels in both cases were similar. These lower levels of emissions would have counterbalanced in part the effect of the shorter time period in which they took place, to produce lower yearly quantities than expected had the same context persisted from the colonial era.

b. The levels of salt, copper sulphate, calomel, liquid mercury, waste minerals voided into the waterways and woodland consumed for amalgamation are higher for Mexico than New Spain, reflecting the higher level of amalgamated silver. The stress on the environment of Mexico from these vectors during the nineteenth century would have been on average up to five times greater than in colonial New Spain.

c. Lead (and its compounds) is projected as having been the main heavy metal issued to the air as a result of the refining of silver in both periods, with a ratio of lead to volatilized mercury estimated at an average of approximately 100 to 1. Even if all the consumption of mercury had been by the short-term physical loss to the air (an assumption negated by the arguments presented in previous sections), lead would still have been as important as mercury in any analysis of the environmental impact of heavy metals as a result of historical silver refining. Since calomel is the main cause for the consumption of mercury during patio amalgamation, emissions to the atmosphere of lead and its compounds constitute the main source of heavy metals issued to the air during the historical refining of silver ores in New Spain. This conclusion holds valid even if amalgamation were to have produced 90% of all the silver of the colonial period, a percentage negated by the data from the individual *Cajas*.

d. To what extent the losses of calomel and liquid mercury would ultimately end up contributing to air emissions of mercury over decades and centuries remains to be determined. Until the whole life cycle of calomel in waterways, river beds and landfills is established, its effect as mercury source to the environment in the long term is unknown.[931]

e. Overall, smelting created a much higher level of pressure on the human communities of New Spain than amalgamation, due to woodland depletion and to the large amount of heavy metal (lead and its compounds) deposited in the areas around each smelting *hacienda*. To this should be added the pollution due to the dressing of the ores using water, and the fact that its potential as a household industry would have been a major source of toxic fumes to the local community. Amalgamation on the other hand shows a more attenuated environmental impact

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[931] Calomel is a mercury compound that has not been studied regarding its life-cycle in aquatic environments, or its impact on organisms at different levels of concentration. What is reported in the historiography on calomel is very limited: it has been used as a diuretic, a laxative, a means to increase the rosiness of the cheeks of babies and as a topical disinfectant.

profile. Calomel in the short term would have trapped most of the mercury consumed into a non-soluble solid entombed within tons of fine mineral silt. In the long-term no conclusion can be made as yet. The remaining 15% lost as liquid mercury to the ground and water is still an important fraction, but in absolute terms it was lower than the loss of lead as metallic lead or in lead compounds for the same amount of silver refined. Amalgamation required much less fuel (except for the minority barrel or *cazo* processes) than smelting, and its impact on woodland some 60 times lower per kg of silver produced. Fine mineral silt was its main waste in terms of weight to the environment, then salt, both intrusions on the environment but of another class to losses of lead and lead compounds or to the decimation of woodlands. Amalgamation was the lesser of the two evils.

In relative terms, was the overall level of environmental impact similar to other historical industrial processes up to the eighteenth century? There is no historic benchmark for amalgamation, since it was only used at an industrial scale in the New World. In the case of lead from smelting the most relevant comparison is with the level of lead emissions estimated to have taken place during Roman times, when the lead industry reached levels not to be seen again until the modern industrial era. It has been estimated that 5 to 10,000 t/y of lead were lost as air emissions at the peak of its use during Roman times, 10 to 20% of the total peak production of 50,000 t/y.[932] In the case of my projection for New Spain, a conservative range of 90 to 180,000 t of lead has been proposed as being lost over the whole colonial period as air emissions, approximately 5 to 10% of the total lead required for smelting silver ores of 2% silver content (Chapter 2).

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[932] Nriagu, "Tales Told in Lead," 1622-23.

Over the whole of New Spain this would correspond to a range up to 900 t/y of lead. The *Cajas* whose refiners would have exhibited the highest peaks in yearly averages of lead emissions are Durango (1750s) and Zacatecas (1680s) with over 400 t/y, then Guanajuato (1750s) and Sombrerete (1800s) with over 300 t/y, followed by San Luis Potosi with under 200 t/y (1650s and 1790s). For nineteenth-century Mexico it is not possible with the data available to calculate regional peaks. Overall, an average of at least 1,200 t/y of lead would have been reached in republican Mexico, especially towards the end of the nineteenth century. These levels have two important implications. First, taking into account the disproportion between the levels of Roman lead production and the production of silver in New Spain, the levels of historical lead emissions associated with silver smelting in New Spain and Mexico reveal a strongly polluting industry per kg of silver obtained.

Second, studies on historic levels of lead deposition in Europe detect the spike in ambient levels of lead that correspond to the Roman period and to silver refining in Germany.[933] Now the average production of silver by smelting and amalgamation was approximately 190 t/y in New Spain and 580 t/y in nineteenth century Mexico. During the colonial period these are production levels over a continuous period of some 250 years that were not matched elsewhere in the world. China produced on average 7 t/y between 1401 and 1440, then on average less than 2 t/y between 1441 and 1520, but by 1636, bullion production in China was negligible.[934] Japan between the sixteenth and seventeenth century is cited as exporting up to 200 t/y to China but was unable to maintain this level of production beyond a few decades.[935]

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[933] For example Martinez Cortiza A et al., "Atmospheric Pb Deposition in Spain During the Last 4600 Years Recorded by Two Ombrotrophic Peat Bogs and Implications for the Use of Peat as Archive," *The Science of the Total Environment* 292(2002).; Ingemar Renberg, Richard Bindler, and Maja-Lena Brännvall, "Using the Historical Atmospheric Lead-Deposition Record as a Chronological Marker in Sediment Deposits in Europe," *The Holocene* 11, no. 5 (2001).
[934] Atwell, "International Bullion Flows," 76,78.
[935] Atsushi Kobata, "The Production and Uses of Gold and Silver in Sixteenth- and Seventeenth-Century Japan," *The Economic History Review* 18, no. 2 (1965): 248.

Africa and the sub-continent of India do not figure as historical global sources of silver. Europe was the only alternate source for silver to the Hispanic New World until mid-nineteenth century, but the production figures are an order of magnitude lower with respect to the New World. The peak figure available for the mines of Freiberg indicate nearly 12 t/y by the end of the eighteenth century, while at nearby Hartz the highest annual average between 1718 and 1724 was 14 t/y. The mines at Konigsberg, Norway, produced on average 3 t/y between 1624 and 1805.[936] According to Humboldt just the silver sulphide in the ore from Valenciana (Guanajuato) produced in one month 7 t of silver, half of what all the mines of Saxony were producing in one year.[937] In the case of the Slovakian mines, the highest peak of production was reached at around 25 t/y.[938] This comparative review of silver production levels indicates that it should be possible to detect pre-twentieth century spikes in deposited lead in those provinces of New Spain / Mexico where smelting of silver ores was the main historic refining technique.

With respect to the level of woodland depletion, a high ratio of 1,000 to 1 of charcoal to silver was observed both in Europe and New Spain up to the end of the eighteenth century. A total of 7 million ha of woodland in New Spain are projected to have been required for refining of silver, ignoring natural cycles of regeneration. Had Western Europe been forced to supply an equivalent amount of silver from hypothetical silver deposits within its territory, its forest cover would have been depleted by this amount up to the year 1800. This is another instance of the concept of 'ghost acreage', now applied to silver refining.[939] What would have

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936 Burkart, "Memoria Real del Monte," 97, 98, 100.
937 Humboldt, *Essai politique*, Tome III, 363.
938 Teich, "Born's amalgamation process," 310.
939 The concept of 'ghost acreage … the computed, non-visible acreage which a country would require as a supplement to its visible agricultural acreage … in order to be able to feed itself' was first introduced by Georg Borgstrom in 1965 to denote how trade or fishing allowed a country a virtual expansion of its food production capacity without having to sacrifice its own land. Georg Borgstrom, The Hungry Planet; the Modern World at the Edge of Famine (New York: Macmillan, 1965), 71. The same concept can be applied to silver refining, substituting

been the impact on European economies from this additional depletion of their woodlands? It is not easy to find an estimate of residual woodlands for Europe in the Early Modern Period, since even the definition of the historical term for forests is under scrutiny. The latest estimation by Kaplan et al, which in the words of the authors is the lowest of recent research, concludes that the forest cover in the area defined as Western and Central Europe dropped from 24.9% in the year 1400 to 5.8% by 1850.[940] Using the modern land areas for the countries in their table, I arrive at a decrease of 47 million ha in this period, leaving this part of Europe by 1850 with just 14 million ha of woodlands. Another estimate is by Williams, who proposed that between 18 and 25 million ha of land were cleared for agriculture in Europe between 1650 and 1749.[941] Under both scenarios, had another 7 million ha of woodland been cleared during this period to refine silver, the economic impact on Europe would have been major.

How would this level of forest depletion have impacted the forest cover of colonial New Spain or Mexico in the nineteenth century? In the absence of data on forest cover in the region during the historical periods of interest, I will use data from the present century. The forest cover of Mexico in the year 2010 was 65 million ha. The forest depletion rate between 2005 and 2010 was measured at 0.24% per year.[942] A loss of 7 million ha represents 10% over 250 years, without the attenuation of natural recovery or forest husbandry. It could be argued that modern population pressures on these natural resources are greater than what would have been the pressure from the colonial silver refining processes.

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food for the amount of silver imported and the agricultural acres for the amount of woodland required to produce the fuel for refining. Analogous calculations can be made on the basis of 'ghost emissions' of lead, calomel, mercury, salt and copper salts. It can be extended to the effects on health of workers and communities if the appropriate quantitative factors can be estimated.

940 Jed O. Kaplan, Kristen M. Krumhardt, and Niklaus Zimmermann, "The prehistoric and preindustrial deforestation of Europe," *Quaternary Science Reviews* 28, no. 27–28 (2009): 3023.

941 Michael Williams, *Deforesting the Earth from Prehistory to Global Crisis : an Abridgment* (Chicago: University of Chicago Press, 2006), 172.

942 *Global Forest Resources Assessment 2010*, 228, 233.

The environmental impact from smelting, plus the historically unprecedented anthropogenic loss of liquid mercury to the rivers and soil at an average of 40 t/y continuously over 250 years of the colonial period (over 100 t/y in Mexico during the nineteenth century), is high considering the modest level of metallurgical activity in New Spain compared to metallurgical output in England during a similar period. In New Spain the refining of metals was basically limited to silver, and went from an average annual production of approximately 120 t in the decade 1601-1610 to an annual average of 480 t in the decade 1791-1800.[943] In England annual production from 1600 to 1800 via smelting went from 4,000 to 50,000 t of lead, 600 to 2,000 t of tin, 50 to 6,000 t of copper and from around 15,000 to 25,000 t of bar iron.[944] These amounts exceed by far in raw ore processed and final metal refined the statistics for the silver industry of New Spain. The problem lies in how to judge the relative environmental impact of both activities (silver refining and the effects of the metallurgical activity in England) in terms of the net economic benefit that ultimately derived to the various players involved: the local economy of New Spain, the economies of Spain and of England.

The main challenge is that silver did not remain within the country that produced it (Spain or Mexico) and that its production ultimately benefited a global economy reaching from Europe to India and China. Thus the ultimate benefactors of the 'refining ghost acreage' (and lead and mercury 'ghost emissions') are many, not all at the core of European based empires, some at the non-European periphery, and even a residual value benefited the single region that bore the environmental consequences. Defining the total distribution of benefits and quantifying the environmental cost of a process that impacted in unknown ways the health and

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943 TePaske and Brown, *Gold and Silver*, 115-16.

944 Roger Burt, "The Transformation of the Non-Ferrous Metals Industries in the Seventeenth and Eighteenth Centuries," *The Economic History Review* 48, no. 1 (1995): 28.; Peter King, "The Production and Consumption of Bar Iron in Early Modern England and Wales," ibid.58 (2005): 6.

culture of the local communities is not an evident task, both as a unique historical event or in comparison to other non-European industrial processes that have been game-changers in the world economy, i.e. the porcelain industry of China or the textile industry of India.

6.2 A change of paradigm.

The problem that has been faced in each of the chapters of this thesis is identifying what exactly is the current paradigm that guides the discussion on the environmental history of silver refining in the New World. As Kuhn argued, 'in the absence of paradigms all the facts that could possibly pertain to a development … are likely to seem equally relevant'.[945] This would explain the constant contradiction in views that introduce each chapter: silver ores in the New World are poor/rich in silver; smelting is more complex / more simple than amalgamation; volatile mercury / calomel are the main reason for the consumption of mercury during amalgamation; lead is / is not a major factor in air pollution from silver refining; the same / more woodland was consumed for smelting than for amalgamation; mercury was subsidized by the Spanish Crown / by the Fuggers; the production cost of amalgamation is less / more than smelting; mercury was the only / just another option for Spain to extract silver from the New World. Each of these dichotomies, which are definitely not incommensurable, have to be resolved in order to understand the human actions behind the historical events. Again citing Kuhn, the advantages of an explicitly accepted paradigm that can be verified by hard data is that it is 'not necessary to build a field anew once a paradigm is taken for granted'.[946] Many of the branches in the path of this dissertation have been the result of an absence of a clear paradigm that applies to the quantitative facets of this history.

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[945] Thomas S. Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1965), 15.
[946] Ibid., 19.

Environmental history is a prime example of interdisciplinary research, since it is based on the interpretation of historical texts and architectural studies, and on the disciplines of chemistry, physics and economics. It certainly seems feasible to establish a model for the interpretation of historical events based on quantitative data.[947] In Kuhn's terminology, the paradigm under whose temporal aegis the quantitative study of the environmental history of silver refining in the New World is carried out should be clearly identified and its evidence laid out for critical analysis by all parties of the relevant community. The transparency of the method becomes paramount over the numerical data itself, since the latter is always open to new sources of better data. I have used as a guide two of the most intuitive definitions of paradigm used by Kuhn: the map agreed upon or the set of rules to guide the activity of the interested community in their common field of research.[948]

The only explicit paradigm that has guided most of the recent research in various fields on the environmental legacy of historic silver refining is based on the assumption that all the mercury consumed during amalgamation was in the form of physical losses, of which the majority (65 to 85%) is posited as having taken place during the heating stage of the amalgam. This paradigm was initially adopted in order to estimate projections of global deposition of mercury over time. The origins of this paradigm were not experimental, born from field trials of clay *caperuzas* or metal *capellinas* under controlled conditions to measure the escape of mercury vapour and the ambient concentrations in the workplace. The only research carried

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[947] As Thommen has stated in his studies on the environmental legacy of ancient Greece and Rome: 'for a more adequate reconstruction of ancient environmental conditions, [an attempt is made] to include research from other disciplines, even if no comprehensive interdisciplinary approach can as yet be realized'. Lukas Thommen, *An Environmental History of Ancient Greece and Rome* (Cambridge; New York: Cambridge University Press, 2012), 1.

[948] A more formal definition given by Kuhn is that paradigms are 'achievements that are sufficiently unprecedented to attract an enduring group of adherents away from competing modes of scientific activity' and 'also sufficiently open-ended for the refined group to continue' working in the area so as to resolve further issues in the field of the paradigm. Groups 'whose research is based on shared paradigms are committed to the same rules and standards', in Kuhn, *Structure of Scientific Revolutions*, 10, 11, 90.

out in a laboratory at the end of the twentieth century was the paper published by Johnson and Whittle which confirmed the formation of calomel during amalgamation, but it was ignored.[949] The current paradigm also ignored the observations made in the historical texts up to the nineteenth century and only retained the gross figures of mercury consumed as recorded by historians.[950] I can conjecture that the track record of modern artisanal gold amalgamation determined this paradigm, but I cannot explain why calomel disappeared from every model on global deposition of mercury, in spite of the wealth of data in the historiography of the nineteenth century.

According to Kuhn a paradigm begins to be questioned when it is unable to explain anomalies in its field.[951] Three major anomalies persisted that were not be explained by the paradigm based on 100% physical loss of mercury and no mention of lead:

a) the silence by first-hand observers of the nineteenth century on the assumed losses of volatile mercury during the heating of the amalgam,

b) the historical silence on mercurialism, incompatible with the amounts of mercury deemed to have been issued to the air, and

c) the absence of historic high levels of mercury deposited from the air in areas close to amalgamation centres of silver ores, as has been evidenced by Cooke et al and Engstrom et al.[952]

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[949] Johnson and Whittle, "The Chemistry of the Hispanic-American Amalgamation Process."
[950] Nriagu, "Legacy of Mercury Pollution."; Robins, *Mercury, Mining and Empire*.
[951] Kuhn defines an anomaly as an observation or issue 'that cannot be aligned with professional expectation' Kuhn, *Structure of Scientific Revolutions*, 6.
[952] Colin A. Cooke et al., "Over three millennia of mercury pollution in the Peruvian Andes," *Proceedings of the National Academy of Sciences* 106, no. 22 (2009).; Engstrom et al., "Atmospheric Hg Emissions from Preindustrial Gold and Silver Extraction in the Americas: A Reevaluation from Lake-Sediment Archives."

Yet by the end of the nineteenth century all the relevant empirical facts required to establish the road map for future research in any field related to historical silver refining had already been reported:

- The dangers of mercurialism from accidents during the heating of the amalgam, but not under normal operational practice
- the toxic nature of the smoke from smelting *haciendas*
- deforestation
- the effect of solid wastes, including mercury, on water sources
- the formation of a chloride of mercury as a by-product of amalgamation

None of these conclusions can be faulted even with the benefit of hindsight. The absence of detailed theoretical or analytical tools and software programs to model air emissions did not impair the empirical notations of these first-hand observers of the refining processes being applied, even if they could not have known the structure of all the chemical compounds, or measure their concentration in the water, soil or air. Most of these historical testimonies became invisible in the second half of the twentieth century, victims to a scientific version of historicity. This was not a shift of paradigm, since no paradigm had previously existed. This was the creation of a paradigm devoid of hard data, which decided to focus solely on the one vector of environmental impact that was considered irrelevant in the historiography of the nineteenth century: copious emissions of volatile mercury during the heating of the amalgam.

An alternative paradigm can be proposed based on the historiography up to the end of the nineteenth century, complemented by modern chemical and economic analysis. It is not novel in the sense that every vector included had already been identified in the historical sources, but I have accompanied it with an explicit quantitative base on which it can be judged and improved. This paradigm is based on the following general scenario, defined by the numerical ratios ratios which have been presented in the previous sections and chapters:

1. Amalgamation accounted for just over 60% of the silver produced in New Spain, smelting just under 40%.

2. Lead (and its compounds) is the main heavy metal issued to the atmosphere as a consequence of the refining of silver ores in New Spain / Mexico.

3. The main consumption of mercury is via the formation of calomel. The loss of liquid mercury in the water used to separate the amalgam, or that percolated to the soil within the *haciendas*, plays a secondary role. The loss of volatile mercury in the heating stage of the amalgam was only due to accidents and overall is considered to be very low.

4. The *correspondecia* is not an empirical number but the reflection of the stoichiometric relation between mercury and silver derived from the chemistry of the reactions that take place during amalgamation.

5. Fine mineral silt washed away from *haciendas* into streams and landfills constituted the main source by weight of solid waste from amalgamation *haciendas*.

6. Salt was the second major component in weight voided in major amounts into the water basins downstream of the *haciendas*.

7. Copper compounds were voided into waterways in at least equal amounts as calomel.

8. The consumption of woodland was due primarily to smelting, with amalgamation playing a minor role.

9. The relative costs of production between amalgamation and smelting varied according to the historical period, and at times overlapped. Neither one nor the other was more profitable across all regions and across all time periods.

10. It is the chemical nature of the silver ores that determined in the first instance the choice of refining process.

6.3 The human choices.

The main conclusion of this thesis is that a paradigm based on lead and calomel determined the material impact of the environmental history of silver refining in the New World. The previous sections have proposed the chemistry that sustains this paradigm, and have calculated the resulting quantitative ratios that define the mass balances of each process and their economic consequences. This paradigm is only the initial stage for a revision of the technical, scientific and historical narrative to date:

- on the technical side, the *patio* process needs to be replicated to be studied in depth. How the very dense mercury droplets managed to interact with silver compounds embedded within the matrix of the milled ore just some 25 cm thick without the majority percolating by gravity through the planks or paving stones into the soil below over a period of weeks is still an open question
- the search for calomel in river beds and landfills, and the study of its environmental life-cycle is needed
- the mapping of historical airborne lead depositions up to the end of the nineteenth century within the territory of Mexico will confirm or question the paradigm proposed

- the detailed reconstruction of the architecture of the various phases of refining *haciendas* is a work in progress, but is of vital importance in the modelling of dispersion of airborne lead fume
- once detailed information on refining, agricultural and other economic activities in relation to population centres and water basins can be expanded over all mining and refining regions within New Spain, it will provide the framework for a more detailed analysis on the impact of the chemicals on the health of the workers and the communities, both at the time and their residual impact up to modern times.

Beyond the technical issues conscious choices on policy were also made at each stage of the process, not always guided by full knowledge of the science involved, but certainly within a continuum of the technical know-how available in each period. I will briefly review some of the human choices that were exercised and that also played a major role in the environmental history of silver refining as a whole.

6.3.1 What did they know and when did they know it?

The wide use of lead during Roman times has been widely documented, as well as the relative silence in the texts up to the nineteenth century on the effect of lead exposure on the workers involved.[953] When smelting was applied in the New World, the dangers and precautions of working with lead were sufficiently recognized in practice, if not in medical theory. Viceroy Toledo in Potosí specified that smelting furnaces had to have higher chimneys than those used within amalgamation *Ingenios* due to the greater hazard from lead fumes:

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[953] Jerome O. Nriagu, "Occupational Exposure to Lead in Ancient Times," *Science of the Total Environment* 31, no. 2 (1983).; Sven Hernberg, "Lead Poisoning in a Historical Perspective," *American Journal of Industrial Medicine* 38, no. 3 (2000).

‘The danger of lead poisoning from vapors given off during the preparation of lead flux for smelting silver, or in the recovery of lead after smelting, was recognized in Toledo’s mining ordinances of 1574. To recover lead, refiners should use an enclosed building with chimneys some 7 meters tall (4 estados) … the furnaces used to drive off mercury as vapor should be set apart from the refinery itself, and equipped with chimneys some 5 meters in height (3 estados) “so that the Indians shall not receive the smoke in any fashion”’.[954]

Equally, Garcilaso de la Vega’s (1539-1616) views on the responsibility of a monarch to any of his subjects handling mercury quoted in the Introduction reflects a perfect understanding of the risks posed by mercury. Amalgamation was much more recent than smelting, but mercury had been known to be a poison for workers involved in its handling many centuries before the Spaniards used it indiscriminately for silver refining in the 16c. Pliny in Roman times had commented on its toxicity.[955] Biringuccio wrote: ‘[Mercury] is numbered among the poisons. It has the property of contracting the nerves of those workers who extract it from ore if they are not very careful, and it makes the limbs of those who continually handle it weak and paralyzed’.[956] Martin del Rio, s.j. (1551-1608) argued against the use of alchemically transmuted gold for medicinal purposes due to the ‘noxious qualities’ it retained of mercury used in the alchemical process.[957] The dangers of using mercury were published throughout the period of silver refining in the New World.[958]

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954 Bakewell, *Miners of the Red Mountain*, 150.
955 Pliny, *The Elder Pliny's Chapters on Chemical Subjects* (London: E. Arnold & Co., 1929), 111.
956 Biringuccio, *The Pirotechnia*, 81.
957 Quoted in M. Baldwin, "Alchemy and the Society of Jesus in the Seventeenth Century: Strange Bedfellows?," *Ambix* 40, no. 2 (1993): 44.
958 Rosen has listed the following authors on mercury poisoning: Gabriele Fallopius (1523-62) in his treatise De Meteallis et Fossilibus noted the poisoning by mercury of workers at the mines and mentioned they could not work more than three years as a result; Andrea Mattioli, a contemporary of Fallopius, comments on the chronic mercurialism of the workers at the mercury mines at Idria (modern day Slovenia); Pieter van Foreest (1522-1597) of Delft; Paracelsus dedicates the third book of his monograph on miners’ diseases to mercury poisoning (1567); in 1665 Walter Pope comments with detail on the symptoms of mercury poisoning in workers; Bernard de Jusein in 1719 presented a memoir on the situation of workers at the Almadén mercury mine in Spain to the Academy of Sciences; some fifty years later Giovanni Scopoli described the effects of mercury poisoning on miners of Alto Isonzo. As to the growing awareness of the age on the health concerns of miners, in 1700 Bernardo Ramazzini published in his treatise on occupational medicine (as quoted in Rosen): ‘We must own that some arts entail no small mischief upon the respective artisans, and that the same means by which they support life, and maintain their families, are oftentimes the cause of grievous distempers which hurry them out of this world’. George Rosen, *The History of Miners’ Diseases. A Medical and Social Interpretation* (New York: Schuman’s, 1943), 39-133. A

Even more important, Spanish workers had been producing mercury from Almadén before the New World was conquered, making Spain one of the two places in Europe with first-hand experience on the occupational hazard of working with large quantities of mercury. By the 1550s the workers at Almadén had lobbied for special dispensations such as tax exemptions since their work 'damaged their mouths' and led to a doctor 'to cure the *azogados* [the victims of mercurialism]… since there are no people on Earth … so subject to illness as the *azogados*'. An apothecary was assigned, with free medicine supplied for the poorer workers. Such were the perceived dangers of that workplace that in the absence of free workers first slaves, then prisoners sent initially to the galleys, were required to help at Almadén.[959] In the 1560s the Fuggers had requested additional manpower for the mercury mines at Almadén in order to meet the increasing demand from the New World. Some 40 convicts destined to serve their sentence as galley-slaves were now sent to work at Almadén, a punishment that must have been deemed not much better than the death sentence of rowing on a Mediterranean galley. In 1593 a special judge, Mateo Alemán, drew up a report for the Spanish King on the conditions under which these slaves and other workers were exposed to the effects of mercury while working in the mine managed by the Fuggers. Among his detailed conclusions:

'it is harmful to the men to assist in the vats used to cook the ores from where mercury is obtained and to rake the ashes because they get into the eyes, mouth and nose … from that the men are *azogado* [stricken with mercurialism] and become dim-witted and lose their mind and become gravely ill'.[960]

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useful though older review on the reporting of occupatiotanl helath isses through history is by H.E. Sigerist, "The Wesley M. Carpenter Lecture:" Historical Background of Industrial and Occupational Diseases"," *Bulletin of the New York Academy of Medicine* 12, no. 11 (1936). Articles on specific cases are: K. V. Fox, "Pedro Muñiz, Dean of Lima, and the Indian Labor Question (1603)," *The Hispanic American Historical Review* 42, no. 1 (1962).; Z.Z. SIavec, "Occupational Medicine in Idria Mercury Mine in 18th century," *Vesalius* IV, no. 2 (1998).; C. Serrano, "Minería salud en el Potosí colonial; Mining health in the colonial Potosi," *Arch. boliv. hist. med* 11, no. 1/2 (2005).; Alfred Bogomir Kobal and Darja Kobal Grum, "Scopoli's Work in the Field of Mercurialism in Light of Today's Knowledge: Past and Present Perspectives " *American Journal of Industrial Medicine* 53, no. 5 (2010).

[959] '*se azogaban y se les "dañaban las bocas"….medico … para curar los azogados … no hay en el mundo gente … tan sujeta a enfermedades como los azogados*' Matilla Tascón, *Minas de Almadén (to 1645)*, 79.

[960] '*dañoso a la salud de los hombres es el asistir en los buitrones a el cocimiento de los metales de que se saca el azoque y el cerner las cenizas porque se les entran por los ojos y boca y narizes … dello se azogan los hombres y quedan tontos y fuera de juyzio y uienen a enfermar grauemente*'. There are more quotes on the dangers to

Alemán would then emigrate and die in New Spain ca. 1615, though little is known of his activity in the New World.[961] He represents at least one direct channel for the transmission of knowledge on the toxicity of mercury to the authorities and mining community in New Spain during the period that saw the introduction of major quantities of mercury to refine silver. As far as I can ascertain, no similar study was commissioned by the Crown on the effect of mercury on the workers in the New World that refined silver by amalgamation.

The answer to the question that heads this section is therefore straightforward. The historiographical evidence points to the fact that the impact on worker's health of smelting with lead or working with mercury were well known in the sixteenth century at the highest levels of policy makers in Spain, as they were even better known to the English investors who flocked to Mexico in the nineteenth century. There is no evidence that this knowledge at any point in time influenced any major decision related to the refining of silver ores in the New Spain / Mexico up to the end of the nineteenth century. Overall the production of silver remained unfettered by strict controls on the use of lead and mercury. To judge the *mentalité* of the period on occupational health, it should be borne in mind that as late as nineteenth century Germany, one of the important reasons to protect workers from the toxic smoke of the smelting furnaces was because it tended to kill the best and most skilled of the smelters.[962]

The collateral damage on the health of the smelters or amalgamation workers caused by both lead and mercury was judged by the norms of the period to be an acceptable cost of each process. The fact that even in the nineteenth century the English managers and investors

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health from working with mercury from interviews held by Alemán with workers at Almadén in German Bleiberg, *El Informe Secreto de Mateo Aleman sobre el trabajo forzoso en la Mina de Almaden* (London: Tamesis Books Ltd, 1985), 81.

[961] Alemán is better known as the author of a novel, *Guzman de Alfarache*, that together with the now more famous *Don Quixote* by Cervantes became a widely quoted example of the Spanish picaresque style. Irving A. Leonard, "Mateo Alemán in Mexico: A Document," *Hispanic Review* 17, no. 4 (1949).

[962] Schlutter, *De la fonte des mines*, 2 2.

at Regla did not comment on this topic indicates that it never became a major issue of concern within its workforce.[963] In the case of mercury it has been argued that its transformation into calomel attenuated to a high degree the impact on the human environment, though a loss of 15% as elemental mercury is still a major historical health concern to all the communities exposed to its effects. What would have been the response of refiners to a much higher level of toxicity?

On the 7th February 1561 a petition was forwarded to the Viceroy of New Spain, Luis de Velasco, requesting a *merced* for a new amalgamation recipe that included the addition of *solimán*, mercuric chloride.[964] To prove that its use was not injurious to health, the promoter of the method, Pedro Martín from Tasco, swilled his mouth with the water used to wash the ore after treatment, though the only ones forced to actually swallow the liquid were a cockerel from Castille and a horse, to no apparent ill effect. On the 10th March 1561 the authorities in Seville were quickly appraised of the benefits of this new recipe and requests made for new shipments of *solimán* at an attractive price. By July of that year the same authorities in New Spain would start to point out the hazard posed by the use of *solimán*: 'it is dangerous for the blacks [slaves], we give notice to Your Majesty of this fact' (24 July 1561). By the time a year had gone by it was clear that 'there are great dangers to using *solimán*, for which reason the miners do not make use of it' (2 April 1562).[965] Such was the risk involved, and its lack of

963 In the case of amalgamation Sonneschmidt takes the trouble of addressing this issue in a separate section of his work to conclude that in spite of negative reports in Europe on the effects of amalgamation on the workforce, he had met in his visits to *Reales de Minas* amalgamation workers with up to 40 years working in amalgamation haciendas who did not show any health problems as a result. Sonneschmidt and de Fagoaga, *Tratado de la amalgamación de Nueva España*, 94-95.

964 Almadén converted part of its mercury production into solimán. Sánchez Gómez, *Minería no férrica en el Reino de Castilla*. pp. 275-276 check. What a difference a state of oxidation makes in life. *Solimán* and calomel are both chloride salts of mercury, the former a mercuric salt (Hg^{+2}), the latter a mercurous salt (Hg^{+1}). *Solimán* is an extremely toxic mercury compound, while calomel is not.

965 '*es peligroso para los negros, damos a vuestra majestad noticia de ello'; 'hay grandes peligros de beneficiarse con soliman, de cuya causa los mineros no se aprovechan de ello*' as quoted in Castillo Martos, *Bartolomé de Medina*, 210-13.

technical success, that it soon disappeared from the repertoire of refining methods in New Spain.

The toxicity of mercuric chloride, which is soluble in water, is much higher than that of mercurous chloride (calomel), which is not.[966] Its effects on the human body are much more immediate and evident than the longer term and more insidious effects of either mercury or lead poisoning. Retention of urine, vomiting and bloody diarrhea leads to death unless treated.[967] Even if *solimán* had been an effective amalgamation reagent, the very high level of toxicity would have precluded its widespread use in the New World. Even if the tolerance to occupational risks remained high until the twentieth century, the natural reticence of humans to work with evident poisons was the ultimate threshold. Had the short-term toxicity of mercury been equivalent to that of *solimán,* amalgamation would not have been used to refine silver ores.

6.3.2 Historicity and the reality of the refining process

One of the anomalies to the paradigm based on copious emissions of volatile mercury to the air from the heating of the amalgams is the silence in the historiography on widespread mercurialism, more so in historical accounts of large population centres such as Potosí in the immediate vicinity of a major concentration of amalgamation units.[968] More mercury was

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[966] Solubility in water is critical in aiding the diffusion of any chemical into the body via skin absorption, through the digestive system or even via the respiratory tract, thus hastening its presence in the blood stream and tissues. This in turn will aid in promoting any toxicity inherent to the chemical. For an example of pathways into the human body see Jaroslava Svarc-Gajic, *General Toxicology* (New York: Nova Science Publishers, 2009), 17-47.
[967] See for example Laszlo Magos and Thomas W. Clarkson, "Overview of the Clinical Toxicity of Mercury," *Annals of Clinical Biochemistry* 43(2006).
[968] New Spain did not have a similar example, since its silver production via amalgamation was more widely disseminated. Guanajuato was one of the few cases of major amalgamation haciendas clustered close to the town.

handled by workers at these *haciendas* than was used by hat makers in England, yet no Mad Amalgamator appeared to displace the better known Mad Hatter of the literature.[969]

The silence on any sign of widespread mercurialism extends to all textual sources. There is no mention in the selections of letters that have been published from Spanish immigrants to New Spain to their families in Spain.[970] The more militant and vocal workers of the eighteenth century, when the yearly average of mercury consumption would have reached its peak in New Spain, did not include mercurialism among their list of workplace grievances.[971] I have not come across any reports on mercurialism from the English expatriates supervising the refining of silver in the *haciendas* of the Real del Monte Company.[972] Nor have I come across reports of complaints against toxic smoke from amalgamation *haciendas*. The

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[969] The only exception being the the strange story of Fulgencio Orozco, recounted at the end of Chapter 6 in Timothy Brooks, *Vermeer's Hat* (London: Profile, 2008), 181-84. Brooks however does not make an explicit connection between mercury and the derangement of the Spaniard who worked in the amalgamation *Ingenio*. De Gamboa makes one of the few extant comments on the poisonous nature of amalgamation haciendas in de Gamboa, *Comentarios Ordenanzas de Minas*, 462.

[970] Enrique Otte and Guadalupe Albi Romero, *Cartas privadas de emigrantes a Indias, 1540-1616* (México: Fondo de Cultura Económica, 1993).; Marta Fernández Alcaide, *Cartas de particulares en Indias del siglo XVI : edición y estudio discursivo* (Madrid; Frankfurt am Main: Iberoamericana ; Vervuert, 2009).

[971] Ladd, *The Making of a Strike*, 19 ff.

[972] In 1825 a very graphic portrayal of the deemed toxicity of the amalgamation process was published in England: 'the men employed barefooted [in mixing the amalgamation *tortas*] soon became salivated and paralytic, by the absorption of the mercury, and ultimately died the most painful deaths', from Rawson, "The Present Operations and Future Prospects of the Mexican Mine Associations Analysed, by the Evidence of Official Documents, English and Mexican, and the National Advantages Expected from Joint Stock Companies, Considered, in a Letter to the Right Hon. George Canning," 19. The text is very relevant, not for the improbable scenario it depicts, but for being an early example of a strand of thought that still survives in the modern historiography, that has judged the indigenous workforce as being incapable of running an efficient operation with regards to the recovery of mercury and of a supine docility in the face of such claimed immediate mortal dangers. Indigenous workers suffered great hardships in the mining and refining industries of New Spain and Mexico in order to feed their families, but there is no evidence they were a completely inefficient and passive workforce. Not even an industry based on a slave workforce could bear the economic impact of workers sickening and dropping like flies soon after trampling amalgamation *tortas*. The gist of the first part of the letter is that English know-how will allow the wealth of the silver mines in Mexico to be properly extracted. It was written before operations at Regla under its new English investors were underway. There is no evidence that Sir William Rawson ever travelled to Mexico, his source is not identified, and by providing a lurid caricature of events he diverts attention from the real problems of historical refining of silver ores. His letter seems to be a later version of the type of negative European reports mentioned by Sonneschmidt, see footnote 963.

only reports of mercurialism come from accidents during the heating stage of the *capellinas*, as for example:

'it is not too many years since capellinas have begun to be used, previously having used in general clay pots. These broke frequently with greater risk to those who approached to quench the fire. I have found various individuals that in such circumstances were poisoned by mercury, and they fell to the floor senseless, and in spite of this they recovered nearly completely, only left with a minor tremor of limbs that is triggered after much exercise.'[973]

Was historicity at work, with the Spanish and English sources hiding the truth on the ravages of mercurialism behind the nested stories within a story so aptly described by Atwood at the beginning of this chapter?[974] The initial answer is that there was no mention of widespread mercurialism either in Peru, New Spain or Mexico simply because the aggregate amounts of volatile mercury issued to the air over time were the results of isolated accidents, not part of standard amalgamation practice, and were confined to the immediate surroundings of the heating area of the *capellinas*.[975] When volatile mercury did escape, there is no doubt its effects on the workers was immediate and toxic, but it was never a case of major losses of volatile mercury affecting both the *hacienda* and the surrounding communities.[976] It was solid,

[973] '*no hace muchos años que las capellinas están en uso, habiéndose servido antes casi generalmente de ollas de barro. Estas se reventaban con freceuencia en el mayor riesgo a los que acudieron para apagar la lumbre. He encontrado a varios sujectos que en tales circunstancias se han azogado, y cayeron en el suelo privados de sentidos, y sin embargo de esto se restablecieron casi enteramente, restándoles solo un leve temblor de miembros que les acomete después de mucho ejercicio*' in Sonneschmidt and de Fagoaga, Tratado de la amalgamación de Nueva España, 51. An exaggerated version of the immediate effect of mercury fumes upon life is provided in the accounts of a visit to the refining hacienda of Fresnillo in Albert M Gilliam, *Travels Over the Table Lands and Cordilleras of Mexico, During the Years 1843 and 44* (Philadelphia: John W Moore, 1846), 260. As argued in Chapter Three, metal *capellinas* were widely used in the eighteenth century, and Barba suggested strongly the use of metal caperuzas as of the 1600s, to avoid the operational problems mentioned by Sonneschmidt.
[974] Margaret Atwood, *MaddAddam : a Novel* (New York: Doubleday, 2013), 56.
[975] Robins provides historical texts on the dangers of processing cinnabar at Huancavelica and from the mills crushing ores, but no historical quotes on wide-spread mercurialism either in the refining workforce or among the inhabitants of Potosí. Robins, *Mercury, Mining and Empire*.
[976] This conclusion only applies to amalgamation refining haciendas. The issue of mercurialism was very much present in the mercury mines of Huancavelica and Almadén. For a historical analysis of the hazards of mercury at Huancavelica see Brown, "Workers Health and Colonial Mercury Mining at Huancavelica, Peru."

water-insoluble calomel and liquid mercury that were handled and spread in major amounts during the amalgamation process.

The only problem with this answer is that while mercury is the usual suspect in any environmental issue related to historical silver refining, so too should be lead. This was a heavy metal that together with lead compounds was issued to the atmosphere in major amounts within and around each smelting *hacienda*, under workplace concentrations that exceeded any modern guideline. The greatest harm would fall on the smelting teams closest to the furnaces and then on the rest of the workforce within the smelting *hacienda*, but as reported in Chapter 2 even the communities around smelters were aware of the toxic nature of the smoke from the smelting furnaces. The visual evidence from historical photographs and drawings leave no doubt as to the degree of air pollution from these smelting *haciendas*. Yet again specific references in the historiography to lead poisoning as a consequence of the smelting of silver ores are few and far between.[977]

The general silence on occupational hazards began at home, with the way Spain ignored its own workers at Almadén: 'During the firing of the ores, the vapours from the furnaces ...extend over the town [of Almadén] so that its inhabitants are under the pernicious effect of a mercurial atmosphere'.[978] It would be hard to argue that the Spanish Crown would take greater care of its new subjects in the New World than it took of its old ones in Spain. The prejudiced view on the inhabitants of the New World and their role in relation to the wealth of silver and gold is well described by the contents of the *Parecer de Yucay*. This was an anonymous

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977 One of the few exceptions is the following observation 'poisonous are the Smelters and amalgamation haciendas' - '*venenosas las Fundiciones y las Azoguerias*', in de Gamboa, *Comentarios Ordenanzas de Minas*, 462.

978 '*en la época de fundición, los vapores de los hornos ... se extienden por el pueblo [de Almadén] con lo que todos sus moradores quedan sometidos a la perniciosa influencia de una atmosfera mercurial*' José María Pontes y Fernández, *Historia de la antigua ciudad de Sisapón, hoy Almadén del Azogue* (Madrid: Enrique Rojas, 1900), 12.

pamphlet against the arguments put forward by La Casas in defence of the inhabitants of the New World and published in 1571, the same year the ViceRoy Toledo implemented the *mita* to provide indigenous labour by forced mass migrations to the silver industry of Peru. Its authorship has been attributed to a Dominican author, fray Garcia de Toledo. It also contains an appendix on mining that has been fiercely criticized by the Spanish historian Isacio Perez Fernandez, O.P. (Dominican Order), who has termed it 'cheap theology … an irritating literary sanctimoniousness, an insipid, boring and cheap theological focus', assumed to be authored by Polo de Ondegardo.[979] The appendix merits quoting at length, since even as a caricature of a theological tract it still serves as a guide to the manner in which some in Spain regarded their right to the treasures of the New World and their views on the indigenous population. It begins by stating that the Indies were the prize given by God to the Spanish Crown for the reconquest of Spain from the enemies of Christianity. The author then goes on to criticize the stand taken by Bartolomé de Las Casa in favour of the indigenous inhabitants of the New World, by way of the following argument:

'what was meant when God placed these indians with such miserable souls and so bereft of God, brutes so lacking in skills … in kingdoms … so full … of gold and silver … what does this mean except that God found himself, with these miserable people and with us, like a father that has two daughters, one very white, very discreet and graceful … the other very ugly, bleary-eyed, stupid and bestial? If he is to marry … the ugly, clumsy, stupid, wretched one [he will have to] provide a large dowry: many jewels, rich clothes … it is with all this that God comes to aid'.[980]

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[979] '*teología barata ... una gazmoñería literaria irritante, un enfoque teológico insulso, ñoño y barato'*. Isacio Pérez Fernández, *El anónimo de Yucay frente a Bartolomé de Las Casas : estudio y edición crítica del Parecer de Yucay, anónimo (Valle de Yucay, 16 de marzo de 1571)* (Cuzco, Perú: Centro de Estudios Regionales Andinos "Bartolomé de Las Casas," 1995), 10, 103.

[980] '*que quiere decir el haber puesto Dios a estos indios tan miserables en las almas y tan desamparados de Dios, tan inhábiles y bestias .. en unos reinos ... tan llenas .. de oro y plata .. que significa esto sino que se hubo Dios con estos gentiles miserables y con nosotros, como sea un padre que tiene dos hijas, una muy blanca, muy discreta y llena de gracias .. la otra, muy fea, laganosa, tonta y bestial? Si ha de casar ... a la fea, torpe, necia, desgraciada [habrá que] darle gran dote: muchas joyas, ropas ricas ... con todo esto Dios y ayuda' excerpt from the Appendix titled 'On the working of the mines*' - 'Sobre el beneficio de las minas' in the Parecer de Yucay, as reproduced in ibid., 157-62.

The analogy becomes clearer when the author argues that Europeans were so graceful it was easy to be saved (married, without the need of an expensive dowry) by the Christian religion, while for the brutish and ugly inhabitants of the New World their only path to salvation lay in the size of their dowry as given by God, in the wealth of the mines that attracted both soldiers and the spread of the Catholic faith, since 'in the lands where there is no dowry of gold and silver, there is no soldier or captain that wants to go, not even an evangelizing missionary'.[981] To oppose mining as Las Casas was doing was to take sides with the Devil, the same Satan who convinced the locals to hide the location of mines from the Spaniards. In the end, 'the mines, from a moral point of view, are as necessary as the King himself, since without them it will not be possible to conserve … the Gospel. Therefore, saintly and good they are, and blind are the men who deny this, a sign of evil from the devil and his work'.[982] Under this line of reasoning any negative consequences from the use of mercury or lead on the health of the local communities was no greater than the risks already borne in Europe, and were all for the greater good carried out by the Crown.[983]

Rosen in another context has argued that while mining was the activity of slaves and criminals it impeded any interest in documenting systematically their diseases, and that only the appearance of free men as miners, with an intrinsic value now placed on their welfare and the need to safeguard their increased technical knowledge, transformed them into capital assets that justified the creation of a corpus of detailed medical literature related to their occupational

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[981] '*a tierra donde no hay este dote de oro y plata, ni hay soldado ni capitan que quiera ir, ni aun Ministro del Evangelio*', in ibid., 160.
[982] '*las minas, moralmente, tan necesarias son como es haber rey, pues sin ellas no se conservara … el Evangelio. Luego, santas y buenas son, y gran ceguedad en los hombres negarlo, y malicia en el demonio, y obra suya'*.Ibid., 161.
[983] This disdain of the local workforce is not a phenomenon restrained to the Spanish Crown, authorities and miners of the sixteenth century. The silence of the English managers, investors and technical staff on mercurialism can be explained by calomel, but the absence of measures to control the lead in the smoke from the smelting furnaces signals that the workforce in the Mexico of the nineteenth century may not have yet been considered an asset in the eyes of the English investors or their Mexican successors.

diseases.[984] To complement Rosen it can also be argued that in the context of the perils of mining and in the light of the immediate harm caused by silicosis due to the fine milling of ores or the incidence of hernias on the workforce, or mortal accidents within the mines, long-term lead poisoning or mercurialism was the least of the worries in the minds of the miners and refiners.[985] It is thus much more common to find references to the hazards of mining or of milling than to the perceived hazards of lead and mercury within the labour-force. This normal response to the clearest and most present dangers lowered the visibility of the potent but longer term threat of lead emissions in those areas where smelting was carried out, though it did not quite erase it from the historiography.

Was there a conscious decision to downplay the occupational, safety and health aspects of the refining *haciendas* up to the end of the nineteenth century? Smelting would have created more problems among the workers and surrounding communities than amalgamation, since mercury in calomel would have posed a negligible short-term health hazard compared to lead fume. The fact it did not receive any major attention in the historical texts points to a more complex answer to this question. Mining and refining drove the economy of New Spain and Mexico during the period of interest. The overriding interest of the Crown to maximize the extraction of silver, the merging of refining and farming interests in the hands of strong owners of capital within New Spain, and finally the entry of overseas investment allied to newly emerging capital and industrial Mexican groups, created overall a very strong reason to accept and downplay the negative effects of refining within official texts, accepting them as a necessary consequence of capital and industrial growth. In private letters or journals written by

[984] Rosen, *History of Miners' Diseases*, 8-38.

[985] During a panel discussion on modern artisanal gold mining at the 11th International conference on Mercury as a Global Pollutant (Edinburgh, 2013), members of the audience pointed out that the concerns of researchers did not necessarily match the concerns of the artisanal refiners on the subject of workplace safety, for whom the dangers of inhaling mercury fumes were the least of their daily problems.

Europeans I would argue that the paradox of Father Brown's postman was also at work, in the sense that the social biases of observers can render certain groups of people mentally invisible to them.[986] The indigenous population of refining workers was for the most part invisible to most European observers of the nineteenth century, where they barely figure in the commentaries. Whatever their illnesses may have been, they were not part of the mental landscape covered by these texts. I have already cited the observation on the toxicity of copper sulphate on *patio* horses that avoids any mention of its toxicity on the local workers.[987] The environmental history of silver refining through the eyes and words of the indigenous workers of the New World remains to be written.

6.3.3 The option of smelting all the ores in New Spain

In sharp contrast with later events in Peru, the statistics on silver production show no sign of a silver crisis in New Spain at the time amalgamation was being implemented for the first time. The first dip in production is only observed in the decade of the 1580s, well after amalgamation was first implemented.[988] Before mercury arrived on the scene total production levels of silver in New Spain in the decade 1541 to 1550 corresponded to a yearly average around 27 metric tons of silver. This was a level two to three times the yearly average for the same period of all the main German/Central European mines, the main source of silver up to that point.[989] In the longer term smelting would produce just under 40% of the total silver from

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[986] From G.K. Chesterton's short story "The Invisible Man" in G.K. Chesterton, *Father Brown, Selected Stories* (London: Oxford University Press, 1961), 74-94.

[987] See footnote 427.

[988] Lacueva has argued that the absence of a production crisis of silver in New Spain at the time amalgamation was implemented, together with the level of new capital investment that was required to switch from smelting to amalgamation, are two very strong arguments against the accepted narrative that places amalgamation as a necessary and natural next stage for the evolution of silver production in New Spain in the second half of the sixteenth century. He suggests amalgamation represented an opportunity for the owners of capital to subordinate the needs of the cash-strapped class of small refiners and miners. Lacueva Muñoz, *La plata del Rey*, 148-167.

[989] Data for New Spain from TePaske and Brown, *Gold and Silver*, 113.; for Europe from John H. Munro, "The Monetary Origins of the'price Revolution': South German Silver Mining, Merchant Banking, and Venetian Commerce, 1470-1540,"(Department of Economics, University of Toronto, 2003), 43. Nef cites a maximum

New Spain, even after all the assistance provided to amalgamation through the periodic decreases in the pricing of mercury over the period. Yet Juan Suarez de Peralta, one of the earliest voices on the history of New Spain, was one of the first of many in the historiography to claim that without mercury there would have been no silver from the New World.[990]

Without recourse to Almadén and Huancavelica it is probable that Spain would have proceeded to smelt the remaining 60% of silver in New Spain that was ultimately refined by amalgamation. Smelting was the traditional European refining method for silver ores in the sixteenth century. In contrast to the case of England, where by the year 1400 already only 17% of England and Wales' usable land was covered by forests, Spain found in the New World a far vaster virgin resource of wood for making charcoal.[991] Even nearly five hundred years later, the modern states of Mexico, Bolivia and Peru figure among the world's top ten countries with the largest areas of primary forest cover in the world.[992] Even so, dressing of the ore would have been a necessary pre-requisite to smelting, otherwise the need to heat the totality of an ore containing on average 0.2% silver would have required an estimated additional 105 million ha of woodland for charcoal, more than twice the area of woodland existing in Mexico in the year 2010.[993] Dressing the ore to a final silver content greater than 0.6% would have brought down the additional requirement of woodland to at least one third of the previous estimate, and

production of silver from all central European mines in the decade 1526 to 1535 of nearly 3 million ounces (approximately 94 tons). Nef, *Conquest of the Material World*, 42.

990 As quoted in Bargalló, *Minería y metalurgia colonial*, 240.

991 Kaplan, Krumhardt, and Zimmermann, "The prehistoric and preindustrial deforestation of Europe." p. 3023.

992 *Global Forest Resources Assessment 2010*, 13.

993 A split of 60:40 in silver produced by amalgamation and smelting, based on an average silver content of 0.2% for amalgamation and 2% for smelting, corresponds to a 15 to 1 ratio in the weight of ore processed by each route. Thus if 7 million ha were required to heat all the ore used for smelting in New Spain, 15 times that amount would be needed to heat the ore that would have otherwise been amalgamated. The data on the forest cover in Mexico in 2010 (65 million ha) are from ibid.

at the same time offered a comfortable degree of profit to the smelters, net of dressing costs (see Figure 5.23).[994]

Lead would not have been a material bottleneck either had Spain chosen to smelt all the ore. Up to an additional 300,000 t over 250 years would have had to be sourced locally or imported from Europe (and serving as needed ballast to the outgoing convoys from Seville) in order to make up for losses during the smelting of the additional ore. Mexico produced over 2 million t of lead just between 1931 and 1941, so if the Spanish Crown had promoted the mining and production of lead the local deposits would have been sufficient to sustain the requirements of smelting.[995]

When the initial wave of complaint rose from the ranks of amateur refiners in New Spain that they were running into problems refining silver, the Crown had the option of improving the smelting skills of this population, promoting the search for lead within New Spain or even as market leader adjusting the price of silver to compensate the need for charcoal or imported lead flux. Smelting was the universal refining process, not limited like amalgamation to a certain types of ore. The rapid response of the Crown to the potential use of mercury to refine silver ores, commented upon in Chapter 3, raises the unsurprising issue that the ownership of the Almadén mine played a critical role in the refining policy, explicit or tacit, made by the Crown. There is no doubt that amalgamation was a technique better suited to the majority of ignorant refiners set loose in New Spain after its conquest. However, as the history of San Luis Potosí shows, from the late sixteenth century as refining became more technical,

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[994] I am not adopting a defence of a policy that would have decimated the forests of Mexico along European lines, but simply pointing out that from a material point of view a policy that was acceptable at the time could have been adopted, even more so if forest regeneration cycles operated over a 250 year span, as would be expected. The future use of coal, local or imported, to substitute charcoal in smelters cannot be ruled out in this counterfactual scenario.
[995] González Reyna, *Minería y Riqueza de México*, 3.

smelting was the natural choice when refiners were faced with silver-rich lead ores. With sufficient lead and after dressing ores, the experience at San Luis Potosí could have been the model for the expansion of silver production in New Spain as of the seventeenth century, and for 100 years smelting refined silver ores on par with amalgamation in New Spain.

The use of smelting would however have posed an opportunity cost to the Crown. If mercury was used, it opened up a revenue stream to the Treasury, in parallel to the revenues from the royalty and other taxes on silver, as discussed in Chapter 5. This opportunity cost could have reached some 10% of the total revenues to the Crown in the early seventeenth century, a major sacrifice in earnings. Thus to the operational advantages of patio amalgamation must be added the fiscal advantage over smelting it represented to the Royal Treasury, made even more attractive during the first century of amalgamation in New Spain by the role of the Fuggers.

I thus approach the end of my arguments by adding to the technical factors the human choices, from the policy of the Spanish Crown to the historiography of the modern era, that have played a decisive role in determining and then reporting the environmental history of silver refining in New Spain and Mexico. Amalgamation was not the only technical key available to unlock the silver from its ores in the New World, it was not the sole option to process ores claimed to be too low in silver content for smelting. In the case of New Spain smelting remained until the end of the colonial period a very viable and competing alternative, as shown by its contribution of under 40% of the total silver produced even after efforts by the Crown to sustain amalgamation. By choosing for fiscal reasons to favour the path of amalgamation over smelting, a decision evident from the actions of the Crown and its colonial authorities, the population and the environment of New Spain was spared a worst-case scenario of even more lead issued to the air around each of the smelting *haciendas* and a wide-spread consumption of woodland. Instead they would be subject to millions of tons of silt suspended in water and settling along river beds, entombing mercury transformed into calomel, together with liquid mercury entrained with dissolved salt and copper compounds. Within the *haciendas* the environmental legacy would be residues of fugitive lead and soil soaked in mercury. Finally, but significantly in terms of quantity and impact, air emissions of mercury would be two orders of magnitude lower than lead and its compounds exiting the chimney stacks, a devil's alternative for the indigenous population

Epilogue

During 250 years Spain would control both the world's largest reserves of silver and of mercury, a historically unique geological and geopolitical triangulation that would make it the master of the silver market for nearly three centuries. By conquering the western chain of mountains from the Andes to the Cordillera of North America it conjoined its own vast reserves of mercury at Almadén with the major deposits of silver that had been generated by a process of subduction of tectonic plates all along the eastern Pacific Rim. Nowhere else in the world is subduction as active, nor such a chain of silver deposits to be found, much younger and of different geological origin than their more modest counterparts in *MittelEuropa*. The only common denominator was the presence on both sides of the Atlantic of lead ores rich in silver. In general the ore deposits of Europe were mined for copper or lead rather than silver, while silver was the only economic reason to refine the ores of the New World. The absence of major pre-Conquest extractive industries kept intact the composition of their weathered surface, native silver and silver chlorides.

Due to the scavenging instincts of the initial swarm of Spanish colonists, avid for wealth and lacking skills, they left behind generous mounds of discarded weathered ores, all the mineral that did not immediately promise silver to their untrained eye or yield it to their primitive smelting efforts. To the authorities they complained of decreasing silver content, when in reality what was changing was the nature of the mineral, from weathered silver ore to deeper and more intractable silver sulphides. The initial technical challenge was solved thanks to imported German know-how in smelting. The environment of New Spain would feel the first wave of volatile lead products from the smoke of smelting furnaces and of charcoal burners smoldering their way through woodlands.

As the mountains of discarded ore grew, so did the frustration of the first generation of self-taught refiners. In New Spain amalgamation did not arrive on the back of a sudden decrease in silver production. It arrived from Europe as a process that was known to work with gold, and was a much simpler method that suited untrained refiners better than smelting. Spain saw a quadruple opportunity open up: more silver could be produced by its untrained colonists foiled by smelting, it could gain much more revenues from its mercury mine at Almadén, it could use the Fuggers to provide the mercury on credit as well as collateral for future loans, and by controlling the mercury as a State monopoly it could gain a measure of control over the contraband of silver. The hazard posed by mercury was well known, but in practice was not seen to be worse than the toxic fumes from smelting, and certainly no greater than the burden imposed upon its own people at Almadén.

Mercury, aided by its aura as the alchemical precursor to silver and gold, was thus applied to the mounds of cheap discarded ores and to existing superficial deposits. These responded well to the primitive amalgamation recipe that was known to work with gold. Had the first generation of refiners been thorough in their triage and smelting, only lead-rich slags would have been left behind. In such a case the primitive amalgamation recipe would not have worked either on these or on the deeper silver sulphides or *negrillos*. As the mounds of discarded but easy to amalgamate ores were run down, so did silver production suffer. Then events in the *altiplano* of the Andes would radically change the industrial potential of the basic gold amalgamation recipe. In a short burst of impressive technical creativity within the Spanish refining haciendas of the Andean *altiplano*, the amalgamation recipe was converted into a powerful chemical tool that was able to reduce the silver sulphide present in *negrillos* into amalgamated metallic silver. Though an earlier incarnation had been applied previously in the Schio mines by Venetians in the early sixteenth century, it was recreated independently through the stubborn efforts of the self-made refiners around Potosí.

As amalgamation gained momentum, mercury was consumed in quantities never observed before in any human industry. The workers of the amalgamation *haciendas* and the population of New Spain were spared the ravages of mercurialism on a major scale both by the safeguards adopted during the heating cycle of the amalgam and by the chemistry of the amalgamation process that consumed mercury by converting it to solid, insoluble calomel. Nevertheless tons of liquid mercury were squeezed through the fingers of workers onto the slurries of ore, and liquid mercury was still washed away in water or lost by seepage to the soil. Very little mercury escaped to the air during the regular heating cycle of the amalgams. Streams and water basins around the clusters of amalgamation *haciendas* became their waste disposal units. Salt seeped into the ground of the patios and was washed away together with copper compounds and the millions of tons of fine mineral silt that were useless to the refiner once all possible silver was extracted. All these materials would contaminate the water downstream from each refining unit, and compromised its use for consumption and irrigation.

Patio amalgamation represented a technology best adapted to the medium where it was implemented, competitive with the more traditional route of smelting. The longevity of its recipe was never a sign of backwardness or technical stagnation, nor was the chemical immutability of the smelting process over thousands of years. Amalgamation embodied all the elements of a modern industrial process: planning of inventories, carefully concatenated stages of physical treatment and chemical reactions, avoidance of operational bottlenecks to achieve a smooth production output. The *patio* reactor that evolved in New Spain was the most efficient answer to the amounts and nature of the ore that had to be treated, and to the materials at hand.

Nevertheless, the environmental history of silver refining in New Spain was determined as much by smelting as by amalgamation. Smelting contributed with just under 40% of all the silver produced during the colonial period, and possibly one quarter to one fifth during the most of the nineteenth century. Lead and its compounds represented the main source of heavy metals issued to the air from the historical silver refining in New Spain, on average two orders of magnitude greater than the total air emissions of mercury. The historical impact of emissions of lead and lead compounds from the smelting and refining furnaces was the aggregate of multiple but singular depositional footprints determined by the local wind rose, furnace efficiency, skill of the smelter, lead content of each ore, and by the architectural trace of the *hacienda* and the location of its mounds of *grasas*. Some mining regions in New Spain would never be exposed to much lead, others would have known no other airborne heavy metal, but those who did live in the vicinity of smelters had no doubts on the toxicity of its smoke on animals and humans. The other major environmental impact of smelting was on woodlands, consuming them at a rate over 50 times higher than amalgamation would. This depredation of woodlands was only attenuated by the increased efficiency of blast furnaces in the nineteenth century, which decreased by an order of magnitude the rate of consumption of charcoal per kg of silver smelted.

The environmental cost from silver refining as imposed on the indigenous communities and the new settlers was never addressed in a significant manner in the texts of the period. The silence is a reflection of many realities: the greater, more immediate dangers of mining silver ore or processing cinnabar; the acceptance of occupational health risks from a workforce whose pressing issue was to earn a living for their families within a context of limited labour options; the cloak of social invisibility that covered most of the indigenous population in the eyes of others. The silence encompassed both the Spanish and English contingents who came to extract silver from New Spain and then Mexico, as well as the new local owners and operators of the later republican period.

The silver of New Spain and Mexico could have been extracted only with smelting, had this been necessary. Enough lead and woodland existed in its vast territory to have covered the needs of this refining process. Without recourse to mercury, refiners would have sought a greater efficiency from the furnaces, recovered lead from the fumes, spent more manpower in dressing the ores and would have developed a secondary market for its smelted non-precious metals, much as republican Mexico finally did as of the late nineteenth century. Had smelting prevailed, the total environmental impact of its lead emissions and destruction of woodland would have been more severe than from the historical mix of amalgamation and smelting. Mercury as the lesser evil: this was the ultimate paradox of the environmental history of silver refining in New Spain and Mexico.

APPENDICES

A. Silver production in smelting *haciendas*

Table A-I. Account book prepared by Lopez de la Madriz, Valle de Pozos, AHSLP, Fondo Alcaldía Mayor 1650.3, expediente 8.

year	month	marks	*pesos* silver	*pesos* gold	kg silver
1660	may	307	2,540	1,205	
	july	648	5,354	2,334	149
	august	220			
	september	350	2,895	1,100	
	october	250	2,134	1,058	
	november	134	1,106	654	
	december	308	2,446	1,169	
	total	2,217	16,475	7,520	510
1661	january	455	3,757	1,685	
	february	400	3,304	1,532	
	march	159	1,319	640	
	april	271	2,128	857	
	may	315	2,604	852	
	june	625	5,082	1,454	144
	july				
	august	439	4,233	1,644	
	september	295	2,454	808	
	october	373	3,080	403	
	november	359	2,962	610	
	december	152	1,258	247	
	total	3,843	32,181	10,732	884

Table A-II. Weekly accounts of the *Hacienda* de Nuestra Señora de los Dolores, corresponding to the year 1773, signed by Lorenzo Mata. AHSLP, Fondo Alcaldía Mayor 1773.2.

	dates	*cargas* ore	marks silver	% silver in ore	silver per week, marks	silver per week, kg
1773	12/10 to 17/10	29	4	0.07%	4.0	0.9
	15/8 to 22/8	160	10.0	0.03%	10.0	2.3
	30/5 to 6/6	40	8.3	0.10%	8.3	1.9
	23/5 to 30/5	76	9.4	0.06%	9.4	2.2
	16/5 to 23/5	60	8.6	0.07%	8.6	2.0
	9/5 to 16/5	59	11.0	0.09%	11.0	2.5
	3/5 to 9/5	60	8.6	0.07%	8.6	2.0
	28/3 to 4/4	64	7.9	0.06%	7.9	1.8
	21/3 to 28/3	96	8.3	0.04%	8.3	1.9
	14/3 to 21/3		11.5		11.5	2.6
	8/3 to 14/3	160	13.1	0.04%	13.1	3.0
	23/2 to 28/2	96	12.1	0.06%	12.1	2.8
	14/2 to 21/2	270	14.8	0.03%	14.8	3.4
	31/1 to 7/2	68	8.0	0.06%	8.0	1.8
	24/1 to 31/1	68	12.5	0.09%	12.5	2.9
	17/1 to 24/1	76	11.6	0.08%	11.6	2.7
	10/1 to 17/1	165	10.5	0.03%	10.5	2.4
1772	27/12 to 3/1		14.5		14.5	3.3
	average			0.06%	10.3	2.4

note: the % of silver in the ore is calculated on the assumption all the silver refined in the week has been extracted from the total *cargas* of ore reported

B. The accounting books of Regla

The account books that were consulted in the Archivo Histórico de la Compañia Real del Monte y Pachuca (AHCRMyP) as the source of the economic production data correspond to the Fondo Siglo XIX. They comprise the following sections, series and sub-series:

1. Sección: Explotación y Beneficio, Serie: Informes de Haciendas de Beneficio, Subserie: Informes Mensuales Hacienda de Regla Vol 225, Exp. 3: 29 Jun 1872 – 27 Oct 1888

This has been the main source of the monthly data on production and costs for Regla. I have named this source as the *Contabilidad Mensual de la Hacienda de Regla, June 1872 to August 1888* or as *Contabilidad Mensual* for short. The months correspond to either four or five week periods, and the accounts are dated according to the final day of each period. The data only correspond to refining operations at Regla.

2. Sección: Negociaciones, Serie: Haciendas de Beneficio, Subserie: Hacienda de Regla I, Vol 22: 1875-1878.

I have referred to this source as the *Extracto de Memorias, 1875 – 1878*. Each *Memoria* is numbered and corresponds to a weekly account of certain expenditures (*gastos*) at Regla.

3. Sección: Contabilidad de la Dirección, Serie: Producción y Gastos, Subserie: Estados Comparativos, 1853-1855, 1859-1865, 1869-1873.

This source is referred to as *Estados Comparativos*, a monthly and yearly comparative summary of selected expenditures and costs per *montón* or *carga* of refined ore, for all the refining *haciendas* active in any given period.

There is minimal overlap between these three sources for the period between 1853 and 1888, though the monthly and weekly accounts for Regla do coincide for at least a period of three years (1875 to 1878). The comparative accounts for all the *haciendas* only coincide with the monthly accounts for Regla in the year 1873. Even these limited overlaps have been very useful in establishing what the accountants chose to include under any of the main headings. By cross-checking the data from overlapping primary sources I have been able to arrive at the following guides.

Contabilidad Mensual de la *Hacienda* de Regla, June 1872 to August 1888.

The *Contabilidad Mensual de la Hacienda de Regla,* June 1872 to August 1888 (referred to as *Contabilidad Mensual*) is the only source of accounting data used in this thesis to have signatures that officially (and thus legally) validate each of the monthly accounts presented. The office held by the signatories at times can be identified, such as the Managers of Regla (Mr. Rule in 1872 and 1873) or the Administrator (Mr. Cuatáparo, from November 1876 to June 1877). From January 1881 until August 1888 most of the monthly accounts show two signatures, that of Mr. Torres (who signs all the monthly accounts from March 1878 to August 1888) and a higher ranking official of the Company, Mr. Landaro, who signals his hierarchy by attaching a *Visto Bueno* (a sign of approval) to his signature. As in Chapter Four I have decided to omit the data from January 1874 to March 1875 since this is a non-representative period for Regla where an irregular refining of *grasas* (slag and tailings) and limited amalgamation took place. Each monthly account sheet contains the following information on the costs incurred:

1. A report on the monthly consumption by weight and total cost (in *pesos*) incurred of the following major consumables, under the heading *Almacén* (virtual central warehouse at Regla):[996]

Reagents: salt (*sal*), mercury (*azogue*), copper sulphate (*sulfate de cobre*), litharge (*greta*)[997]

Fuel: charcoal (*carbon*); firewood is only reported in the period 1872 to 1873, and is incomplete (see Chapter Four). A more complete and detailed breakdown of both charcoal and firewood is provided both in the *Memorias* and *Estados Comparativos*.

Animal fodder: barley (*cebada*), straw (*paja*), corn (*maiz*)[998]

Animals: number in stock, losses by death

2. The monthly production costs (*Costo de Beneficio*) are reported within a separate boxed-in area of each monthly account sheet. They are presented under some fifteen different headings, some of which change during the 1872 to 1888 period. However it is fairly straightforward to group these costs under the following sub-sets:

Labour costs: all the costs grouped under the following headings correspond only to labour: stamp mills (*Molienda de morteros*), ore breakers (*Almadaneta*), Chilean mill (*Arrastre*), amalgamation cake workers (*Torteros*), general labour (*Peones*), carriers (*Cargadores*), fine ground ore workers (*Lamadores*), recovery of amalgam from the washings

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[996] I refer to it as a virtual warehouse since horses, mercury and litharge would not have been stored in a physical central warehouse to be supplied as required, but the accountants kept track on paper of the different supplies and purchases required by the operational needs of the hacienda.

[997] Copper sulphate is a different material from *magistral* , the copper containing ore that needed roasting prior to use.

[998] 'straw and corn, the consumption of which is very important to sustain an also large number of mules and horses' - 'la paille et le mais, dont la consommation est fort importante pour l'entretien d'un aussi grand nombre de de mulets et des chevaux' Duport, *Métaux précieux au Mexique*, 231. I am citing Duport since the corn could also have been destined for human consumption.

of ore residues in a *planilla* (*Planillones*), horseshoe fitters (*Herradores*), repairs (*Composturas*), bricklayers (*Albañiles*), sawyers (*Aserradores*), carpenters (*Carpinteros*), roofers (*Techadores*), smiths (*Herreros*), general tasks (*Faenas*), final separation of silver from amalgam, cupellation and casting of silver bars (*Capellinas, afinación y fundición de barras*), amalgamation costs (*Amalgamación en patio*), Stables (*Caballerizas*) and other office and general staff payroll costs (*Gastos Generales*). Not all these headings appear together in any given year, since changes in accounting practice took place during this period, but they all refer exclusively to labour costs. The identification of the nature of these headings was made possible by crosschecking the data in the monthly and weekly accounts for the four week period ending the 29th May 1877 (see below).

During the years (mid 1875 to early 1886) that smelting was also carried out within this period, the heading named 'Smelting' (*Fundición*) corresponds to the labour costs of the smelting process (see below).

Mercury, Salt, Copper Sulphate, Litharge and Charcoal : I use the accounting data of the *Almacén* (virtual central warehouse) section to track the monthly cost of the main consumables for amalgamation (mercury, salt and copper sulphate) and for smelting (litharge, charcoal) and also to calculate the variations in their unit cost over time. Unfortunately these monthly accounts do not provide data on the consumption of fuel for amalgamation, and this information must be derived from the other sources (see below).

Other costs : this heading covers all the remaining production costs registered in the accounts at Regla. For the years in which both amalgamation and smelting are being carried out I take as my starting point the total cost of smelting that is reported as a separate entry by the accountants of Regla. To arrive at 'other costs' for amalgamation I then subtract the total smelting cost from the sum of all production costs, which gives me a total monthly production cost for amalgamation only. I then subtract the total cost of labour and the costs of the three main consumables to arrive at 'other costs' for amalgamation. As shown in more detail below these 'other costs' include all other consumables (from the *Almacén*, or the sundry items from nails to lard listed as *Otros Efectos*, or even supplied by other *haciendas* of the group) plus minor non-operational costs that range from weekly masses to covering the costs to receive visitors at Regla (some of which are grouped under the dire heading of *Gastos Muertos*, Dead Costs).[999] I do not subtract from the total production costs contingent monthly additional revenues such as the rent of a store or the sale of poor lead. The aim of my calculations is not the final profitability of the company but the quantitative breakdown of production costs in each process.

In the case of smelting, I use the accountants' figure on total monthly smelting costs, subtract the costs for litharge, charcoal and labour (reported as *fundición*), and the net amount I register as 'other costs' for smelting. Table B-I summarizes my overall approach. If the total cost of smelting is not available (missing data) it can be arrived at by subtracting from the total cost of production in a month the product of total *montones* amalgamated times the reported production cost per *monton* by amalgamation, including mercury.[1000]

The cost of the ore at the plant gate is not included, nor is the fixed capital cost.

Extracto de Memorias, 1875 – 1878.

The weekly accounts have served to establish what is included under many of the headings used in the monthly ledger that were not self-evident in their description. For

[999] Under modern accounting practices the inclusion of masses as a production cost may be open to fiscal questioning, but in the nineteenth century in Mexico it would have been as necessary for the labour force as the corn they were given.

[1000] A *montón* at Regla is defined as containing 30 *quintales* (10 *cargas*, 1.38 t). A *carga* corresponds to 138 kg or 3 *quintales* or 12 *arrobas*.

example, does ‘Mill Grinding’, *Molienda de Morteros,* encountered in all three accounting sources include all the costs expected from this stage of the process, or did it only cover labour costs? It depends on the source. In the case of the *Contabilidad Mensual,* a comparison of the numbers reported during those periods where the monthly and weekly accounts overlap indicates clearly that the data only correspond to labour costs. The same headings when they appear in the *Estados Comparativos* include both labour and other, unspecified costs (see below).

The *Extracto de Memorias* provide a wealth of detail on the labour component of the two refining processes used at Regla: the name of the worker in most cases, hours worked per week, wage per hour and approximate description of work carried out or skills. The other window into the processes carried out at Regla provided in these weekly accounts concerns the consumption of fuel for amalgamation. As already pointed out in Chapter 4, the *Contabilidad Mensual* only provides the consumption of charcoal for smelting, but apart from some incomplete records for the years 1872 and 1873 does not include any information on fuel used during amalgamation. This can be remedied in part for the period 1875-1878 by the information on total firewood and charcoal consumption that appears in the weekly accounts, as detailed under the heading *Varios Efectos* (Miscellaneous Materials). For the earlier years, 1853-1873, the *Estados Comparativos* provide more information, as set out below.

Monthly Ledger		June 1872-December1873	April 1875 - October 1876	November 1876 - June 1877	July 1877 - November	December 1877-	March 1878 - December 1878	January 1879 - December 1881	January 1881- August 1888	headings for present analysis
Signed by		R. Rule	E. Benoit	N. Cuataparo	Miguel Bustamante	Solorzano for Bustamante	R. Torres	Landero, Torres		
Materials supplied by the Regla warehouse (*Almacen*)	salt, mercury,copper sulphate, greta, charcoal, firewood (only 1872-1873), animal feed (*cebada, paja*), corn, animals (including deaths)									
	Amount by weight (arrobas, pounds, cargas) and total cost (pesos)									
Breakdown of monthly variable costs	Stamp mills (*molienda de morteros*)									Labour costs amalgamation
	Ore breakers (*almadonetas*)									
	Chilean mills (*arrastres*)									
	Amalgamation cake workers (*torteros*)									
	General labourers (*peones*)									
	Carriers (*cargadores*)									
	Fine ground ore workers (*lamadores*)									
	Horseshoe fitters/ironsmiths (*herradores*)									
	Treatment of ground ore residues (*planillones*)									
	Stables (*Caballerizas*)									
	Amalgamation costs (*Amalgamacion en Patio*)									
	Capellina, final refining and casting of fine silver bars (*Capellina, afinacion y fundicion de barras*)									
	Repairs (*composturas*)									
	Bricklayer (*Albañil*)									
	Sawyer (*Aserradores*)									
	Carpenters (*Carpinteros*)									
	Roofers (*Techadores*)									
	Smiths (*Herreros*)									
	General tasks (*Faenas*)									
	General costs (*gastos generales*)									
	Materials from warehouse (*materiales consumidos del almacen*)									Salt
										Mercury
										Copper Sulphate
	Other materials (*varios efectos*)									Other costs
	muertos)									
	Contingent costs (*Gastos Extraordinarios / Gastos Diversos*)									
	Total amalgamation cost		= total production cost - total smelting cost							total amalgamation cost
	Total smelting costs, or smelting cost per carga									total smelting cost
	Smelting (*Fundicion*)									labour costs smelting
	Litharge (*greta*)									litharge
	Charcoal									fuel
	Other costs		= total smelting cost - labour costs - litharge - fuel							other costs

Table B-I. Assignment of account headings in *Contabilidad Mensual* into subsets (labour, mercury, salt, copper sulphate and other costs) used in the analysis of production costs at Regla.

Estados Comparativos 1853-1855, 1859-1865, 1869-1873

The comparative tables of production costs incurred at each *hacienda* contain the following information reported both on a monthly, quarterly and yearly basis:

Variable production costs: all production costs are listed as *pesos* per *montón* in the case of amalgamation, and *pesos* per *carga* in the case of smelting. These are grouped under many of the same headings encountered in the first two accounting sources, such as *Molienda* *de Morteros*, *Arrastres*, *Amalgamación patio*, *Fundición*, etc. However in this case the accountants decided to include both labour and other, unspecified, costs under these headings. This became clear on comparing the data from the *Contabilidad Mensual* for the year 1873 with the data from the *Estados Comparativos* reported for Regla for the same year (Table B-II). The amounts under unambiguous headings such as mercury, salt and copper sulphate only show the very small deviations to be expected from two separate accounting sources averaged over a year. In contrast, the amounts for grinding, *capellinas* and repairs are consistently and significantly higher in the *Estados Comparativos.* This indicates that the accountants are including other (unidentified) costs for each process stage apart from the labour costs already identified for the *Contabilidad Mensual*. This interpretation is strengthened by the content of the 1855 report presented by John Buchan, where in his table of comparative production costs between all the *haciendas* of the company, he explains some of the accounting headings such as stamping and grinding, by adding the words: 'mostly labour'.[1001]

The case of the accounting of the costs of firewood and charcoal also shows how the content of each heading changes from source to source. The *Contabilidad Mensual* to all effects and purposes simply ignores them in the case of amalgamation, only reporting charcoal for smelting.[1002] The *Memorias* provide a very detailed breakdown of the weekly costs of all the types of firewood and charcoal under the heading *Varios Efectos.* The *Estados Comparativos* reports separately and distinctly the costs incurred for two specific but generic headings, firewood and charcoal. In contrast to the *Extractos de Memorias*, it excludes them from the accounting class of *Varios Efectos.*

[1001] Buchan, *Report Real del Monte*, 17.
[1002] This can be explained by the relative small contribution of this consumable to the total costs of amalgamation, while it is a major cost component in smelting, as will be evident in a later section of this chapter.

accounting source	year	selection of account headings						total production cost per kg silver
		grinding costs (*molienda de morteros, almacenetas, arrastres*)	*capellina* , bars	repairs (*reparos*)	mercury	salt	copper sulphate	
Contabilidad Mensual	1873	0.94	0.06	0.56	3.02	2.22	0.78	11.57
Estados Comparativos		1.64	0.12	1.19	3.2	2.25	0.76	11.25
		note: all production costs in pesos per kg of refined silver, calculated from data in primary source, average for the year indicated						

Table B-II. Comparison of amounts accounted for in the *Contabilidad Mensual* and *Estados Comparativos* for the year 1873 for production costs at Regla. See text for analysis.

Information on the ore processed at each *hacienda*: number of *cargas*; the average total silver content (*ley,* expressed in marks per *montón*) of the ore being processed, and the silver actually extracted, reported also as a *ley*; the percentage loss of silver at different stages of the process, the total percentage loss of silver and loss of mercury expressed as ounces of mercury per mark of silver. Some of this information also appears in the monthly accounts of Regla within the *Contabilidad Mensual*.

Information on the consumption of main reagents: total weight consumed of salt, mercury, copper sulphate, *magistral* (only in some years), litharge, firewood, charcoal. Total cost of these consumables is also listed, so that the average yearly cost per unit of weight for each consumable can be calculated.

Information on the consumption of sundry items: the same yearly average (total weight and total expense) is reported for all the sundry materials used at the *haciendas*.[1003]

[1003] *Efectos Diversos* is mostly made up of : tools (*herramientas*), machinery (*maquinarias*), bricks (*ladrillos*), lime (*cal*), planks (*tablón*), wood (*madera*), leather (*cueros*), lead (*plomo*), iron (*hierro*) and steel (*acero*),nails (*clavos*), refractory stones (*piedra refractaria*), limestone (*piedra de cal*),bone ash (*ceniza de hueso*),stones for *arrastres* (*piedras voladoras*), *capellinas,* and dead animals (*animales muertos*). The expense on fodder (maize, barley, straw) is absent.

C. Inventory areas at the *Hacienda* de Regla

Raw ore for amalgamation: the inventory of raw ore ranged from zero to nearly 24,000 *cargas* (3,312 t) over the period (Figure C-1). Under conditions of guaranteed availability, a very low inventory level lowers the amount of capital tied up in storage, and in general up to 1885 Regla maintained low levels of raw ore awaiting amalgamation. The mathematical average for the period is 5,091 *cargas* (703 t) per month of inventory, but it is more realistic to calculate the required storage area on the basis of demands for a peak monthly storage of 15,000 *cargas* (approx. 2,100 t) that repeats over the period. The ore could be stored outdoors but with protection from pilfering behind the high perimeter walls of Regla.

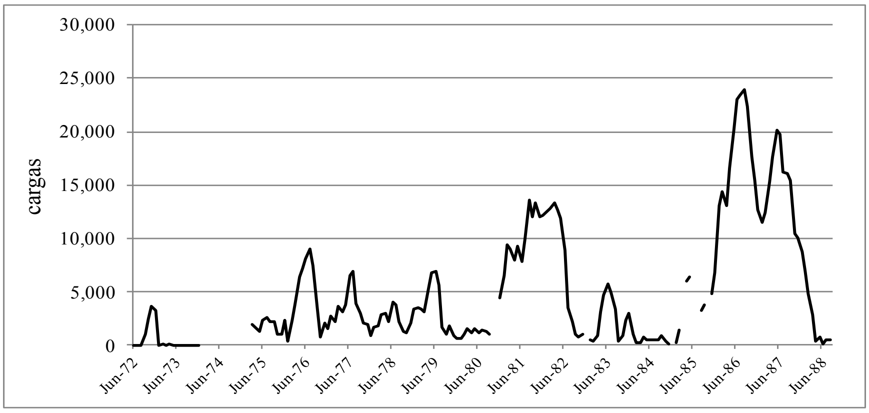

Figure C-1. Inventory of raw ore destined for amalgamation. Raw data from *Informe Mensual.*

Ground ore for amalgamation: the estimate of inventory storage requirements is based on peak levels of 10,000 *cargas* (Figure C-2).

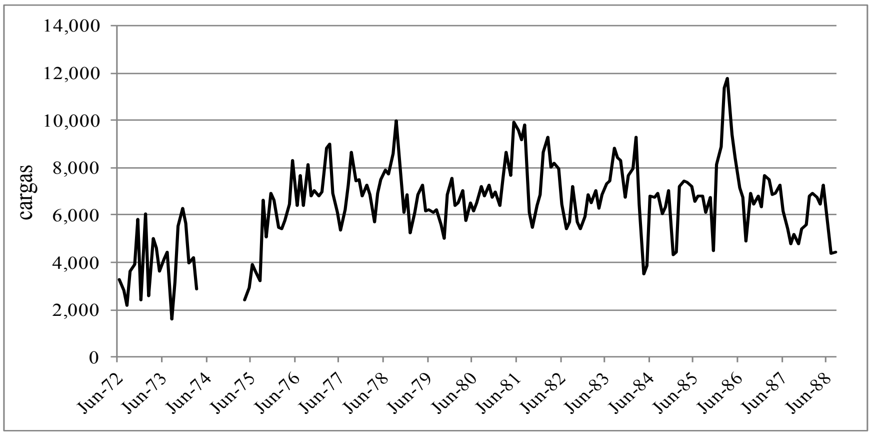

Figure C-2. Inventory levels of ground silver ore destined for amalgamation. Data from *Informe Mensual.*

Salt: The inventory levels show some major oscillations but overall their median is relatively constant compared to what I will show for other ingredients of the recipe at Regla. The average inventory value in this period was 18,459 *arrobas* (212 t), but with peaks of up to 45,000 *arrobas* (520 t) as seen in Figure C-3. The importance of salt for the process is shown by the fact that the average level of inventory covered four months consumption. For the calculation of storage area I will use a peak value of 40,000 *arrobas*.

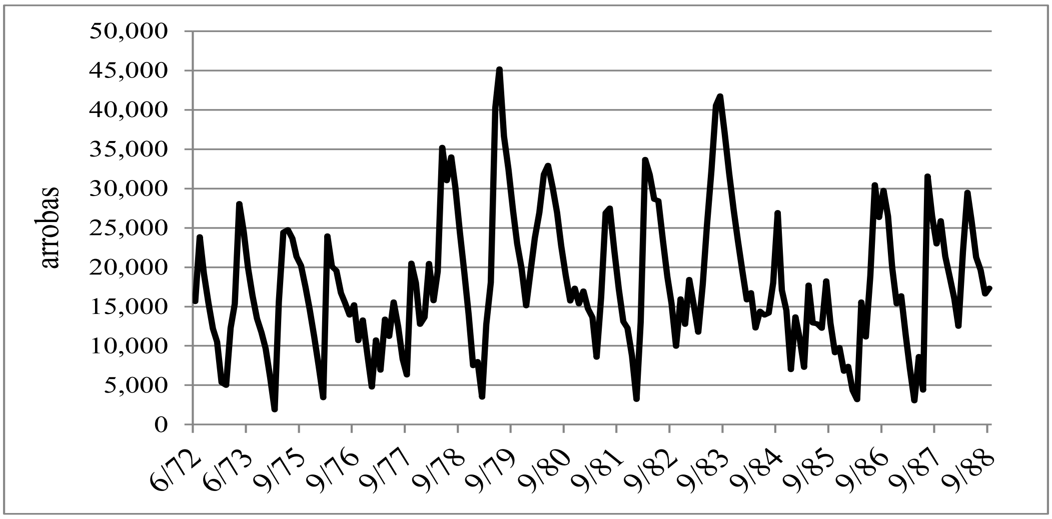

Figure C-3. Monthly inventory levels of salt. Raw data from *Informe Mensual.*

Copper sulphate: The way its inventory was managed throughout the period reflects a reaction to uncertain supply (Figure C-4). The median shows a positive slope after 1877, up to the moment the decision was taken to draw down the inventory after mid 1886, possibly in anticipation of a major decrease in operations at Regla. The threat of losing revenues due to the lack of copper sulphate was real enough, though the alternative option had they run out of copper sulphate would have been to roast the ores with salt prior to amalgamation, a routine operation at San Miguel de Regla and other *haciendas* of the company. On average, with the caveat that the baseline of the data shows a marked positive slope with time, the level of monthly inventory over this period was 15,109 lb (6.9 t), reaching a maximum of 45,672 lb (21 t) towards the end of the period. With an average monthly consumption of 9,774 lb (4.4 t), the inventory represented more than 1.6 months average consumption. I will use 40,000 lb as the peak level of inventory to estimate the storage area requirements.

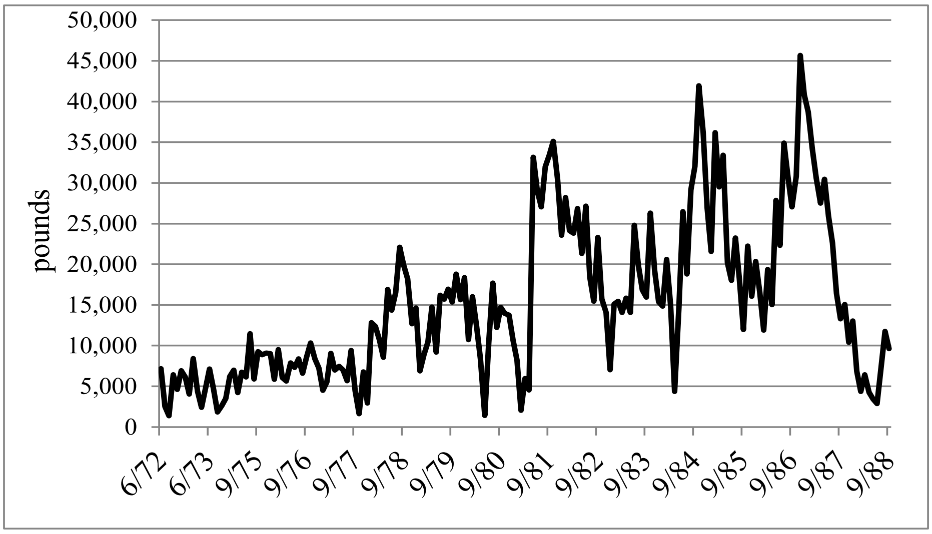

Figure C-4. Monthly inventory levels of copper sulphate. Raw data from *Informe Mensual*.

Mercury: Throughout this whole period Regla maintained an average monthly inventory level of mercury of 29,830 lb (13.6 t), Figure C-5. This represents an average inventory equivalent to 6.8 months of average mercury consumption at Regla. I will use 45,000 lb to calculate peak inventory storage requirements.

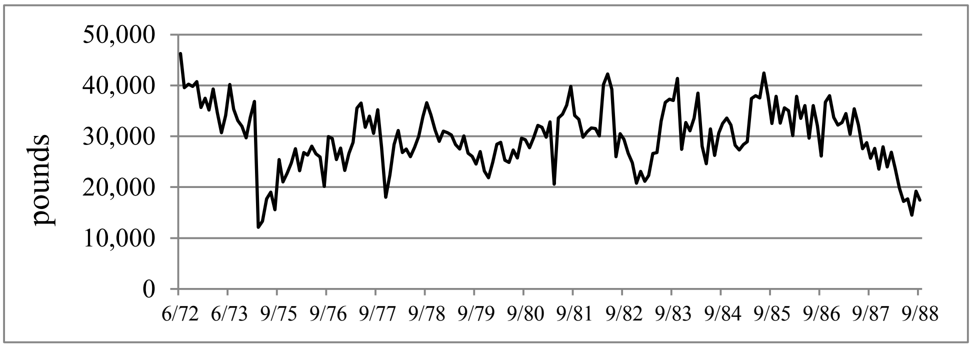

Figure C-5. Monthly inventory levels of mercury. Raw data from *Informe Mensual*.

Raw ore for smelting: the inventory profile shows three stages during this period: first, a period of supply overtaking the capacity of Regla to grind and smelt the ores, leaving a median with a positive slope during the first half of the decade; then a period when smelting output was more balanced with ore supply, leading to very rapid draw-downs of accumulated inventory. It then reverted to the behaviour observed at the beginning, suddenly cut-off in early 1886 when smelting operations ended, most probably with no prior warning, as can be deduced from the behaviour of the other smelting inventories discussed below (Figure C-6). On average

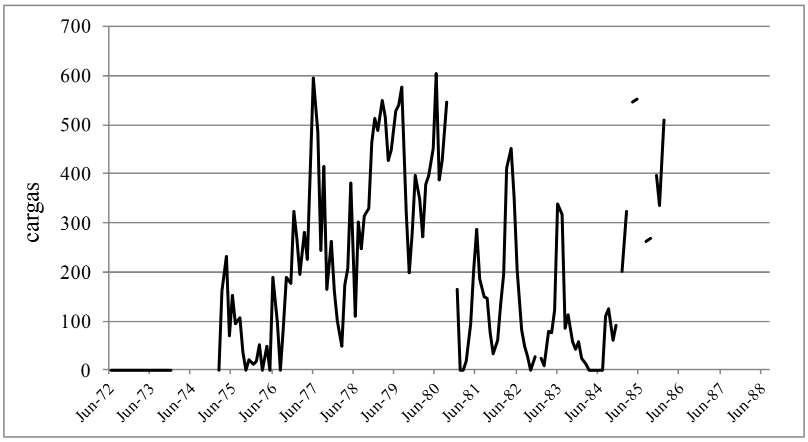

Figure C-6. Inventory levels of raw silver ore destined for smelting. Raw data from the *Informe Mensual Regla.*

a monthly inventory of 216 cargas (29.8 t) was carried at Regla, just over one month of smelting throughput. I will use a peak level of 600 *cargas* to estimate the area required for storage of inventory.

Milled ore for smelting: there were also periods when it would have been necessary to store the milled ore that could not be smelted. It occurred more often at the beginning of the decade, tailing off to discrete monthly peaks piercing plateaus of sustained zero inventory (Figure C-7). This is another case where the mathematical average for the decade, 32 *cargas* per month (4.4 t), says little from a storage point of view. Each peak would have required sufficient storage area to have been available at short notice, capable of storing up to 300 *cargas* (approx. 42 t) of valuable milled silver ore under secure conditions. Overall Figure C-7 reinforces the image of a smelting infrastructure capable of processing all the available silver ore, and only running up important inventories of unsmelted ore during very few months over the whole decade.

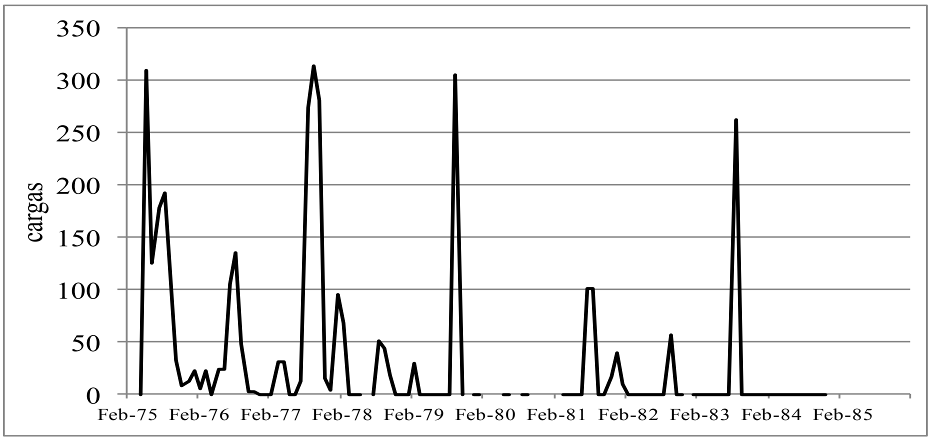

Figure C-7. Inventory of ground silver ore ready for smelting. Raw data from the *Informe Mensual.*

Litharge: the behaviour of the inventory of litharge also shows how Regla had to plan without having any guarantee as to how much ore for smelting was to be provided by the mines (Figure C-8). The inventory built up at the beginning of the year 1886 reflected already a lower expectation on the ores to be smelted, prevalent since the 1882's, but still planned for smelting to take place. The unexpected hiatus on smelting as of February 1886 would see the inventory of litharge slowly erode on other uses, probably refinement by cupellation of silver obtained by amalgamation. The final small jump in inventory belongs to the history of Regla after 1888. Again, the mathematical average over the period of 69,100 lbs does not provide guidance on the space requirements for litharge in this decade. Up to 200,000 lbs (approximately 100 t) would have required storage space, at least up to the early 1880s

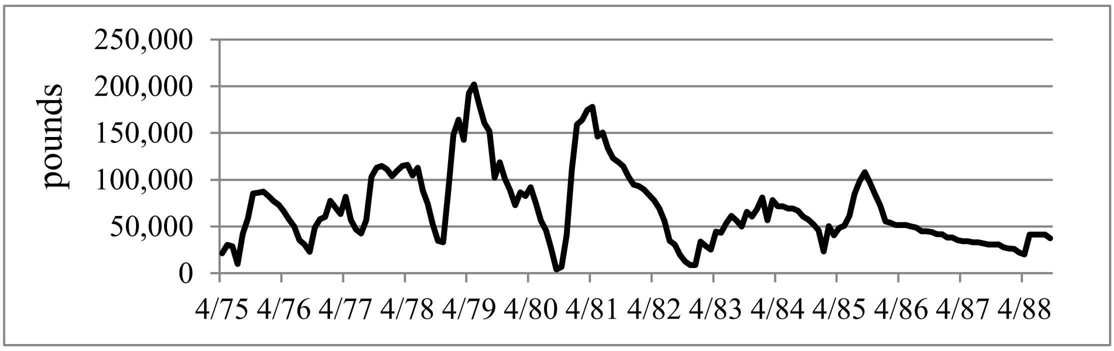

Figure C-8. Inventory of litharge. Raw data from the *Informe Mensual.*

Charcoal for smelting: the flat-lining of the inventory registered from early 1886 to the end of the period in question shows a smelting heart that had ceased to beat (Figure B-9). It would seem that management at Regla was caught unawares at the end of 1885 that smelting would not continue in the months ahead. Why this charcoal was not sold or used for the heating of *capellinas* or casting of silver bars is not clear, though it may indicate that it was kept for future potential smelting runs, at least until towards the end of 1888.

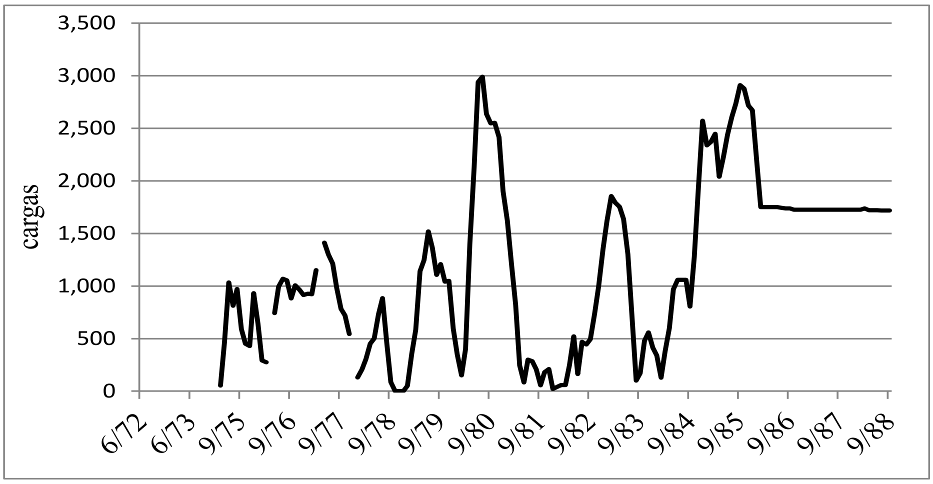

Figure C-9. Inventory of charcoal for smelting. Raw data from the *Informe Mensual.*

Though the mathematical average of the inventory over the period is equal to 1,094 *cargas* (151 t) per month of charcoal, storage would have been required to cope with the peak at 3,000 *cargas* (414 t) of charcoal inventory.

Estimating storage areas within Regla: The areas required for the stockpiling of solids stored at Regla have been estimated based on the analysis of the time series of inventory levels for the period 1872 to 1888 presented above. The calculation of a stockpile area is a well-established procedure based on the bulk density of the solid, the angle of inclination of the stockpile unless the solid is being constrained by walls or partitions, the height restrictions of the area available and the shape of the stockpile. The base area of the stockpile can be calculated via the geometry of the stockpile or the web pages of industries in the field of solids handling can be used to obtain the total area requirements for a given quantity of solid material. Table C-I sets out the relevant figures for the case of Regla. The source of the peak inventory levels will be found in the detailed discussions of each process stage in the following sections of this chapter, and this accounting data was used to calculate the required storage area.[1004] There is a good match between these calculated values and the approximate areas of the storage spaces assigned in Figure 4.7.[1005]

	deemed values					calculated		operational data	calculated	type of space	security level	space assigned	approximate area assigned (m^2)
			per stockpile			per stockpile							
	specific gravity	angle of repose	length (m)	width (m)	height (m)	calculated area (m^2)	amount (t)	Maximum inventory (t)	total area required (m^2)				
raw ore for amalgamation	2.4 (eq. to rock hard blasted)	38.6	10	6	5	300	1,125	2,100	560	open	low	S1	560
ground ore (stamp mill) for amalgamation	2.0 (eq. to rock/stone crushed)	38.6	10	6	5	300	900	1,400	467	open, with protection from wind and rain	low	S2	560
salt	1.9 (eq. to dry gravel)	38.6	5	5	4	165	390	460	195	under roof	medium	SA1	210
copper sulphate	1.9	38.6	5	5	1.6	26	25	18	19	under roof	medium	SA1	
mercury	13.56	n/a	n/a					20	The liquid would take up a volume of under 1.5 cubic metres	under roof	high	SA2	140
charcoal for amalgamation	0.21	n/a	5	5	4	25	21	12	14	under roof	medium	FA	50
raw ore for smelting	2.4	38.6	5	3	2.4	75	140	80	43	open	high	S1	see above
ground ore (stamp mill) for smelting	2	38.6	5	3	2.4	75	120	40	25	open	high	CBI or CBII	840
litharge	2	38.6	5	5	2.4	75	120	100	63	open	medium	CBI or CBII	
charcoal for smelting	0.21	n/a	5	5	4	25	21	400	476	under roof	medium	B1	500
silver	10.49	n/a	n/a					2	The bars would take up a volume of approximately 0.2 cubic metres	under roof	very high	?	n/a

Table C-I. Areas required by the average inventory of the main reagents, fuel and ore, as calculated from the raw data in the *Informe Mensual Regla.*

[1004] I have used the calculator on the website http://www.arthon.com/calculators/stockpile.shtml (18 June 2013).
[1005] In extraordinary circumstances of unexpected peaks of inventory, all available spaces within Regla would have been used to store materials.

D. Report of the costs of refining by cazo amalgamation and smelting, 1801.

Razon de la Compra y Fletes de tres Cargas de Metal y el de su beneficio por Cazo y Patio de ley de tres marcos cada una por ambos beneficios, dividiendo los costos para la mayor claridad en el concepto de que en la compra del Metal no pase de diez pesos cada carga pues de lo contrario disminuirá la utilidad del rescatador proporcionalmente de el mas o menos costo que erogue en la compra de las dichas tres cargas de Metal … A saver

Primeramente por tres cargas de Metal a razón de diez pesos cada una ....030 [p] 0 [rs]
Por el flete de dichas tres cargas a razón de veinte reales carga 007 [p] 4 [rs]
Gastos que se erogan en el beneficio de dichas tres Cargas por el Cazo ... A saber

Quebrador ……………………………………………………………………………	*000 [p] 3 [rs]*
Taonero ………………………………………………………………………	*000 [p] 4 ½ [rs]*
Paja para las Mulas ……………………………………………………………….	*001 [p] 2 ½ [rs]*
Caceadores ……………………………………………………………………	*001 [p] 4 [rs]*
Palma ……………………………………………………………………….	*001 [p] 4 [rs]*
Saltierra ………………………………………………………………………	*001 [p] 0 [rs]*
Taona ………………………………………………………………………	*000 [p] 3 [rs]*
Fondos ………………………………………………………………………	*000 [p] 3 [rs]*
Quema y Afinacion………………………………………………………………	*000 [p] 3 [rs]*
Salarios ………………………………………………………………………	*000 [p] 4 [rs]*
Perdida de azogue………………………………………………………………	*001 [p] 0 [rs]*
[total]	*8 [p] 7 [rs]*

Con las dichas tres carg[d] lama que llamamos cocida se pone una pieza o Monton que produzga tres Marcos de plata q.[e] para venderlo se erogan los gastos …….. A Saber

Saltierra ………………………………………………………………………	*01 [p] 1 [rs]*
Maxistral y Cal ….…………………………………………………………………	*00 [p] 1 ½ [rs]*
Repasos ………………………………………………………………………	*01 [p] 4 [rs]*
Tina y peones ………………………………………………………………………	*00 [p] 2 ½ [rs]*
Azoguero ………………………………………………………………………	*00 [p] 3 [rs]*
Perdida y Consumido de Azogue ……………………………………………….	*01 [p] 5 [rs]*
[total]	*5 [p] 1 [rs]*
Costos	*51 [p] 4 [rs]*

Han producidos por ambos procesos 9 marcos de plata que entregados al Aviador a 7 p[s] valen ……………………………………………………………………………. 63 [p]

Resulta de utilidad al Rescatador …………………………………… 11 [p] 4 [rs]

Para beneficiar por Fuego las dichas tres cargas de Metal han de erogar los costos … A saber
Por su compra ………………………………………………………………… 030 [p] 0 [rs]
Por su flete ………………………………………………………………… 007 [p] 4 [rs]
Por quebrarlas ………………………………………………………………… 001 [p] 4½ [rs]
Plomillos para ayuda ………………………………………………………… 001 [p] 7 [rs]
Rebolturero ………………………………………………………………………… 000 [p] 6 [rs]
Maquila de Horno………………………………………………………………… 009 [p] 0 [rs]
De Carbon ………………………………………………………………………… 007 [p] 2 ½ [rs]
Bazo …………………………………………………………………………………… 001 [p] 2 [rs]
Palma …………………………………………………………………………………… 000 [p] 4 [rs]
Perdida de Liga 18 @ [arrobas] a 15 p carga ………………………… 022 [p] 4 [rs]
Tienen de Costo 081 [p] 2 [rs]
Produciran de Plata por este beneficio quando bien valla siete marcos quatro onzas que a 7 p 4 valen ………………………………………………………………………… 056 [p] 2 [rs]
Resulta de perdida al Rescatad^{r} 025 [p] 0 [rs]

Por lo que no es beneficiable esta clase de Metales por fuego que son los que abundan en el Real de Catorce y si lo será el Metal de ley de diez marcos por carga que tenga algún jugo porque plomoso no lo producen aquellas Minas siempre que los Duenos de ellas vendan a un precio racional.

Resumen de los Costos de las tres cargas por beneficio de Azogue y los mismos por el de Fuego

Ymporta el de las tres cargas por el beneficio de Azogue ………… 014 [p] 0 [rs]

Ydm las mismas por Fuego …………………………………………… 043 [p] 6 [rs]

Exceso por el de Fuego 029 [p] 6 [rs]

Se ha hecho este calculo por los infrascriptos actuales Diputados de Mineria de esta Ciudad en presencia de los Ministros de Real *Hacienda* de esta Tesoreria, San Luis Potosi Abril 21 de 1801.

[fdo.] Matteo Garcia, Jose Ygnacio de Escalante

A nuestra vista y presencia

[fdo.] Cristobal Convalan? Francisco ¿ de Arce

Translation:

Account of the purchase and freight of three *cargas* of ore and their refining by *Cazo* and *Patio*, with a silver content of three marks each, by both processes, dividing the costs for more clarity under the condition that the price of the ore will not exceed ten *pesos* per *carga* otherwise the profit of the buyer will decrease proportional to the greater or lesser cost of the purchase of said three *cargas* or ore. … As follows:

First for three *cargas* of ore at ten pesos each one …………………..	030 [p] 0 [rs]
For the freight of said three *cargas* at twenty reales per *carga* ……..	007 [p] 4 [rs]
Costs incurred in the refining of said three *cargas* by *cazo* ……….	As follows
Bulk miller of ores …………………………………………………………	000 [p] 3 [rs]
Operator of *tahona* …………………………………………………………	000 [p] 4 ½ [rs]
Straw for mules …………………………………………………………	001 [p] 2 ½ [rs]
Operators of *cazos* …………………………………………………………	001[p] 4 [rs]
Palma [?] …………………………………………………………	001 [p] 4 [rs]
Impure Salt…………………………………………………………………	001 [p] 0 [rs]
Tahona …………………………………………………………………	000 [p] 3 [rs]
Deposits …………………………………………………………………	000 [p] 3 [rs]
Firing [amalgam] and refining ……………………………………………	000 [p] 3 [rs]
Salaries …………………………………………………………………	000 [p] 4 [rs]
Loss of mercury …………………………………………………………	001 [p] 0 [rs]
[total]	8 [p] 7 [rs]

With these said three *cargas* of silt we call cooked we prepare a *monton* that produces three marks of silver so that to sell we incur the costs ……………….. As follows

Impure salt …………………………………………………………………	01 [p] 1 [rs]
Magistral and lime ….………………………………………………………	00 [p] 1 ½ [rs]
Mixing the *monton*…………………………………………………………	01 [p] 4 [rs]
Washing vat and workers …………………………………………………	00 [p] 2 ½ [rs]
Master amalgamator ………………………………………………………..	00 [p] 3 [rs]
Loss and consumption of mercury ……………………………………	01 [p] 5 [rs]
[total]	5 [p] 1 [rs]
Costs	51 [p] 4 [rs]

Both processes produced 9 marks of silver that sold to the Supplier at 7 pesos are worth ………………………………………………………………………………. 63 [p]

Result of profit to the Buyer [of the ore] ……………………………………… 11 [p] 4 [rs]

To refine by smelting said three *cargas* of ore the costs incurred are …………	As follows
For their purchase ………………………………………………………………	030 [p] 0 [rs]
For their freight ………………………………………………………………	007 [p] 4 [rs]
For milling ………………………………………………………………	001 [p] 4½ [rs]
Lead rich ore as flux ………………………………………………………	001 [p] 7 [rs]
Mixer ………………………………………………………………	000 [p] 6 [rs]
Rental of furnace ………………………………………………………	009 [p] 0 [rs]
Charcoal ………………………………………………………………	007 [p] 2 ½ [rs]
Cupell ………………………………………………………………	001 [p] 2 [rs]
Palma [?] ………………………………………………………………	000 [p] 4 [rs]
Loss of lead flux 18 @ [arrobas] at 15 p *carga* …………………………	022 [p] 4 [rs]
Total cost	081 [p] 2 [rs]

Will produce silver by smelting when all proceeds well seven marks four ounces that at 7 *pesos* 4 [reales] have a value of ……………………………………………………… 056 [p] 2 [rs]

Resulting loss for the Buyer 025 [p] 0 [rs]

So that this type of ore cannot be refined by smelting, those that are abundant in the Real de Catorce and can be refined is the ore with ten marks per *carga* that contains some [lead] flux because lead-rich ores are not produced by those Mines, as long as the mine owners sell them at a reasonable price.

Summary of the costs for the three *cargas* refined by mercury and the same by smelting

From the costs for the refining of three *cargas* by mercury………..………… 014 [p] 0 [rs]

Idem for the same by smelting ………………………………………… 043 [p] 6 [rs]

Excess [costs] by smelting 029 [p] 6 [rs]

This calculation has been made by the undersigned, at present Mining Deputies of this City, in the presence of the Ministers of the Royal Treasury, San Luis Potosi, April 21 of 1801.

[signed] Matteo Garcia, Jose Ygnacio de Escalante

Witnessed in our presence

[fdo.] Cristobal Convalan [?] Francisco --- de Arce

Source: AGN, Instituciones Coloniales / Minería / 28368 / Volumen 82, folio 86 r,v

E. Sensitivity matrix for refining costs

Table E-I. Amalgamation sixteenth century context

Amalgamation												
	% silver in ore	0.00%	0.04%	0.05%	0.06%	0.08%	0.12%	0.19%	0.60%	1.00%	1.90%	3.00%
	kg of silver in *monton*	0.00	0.43	0.62	0.75	0.99	1.49	2.36	7.45	12.42	23.60	37.26
	value silver *pesos*	0	17	24	28	38	57	90	283	472	897	1416
	variable production costs *pesos* per kg silver	variable production costs in *pesos* per *monton*										
Fuel	0.04	0.00	0.02	0.03	0.03	0.04	0.06	0.10	0.32	0.54	1.02	1.61
Mercury	9.80	0.00	4.26	6.09	7.30	9.74	14.61	23.13	73.04	121.74	231.30	365.22
Salt	1.78	4.21	4.21	4.21	4.21	4.21	4.21	4.21	4.21	4.21	4.21	4.21
Copper Sulphate	0.72	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
Labour	0.13	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
others	1.93	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54
ore	*0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
cost power	1.20	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82	2.82
capital cost	0.50	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18	1.18
total	16.10	14.76	19.04	20.87	22.09	24.54	29.43	37.99	88.12	137.03	247.08	381.58
		variable production costs in *pesos* per *kg silver*										
		n/a	43.79	33.61	29.65	24.70	19.75	16.10	11.83	11.03	10.47	10.24

Table E-II. Smelting sixteenth century context

Smelting														
	% silver in ore	0.00%	0.04%	0.05%	0.06%	0.08%	0.12%	0.20%	0.60%	1.00%	0.80%	1.20%	1.90%	3.00%
	kg of silver in a *carga*	0	0.0435	0.0621	0.0745	0.0994	0.149	0.2422	0.7452	1.242	0.9936	1.4904	2.3598	3.726
	value of silver, *pesos*	0	2	2	3	4	6	9.2	28	47	38	57	90	142
	variable production cost *pesos* per kg silver	variable production cost in *pesos* per *carga*												
Fuel	2.23	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27
Litharge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Labour	0.13	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31	0.31
others	0.85	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
ore	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
total	3.21	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58	7.58
		variable production costs in *pesos* per *kg silver*												
		n/a	174.33	122.03	101.69	76.27	50.85	31.29	10.17	6.10	7.63	5.08	3.21	2.03

Table E-III. Amalgamation seventeenth and eighteenth century context

Amalgamation												
	% silver in ore	0.00%	0.04%	0.05%	0.06%	0.08%	0.12%	0.19%	0.60%	1.00%	1.90%	3.00%
	kg of silver in *monton*	0.00	0.43	0.62	0.75	0.99	1.49	2.36	7.45	12.42	23.60	37.26
	value silver *pesos*	0	17	24	28	38	57	90	283	472	897	1416
	variable production costs *pesos* per kg silver	variable production costs in *pesos* per *monton*										
Fuel	0.04	0.00	0.02	0.03	0.03	0.04	0.06	0.10	0.32	0.54	1.02	1.62
Mercury	2.68	0.00	1.17	1.66	2.00	2.66	3.99	6.32	19.97	33.29	63.25	99.86
Salt	3.66	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64	8.64
Copper Sulphate	0.72	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69	1.69
Labour	0.67	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58	1.58
others	1.93	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54	4.54
ore	*16.7*	*39.3*	*39.3*	*39.3*	*39.3*	*39.3*	*39.3*	*39.3*	*39.3*	*39.3*	*39.3*	*39.3*
cost power	2.84	6.70	6.70	6.70	6.70	6.70	6.70	6.70	6.70	6.70	6.70	6.70
capital cost	1.32	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13	3.13
total	30.51	65.57	66.76	67.26	67.60	68.28	69.63	72.00	85.87	99.40	129.84	167.05
		variable production costs in *pesos* per *kg silver*										
		n/a	153.57	108.31	90.71	68.72	46.72	30.51	11.52	8.00	5.50	4.48

Table E-IV. Smelting seventeenth and eighteenth century context.

Smelting														
	% silver in ore	0.00%	0.04%	0.05%	0.06%	0.08%	0.12%	0.20%	0.60%	1.00%	0.80%	1.20%	1.90%	3.00%
	kg of silver in a *carga*	0	0.0435	0.0621	0.0745	0.0994	0.149	0.2422	0.7452	1.242	0.9936	1.4904	2.3598	3.726
	value of silver, *pesos*	0	2	2	3	4	6	9.2	28	47	38	57	90	142
	variable production cost *pesos* per kg silver	variable production cost in *pesos* per *carga*												
Fuel	2.23	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27	5.27
Litharge	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Labour	0.66	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56	1.56
others	0.85	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00	2.00
ore	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
total	3.74	8.83	8.83	8.83	8.83	8.83	8.83	8.83	8.83	8.83	8.83	8.83	8.83	8.83
		variable production costs in *pesos* per *kg silver*												
		n/a	203.09	142.16	118.47	88.85	59.24	36.45	11.85	7.11	8.89	5.92	3.74	2.37

F. Smelting costs in Europe.

It is stated that ‘German mines could not compete with the lower cost of American silver and stagnated in the sixteenth century’, but there is no study that compares specific silver production costs on both sides of the Atlantic.[1006] The economics of smelting the majority of silver ores in Europe followed a completely different tsructure than the one applied to silver ores smelted in the New World, at least until the end of the nineteenth century. Three cases of European smelting costs from the nineteenth century plucked from a non-exhaustive search in the literature represent Germany, France and England. They show that it is not possible to carry out a straightforward comparison of smelting costs on both sides of the Atlantic. In the case of Europe it is the nature of the ores being treated and the existence of markets for non-precious metals that determines the profitability of refining, not their silver content as in the analysis for Regla.

Under Napoleon the French oversaw silver production in the German mines of the Harz region, and as a result Villefosse drew up a report that contains partial production costs both for mining of lead-silver ores and for their smelting for the years around 1805. On the basis of his data it is possible to calculate that the ores smelted at a profit had between 0.01 and 0.04% silver content. This would not have been possible at Regla using smelting, not for technical reasons, but simply because the value of the silver content alone could not have covered the cost of smelting. However, what allowed the German smelters to obtain a profit was the amount of revenues from the sale of litharge, lead and copper, which in total amounted to 75%

[1006] Brown, *History of Mining*, 42.

(Lautenthal), 94% (Frankenscharer), 104% (Altenau) and 45% (Andreasberg) of the smelting costs.[1007]

From the data on the smelting of ores at Pontgibaud (France) from 1838 to 1849 reported by Rivot, it is possible to calculate that the average cost of refining 100 kg of ore with 0.1% silver was 23.45 francs. The silver content is similar to that of the ores smelted at Regla, but approximately 200 times more lead and litharge was produced than silver, so production costs cannot be apportioned easily to one or the other. The average value of the silver obtained was only 24 francs, thus barely exceeding the refining costs, which approximates the scenario at Regla where the minimum was 0.3% silver to cover costs. Again, the only reason the French smelters were able to operate at a profit were the average additional revenues of 8.2 francs from the sale of lead products per 100 kg of ore.[1008]

Rivot also refers to English smelters in Flintshire in the nineteenth century working with ores that contain mainly lead (ca 75%) and little silver (25 to 35 gr of silver per 100 kg of lead, less than 0.03% silver in the ore). He could not include real production data from these works in his very extensive book on metal smelting since 'the directors do not like to provide strangers with details on their commercial affairs', a sentiment that has dogged most archival research for this topic. His case study for a generic smelter of Flintshire is based on a process using crystallization (Patterson's process) to enrich the lead prior to cupellation (Chapter Four). He assumes a yearly refining of 21,000 tons of ore, producing 15,005 tons of lead and 3,740 kg of silver. Silver represents just 0.03% in weight of the metal sold from this generic plant, but provided 10% of its sales revenues. There is little point in estimating which part of the total

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[1007] Héron de Villefosse, *De la richesse minérale du Royaume de Westphalie*. Raw data for my calculations taken from Table facing p. 102.
[1008] Rivot, *Description des gites métallifères*, 193-197.

production cost of 18.6 francs per ton of ore smelted can be apportioned to silver.[1009] This example encapsulates very well the symbiotic relationship that characterized the silver smelting business in Europe. Lead and copper would bear most if not all of the variable production cost, and silver would bring an important contribution to the revenue stream out of proportion to its output in weight. It is no wonder that Percy reports that in England 'foreign silver ores, chiefly from South America [with a silver content upwards of 0.8%], have been largely imported and smelted for the past 40 years … the business appears to have been highly profitable … not more than 2s 6d was paid per oz of silver in the ore!'.[1010]

[1009] '*les directeurs n'aiment pas à donner aux étrangers des renseignements exacts sur leurs affaires commerciales' Principes généraux* Vol II, 317-19, 386-88.

[1010] Percy, *Metallurgy*, I 524-525. If Collins is correct that 1 peso was equivalent to approximately 2s 6d in the 19c, the price being paid for the ore was around 1 peso per oz of silver, or 8 pesos per mark. I am not sure whether the celebration in the exclamation mark comes from the seller, the buyer or both. Collins, *Metallurgy of Lead & Silver*, Vol. II, 61.

Glossary of technical terms

Afinación: second stage of refining process where silver is separated from lead and litharge (*greta*) is produced (cupellation)

Amalgamation: the original term refers to a physical process whereby mercury can absorb gold, silver, lead and other metals and form a liquid or solid solution which does not alter the chemical characteristics of either mercury or the metals. In the terminology of refining silver ores in the New World it has been applied to represent a method of refining silver or gold using mercury to extract silver in the form of an amalgam

Arrastre: circular grinding equipment using horizontal stones, powered by water or animal power

Assay: analysis or test of an ore to determine the presence and amount of metal

Aviador: person who supplies material on credit to miners and refiners

Azogado: person intoxicated with mercury

Azogar : to intoxicate with mercury

Azogue : mercury

Azogueria: room where mercury was handled (stored, weighed, extracted by squeezing from amalgam)

Azoguero : in New Spain, applied to the master in charge of the amalgamation process

Barra: bar of silver-enriched lead from first stage of smelting (see *refinación*)

Beneficio: term applied to refining, ie *beneficio de plata por azogue* meant refining of silver ores by amalgamation, *beneficio de plata por fuego*, refining by smelting

Blast furnace: a more efficient furnace than the *Horno Castellano*, ore was loaded from the top, a greater current of air was fed by force into the furnace and chimney height was increased

Bonanza: a very rich zone of precious metal in a deposit

Caja: regional Treasury, usually but not always a mining district

Calomel: mercurous chloride (Hg_2Cl_2)

Capellina: 1. Equipment to recover mercury from amalgam by heating, consisting of a metallic top cover and base placed on water channel that condenses mercury 2. In Guanajuato, also applied to building that houses the *capellina* ensemble.

Caperuza: upper part of early version (16c) of equipment to recover mercury from amalgam, made from clay or metal

Carbón: see charcoal

Carcámo: channel to drain waste water that run through amalgamation *hacienda*.

Cazo: a pot or vessel, used by Barba for his *cocimiento* (cooking) process using mercury

Cendrada: bone ash impregnated with litharge, material used to form a cupel (*vaso*) that holds the *barras* for the *afinación*

Charcoal: mainly carbon, is used both to supply heat upon combustion in a furnace and to act as reducing agent to the metal compounds being smelted.

Chilean mill: see *Molino*

Correspondencia: amount of silver, in marks which could be produced by amalgamation that consumed 100 *quintales* of mercury

Cupellation: see *Afinación*.

Deflaction : adjustment of time series of prices by the rate of inflation

Desazogadera: equipment to recover mercury from amalgam by heating, see c*apellina*

Diezmo: tax of a tenth applied to silver registered at each local Treasury (*Caja*)

Dressing: concentration of silver content in ores by decantation in water.

Dry ore: silver ore with little or no lead destined for smelting

Fundición: first step of the refining of silver ores, it involves smelting of silver compounds in the presence of lead to elemental silver. Silver is then absorbed by the molten lead. The silver-enriched lead is then cast into *barras* (pigs)

Flue gas: gas generated in a furnace and channeled via a chimney to the atmosphere

Flux : additive used to facilitate the smelting of an ore

Fume: an aerosol of particles of lead and lead compounds (PbO, PbS, $PbCO_3$, others) that are lost to the atmosphere when lead and lead ores are heated above a threshold temperature

Fundición: smelting of silver compounds in the presence of lead to elemental silver. Silver is then absorbed by the molten lead. The silver-enriched lead is then cast into *barras* (pigs)

Galena / *Galena*: lead sulphide (PbS), which can contain silver that can be extracted by smelting

Gangue: the inorganic matrix with no commercial value that is extracted together with the mineral of commercial interest from a deposit

Grasas: slag from smelting furnace

Greta: litharge, lead oxide (PbO)

Hacienda: original term referred to the creation of wealth, was then applied initially to silver refining units in New Spain (called *ingenios* in Peru) and afterwards to agricultural and livestock economic units

Horno Castellano: initially very simple smelting furnaces, in the form of a pillar with a square or circular cross-section, built from mortar and stones and with a low chimney outlet

Ingenio: originally refers to a machine, and then in Peru was used to denote a silver refining facility (an *hacienda* in New Spain).

Lavado de metales: see Dressing

Litharge: lead oxide, PbO (*greta*)

Maestrazgo: land and mining rents to the Spanish Crown from territories that historically were under the control of Spanish military orders

Manga: vertical cloth filter used to squeeze excess mercury from amalgam

Maquila: business model whereby a refining hacienda accepts to process silver ores that belong to third parties and extracts the silver for a fee that covers its operational costs plus a profit margin

Mark: unit of weight of silver

Metal : ore in Spanish

Metallogeny: the study of how ore deposits are created

Mole: in chemistry, is a standard weight for each chemical element. The number of moles of a reagent or product in a reaction is determined by the chemical equation of the reaction.

Molino: circular stone set on its edge and driven by water or animal power, used to crush ore

Montón: literally mound, was a unit of measure in the amalgamation *patio*, thus a *torta* at Regla was composed of 20 *montones*, and each *montón* represented 30 *cargas* (see Units of Measure). These are not universal values and vary according to local custom.

Mortero: mill that uses stamp-heads made of stone or metal to crush ore, driven by human, animal or water power

Negrillos: term used to denote deeper silver sulphides in a deposit

Opportunity cost: the economic consequence of choosing an investment between two competing business options

Ore : a naturally occuring material from which a mineral can be extracted at a profit

Oxidation: in modern chemistry denotes the increase of the oxidation state of an element, due to the loss of electrons to another element that in turn is being reduced (see Reduction)

Patio: the courtyard where amalgamation cakes (tortas) were spread out until the silver amalgamation process was deemed completed

Pig : English term in smelting for a bar (*barra*) of smelted metal

Placer gold: gold found in alluvial or eluvial deposits

Planillas: inclined planes to separate entrained amalgam, mercury or silver ore from the washings of the amalgamation *torta*

Planilleros: workers stationed at the *planillas*

Plata de azogue: silver refined by amalgamation

Plata de fuego: silver refined by smelting

Real de Minas: legally established mining interests and community recognized by the Spanish Crown and subject to its legislation

Reduction: in modern chemistry denotes a decrease in the oxidation state of an element, by accepting electrons from an element that in turn undergoes oxidation (see Oxidation), for example carbon in charcoal. The ultimate aim of all refining techniques for metals is to chemically reduce the metal from its oxidized state in the ore, for example silver sulphide or silver chloride, down to its elemental state as pure metal

Reverberatory oven: indirect heating reflected from curved roof, fuel is not in contact with *barras* in the *vaso*

Señoreaje : duty paid on coinage of silver

Silver chloride: AgCl, when found as a mineral is called cerargyrite or chlorargyrite

Silver halides: silver chloride, silver bromide, silver iodide

Silver sulphide: AgS, when found as a mineral is called acanthite or in older texts argentite

Slag: fused waste minerals from smelting furnace, may contain lead and lead compounds, iron compounds, traces of arsenic

Slurry: viscous suspension of fine solids in water

Smelting: metallurgical process based on the chemical reduction of metal compounds in ores at high temperatures (see *Fundición*)

Solimán: mercuric chloride ($HgCl_2$)

Stamp mill: see *Mortero*

Stoichiometry: fixed quantitative relation between reactants and products in a chemical reaction

Subduction: geological process whereby an expanding ocean floor slides under continental masses

Sunk cost: losses incurred in past operations that from an accounting point of view are written off from future accounting operations involving the same product

Tahona or *taona*: see *arrastre*

Toll / tolling: see *Maquila*

Torta: amalgamation cake

Tuyere: element in back furnace wall with orifice to hold the nozzle (*cañon*) of the bellows

Vaso: term used for the ensemble of reverberatory oven and cupel used during the *afinación*

Weathered, weathering: as applied to ore deposits means the action of oxygen, water and salinity over hundreds or thousands of years on the chemistry of the surface veins of the deposit

Wind rose: circular plot over 360 degrees of average speeds and direction of winds at a given locality

Zangarro: amalgamation unit smaller than the *hacienda*

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