ROCKS & ORES FROM THE SULLIVAN MINE, KIMBERLEY, B. C.

A PETROGRAPHICAL STUDY

OF

SPECIMENS OF ROCKS AND ORES

FROM THE

SULLIVAN MINE, KIMBERLEY, B.C.

THESIS

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INTRODUCTION

The Sullivan mine was discovered by Patrick Sullivan and three associates in 1895, and during the next year was bonded to Col. Redpath and Judge Turner of Spokane, Washington. The Sullivan Group Mining Company of Spokane was later formed to take over the property, and a smelter, which was designed to treat ore from the mine, was completed in 1903 at Marysville, B.C. The Marysville smelter was finally closed down in 1908, and two years later the properties of the above company were acquired by the Consolidated Mining and Smelting Company of Trail, B.C. Subsequent development work carried out by this company has proved that the Sullivan mine constitutes one of the largest known lead-zinc deposits of the world.

During the summer of 1924 Dr. J.A. Bancroft of McGill University, at the request of the Consolidated Mining and Smelting Company, made an examination of part of the mine. One of the results of this examination was the collection of the material which forms the basis of this thesis. The writer is indebted to Dr. Bancroft for his kindness in placing this material at his disposal, as well as for constant advice and assistance in the writing of this thesis.

GENERAL DESCRIPTION OF THE REGION

The so-called Kimberley district, in which the Sullivan deposit occurs, is situated in the Purcell range of the Cordillera in Canada. It lies about eighteen miles northwest of the town of Cranbrook, which is on the Crows Nest branch of the Canadian Pacific railway.

The Purcell range is, roughly, an elliptical group of mountains two hundred and fifty miles long and sixty miles wide, lying between the Selkirk system on the west and the Rocky Mountains proper on the east. It is separated from the latter by the narrow depression known as the Rocky Mountain trench and from the former by the valley of Kootenay lake -- hence the term "East Kootenay District" commonly applied to this region. These mountain systems and valleys all have a trend slightly west of north.

This section of southeastern British Columbia is of a mountainous character, and three general types of topography may be recognized. In the west the region is characterized by rugged mountain peaks, many of which attain elevations of nine thousand feet. In the central section rough serrated mountains alternate with more subdued types, which appear to consist of softer and more easily eroded rocks. Easterly, towards the Kootenay River Valley, the mountains have a more rounded outline, generally with wooded summits, and, with decreasing elevation, they gradually merge into the prairie land of the Kootenay valley.

As might be expected, valley-head cirques or old glacial amphitheatres are numerous throughout the region, and in places these are somewhat modified by more recent talus slopes.

The master drainage stream of this area is the Kootenay river, which, rising to the north, partly in the Purcells and partly in the Rockies, flows south, crossing the International boundary line at Gateway, and thence turning back by a semi-circular course into Canada, finally emptying into Kootenay lake. The five main tributary streams of this river in the Cranbrook district are the St. Mary, Gold Creek, Yahk river, Moyie river and Goat river, nearly all of which have their sources in rock basins or glacial cirques of the mountainous region.

GENERAL GEOLOGY

The Purcell range is made up of sedimentary rocks, which once occupied the western part of the Rocky Mountain geosyncline. These sediments have been named the Purcell series and they are of Pre-Cambrian or so-called Beltian age. Lithologically they consist of a vast series of quartzites, argillites and limestones, which are all of a more or less constant nature. The old land surface from which these sediments were derived is thought to have lain to the west; but most of the evidence of Pre-Beltian rocks in the Selkirks has been obliterated by granitic intrusions, and subsequent erosion.

Jurassic?----	Orogenic movements; formation of Purcell range followed or accompanied by intrusion of Kootenay granite.
Carboniferous--	Wardner formation.
Devonian-------	Jefferson limestone.
Silurian-------	Erosion.
Ordovican------	Erosion.
Cambrian-------	Erosion.

Purcell Series:-

Pre-Cambrian (Beltian)	<u>Gateway formation</u>. Sandstones, argillites, siliceous dolomites. <u>Purcell lava</u>, <u>Purcell sills</u>. Intrusive gabbro sills and effusive basalt. <u>Siyeh formation</u>. Argillites (red, purple, [illegible] green) sandstone, some limestone. <u>Kitchener formation</u>. Calcareous argillites, argillaceous quartzites, some limestones. <u>Creston fromation</u>. Quartzites, argillaceous quartzites. <u>Aldridge formation</u>. Argillaceous quartzites, quartzites and some limestones.

SEDIMENTARY ROCKS

For the most part the sedimentary rocks of the Purcell series are made up of a great thickness of fine grained quartzites and argillaceous quartzites, together with a relatively very small proportion of limestones. The Sullivan ore-bodies occur within the oldest member of the series, called the Aldridge formation. In thickness, this includes some eight thousand feet of sediments, three-fourths of which are dark greenish-grey argillaceous quartzites, characterized in surface exposures by rusty weathering. Associated with these, and comprising about one quarter of the total thickness of the formation, are some purer quartzites of greenish colour.

An excellent opportunity to examine microscopically these quartzite members of the Aldridge formation in the vicinity of the Sullivan mine was afforded by numerous thin sections prepared from specimens taken from the cores of three diamond drill holes. (Nos. 121, 140, 235 Sullivan mine).

Argillaceous Quartzites.

In places the argillaceous quartzites of the Aldridge formation exhibit a finely banded or laminated appearance, the bands ranging from a fraction of an inch to one or two inches in width. Successive bands are frequently of different light or dark shades, the colour of any band depending on the proportions of the chloritic or sericitic material present.

In thin section under the microscope it is seen that quartz constitutes about 50 per cent of the rock. It occurs in the form of small (0.05 mm) angular interlocking grains which are irregularly distributed in a matrix of fine sericitic flakes. In many of the thin sections examined, narrow streaks of opaque dust-like carbonaceous material arranged parallel to the banding of the rock were observed, and it was noted that they are in greatest abundance in the thinly bedded and more argillaceous sediments.

Less abundant than the quartz and sericite are biotite, chlorite, muscovite, calcite, sphene, zircon, magnetite, tourmaline, pyrite, pyrrhotite, zoisite and epidote.

Biotite.-- This mineral forms prominent plate-like patches of irregular outline in the more argillaceous quartzites. It is of pale brown colour, polarizes in brilliant tints, and the individual patches are commonly of larger size than the surrounding clastic grains. It is for the most part of fresh appearance.

Chlorite.-- Chlorite occurs in similar manner to the biotite, but is usually less abundant. In some sections it forms narrow veinlets traversing the rock, and it may represent an alteration product of the biotite.

Muscovite.-- This mineral occurs in well developed blades, which intersect and penetrate the other constituents, and are frequently enclosed by calcite and biotite.

Calcite.-- Irregular grains and nests of grains of calcite are quite prominent in some of the sections. Minute grains of the other constituents are sometimes poikilitically included in the calcite.

Sphene.-- Granular to dusty aggregates of a pale brownish mineral, which is white in reflected light, are of common occurrence in nearly all the sections. Possessing a high index of refraction, and polarizing in brilliant tints, this mineral is probably sphene, associated with which there may be a little leucoxene.

Zircon.-- Small rounded to subangular grains of zircon, apparentlynretaining their original water-worn forms, are sparsely disseminated in some of the rocks.

Magnetite.-- Minute grains of this mineral are present in some of the sections. In a few places they were observed to be surrounded by a secondary outgrowth of silica from the surrounding quartz grains.

Tourmaline.-- In nearly every section examined small prisms of honey-yellow tourmaline are to be seen. These invariably exhibit a sharp crystal outline, and they cut across and penetrate all the other minerals, with the exception of zoisite, epidote and the sulphides. As the ore-body is approached these prisms increase in number and size, and they are often seen in the ore itself. That they are of pneumatolytic origin seems to be beyond any reasonable doubt.

Pyrite and Pyrrhotite.-- These two sulphides are widely disseminated through the sedimentary rocks in the vicinity of the Sullivan mine. Microscopically they form irregular patch-like grains in the quartzites, and apparently they replace biotite, as in places some individuals of this mineral partially replaced by sulphides were noted.

Zoisite and Epidote.-- The grains of pyrite and pyrrhotite are often bordered by an irregular rim of zoisite and epidote, zoisite being the more common. These two minerals were also noted in association with minute cross-cutting veinlets of calcite and quartz. Their association with the sulphides and occurrence in veinlets leads to the belief that they are undoubtedly connected with emanations which accompanied or immediately preceded the ore-bearing solutions.

Quartzites.

In hand specimen, the purer quartzites, which are intercalated with the more argillaceous members of the Aldridge formation, exhibit a characteristic green to grey shade of colour, and for the most part are medium to fine in grain. As might be expected, they exhibit very much the same mineral associations as do the more argillaceous quartzites, from which they differ mainly in that the quartz grains are often of a larger size, and comprise four-fifths or more of the total volume of the rock. Sericitic flakes again occur in a very fine network interstitially between the quartz grains. All of the other minerals described in connection with the argillaceous quartzites are commonly present; but owing to the increase in the amount of quartz in the purer quartzites, they are relatively less abundant. The only additional minerals noted in these rocks consist of a few rounded grains of striated feldspar and a number of flakes of penninite.

In several of the thin sections examined, both of the purer and the more argillaceous quartzites, the constituent minerals show a distinct tendency to parallelism, and the quartz grains in many instances exhibit marked strain shadows.

From the microscopic study of these sedimentary rocks it is apparent that processes of recrystallization have obliterated the original outlines of the grains of the component minerals, with the exception of the sparsely distributed zircons. New minerals developed by this action are biotite, muscovite, sphene and calcite, which in their present form probably represent recrystallized products, formed from the original binding or cementing material.

IGNEOUS ROCKS

Igneous rocks in the Cranbrook area may be classed under three heads:- (1) the Purcell sills, (2) the Purcell lavas, and (3) granite bosses or stocks.

The Purcell sills are relatively more numerous in the Aldridge quartzites; but they occasionally occur in other formations of the Purcell series. In thickness, they range from a few feet to upwards of two thousand feet, and being more resistant to weathering than the rocks enclosing them, they stand out as striking topographic features.

These sills are of widespread distribution being found both in the East Kootenay district, and to the south in Idaho, where they are associated with the equivalents of the Purcell series. Lithologically they range in composition from a hypersthene gabbro to a very acid granite or granophyre, both of which types may be present as features of differentiation within the same sill.

The Purcell sills are probably of Pre-Cambrian age, and are looked upon as the intrusive equivalent of the lava flows intercalated within the Purcell series.

The last, and what is believed to be a very much later, phase of igneous activity consisted in the intrusion of a number of small stocks or bosses of granite. As has been mentioned previously, the granite stocks are generally regarded as representing satellites of the great granite batholith of the West Kootenay district, and are believed to have been intruded during Upper Jurassic time.

Several dyke-like bodies of igneous rock, of pre-mineral age, traverse the ore-bodies of the Sullivan mine. Two of these dykes are present in the workings on the 1100 level, where the larger of them attains a maximum true width of twenty feet, has a general strike of N.67°W., and dips in a northeasterly dirrection at 55°. The other dyke cuts across the ore-body at its northern end, has a true width of from three to four feet, a strike of N.20°E., and an easterly dip of 18°. Two other specimens of igneous rock were examined— one taken from the surface exposure of a large sill at the northwest corner of the V.A.D. claim, and the other from the southern end of the westerly workings on the 1000 level.

Hand specimens from the larger dyke on the 1000 level, and a sample from the surface exposure in the V.A.D. claim, resemble one another very closely. They are of dark green colour, medium to fine-grained, and consist chiefly of hornblende (typeI). The specimen of the dyke from the northern end of the 1100 level, and that from the southern end of the westerly workings on the 1000 level, differ somewhat from the above, and also from one another, both in mineralogical character and appearance. The first of these is a relatively soft rock of olive-green colour and very fine grain (type II), while the second is a comparatively fresh rock, dark grey in colour, uniformly fine-grained, and containing numerous flakes of biotite (type III).

Microscopic study of these dykes suggests that they represent three closely allied types, now altered more or less intensly by processes of recrystallization.

The most abundant mineral in the first type is pale green to colourless hornblende, occurring in ragged individuals that seem to be of secondary origin, and may have been derived from the uralitization of augite. The feldspathic constituents have been so altered that the polysynthetic twinning has in most cases entirely disappeared, and this mineral is now represented by aggregates of little scales of sericite, together with calcite and sometimes a little epidote. Large ragged patches of zoisite, with which is associated a small amount of epidote, are plentiful, and while some of these may represent altered pyroxenes, others are no doubt due to the metasomatic action by mineral solutions. Ilmenite, in small grains with borders of leucoxene, is abundant, and sphene, sometimes displaying a sharp idiomorphic outline, is present in most of the thin sections examined. An invariable constituent is pyrrhotite, in disseminated patches, and, as might be expected, these become increasingly numerous as the contact with the ore-body is approached. Here, also, garnet, in small sharply idiomorphic crystals, becomes conspicuous. A few small irregular patches of quartz, probably of secondary origin, were noted in most of the slides. Between crossed nicols they are seen to be aggregates of small angular interlocking grains. From their appearance under the microscope it is concluded that these rocks represent a highly altered gabbro or diorite.

The second type of dyke rock is seen to be composed of numerous pseudomorphs of calcite after idiomorphic augite or feldspar, or possibly both. These are distributed within a ground-mass of chloritic scales that surround the calcite pseudomorphs in zonal arrangement, probably representing altered biotite, as secondary magnetite fills some of the cleavage laminae of the chlorite. The remainder of the section is made up mostly of calcite which has formed through the alteration of the original feldspathic material of the ground-mass. A few specks of pyrrhotite, as well as a little granular sphene, are present. This rock in ite original fresh state was probably an augite porphyrite.

Microscopically, the matrix of the third type of rock is seen to be composed, for the most part, of a hash-like mixture of calcite, chlorite (derived from the alteration of biotite), and a little dusty quartz. Distributed through this are larger biotite flakes in part altered to chlorite. The rock also contains numerous small opaque grains that are white in reflected light, and seem to represent partly altered titaniferous magnetite. Apatite, in minute prismatic crystals, is a prominent accessory mineral. Prior to alteration, this dyke was either a kersantite or a minette, probably the latter.

At contacts between the igneous rocks and the ore, extreme phases of alteration have in places resulted in the development of a pink garnetiferous rock, that, in addition to garnet, contains a small amount of pale green hornblende and quartz.

Certain phases of the quartzites that have been subjected to alteration by the mineral-bearing solutions are very difficult to distinguish from the dyke rocks just described, having a very similar texture, and also, owing to the development of hornblende and chlorite, resembling them in colour.

From the point of view of economic development of the property, the recognition of these dykes is of the utmost importance, as mineral-bearing solutions were unable to replace them to form ore, and consequently in places they may have formed effective barriers to the ready circulation of such solutions. They now represent continuous masses of waste rock, the largest of which, in favourable places, can be utilized as pillars.

THE ORE BODIES

The main outcrop of the Sullivan ore-bodies occurs on Sullivan hill, at an elevation of 4700 feet above sea level. In the valley of Mark creek, about one mile south of the outcrop, the elevation, because of the southerly slope of the hill, has descended to 3800 feet. As has been previously mentioned, the deposit is enclosed by the rocks of the Aldridge formation. The petrographical character of these rocks has already been described under the heading of sedimentary rocks. The character and distribution of the dykes and sills of igneous rocks that traverse the Aldridge formation, as well as the dykes which are found in the workings of the Sullivan mine, have also been discussed in a previous section of this paper.

The surface exposures of the ore-body are confined to a few gossan-covered outcrops. This is due to the fact that a heavy mantle of drift, usually ranging from twenty-five to over one hundred feet in thickness, covers most of the bed-rock in the vicinity of the deposit.

The strike and dip of the ore-body conforms faithfully with that of the enclosing sedimentary rocks, which here have a general north-south trend, and an average dip of about 25° towards the east. In the underground workings of the mine, below the 3900 level, this dip has been found to increase to about 35°.

At its extreme southern end, the ore-zone is narrow, and its strike curves sharply from the east; but as it is followed towards the north it widens out into a large lenticular body, which is known as the South ore-body with a length of 700 feet. Them, for about 1500 feet further northward, the ore-zone narrows down somewhat, and is composed mainly of iron sulphides, with very little lead and zinc. At the northern end of this central iron-rich zone, there is a second productive lens, known as the North ore-body. The whole length of the ore-zone, as at present known, is in the neighbourhood of 3800 feet, this length including, both the productive lenses at either extremity, and the non productive central zone.

The deposit represents a selective replacement of certain beds of the Aldridge formation, that were of such a composition or character that the ore-bearing solutions were able to replace them.

The metasomatic nature of the deposit is clearly shown by the typically banded ore, in which the original laminated character of the quartzites has been perfectly preserved. Throughout the deposit, the ore generally has this banded structure, and consists of an intimate mixture of fine grained galena, zincblende and iron sulphides, and contains as an average, 11% lead, 10% zinc, with approx-

-imately one ounce of silver for every three and one-half units of lead. In certain places, however, a purer and more coarsely crystalline galena takes the place of the banded ore.

Structural Features-

The regional structure of the area in which the Sullivan deposit occurs has not as yet been worked out in great detail. The structural features of the sedimentary rocks enclosing the deposit may be divided under three heads;- (1) major strike folds, (2) minor strike folds, and (3) cross folds. The major strike folds, which have a N.-S. trend, and control the strike and dip of the ore-body, were produced by pressure from the west. This pressure developed the wave-like folding of the sedimentary strata in which the dip is steep on the western and more gentle on the eastern limbs.

Superimposed on these broader folds are a multitude of minor strike folds, many of which are overturned or show a tendency to be overturned towards the east; thus proving conclusively that the thrust came from the west.

Cross-folding of the above structure has taken place, the axes of the cross-folds striking north 20°-35°east.

Whether the strike and cross-folds represent two separate periods of folding, or whether they are due to one period, associated with a certain amount of torsion, is a question of purely academic interest. A torsional effect, produced by a locally more rapid relief of pressure on one side of the axial plane of the fold than on the other, would result in cross-folding.

Many examples of the manner in which the folding has controlled the detail of the form of the ore-bodies, might be cited. The local dip of the ore-zone ranges from horizontal to vertical, and in places even a reverse inclination has been developed. Thickening on the crests and thinning on the limbs of the folds is well exemplified. The thickness of the ore-body, due to this cause, varies from a few feet to 240 feet.

The North ore-body appears twice on the 1000 level, and ore is also known to occur in the intervening syncline below this level between the present east and west workings. All of the above features of the ore-body are due to the major strike folds. The contorted character of the banded ore, that is especially noticeable on the western limbs of the major strike folds, is a direct result of the overturning, caused by the minor strike folds. The cross-folding is responsible for the peninsula-like bulges, which project into the hanging wall; as well as for the formation of sags, that, in many places, lower the backs of the stopes almost to the sill floor.

The above brief outline will serve to show, in a general way, some of the consequences of the three types of folding. The recognition of the part played by the folding, in controlling the form of the ore-bodies, is essential from the point of view of intelligent development and mining of the deposit.

In a number of places, fractured zones of post-mineral age traverse the Sullivan ore-bodies. These have a general strike of N.15°W. and a dip of 80°E. Although the rock in the zone of the fractures is slickensided, no appreciable displacement has taken place. Dr. J.A. Bancroft has applied the name of "shudder" planes to these fractures, and the slickensiding is accounted for by the vibratory motion that took place along these zones. Many of these fracture planes have been the channels for cold mineral bearing solutions, that in favourable places, have crystallized out, giving rise to such minerals as aragonite, calcite, quartz and marcasite, the last mentioned forming botryoidal masses on top of the calcite.

Mineralogical Character of the Ore.

The most striking features of the main part of the Sullivan ore are its dense, fine-grained character and banded appearance. The bands range from a fraction of an inch to three inches in width, and consist of alternating bands of galena and zincblende, both very fine-grained. Associated with these bands, in greater or less abundance, are laminae of altered and partly replaced quartzite, as well as occasional bands of fine-grained pyrrhotite, with which there may be a small amount of pyrite. Due to the minor strike folding, and selective replacement of favourable laminae, the banded ore often exhibits a contorted appearance, sometimes with a relative shortening of the individual laminae of about four to one.

Other and minor phases of the ore are small bodies of coarsely crystalline galena and zincblende, usually associated with some pyrrhotite and a very small proportion of gangue minerals. These high grade bodies seem to have had a tendency to form at the crests of anticlinal folds. Gradational phases are not general, the line of demarcation between merchantable ore and barren rock being usually sharp; but near the walls of the ore-body, there appears to be a greater proportion of unreplaced quartzite laminae, and also an increase in the number of pyrrhotite and pyrite bands.

In thin section, under the microscope, the typical ore is seen to be composed of alternating bands consisting essentially of very finely crystalline galena and zinc-blende respectively. The bands of galena always contain a certain amount of zincblende, and vice versa, while pyrrhotite and sometimes a little pyrite is present in both sets of bands. In this phase of the ore, gangue minerals are limited to relatively very small proportions of chlorite, muscovite, siderite, zoisite and epidote. A certain tendency of these gangue minerals to occur in streaks or bands was noted. This is no doubt due to their development in former original laminae of the sediments. All of the gangue minerals are surrounded, corroded and partly replaced by the sulphides, and only muscovite and chlorite show any semblance to idiomorphic outlines. Some of the chloritic crystals polarize in dull grey tints, show repeated twinning, and may be ottrelite. The order of crystallization of the sulphides is pyrite, pyrrhotite, zincblende, and galena. In the case of the last three overlapping has taken place to some extent, and this accounts in some measure for the intimate mixture displayed by the sulphides.

Several thin sections of the more coarsely crystalline galena and zincblende ores were examined. In the coarse galena ore, the gangue minerals occur only in very small amounts, and may be entirely lacking. They consist of muscovite, chlorite, quartz, calcite, siderite and tourmaline, and all of them are corroded and partly replaced by the sulphides. The sulphides in this phase of the ore are coarsely crystalline galena, with included patches of pyrrhotite. Large, partly idiomorphic, individuals of quartz, containing minute gas bubbles, are present, and they seem to have been developed just prior to the pyrrhotite. A few irregular patches of calcite are also present. Muscovite and chlorite form blade-like crystals, that have been only slightly attacked by the solutions that deposited the sulphides. An irregular patch of siderite, enclosing some crystals of muscovite and chlorite, as well as one prism of tourmaline, is to be seen in one of the thin sections.

In hand specimens the coarsely crystalline zinc-blende ore is almost black in colour, and in addition to zincblende contains numerous pale green idiomorphic crystals of hornblende. In thin section under the microscope this phase of the ore is seen to consist of zincblende, in which are distributed numbers of idiomorphic blade-like crystals of actinolite. Associated with the actinolite, there are a number of apparently later and somewhat corroded calcite crystals. Both the hornblende and calcite are partly replaced by the zincblende.

The last, and what may be called a gradational, phase of the ore, is represented by laminated argillaceous quartzite containing a number of thin bands of ore. As might be expected, gangue minerals are more abundant in this phase, than in those described above. These gangue minerals have been formed largely in the bands of unreplaced quartzite, and consist of the same minerals as those previously discussed, with the addition of a pink manganese bearing garnet that appears, usually in idiomorphic form, both in the ore and in the wall rocks near the ore-body. An analysis was made of this garnet, the material being obtained from a sample of pyrite ore, that, in addition to numerous small (1/8") idiomorphic garnets, contained a little pyrrhotite. A thin section prepared from this sample showed that the garnets were crowded with minute particles of pyrite, that had a tendency to zonal arrangement. After crushing, the garnet was carefully picked out and ground to 200 mesh, and the resulting material treated in weak nitric acid until all the iron sulphide had been dissolved. Two complete analyses and a third partial one were made on sa samples that weighed respectively 0.50 gms.,0.29 gms. 0.20gms. As might have been expected from the smallness of the samples, the results obtained did not check very closely, and they were mainly of interest in showing that the garnet is a manganiferous variety, containing approximately 13% MnO.

The paragenesis of the ore and gangue minerals was difficult to determine with any high degree of accuracy, due to the massive character of the ore. It was however, concluded from the microscopic study of the ores, that all of the gangue minerals, with the exception of the garnet, were of an earlier generation than the sulphides. The garnet is plainly contemporaneous with some of the pyrite and pyrrhotite. The order of formation of the minerals composing the gangue, as determined, was chlorite and muscovite, followed next in order by tourmaline and hornblende, and later, in undetermined order, by calcite, siderite, quartz, epidote, zoisite and garnet.

That the folding, to which the rocks that enclose the Sullivan ore-bodies have been subjected, is of pre-mineral age, is definitely shown by a study of polished specimens and by the microscopic investigation of thin sections. Intense crushing of the ore and gangue minerals, such as would have undoubtedly taken place if the folding had been of post-mineral age, is entirely lacking. Only two of the specimens examined showed traces of slight fracturing of the gangue minerals, prior to the introduction of the sulphides.

Horses and False Hanging-Walls.

In the course of mining operations, bodies of barren or slightly mineralized rock are occasionally encountered within the ore-bodies of the Sullivan mine.

These horses represent (1) pre-mineral dykes, (2) remnants of those beds of quartzite which inherently were most resistant to replacement, and (3) remnants of those portions of folded structures in which even those beds inherently susceptible to replacement were rendered so dense and compact as to preclude the ready passage of the ore-bearing solutions.

(1) The petrographical character of the dykes that traverse the North ore-body of the Sullivan deposit has been discussed under the heading of igneous rocks. Because they are not susceptible to replacement, these dykes formed effective barriers to the ready circulation of mineral-bearing solutions. In the workings on the 1100 level two dykes have been encountered forming continuous horses in the ore-body. One of them near the centre of the ore-zone, has a width in places of twenty feet, while the other near the north end of the ore-zone is about three to four feet wide. The larger dyke has a somewhat irregular form and at one place along its course spreads out for a considerable distance along the strike of the ore-body. Many ways in which such dykes would prove to be effective ore-barriers may be thought out. For instance, one of them might readily seal off the nose of a fold and prevent the replacement of an otherwise favourable structure. If, with the extension of the workings one of these dykes should be encountered trending parallel to the strike of the ore-bearing horizon, one would expect to find, little if any ore developed within the extension of the favourable beds up the dip above the dyke for at least the major part of the length of the latter.

(2) In many parts of the ore-body portions of altered and more or less barren quartzite bands are encountered in mining operations. These are found in greatest abundance near the hanging-wall of the ore-body, and for this reason may be mistaken for it; whereas, in reality they are horses behind which there is often concealed a considerable thickness of high grade ore. These false hanging-walls represent remnants of those beds of quartzites which inherently were more resistant to replacement than those immediately adjacent to them. Typical examples of false hanging-walls are to be seen in very many places within the workings in the 3900 level, selective replacement of favourable beds, having developed this alternation of almost barren beds with those that have been completely replaced to solid sulphides.

(3) The portions of folded structures that form horses in the ore-body are limited to those tightly compressed sections of the favourable beds that the mineral-bearing solutions were unable to penetrate, owing to their relatively more dense and compact nature. These structures are commonly found on the limbs of the folds where the replaceable beds have been thinned and compressed by the action of the folding. This would tend to produce a gradational or diminishing effect on the degree of mineralization in these locally compressed areas. Especially has the formation of ore been locally impeded, because of compression and thinning of the replaceable beds, on the reverse limbs of overturned folds.

Mineral Bearing Solutions.

The source of the mineral bearing solutions that formed the Sullivan deposit has not as yet been determined. It is thought, however, that they have been developed by solutions circulating from some magnetic source at an unknown depth. Considering the Kimberley district as a whole and noting the numerous small cupola-like masses of intrusive granite within the area, it seems possible that a larger batholith of igneous rock, not yet exposed by erosion, underlies either the whole or extensive portions of the region. Given such a body of igneous rock it might well, while cooling down from a molten condition, have been the source of the ore-bearing solutions.

The solutions that developed the ore-bodies plainly ascended along bedding planes within a horizon of the Aldridge formation, where the beds were of such a physical and chemical nature as to be favourable to replacement by the ore-bearing solutions. This favourable horizon may have included certain beds, that were of a slightly more calcareous nature than those immediately above and below them.

The pre-mineral folding of the beds favourable to replacement was an important factor in controlling the circulation of the ore-bearing solutions and hence the varying degree of replacement of these beds in different localities. Where these rocks had been subjected to relatively the greatest compression, as on the limbs of certain folds, the susceptible beds were locally rendered so relatively dense or impermeable that only those beds of most favourable composition were replaced. On the other hand, where pressure was locally relieved by the folding, as in the crests of anticlines and the troughs of synclines, and especially in the former, beds that would ordinarily resist replacement were rendered favourable and hence, within these portions of the folded structures, the ore-bodies are much thicker than elsewhere.

Inferences as to the character of the solutions w which, with their accompanying vapors, produced the meta-somatic changes in the rocks and finally replaced them to form ore, may be drawn from the mineral associations produced as a result of these changes. The gangue minerals, all of which, with the exception of garnet, were formed by emanations that probable preceded those carrying the sulphides are tourmaline, actinolite, manganese-bearing garnet, epidote, zoisite, chlorite, muscovite and lesser amounts of quartz, calcite and siderite. Later metallic minerals, in order of deposition, are pyrite, pyrrhotite, zincblende and galena. This assemblage of minerals indicates that these ore-bodies were formed under conditions of high temperature and intense pressure. Muscovite, chlorite, zoisite and epidote are hydrous minerals, and tourmaline contains the element boron; the occurrence of these hydrous minerals and of the tourmaline, give evidence that at least two of the so-called mineralizers, namely water and boron, were present.

From the study of thin sections prepared from specimens of the ore and wall rocks; and in particular several specimens of partly replaced quartzites from the hanging-wall at the face of the 3900 level tunnel, certain conclusions as to the manner of replacement were arrived at. The first minerals in the recrystallized argillaceous quartzites, to be attacked and replaced by sulphides were biotite, chlorite, sericite and any calcite that may have been present. In general, the quartz grains were next replaced, while the actinolite, muscovite and tourmaline were in some measure corroded by the sulphide-bearing solutions.

Alteration of Wall Rocks

The alteration of the wall rocks enclosing the deposit may be divided into a hanging-wall and a foot-wall phase. The first of these has to do with the development within the hanging-wall quartzites of tourmaline, garnet, actinolite, zoisite, epidote, chlorite, muscovite, calcite and quartz. The second phase is the formation, by somewhat different processes, of the dense black flint-like chert, that, in extensive areas, forms the foot-wall of the ore-bodies.

By virtue of their fluidity, the hot solutions and vapors were able to penetrate the hanging-wall quartzites for long distances, as tourmaline crystals are found as much as 600 feet vertically above the ore horizon. This tourmaline, however, may have been deposited by boron vapors ascending along the bedding planes of the strata above the deposit. Other minerals that have been introduced in conjunction with the tourmaline are chlorite and muscovite. Small amounts of zoisite, epidote, calcite and pyrrhotite form minute veins in the hanging-wall quartzites. Near the walls of the ore-body, and in the ore itself, garnet and actinolite make their appearance in association with the other gangue minerals.

Specimens of the characteristic black chert of the foot-wall have a conchoidal fracture, contain disseminated particles, parallel streaks, and veinlets of iron sulphides; and, on careful inspection, the original laminated character of the quartzites, from which they formed, may still be recognized. Microscopically they consist of about two-fifths quartz, in the form of minute angular to sub-angular grains, that are distributed through a matrix of crypto-crystalline to isotropic silica, with which is associated a large amount of very finely divided chlorite and possibly a little sericite. In one of the thin sections examined, a few irregular individuals of twinned feldspar, as well as a number of small rounded zircons were present. Several larger flakes of chlorite and muscovite, and also two or three very small prismatic crystals of tourmaline were noted. An interesting feature of two of the specimens of the chert examined was the occurrence of a little chalcopyrite in the pyrrhotite veinlets.

The development of the chert is probably due to a process of interchange, whereby the silica dissolved from the overlying strata by the ore-solutions, has permeated the argillaceous quartzites of the foot-wall, and replaced them with the isotropic or cryptocrystalline silica of the cherts. The chert however, may have possibly been formed by the silicification due to an early silica-bearing phase of the ore solutions. The first explanation appears to be the more probable one, as silica-rich solutions would hardly be expected to be capable of dissolving the enormous quantity of silica that must have been removed from the overlying strata in the development of the sulphide ore-bodies.

In several places, the cherty character of the foot-wall grades over into quartzites that are only slightly altered. It is to be noted, however, that in some places the structure of the beds has been of such a nature that the silica-rich solutions were unable to penetrate them, due to their tightly compressed nature.

Comparison with Coeur D'Alenes Deposits.

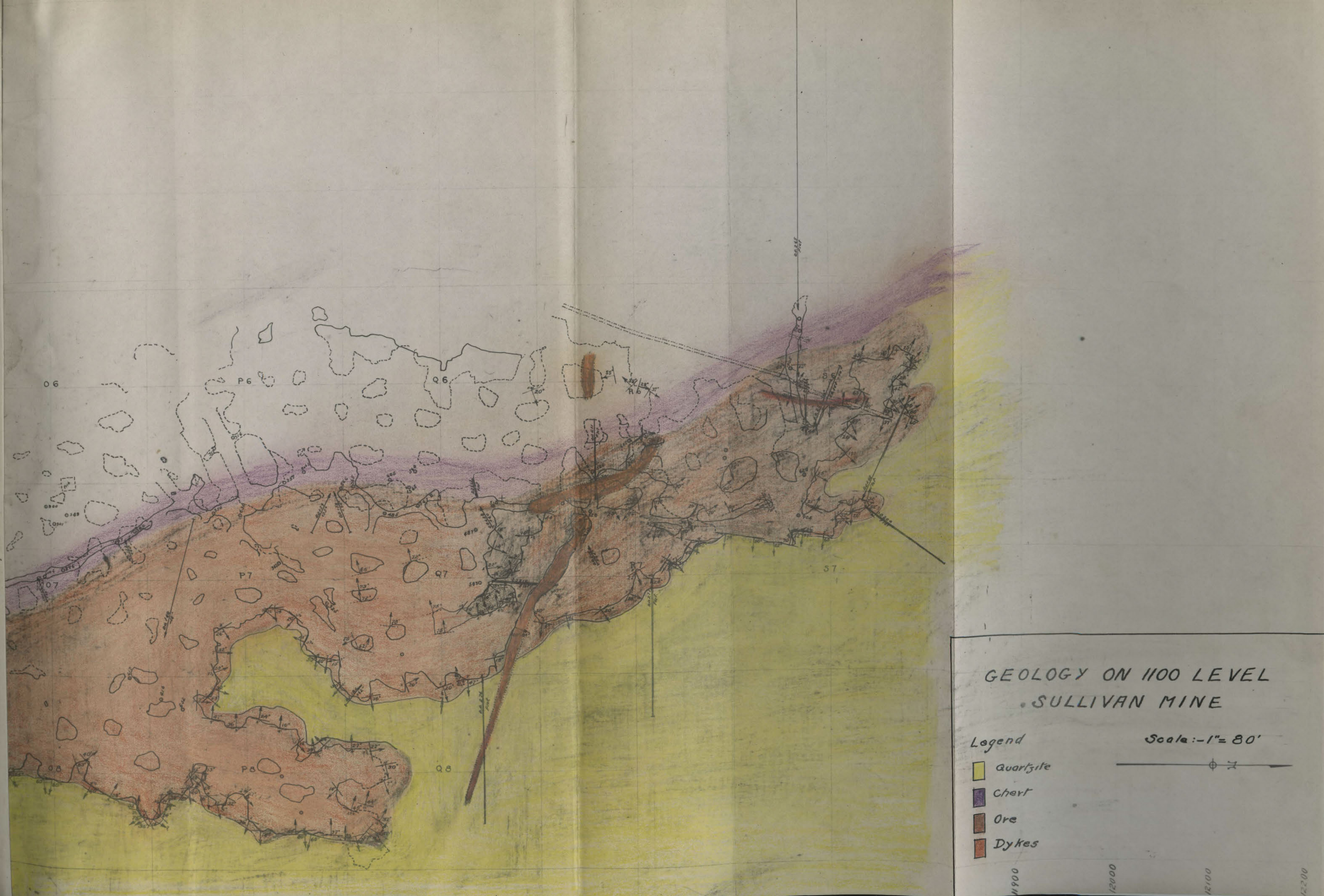
There is a striking similarity between the Sullivan ore-bodies and certain deposits in the Coeur d'Alenes region of Idaho. The Coeur d'Alenes region lies across the International boundary line, about one hundred and forty miles south of the Kimberley district. Nearly all of the deposits in the Coeur d'Alenes occur in the Revett and Burke formations, which may be correlated with the Creston formation that overlies the Aldridge of the Purcell series in Canada. The Revett and Burke formations are composed principally of fine-grained sericitic quartzites, that have been folded and intruded by large bodies of monzonite.

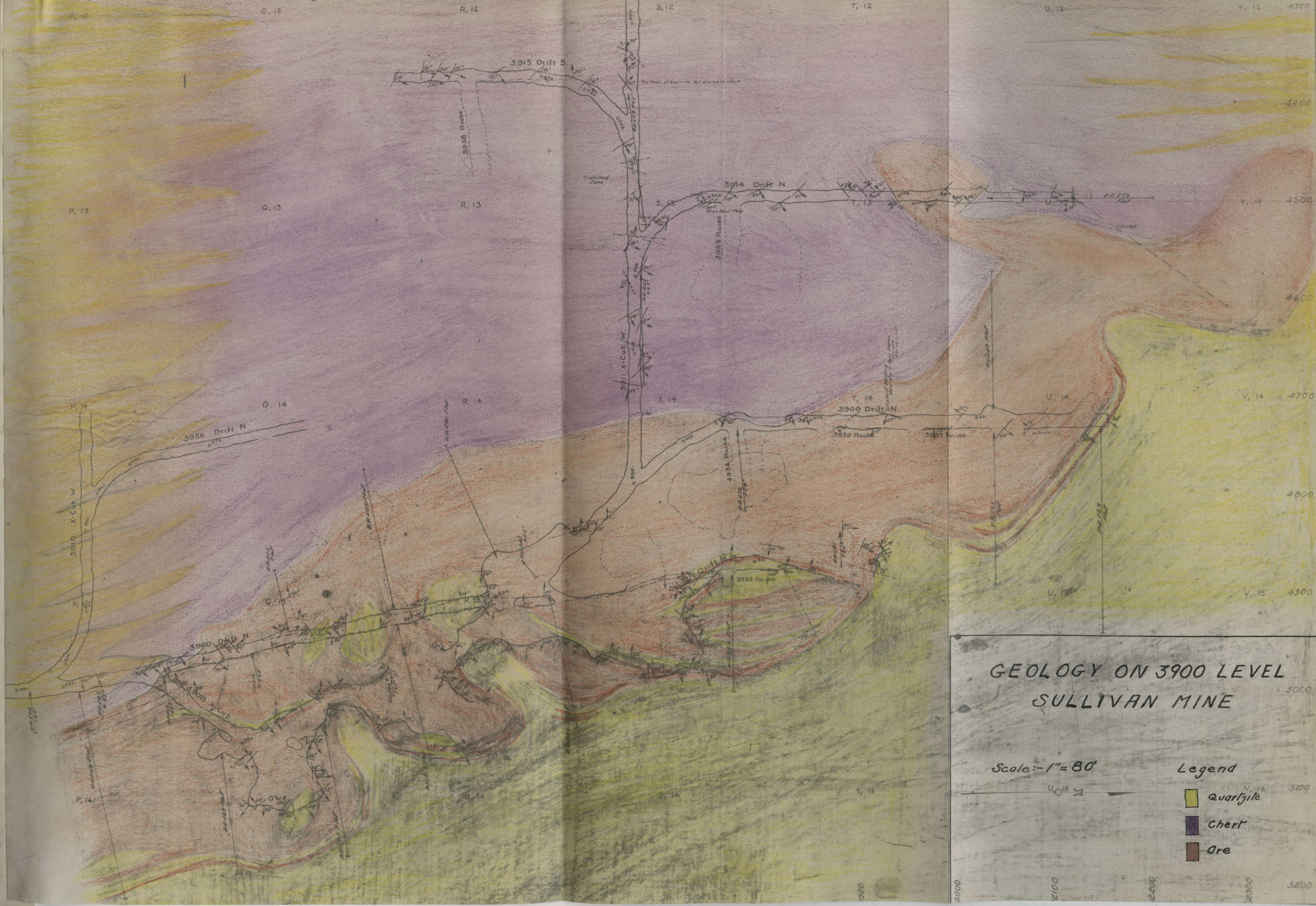
The ore-bodies, in this region, have been developed by processes of replacement along sheared or fissured zones in the sericitic quartzites. The monzonite intrusions that in numerous places have been exposed by erosion are believed to have been the source of the ore. At the contact of these intrusives and the quartzites, metamorphism has resulted in the development of garnet, biotite and pyroxene in the sedimentary rocks. From a mineralogical standpoint the ore-bodies of the Coeur d'Alenes, especially those near the contact of the monzonite, exhibit an association of minerals very similar to that of the Sullivan deposit.

The principal ore minerals in the former deposits are argentiferous galena, zincblende, a very little tetrahedrite rich in silver, pyrrhotite, pyrite and a small amount of chalcopyrite. The silver content of the ores from the various mines ranges from 0.25 oz. to 1.0 oz for each unit of lead. Of the ore minerals, galena and pyrite are the most abundant, zincblende and pyrrhotite being subordinate, except in the case of ore-bodies near the contact of the monzonite and quartzites. In this district, the galena occurs in massive form, most commonly as a finely granular aggregate, often referred to as "steel galena" by the miners. As a rule zincblende is not abundant in the ores rich in lead, although it, and also pyrrhotite, appear to become more abundant in some of the mines as they become deeper. The most important gangue minerals are siderite, quartz, garnet, pale green pyroxene and muscovite. Tourmaline, while not strictly a gangue mineral, occurs widely disseminated in the quartzites and has been proved to be a pneumatolytic product formed by vapours from the intrusive monzonites. The most abundant and characteristic gangue mineral is siderite which occurs over considerable areas near the ore-bodies as a replacement mineral in the quartzites. The garnet, pyroxene and quartz, are relatively more abundant as gangue minerals in the deposits that are most closely connected with the intrusives.

The property in the Coeur d'Alenes that most closely approaches the Sullivan deposit, in so far as its mineralogy is concerned, is the Granite or Success mine. Both ore-bodies have been formed by replacement of argillaceous quartzites by a more or less intimate mixture of galena, zincblende and iron sulphides. The gangue minerals are almost identical, with the exception that the pyroxene of the Success deposit is represented by actinolite in the Sullivan. Also, as yet, no siderite has been found in the Success mine; but the presence of a little quartz within the ore has been noted. This Idaho ore-body is genetically related to an intrusion of monzonite, and as might be expected, the heavy silicates show a wider range of development in the wall rocks here, than in the case of the Sullivan deposit. From the above considerations, it is probable that the temperature at the time of deposition was somewhat higher in the Success than in the Sullivan deposit.

In the mines of the Coeur d'Alenes region some of the ore-bodies have been followed to depths of over 3000 feet, with apparently very little change in the average tenor of the ores. In some of the deeper workings of the mines, a slight increase in the amount of pyrite, pyrrhotite and zincblende indicates that the ore-bodies, wonderfully persistent as they are, are likely to become poorer at depths not much greater than the present workings in these deep mines. The depth at which the grade of ore becomes leaner in any deposit is controlled, to some degree, by the local geological structure. For example, an ore-body enclosed by a formation that is relatively higher in the geological column, is in a more advantageous situation than one placed in a relatively lower formation.


GEOLOGY ON 1100 LEVEL
SULLIVAN MINE
Legend
Quartzite
Chert
Ore
Dykes
Scale:-1"= 80'
O6
P6
Q6
R6
O7
P7
Q7
R7
S7
O8
P8
Q8
11900
12000
12100
12200



GEOLOGY ON 3900 LEVEL
SULLIVAN MINE
Scale:- 1" = 80'
Legend
Quartzite
Chert
Ore
3915 Drift S.
3914 Drift N.
3900 Drift N.
3956 Drift N
3911 X-Cut W
3910 X-Cut W
3938 Raise
3965 Raise
3936 Raise
3939 Raise
3937 Raise
3934 Raise
Crushed Zone
P, 13
Q, 13
R, 13
S, 13
T, 13
V, 13
P, 14
Q, 14
R, 14
S, 14
T, 14
U, 14
V, 14
P, 16
R, 16
S, 16
T, 16
V, 16
Q, 12
R, 12
S, 12
T, 12
U, 12
V, 12
U, 15
V, 15
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