A Geological and Geochemical Transect of the Volcanic Stratigraphy in the D'Alembert-Cléricy Area, Noranda, Québec

by

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LITHOGEOCHEMICAL TRANSECT, D'ALEMBERT-CLÉRICY, NORANDA, QUEBEC

ABSTRACT

The Archean rocks in the D'Alembert-Cléricy area of the Noranda district were mapped along a transect across stratigraphy. Located within the youngest part of the Blake River Group, this six km thick volcanic assemblage trends northwest, youngs northeast, and has increasing dip from ~45° in the west to subvertical in the east, with some folding within the sequence.

Chemostratigraphic units were established using Zr/Y, La_N/Yb_N, and other immobile and incompatible HFSE ratios, and AFM and Miyashiro major element plots. Lithogeochemical technique based on the HFSE and other immobile and incompatible elements have been applied to both fresh and altered rocks; the trace element parameters are more specific than the major element discriminants.

The stratigraphy along the D'Alembert-Cléricy transect is subdivided into three major chemostratigraphic units: Lower Transitional Series, Middle Tholeiitic Series, and Upper Mixed Tholeiitic-Transitional Series. Overall, the lithologies comprise ~65% tholeiitic and ~35% transitional volcanics. The tholeiites are mainly represented by basalts and rhyolites, whereas the transitional rocks are mostly andesites and rhyolites.

The geological, stratigraphic, and lithochemical attributes along the transect indicate the potential for massive sulfide deposits is comparable to that of the Central Mine Sequence. Although the thesis area contains a greater proportion of basalts and volcaniclastic material than the Central Mine Sequence, both areas contain major tholeiite basalt-rhyolite bimodal sequences, several thick felsic units, and andesite-rhyolite transitional suites.

RESUMÉ

Les roches d'âge archéen de la région D'Alembert-Cléricy du district de Noranda ont été cartographiées le long d'une traverse perpendiculaire à la stratigraphie Cet assemblage volcanique, d'une épaisseur de 6 km et de direction générale nord-ouest, est compris dans la portion supérieure du Groupe de Blake River La séquence volcanique est d'âge plus récent vers le nord-est et a une pente qui augmente de ~45° à sub-vertical d'ouest en est, et est affectée de plissement vers sa partie centrale

Les unités chemico-stratigraphiques ont été définies en utilisant les rapports Zr/Y, La_N/Yb_N, ainsi que les rapports d'éléments immobiles à champ de force élevé (HFSE), en plus de profiles de terres rares, et des diagrammes AFM et Miyashiro Les méthodes lithogéochimiques sont utilisables pour les roches fraîches et alterées et elles sont plus spécifiques que les discriminants d'éléments majeurs

Trois unités chemico-stratigraphiques majeures composent la stratigraphique soit. la série transitionnelle inférieure, la série tholéiitique moyenne et la série mixte tholéiitique-transitionnelle supérieure Les principales unités lithologiques sont constituées de ~65% de roches volcaniques tholéiitiques (surtout des basaltes et rhyolites) et de ~35% de roches volcaniques transitionnelles (surtout des andésites et rhyolites)

Les attributs géologiques et lithogéochimiques indiquent un potentiel pour la presence de gîtes de sulfures massif, comparable à celui de la Séquence de Mine Centrale Malgré le fait que le terrain de thèse contient une plus grande proportion de basaltes et de matériel volcanoclastique, la stratigraphie de celui-ci est comparable avec celle de la Séquence de la Mine Centrale Les deux région contiennent des séquences bimodales de basalte-rhyolite tholéiitique majeures, quelques unités felsiques épaisses et des suites d'andésite-rhyolite transitionelles

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Chapter 1

INTRODUCTION

OBJECT OF THE RESEARCH

The focus of this thesis is the geology of the large terrain of volcanic stratigraphy between the Norbec and Mobrun mines This area of study lies adjacent to the economically important Central Mine Sequence (CMS) in the central part of the Noranda mining district. The geology of the CMS, along with the numerous massive sulfide deposits found therein, has been the subject of many studies (e.g , Gilmour 1965, Spence and de Rosen-Spence 1975, Gélinas et al 1977, 1982; Dimroth et al. 1982, Gibson and Watkinson 1990, Paradis et al 1989, Barrett et al. 1991, Shriver and MacLean 1993) However, the geochemical characteristics and lithostratigraphic relationship of the terrain in the thesis area to that of the CMS are still poorly known and not well understood. The question is: does this stratigraphy have the potential for volcanogenic massive sulfide (VMS) deposits in the same abundance as the rest of the district? The objective of this thesis is to determine the stratigraphy and lithogeochemistry of the terrain between the Norbec and Mobrun mines, and to compare these features with those of the Central Mine Sequence.

Successful mineral exploration requires an integrated approach with accurate field-based mapping, structural and stratigraphic interpretive analysis, combined with effective lithogeochemical analysis and geophysical techniques This study aims to assess the potential for massive sulfide mineralization, using stratigraphic and geochemical data in an area between the very productive Central Mine Sequence and the Mobrun mine

THE NORANDA MINING DISTRICT

The Rouyn-Noranda mining district is located in the Abitibi-Témiscamingue region in northwestern Quebec, close to the Ontario border (Fig 1) Situated about 600 km northwest of Montreal, in the south-central part of the Abitibi granite-greenstone belt, this massive sulfide mining camp is within the eastern and central sectors of the volcano-sedimentary Blake River Group The first mine found at Noranda, the 65 million tonne copper-gold Horne deposit, is the largest ore deposit thus far discovered in the district.

The Horne orebody and the more than twenty other nearby massive sulfide deposits have made the Noranda area one of the premier mining districts in Canada Numerous small deposits of base and precious metal have been discovered and worked on in recent years Most geological studies and reports concur, as these new finds suggest, that there is still potential in this region for continued productive mining

Closer review of compiled data indicates a less than healthy economic situation for the resource industry at the present time, judging by the depletion in ore reserves in the Noranda district New discoveries brought into production in the last few decades have not kept pace with depletion of reserves in mined-out deposits Many VMS deposits outside of the Horne are copper-zinc ores and are in the 0 5 to 6 million tonne range Most of these mine are located in the central part of the district, in the Mine Zone rhyolites (Spence and de Rosen-Spence 1975) of the Central Mine Sequence (extending from the Flavrian Andesite through the Amulet Andesite) It is important to note that only one large (≥10 million tonnes) VMS or base metal deposit, the Mobrun mine, has been discovered in the district in the last 30 years

Geology of the Noranda District

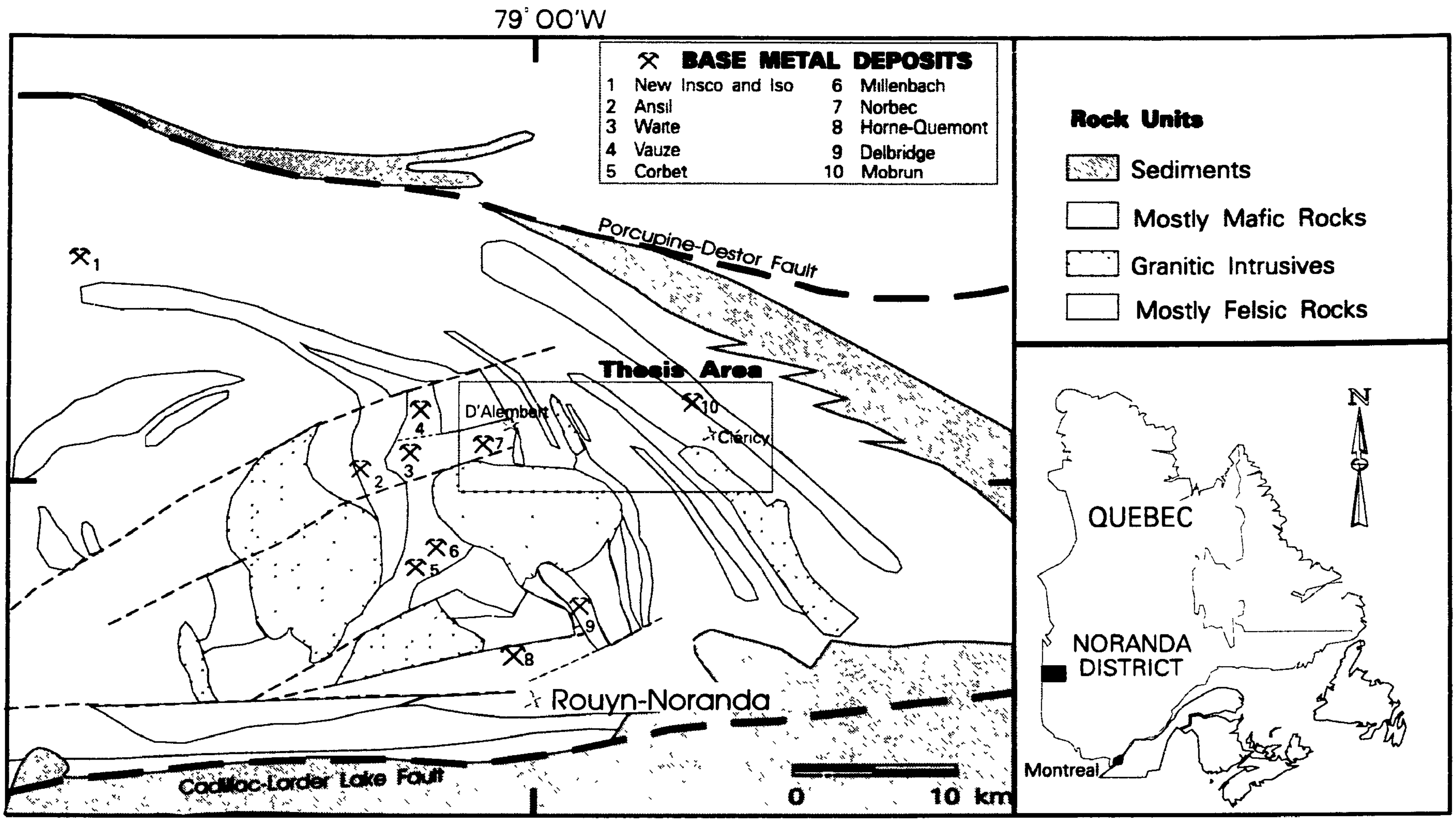


Fig. 1. Generalized geological map of the Noranda District.

Following the time-honoured prospecting axiom "Gold is where you find it", exploration efforts have been concentrated near existing deposits and mostly within the stratigraphy of the Central Mine Sequence. Company mineral exploration and geological studies have been restricted outside this domain.

ACCESS TO THE FIELD AREA

The research area for this thesis study is located 10 km to the northeast of Rouyn-Noranda, roughly between Lac Dufault and Lac Dufresnoy. As shown on the district map (Fig. 1), the area lies between the towns of D'Alembert to the west and Cléricy to the east. It is accessible by Highway 101 from Rouyn-Noranda to D'Alembert, and then eastward along the road to Cléricy. The entire thesis area is transversed by the Cléricy road and local side roads, and covers an east-west transect of terrain about eight km in length and three km in width, north-south.

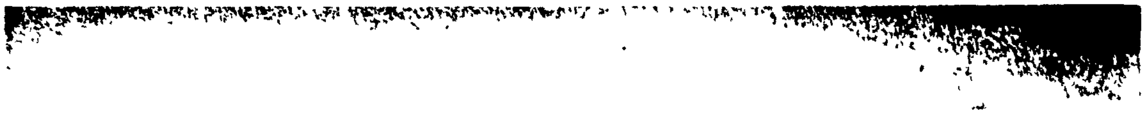
TOPOGRAPHY

Outcrop averages about 20 percent in the area, and is easily accessible by foot and vehicle traverse. Relief in the area is less than 100 m, with gentle hills and valleys (Fig. 2a) and flat agricultural land, most of the terrain at around 290 m to 330 m above sea level. In the western part of the thesis area, andesites make up the high ridges of the Waite Hills (highest elevation in the region at 480 m). In the central part, low terrains of eroded basalts and basaltic-andesite are separated by topographic highs and outcrops generally composed of rhyolites, granodiorite intrusives, and diorite dikes. Towards the eastern part near the Mobrun mine area, the resistant rhyolite rocks form

Fig 2 Field Area Landscape and Topography

a Typical topography of the thesis area, with outcrops of gentle hills and low-lying wooded area and swamps View from an outcrop of diorite and mafic rocks in Cléricy Road Basalt unit north of the Cléricy Road, looking northeasterly toward ridges in the Mobrun mine area

b Landscape of Lac Dufault and surrounding area View from Amulet Andesite ridge at Waite Hills, looking south toward Lac Dufault and Central Mine Sequence area of the Noranda District




a


b

a series of high ridges, with andesites underlying the intervening low valleys Apart from the outcrops, forests, and swamps, the land is largely cultivated fields and pasture

Small streams and wetland occupy the low lying area The larger lakes in the thesis area are Lac D'Alembert and Lac Dufresnoy to the north, and Lac Dufault to the south (Fig 2b) The Kinojevis River, a tributary of the Ottawa River system, is the major waterway in the region (lowest elevation in the thesis area at 270 m) Flowing southward, it cuts a winding river valley through the landscape This vital waterway was the means of access to distant parts of the Noranda district by prospectors and geologists in the early part of the twentieth century

RESEARCH METHODS

Field mapping in this eastern Blake River Group (BRG) along the D'Alembert-Cléricy transect was carried out to delineate the stratigraphic succession Rock samples were collected for detailed examination of the volcanic stratigraphy

This project establishes a chemostratigraphic framework for the transect using immobile element and trace element lithogeochemistry This is used because most major element classifications are affected by metamorphism and hydrothermal alteration The use of immobile-incompatible elements can more effectively monitor alteration and mass changes, and determine precursor rock compositions (MacLean and Kranidiotis 1987, MacLean 1990) Immobile major and trace elements are utilized to establish igneous fractionation trends, and identify chemical variations that result from alteration (MacLean 1990) This lithogeochemical technique allows the recognition of precursor compositions even in intensely altered rocks

The combination of detailed field work and lithogeochemical study assists in establishing the relationship between the eastern Blake River volcanic stratigraphy and the Central Mine Sequence This study provides insight to the evolution of the Archean volcanic rocks in the eastern Blake River Group of the Noranda district

ORE DEPOSITS IN THE DISTRICT

The Noranda mining camp has been Canada's leading base metal and gold producer for many decades Since the start-up of the Horne mine in 1923 to the present time, there have been about 22 massive sulfide and 17 gold deposits discovered in this historically important mining camp (Chartrand and Cattalani 1990) The base metal mines of the district are the subject of a number of economic geology reports and studies These are referred to and described as the type examples of Archean volcanogenic massive sulfide deposits (Sangster 1972, Franklin et al 1981)

With the notable exception of the giant Horne copper-gold deposit, most of the VMS mines are located in the Mine Zone (Spence and de Rosen-Spence 1975) which is part of the Central Mine Sequence This is a bimodal andesite-rhyolite volcanic succession bounded by the Horne Creek fault, the Hunter Creek fault, and the Flavrian and Lac Dufault plutons

HISTORY AND PREVIOUS WORK

The initial geological and prospecting activities were carried out along water routes in the Rouyn-Noranda region, and are reviewed by Cooke et al (1931) The earliest of these traverses and a summary report was made by MacOuat (1872) Sporadic geological investigation and mapping was carried out along lakes and rivers by J F E Johnston (1901) and W J Wilson (1901) During the construction of the

Canadian National railway through the area between 1910 to 1915, geological mapping and field work was undertaken by M E Wilson, J A Bancroft, W J Wilson, and T. L Tanton (see Cooke et al 1931)

Edmund Horne Comes to Lake Osisko[1]

*Condensed from **Noranda** by Leslie Roberts (1956)*

The important turning point in the geological exploration and economic development of the Rouyn-Noranda district came during the 1910s The pioneering prospector Edmund H Horne began exploring the Rouyn area in 1911 Ed Horne was an experienced miner and prospector before he ventured into the wilderness of Northwestern Quebec, having worked in Nova Scotia, Labrador, northern B C , Colorado, California, and England In 1908 he joined the gold rush in Northern Ontario and worked in the booming Cobalt mining camp Ed Horne then prospected in the Kirkland Lake and Cobalt areas to seek his own fortune, and liked what he saw in the rock formations He wondered what mineral riches lie across the provincial boundary in Quebec, while others prospected in Northern Ontario Horne later recalled, "Well, it didn't seem sensible to believe that all the good geology would quit at the Ontario border, just because somebody had drawn an imaginary line there."

Coming from the Ontario side along the Ottawa River, Horne and another prospector, Bob Bryden, canoed through the Kinojevis waterway in 1911 The unexplored country of Northwestern Quebec left favourable impressions in Horne's mind He believed the area held much promise for mineral wealth Ed Horne returned in 1914 with two prospector partners, Bert Armstrong and Bert McDonell This time they found a showing of mineralized and heavily fractured rhyolite along the shore of

Lake Osisko, which later became the Horne mine With more sampling and prospecting in the following years, Ed Horne was convinced that he was onto a major mineral discovery

Lacking the financial resources for a grubstake expedition to stake claims and do the assessment work, Ed Horne had to wait for better financial times after World War I For a long while, he found few backers for his venture It was only in 1920 that Ed Horne was able to procure funds to stake the ground He raised the money through the Trémoy Lake Prospecting Syndicate which Horne founded with a total of twelve partners in the Grand Union Hotel in New Liskeard, Ontario The syndicate was established to finance Ed Horne's venture in Rouyn Township in Quebec to develop the Horne property, which eventually became Noranda Mines, Limited, Further surface work and trenching led to the discovery by diamond drilling of the giant 'H' orebody in 1923 Edmund Horne, with the Mine now bearing his name, and the Noranda company were on the way to fame and fortune, and a prominent place in the economic geology and mining history of Canada

Accounts of the prospecting and geological work on the property and in the mine are found in the studies by Price (1933, 1934) and a GSC report on ore deposits in the Noranda district (Wilson 1941) The complete story of Edmund H Horne's prospecting activities in the area and the development of the Horne mine are narrated in the book "Noranda", a history of the company by Leslie Roberts (1956)

GSC Mapping

Geological mapping was undertaken by the Geological Survey of Canada from the 1920s onward (James 1923, James and Mawdsley 1924, Cooke et al 1931, Ambrose 1941a,b, Wilson 1941) Their field work and summary reports laid the framework for all subsequent geological studies in the district This work and interpretation led to the definition and delineation of the major volcanic, sedimentary and intrusive rock groups, and assisted in the discovery and development of many mines in the district

Recent Mapping

Recent works, up to the 1980s, were carried out on the volcanic rocks in the Rouyn-Noranda district by Baragar (1968), Jolly (1974), Spence and de Rosen-Spence (1975), Gélinas et al (1977), Jolly (1978), and Goldie (1979) In the 1980s to the present, geological studies and regional syntheses have been made by Dimroth et al (1982, 1983a,b), Gélinas et al (1982, 1984), Ludden et al (1982), Paradis et al (1989), Gibson and Watkinson (1990), Péloquin et al (1990), Cattalani et al, (1990, 1991a,b), and Barrett et al (1991a,b, 1992) These studies and new advances of the ore deposit modelling for the Noranda district are discussed in subsequent chapters

Major studies of the mineral deposits in the Noranda district were made by Cooke et al (1931), Price (1934, 1948), Gilmour (1965), Dugas (1966), Boldy (1968), Simmons (1973), Riverin and Hodgson (1980), Knuckey et al (1982), MacLean and Hoy (1991), Barrett et al (1991a,b, 1992), and Shriver and MacLean (1993)

In the last few years, a series of Quebec government reports on the VMS deposits of the Noranda camp have been made by the Mineral Exploration Research Institute (MERI-IREM) These studies have also been published in scientific journals (the first reference is to the government report and subsequent ones to respective journal papers) Horne (Cattalani et al 1990, Barrett et al 1991b, MacLean and Hoy 1991), Aldermac (Cattalani et al 1991a, Barrett et al., 1991a), Ansil (Cattalani et al 1991b, Barrett et al 1991c), Delbridge (Cattalani et al in press, Barrett et al 1993), Mobrun (Riopel et al 1993, Barrett et al 1992), Norbec (Cattalani et al 1992, Shriver and MacLean 1993), and Corbet (Barrett et al in press)

Theses Studies in the District

In addition to the government reports and journal papers, there are many university research theses on the geology and ore deposits of the Noranda district Those theses known to the author are listed in the Appendix

Studies in the Thesis Area

Early mapping in the thesis area was carried out by the Geological Survey of Canada (GSC) and Quebec government geologists in the 1920s following the discovery of gold and base metals in the Noranda district The resulting GSC memoirs and reports contain only brief descriptions and discussions of the geology in the thesis area, which covers the central part of Dufresnoy Township The volcanic stratigraphy, however, extends into the adjacent townships of Clericy, Joannes, Rouyn, Duprat, Duparquet, and Destor for which more detailed reports are available

The western half of Dufresnoy township was mapped by James (1923) as part of his reconnaissance work in the Noranda district A cursory report and preliminary map by Harvie (1924) is available for the eastern half of the township Among the early regional mapping and geological assessment projects completed in the Noranda district by the GSC, only these two reports are specific to the thesis area In addition, the Ministére de l'Energie et des Ressources compilation maps of the district include revisions of the geology of the thesis area

STRATIGRAPHIC NOMENCLATURE IN THE DISTRICT

The initial mapping by the GSC in the Abitibi region, including the Noranda district, produced a two-fold subdivision of the Archean (Pre-Huronian) rocks encountered in the area The volcanic sequences were grouped into the Keewatin Series, and sedimentary rocks into the Timiskaming Series (James 1924, Harvie 1924, James and Mawdsley 1924, Cooke et al 1931) The Keewatin Series included all basalt, andesite, rhyolite, tuff, and basic intrusives, while the 'Timiskaming Series' included mainly of greywacke, conglomerate, arkose, and schist

Mapping in the Cadillac township, Gunning (1937) proposed a new subdivision of the rocks in the region north of the Cadillac Break, dividing them into four mappable groups of major lithological units He dropped the Timiskaming and Keewatin

TABLE 1. Geological Subdivision after Gunning (1937).

Cadillac Sediments	- greywacke, slate, tuff, conglomerate
Blake River Volcanics	- volcanic rocks, minor greywacke
Kewagama Sediments	- greywacke, slate, conglomerate, and minor volcanics
Malartic Volcanics	- mostly volcanic rocks

subdivisions, and defined the rocks solely on the basis of lithology Local geographical names were used in this classification From north to south toward the Cadillac Break, going from oldest to youngest, the rock units are Malartic volcanics, Kewagama sediments, Blake River Group, and Cadillac sediments (Table 1)

Subsequently, in a treatise on the Timiskaming-Keewatin problem in the Proceedings and Transactions of Royal Society of Canada, Gunning and Ambrose (1939) discussed the lithological characters and stratigraphic relationships of the rocks in the area They formally recommended the abolition of the equivocal general designation of Timiskaming and Keewatin Series for the arbitrary subdivision of volcanic and sedimentary rocks, respectively The lithological affiliations were dropped, and the rock sequences were given Group status (Gunning and Ambrose 1939) The four well-defined Groups, with geographical names from the area, have since then been adopted and widely used

TABLE 2. Stratigraphic Subdivisions after Gunning and Ambrose 1939.

EARLY	Gunning (1937)	Gunning and Ambrose (1939)
Timiskaming Sediments	Cadillac Sediments	Cadillac Group
	Blake River Volcanics	Blake River Group
Keewatin Volcanics	Kewagama Sediments	Kewagama Group
	Malartic Volcanics	Malartic Group

Lithology in the Noranda Area

The Blake River Group, along with the Kewagama and Cadillac Groups, occurs as thin east-trending linear belts in the Cadillac area, the Malartic volcanics thicken in the north To the west, the Blake River Group broadens into thick volcanic assemblages in the Noranda district, reaching to about 30 km wide north-south The Kewagama Group likewise expands towards the northwest into La Pause, Cléricy, Dufresnoy, and Destor townships, where this thick sedimentary package is known as the 'Cléricy Band' (Ambrose 1941a) South of Rouyn-Noranda, the Pontiac and Timiskaming Groups are partial facies equivalent of the Cadillac sediments (Dimroth et al 1982) Detailed discussion of lithological correlation of the rock groups, formations, and various subunits in the Noranda area can be found in studies by Goodwin (1979) and Dimroth et al (1982) All rocks in the region have been further grouped into the Abitibi Supergroup of the volcano-sedimentary rocks of the Abitibi Greenstone Belt (Goodwin 1977)

The famous Blake River Group, the volcanic assemblage hosting much massive sulfide and gold deposits in the Noranda district, was described from the exposures in the narrow part of the belt near the *Blake River* in the Cadillac area (Gunning, 1937) This small river flows north into Kewagama Lake in the north part of Cadillac Township The original name for the river is shown only on a few of the early maps Unaccountably, the name has since been altered, probably erroneously, to *Black River* at some later date Subsequently, this precursor toponym has been converted to *Rivière Noire* on recent government topographic maps As well, it should be noted that the Kewagama Group is named after Lake Kewagama, which has been renamed Lac Preissac on current maps. These groupings of rock units based on the original derivative names of geographic features in the region have been fixed in the geology literature and consistently followed by later workers, notwithstanding their absence on current maps

ORE DEPOSIT MODELS

A major contribution to the understanding of the geology and genesis of ore deposits in the Noranda district was made by Gilmour (1965), who was the first to propose a volcanogenic origin for the massive sulfide deposits in the area Since then, a majority of geologists working in the district have favoured this interpretation, and have generally discarded the previously held epigenetic-replacement theories Gilmour recognized the relationship of the ores to the volcanic stratigraphy, particularly to the tops of thickened parts or domes of rhyolite in andesite-rhyolite sequences It was also one of the earliest reportings of the association of massive sulfide mineralization with the rhyolitic breccias and fragmental rocks, and the pipe-like alteration zones below the ores (Gilmour 1965) Subsequent studies and compilation reports have documented the volcanogenic origin of Archean massive sulfide ores and comparing them to the Kuroko deposits. They are now known as 'Noranda-type VMS deposits', a major type of base metal deposit in Archean greenstone belts (Sangster 1972, Franklin et al 1981, Lydon 1984a,b)

Chapter 2

REGIONAL GEOLOGICAL FRAMEWORK

INTRODUCTION

This chapter provides a overview of current understanding of the stratigraphic, geochronologic, structural, and economic geology of the Blake River Group in the Noranda district There have been a number of geological models proposed for the volcanic stratigraphy in the area, and these have been modified and evolved with new mapping and research work carried out by government surveys, industry, and universities The various interpretations and ideas are presented as they provide the framework for the present research on the volcanic stratigraphy in the D'Alembert-Cléricy area

BLAKE RIVER GROUP AGE DATES

Studies by Mortensen (1987), Corfu et al (1989), and others using U-Pb zircon method have indicated an age of approximately 2703-2698 Ma for the entire Blake River Group The geochronology data have been interpreted to support the tectonic model of the volcanic succession evolving from west to east, with stratigraphic tops younging toward the Cléricy area In the Noranda district, the youngest age date was obtained from the 'Cycle V' felsic volcanics at the eastern end of the region This rhyolite breccia located 1 km east of the town of Cléricy was dated at 2697 9 Ma (Mortensen 1987) The lowermost, hence the oldest, felsic unit in the district had an age date of 2698 7 Ma It is a rhyolite flow belonging to "Cycle I" volcanics near the

Four Corner VMS occurrence just west of the Lac Flavrian pluton (Mortensen 1987) Within the Noranda mining camp, the volcanic assemblage therefore could well been formed within a very short 1 to 2 Ma interval

The oldest date for the whole Blake River Group was from the western section of this volcanic succession, just past the Ontario-Quebec border This sequence of quartz-feldspar porphyry and associated rhyolite yielded an age date of 2703 ± 2 Ma (Nunes and Jensen 1980) Thick volcanic successions of the Blake River Group would likely have been extruded within a 5 Ma interval, and even less for the sequence in the Noranda area This is a remarkably short span of geological time for the development of a sizable package of volcanic rocks These modern age-dating techniques have thus enhanced our historical understandings and added new insight to the continuing evolving ideas on regional and stratigraphic synthesis The Noranda district is seen to have evolved as a rapid construction of volcanic complexes in a very active tectono-magmatic environment

Zircon U-Pb analysis yielded an age of intrusion of the Lac Dufault Pluton of 2694 Ma, whereas the Flavrian Pluton has an age date at 2700 Ma (Mortensen 1987) These age dates are in agreement with the model that the Flavrian Pluton is syn-volcanic and co-magmatic with the units at the intermediate level of the Noranda volcanic sequence (Goldie 1979, Paradis et al 1988, Mortensen 1987)

STRATIGRAPHIC AND STRUCTURAL MODELS

Gunning and Ambrose (1939) interpreted the east-west trending succession of the volcano-sedimentary belt of the region as forming an isoclinally-folded syncline, with the Cadillac Group at the axial core This structural interpretation has been widely adopted in subsequent geological studies and compilation reports (Wilson 1941, Dresser and Denis 1944, Baragar 1968, Goodwin et al 1972, Spence and De Rosen-Spence 1975, Gélinas et al 1977, Dimroth et al 1982)

After the interpretation of Gilmour (1965), the relationship and connection of volcanic stratigraphy to massive sulfide mineralization in the Noranda district have been widely accepted There have subsequently been, from the mid-1970s to the present, several important examinations and new concepts of genetic models for the volcanism and ore deposits in the area

Spence (1967) first suggested the occurrence of a series of rhyolite belts in the central area of the district, with thickened volcanic successions forming an anticlinorium structure Spence and de Rosen-Spence (1975) presented a more detailed review and outline of the volcanic stratigraphy, particularly the **Mine Zone** which hosts many massive sulfide deposits in the central part of Noranda area An integral part of their work was the establishment of five rhyolite zones, representing successive periods of acidic volcanic activity These five rhyolite zones are separated by major units of basalt and andesite flows The Noranda volcanic pile was considered to be a large east-trending anticlinorium containing the west to east succession of Zones I to V rhyolites, Zone III is the Mine Zone This new regional interpretation formed the framework for most subsequent studies The present thesis area includes segments of Zones IV and V, which are the later phases of extrusive activity of the evolving and eastward migrating volcanic center (Spence and de Rosen-Spence 1975)

In the 1970s, regional studies of the metamorphic history and characterization of the low grade greenschist to pumpellyite facies volcanic rock of the Noranda area were made by Jolly (1974, 1977, and 1978) He documented the metamorphic assemblages of the volcanic rocks, and the mineral reactions that took place during stages of regional metamorphism

Using major element geochemistry and discrimination plots, Gelinas et al (1977, 1982) subdivided the volcanics in the Noranda area into nine tholeitic and calc-alkaline units Ludden et al (1982) provided substantiation for this geochemical characterization using rare earth and other trace elements Gélinas et al (1984) compared the Noranda volcanism to that of large caldera systems The tholeiitic and calc-alkaline successions were assigned to distinct episodes of caldera activity The Flavrian and Lac Dufault plutons were interpreted as subvolcanic co-magmatic intrusions feeding the extrusive volcanism, as proposed and documented by Goldie (1978, 1979) In the classification system of Gélinas et al (1977, 1982), volcanic rocks in this thesis study fall within the Dufault calc-alkaline, Dufresnoy tholeiitic, and Reneault calc-alkaline units

A major stratigraphic synthesis and new tectonic evolution model was presented by Dimroth et al (1982, 1983a,b) The regional structure as documented was composed of a large Blake River synclinorium with its two branches of synclinal zones in the Noranda area cored by several domical anticline and various smaller second and third order folds (Dimroth et al 1982, 1983a) The Noranda volcanic complex was thought to correspond to an analog of Cenozoic oceanic island arc systems The volcanic succession in the region was considered to have formed by the coalescence and overlapping of several island arc volcanic centers built up on pre-existing oceanic crust of ultramafic and mafic material

A revised regional model was proposed by Gibson and Watkinson (1990) the volcanic assemblage in the central part of the district constituted a major **Cauldron** complex They combined stratigraphic changes, variation in thickness, structural interpretations, and volcanic facies relationships to establish the Cauldron model, and also revamped some of the stratigraphic correlations in the area The volcanic stratigraphy is the district formed the Pre Cauldron, Cauldron, and Post Cauldron sequences Of these, the Cauldron sequence is approximately equivalent to Zone III or Mine Zone of Spence and de Rosen-Spence (1975)

Péloquin et al (1990) also presented a geological synthesis of the region This study, along with Gibson and Watkinson (1990), subdivided the terrain of the Noranda district into blocks bounded by major faults The correlation of volcanic sequences between the blocks provides a working stratigraphic framework for the district

REGIONAL GEOCHEMICAL STUDIES

A geochemical study by Baragar (1968) using major elements compared the Blake River mafic volcanics to 'circumoceanic basalts' He suggested the basaltic magma was generated at depth, and "acidic magmas may be due to eventual melting of parts of the crust" Goodwin (1977) made an extensive study of the geochemistry of volcanic rocks of Superior craton, including the Blake River Group at Noranda, and developed a general framework of volcanic evolution for greenstone belts The volcanic successions have repeated mafic to felsic cycles, with a predominance of mafic and intermediate rocks, and an increasing proportion of felsic volcanics toward the top. Goodwin (1977) concluded that the volcanic successions changed upward from a base of tholeiitic basalts, to calc-alkaline andesites, dacites, and rhyolites at the top The intermediate and felsic volcanic products were considered to be derived from an evolving magma source, either through fractional crystallization or mixing with crustal components

Along with the geochemical studies by Gélinas et al (1977, 1982) and Ludden et al. (1982), many papers on the ore deposits have provided data on the geochemical characterization of the volcanic rocks and the effects of hydrothermal alteration Recent work in the Mobrun mine area by Caumartin and Caillé (1990), Barrett et al (1992), and Laflèche et al (1992) has provided geological, lithological, and lithogeochemical data and interpretations This has resulted in a modified subdivision of the volcanic stratigraphy in parts of the thesis area

BLAKE RIVER GROUP STRATIGRAPHY

Regional Stratigraphy

The volcanic successions in the study area, in Dufresnoy Township, belong to the Blake River Group (BRG) as defined by Gunning (1937) and Gunning and Ambrose (1939) Rocks of BRG are bordered at the north and south in part by the Kewagama and Cadillac Group sediments, respectively, and also by two major fault zones the Porcupine-Destor Break to the north, and the Cadillac-Larder Lake Break to the south (Fig 1)

The BRG is composed of a series of bimodal mafic to felsic volcanic successions, and is intruded by syn- to post-volcanic granitic and granodiorite plutons, and late dioritic to diabase sills and dikes Faulting is widespread in the region, resulting in some problems for stratigraphic correlation due to uncertainties in amounts of vertical and lateral displacements The Blake River Group in the Noranda district, as compared to other greenstone belts, contains unusually large proportions of felsic rocks massive rhyolites, rhyolite breccias, and pyroclastic material

Noranda District Volcanic Stratigraphy

The Noranda district is usually ascribed to include the Beauchastel, Dufresnoy, Dupiat and Rouyn townships (Wilson 1962) The basaltic flow-dominated lavas south of Rouyn-Noranda change northward into thick conformable basaltic-andesitic to rhyolitic sequences of the Noranda Complex (Dimroth et al 1982) Massive sulfide deposits are associated with felsic volcanic units in the central part of the district. Ore horizons are commonly found at the top of thickened felsic volcanic successions, especially along the contacts with overlying andesites, and are usually associated with laminated cherty tuff units (Gilmour 1965, Spence 1967)

In a regional stratigraphic context, the rocks in the thesis area (Fig 3), between D'Alembert and Cléricy, constitute a volcanic assemblage to the east and northeast of the Central Mine Sequence The stratigraphy extends from the top of the Amulet Andesite near the Norbec mine, east to the thick rhyolite units at the Mobrun mine.

The general lithology, geology, and structure of the Noranda area are documented on the Compilation Map U-265 (Dugas and Hogg 1962), Carte de Compilation Geoscientifiques 32D/6 and 32/D7 series (MERQ 1982), and Lithostratigraphic Map of the Abitibi Subprovince (MERQ-OGS 1984) Other compilation maps in published studies and reports can be found in Spence and De Rosen-Spence (1975), Gélinas et al (1982), Dimroth et al (1982, 1983a), and Péloquin et al (1990)

D'Alembert-Cléricy Area

The rocks of the Blake River Group in the D'Alembert-Cléricy area are included in the Noranda district volcanic sequence in the above mentioned regional geological studies The stratigraphy is commonly divided along the D'Alembert Pluton and/or the D'Alembert Fault into two parts the upper part of the Central Mine Sequence in the Flavrian Block to the west, and younger units of the BRG to the east

The western section of the transect extends from the top of the Central Mine Sequence east of the Waite Hills to the D'Alembert fault on the east side of the D'Alembert pluton This section of stratigraphy is commonly regarded as being on the periphery of the Noranda volcanic complex (Dimroth et al 1982) It contains the Zone IV rhyolites of Spence and De Rosen-Spence (1975) The western section is included in the Dufault calc-alkaline unit by Gélinas et al (1977), and later separated into the Trémoy tholeiitic unit (Gélinas et al 1984) In other regional models, the western section has been assigned to the Post-Caldera sequence by Dimroth et al (1982), the Post-Cauldron (Cycle 4) sequence of Gibson and Watkinson (1990), and within the Flavrian Block as outlined by Péloquin et al (1990)

The eastern or Cléricy section extends from the D'Alembert fault eastward to the vicinity of the town of Cléricy, and includes the Mobrun mine It contains the Cléricy rhyolite (Gélinas et al 1978) and Mobrun rhyolites, which constitute parts of the Cléricy volcanic complex as described by Dimroth et al (1982) This eastern section belongs to the Zone V rhyolites of Spence and De Rosen-Spence (1975), and the Cycle 5 volcanic sequence of Gibson and Watkinson (1990) It is placed within the Dufresnoy tholeiitic and Reneault calc-alkaline units by Gélinas et al (1977) They later regrouped this succession into the Cléricy calc-alkaline, Destor tholeiitic, Reneault calc-alkaline, and a part of the Trémoy tholeiitic unit (Gélinas et al 1982) This section lies within the eastern sector of the Blake River Group of Péloquin et al (1990) The volcanic rocks in this section were considered to be derived from a separate volcanic complex that was contemporaneous with the Noranda caldera, in the regional stratigraphic synthesis by Dimroth et al (1982, 1983a,b) These regional models form an important basis for the correlation of volcanic rocks and the exploration for VMS deposits in the outlying parts of the Noranda district

Massive Sulfide Deposits

Three massive sulfide deposits occur in the general vicinity of the thesis area The Newbec VMS orebody is located in the western end of the transect It was exploited in the late 1920s and had an output of 278 tons grading 6 74% copper (Wilson 1941, MERQ 1982) This small quantity likely represents development ore, and not economic mine production The Mobrun mine is the large VMS deposit in the thesis area It contains the only major orebodies discovered east of the Central Mine Sequence, with a total ore reserve of about 11 5 million tons (Barrett et al 1992) The mine contains several large orebodies in the '1100' and 'C' lenses, hosted mainly by massive and fragmental rhyolites and lesser andesite (Caumartin and Caillé 1990)

The VMS deposit at Mine Gallen (formerly West MacDonald mine) occurs just to the south of the thesis area It is in a volcanic roof pendant of the Lac Dufault granodiorite (Watkinson et al 1990), and is assumed to be belong to the southern extension of the volcanic stratigraphy in the D'Alembert-Cléricy area

Chapter 3

GEOLOGY AND LITHOCHEMISTRY

INTRODUCTION

This chapter presents the results of field work, and petrographic and geochemical studies of rock samples collected along a transect in the thesis area. The results are displayed in a series of maps, stratigraphic sections, tables of analyses, and plots of the geochemical data on selected discrimination diagrams.

Field Work and Sample Collection

Field work for the thesis project was carried out in the summer of 1991. Mapping of the terrain focused on the stratigraphic relationship of the volcanic units, bedding tops and facing directions, as well as documentation of geological features and structures. Detailed field mapping and sampling was carried out at selected localities along the transect where the volcanic rocks were well exposed. A total of 56 rock samples were collected. An additional 10 samples were available for the project area from the collection of Prof. W. H. MacLean, obtained on a reconnaissance survey in the previous year.

Sample Preparation and Laboratory Work

Forty representative rock samples were selected and cut into slabs to make petrographic thin sections. These were prepared by McGill's rock preparation facility and also by Vancouver Petrographic Limited of Langley, B.C.

In the preparation of samples for chemical analysis, each sample was crushed to < 1 cm, and then reduced to -200 mesh in a tungsten carbide puck grinder The powders were fashioned into fused glass disks using a Li-tetraborate flux for major element analysis (SiO_2, TiO_2, Al_2O_3, Fe_2O_3, MnO, CaO, Na_2O, K_2O, and P_2O_5), and into pressed powder pellets for the trace elements Zr, Y, Nb, Sr, Rb Fifty-three rock samples were analyzed by X-ray fluorescence (XRF) methods (Philips PW 1400 X-Ray spectrometer, with 100 kv generator and Rh X-Ray tube) in the Geochemical Laboratory of the Department of Earth and Planetary Sciences at McGill University The detection limit for the major elements was 0 01%, and 2 ppm for the trace elements Rare-earth elements (REE) and additional trace elements were analyzed on 27 samples by instrumental neutron activation analysis (INAA) by Activation Laboratories Ltd of Ancastor, Ontario Detection limits varied from 1 0 to 0 01 ppm for the different REE

Mineral compositions were analyzed on eight polished thin-sections by electron microprobe (CAMECA MBX fully-automated microprobe, wavelength dispersive system with the PAP correction procedure) in the Department of Earth and Planetary Sciences, McGill University

GEOLOGICAL DESCRIPTION

The geology of the transect is described from west to east, that is, from one km east of the Norbec mine to the Mobrun mine The thesis area map (Fig 3) illustrates the geological features and the rocks types, together with some field data and measurements The locations of rock samples taken during field work is shown in Appendix Fig 1 A general stratigraphic column has been constructed for the thesis

Geological Map of the Thesis Area

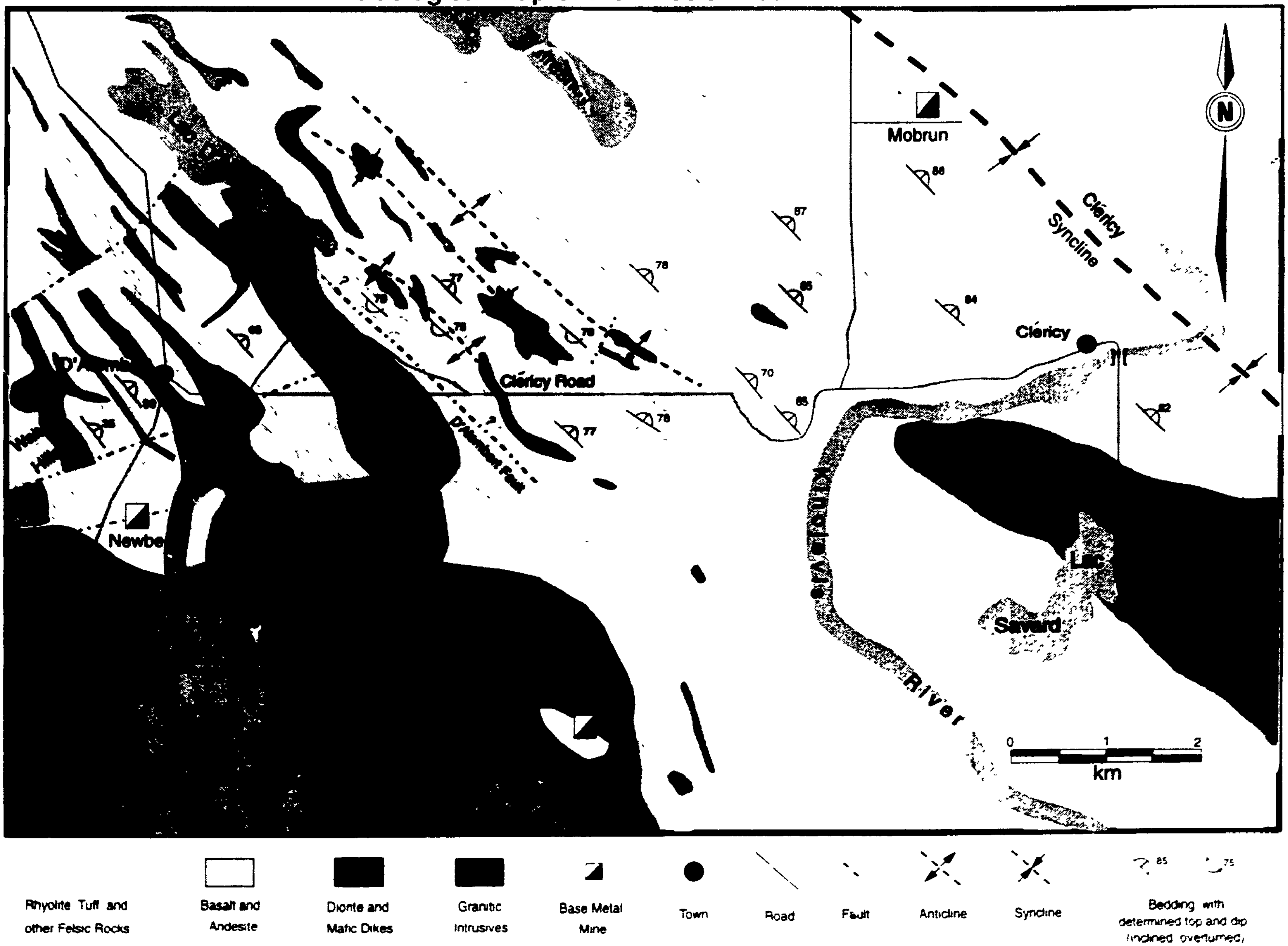


Fig. 3 Geological map of the D'Alembert-Cléricy transect, Noranda District.

area that ties into the stratigraphy of the Central Mine Sequence (Fig 4)

The Ministere de l'Energie et des Ressources du Québec (MERQ) 1 10,000 scale maps, Cartes de Compilation Géoscientifiques, and 1 15,000 scale air photos provided preliminary guides for the field work The maps covering this area are 32 D/6-0304, 32 D/6-0204, 32 D/7-0301, and 32 D/6-0201 These maps illustrate the generalized regional geology and lithologic outlines as compiled by MERQ from company reports, government documents, prospecting assessments, and drill and mine records

Field mapping for the thesis project has mostly corroborated the contacts and the extent of the major lithological units in the previous studies The present thesis work also has added more detail to the existing geological maps, resulted in the clarifications of the extent and composition of some of the units, and has revised the magmatic affinities of the major volcanic sequences It has also produced some modifications to the geology of this section of the Noranda district

Structural Geology

All rock units in the field area have a northwest-southeast regional trend, varying in strike from 300° to 340°, dips are ~35° easterly near Norbec but are steep to subvertical from D'Alembert to Cléricy This change in dip is abrupt and occurs in the vicinity of the town of D'Alembert The whole volcanic succession of this part of the Noranda district is intruded by granodiorite plutons and large medium to coarse grained gabbro-diorite dikes The dikes are generally aligned with the northwest regional trend Some of them offset and displace the volcanic units, and are interpreted to have intruded along faults Dikes are more abundant in the Waite Hills in the uppermost section of Central Mine Sequence, here these late intrusive bodies occupy east-dipping

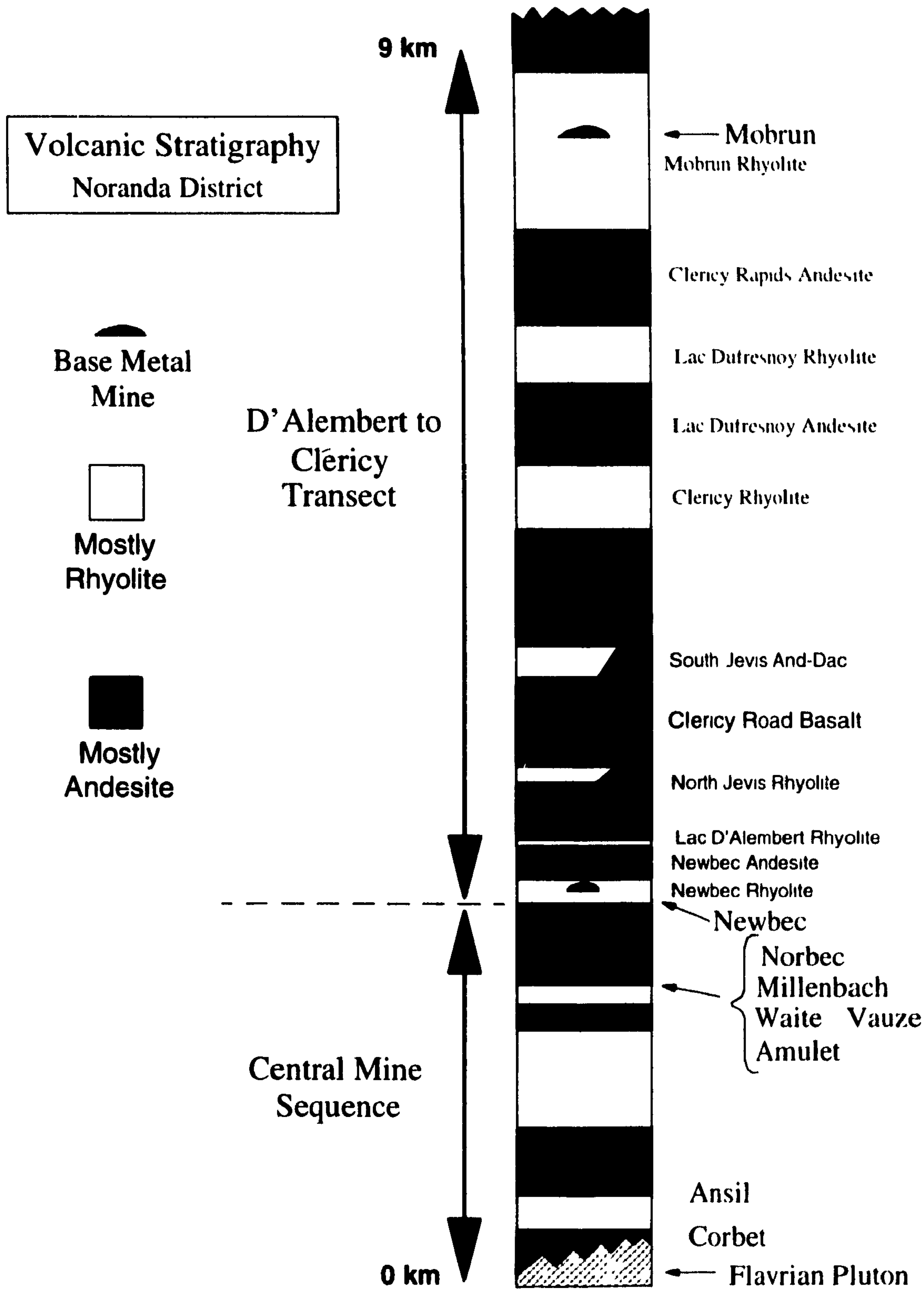


Fig. 4. Generalized stratigraphic column of volcanic lithology in the Central Mine Sequence and Thesis Area

reverse faults that uplift and repeat some of the volcanic stratigraphy (Spence 1967).

Faulting Two fault systems are prominent in the D'Alembert-Cléricy area One system trends northeast-southwest, and the other northwest-southeast, the latter being concordant with regional lithological and foliation trends The D'Alembert fault (also known as D'Alembert shear) is a regional northwest trending break It is reported in a number of regional studies (e g Dimroth 1982, MERQ 1982, Péloquin 1990, Gibson and Watkinson 1990), but not in others (e g Gélinas et al 1977, 1982) This structure occurs as a lineament on maps and air photographs, and truncates the eastern margin of the D'Alembert pluton It is considered to extend from north of Lac D'Alembert southeast through the thesis area, and is considered by Péloquin et al (1990) as the boundary of the Flavrian and East Blake River structural blocks A zone of strong foliation fabric was observed during field work for this study in the rhyolite-andesite succession along the projected fault zone on the eastern side of the D'Alembert pluton The displacement vector along this break is unknown

Folding A number of folds have been reported and proposed in the transect area (Trudel 1978, Gélinas et al 1982, Dimroth et al 1982, 1983a, MERQ 1982) The Baie Fabie and Cléricy synclines are second order isoclinal folds that have been documented in this D'Alembert-Cléricy region by Dimroth et al (1983a). Their southern extensions were traced into parts of the thesis area at some localities during field work for this study

Stratigraphic top determinations from the present work and previous studies (e g Trudel 1978) define the second order and some third order folds in the parts of the thesis area (Fig 3). The two large second order synclines extend easterly from the Lac Duparquet area, and curve southeasterly through the thesis area to the east of the D'Alembert and Lac Dufault plutons Between these two large folds are several third order folds of smaller amplitude and strike length These were documented using facing reversals in the volcanic assemblage

The presence and the positions of these folds differ in some of the regional maps and interpretations The small third order folds were difficult to verify in the field From this study there appear to be fewer third order folds than previously reported, hence there are probably also fewer repetitions of stratigraphy

The second and third order fold structures become less evident and die out south of the Cléricy road Gélinas et al (1982) and Dimroth et al (1982) indicated a fault along this highway, but little evidence was found in the present study to support this inference The decrease in intensity of the southeasterly fold structures is likely due to a gradual structural transition, passing from zones of high to lower strain The second order folds are thought to result from the regional kinematic strain regime during Kenoran deformation (Dimroth et al 1983a) The rocks in a lower strain zone to the south likely have escaped deformation due to the buttressing effect of the Lac Dufault pluton at the time of regional deformation

LITHOLOGIC AND PETROGRAPHIC EXAMINATION

In this section, field geology is integrated with data from petrography, mineralogy, and lithogeochemistry Field data come from pillow top indicators, graded beds, flow top breccias, volcanic facies changes, lava flow thickness, and other primary and secondary features This forms the basis for the examination, classification, and interpretation of the volcanic stratigraphy In addition, major and trace element discrimination plots (such as K_2O vs SiO_2 and REE profiles) and HFSE ratios (such as the Zr/Y values) are used to assist in the identification and classification of the lithologies

On the K_2O vs SiO_2 diagram (Fig 5), the K_2O range and geochemical affinities (Low-K to High-K) of the freshest rocks and their fractionation range (basalt-andesite-dacite-rhyolite) are shown Altered samples showing varying degrees of silicification, sericitization, albitization, and chloritization have been screened and omitted from this plot As can be seen, the rock units range from basalt to rhyolite, which is typical of the Noranda region (Gélinas et al 1984, Thurston et al 1985, Paradis et al 1988) The majority of rocks belong to a Low-K series, as also has been documented in the Central Mine Sequence in the district (MacLean and Hoy 1991, Barrett et al 1991b)

The greenschist mineral assemblage is discussed in a later section along with the lithologic and petrographic descriptions Plots of mineral chemistry are used to assist in the documentation of the secondary minerals actinolite, epidote-zoisite, chlorite, sericite, K-feldspar and albite The data are collected from seven rock samples from intervals along the transect, the samples represent the variety of volcanic rocks encountered

On the basis of Zr/Y ratios, K_2O-SiO_2, and other data, the volcanic sequence has been classified into several lithological subdivisions as shown on the lithological map of the area (Fig 6) These are presented and discussed more fully in the following chapter Average chemical analyses of individual units for the units are listed in Tables 3, 4, and 5 in the following text Analyses of all samples are presented in Appendix Table I

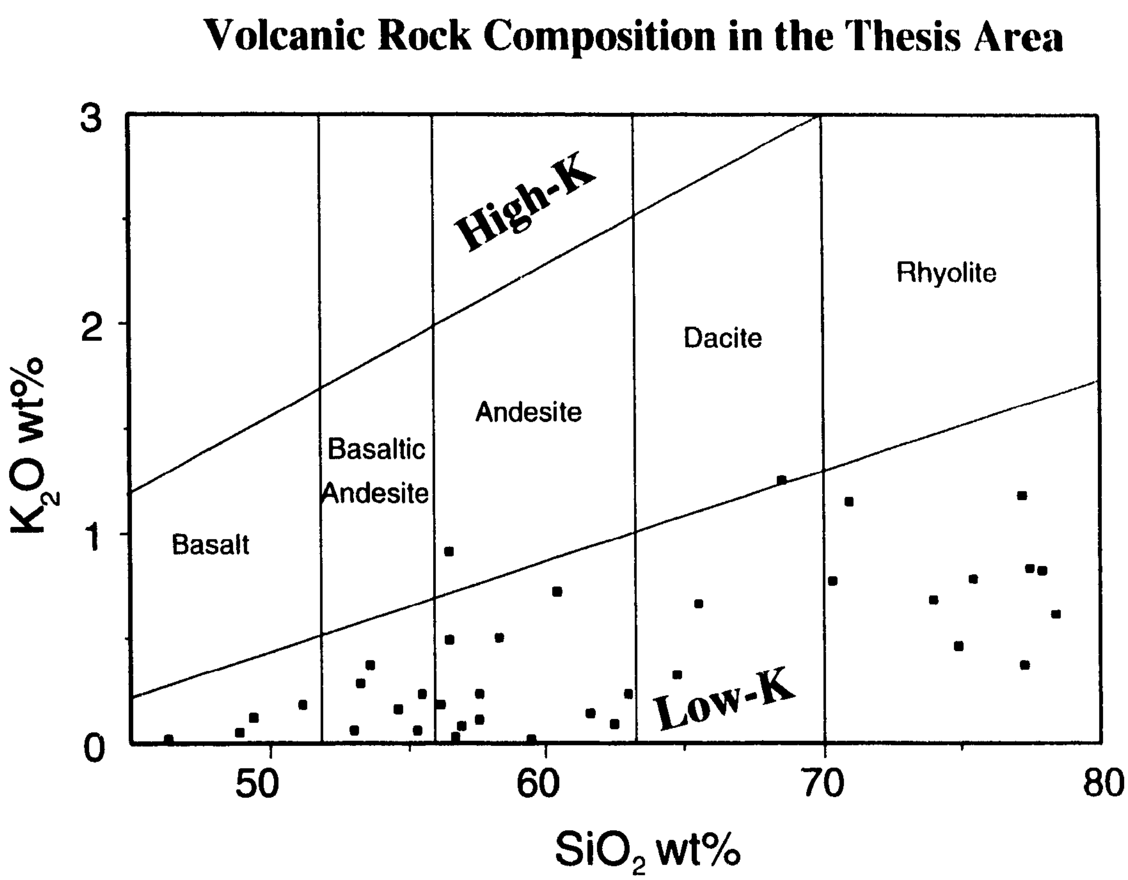


Fig. 5. Plot of K_2O vs. SiO_2 showing the range of volcanic composition in the study area, as given by least]altered samples. After Peccerillo and Taylor (1976).

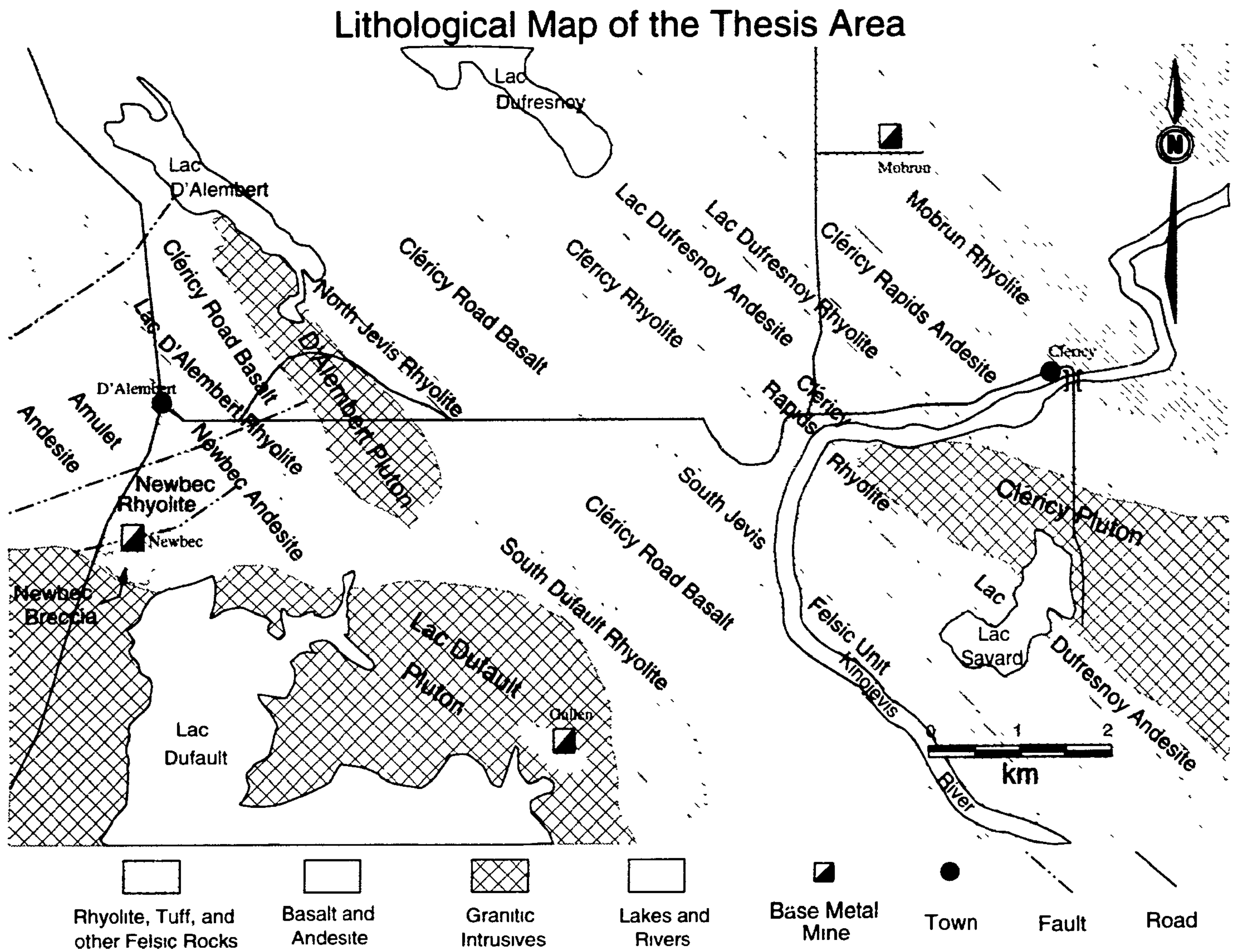


Fig. 6. Map of the volcanic stratigraphy in the D'Alembert-Cléricy transect.

Amulet Andesite

The starting point of the traverse was from the middle of the Amulet Andesite in the Waite Hills It is commonly shown as the uppermost formation of the Central Mine Sequence The Norbec Cu-Zn VMS orebody occurs at the contact of this unit and the underlying Waite Rhyolite

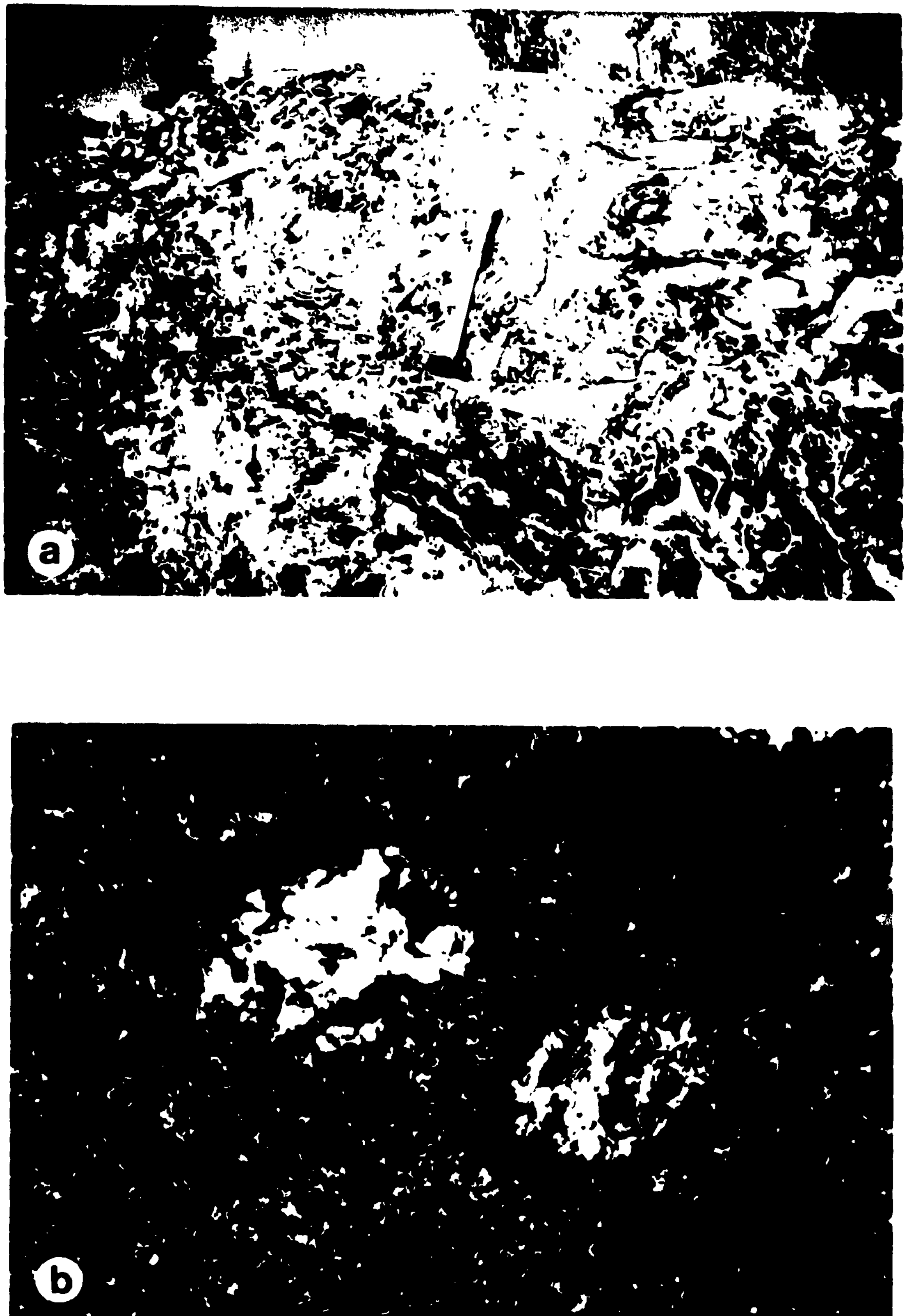
The Amulet Andesite is a succession of pillowed and massive flows, commonly amygduloidal, and aphyric to slightly plagioclase porphyritic The unit is intruded by gabbro-diorite dikes Its average composition is in the andesite range and its Zr/Y value of 4 7 suggests a transitional affinity (Table 3) On the K_2O-SiO_2 diagram, samples of the unit plot in the low-K basaltic-andesite to andesite range

Individual lava units range from three to about twenty meters thick, striking ~330° and dipping 35° to 40° NE Pillow tops and flow top breccias face northeast At several localities with good outcrop exposure, lava flows have well developed massive units grading upward into pillow lava capped by flow top breccia Flow front breccias were also observed containing pillow fragments (Fig 7a), dipping at 20° to 30° relative to the body of the unit (this produces an apparent dip for the flow unit) The massive to pillow flow succession is commonly repeated in the Amulet Andesite stratigraphy in the Waite Hills

Fig 7 Amulet Andesite

a Pillows and pillow breccia, Waite Hills.

b Photomicrograph of fine grained, spilitized andesite with quartz-epidote amygdules Scale bar = 0 5 mm


a
b

Petrographically, the Amulet Andesite has an intersertal texture Spilitization and low grade metamorphism have produced an assemblage of albite, zoisite, epidote, chlorite, sericite, quartz, and actinolite Plagioclase grains are albitized, likely after andesine-labradorite Both zoisite and epidote occur in the matrix, and as large blades and fan-like radiating grains in amygdules and other open space fillings (Fig 7b) The amphiboles occur as prismatic, fibrous grains, in the range of actinolite with Fe/Fe+Mg ratios of 0 34 to 0 45

Chlorite generally occurs as a fine grained replacement of mafic matrix components and also as large open-space filling aggregates Most of the chlorite is khaki-brown, with an Fe/Fe+Mg ratio ranging from 0 35 to 0 45, and plots in the ripidolite field The khaki-brown birefringent chlorite in the presence of blue zoisite (low Fe) form an equilibrium assemblage These are distinctive of the low bulk iron contents of these andesites

Newbec Rhyolite

The occurrence and approximate extent of the Newbec Rhyolite, Newbec Andesite, and Newbec breccia were first outlined by Wilson (1941) The Newbec Rhyolite is usually placed stratigraphically above the Mine Sequence, in the post-caldera volcanic succession The main body of rhyolite occurs at the Newbec Mine near Highway 101, in the vicinity of the northwest corner of Lac Dufault (Fig 3), but it extends close to the town of D'Alembert

Samples of the Newbec Rhyolite are from the old Newbec mine The unit is a massive greyish-white quartz porphyry, with euhedral quartz phenocrysts (1-4 mm)

Table 3. Average chemical analyses of the western volcanic units (least altered samples).

Units	Amulet	Newbec	Newbec	D'Alembert
Rock Type	Andesite	Rhyolite	Andesite	Pluton
n	3	2	1	2
SiO_2 wt%	55 78	79 41	54 99	65 99
TiO_2	1 12	0 18	0 64	0 48
Al_2O_3	16 02	11 14	16 48	13 29
FeO	7 15	1 39	7 78	4 24
MnO	0 16	0 01	0 13	0 14
MgO	4 83	0 22	5 61	1 57
CaO	7 12	0 70	5 88	3 27
Na_2O	4 53	5 42	5 28	4 31
K_2O	0 30	0 29	0 04	1 15
P_2O_5	0 17	0 03	0 09	0 12
LOI	1 66	0 60	2 76	4 64
Total	98 84	99 37	99 68	99 18
V ppm	221	18	165	56
Cr	93	58	127	90
Ni	49	14	60	31
Ba	57	66	154	399
Rb	7	6	0	31
Sr	97	41	204	103
Y	19	35	19	23
Zr	90	304	89	141
Nb	8	15	7	9
n'	(1)	(2)	(1)	
Hf	2 1	7 7	2 6	
Th	0 7	3 0	1 7	
Ta	0 3	2 4	1 0	
Sc	25	6	26	
La	9 2	22	17	
Ce	20	48	38	
Nd	11	27	22	
Sm	2 6	6 1	5 9	
Eu	0 82	1 00	1 60	
Tb	0 50	1 15	1 00	
Yb	1 53	4 92	4 14	
Lu	0 23	0 78	0 66	

n - number of samples

n' - number of samples with REE analyses

One sample has an abnormally high Zr/Y ratio of 13 5 (Appendix Table I) which places it in the calc-alkaline affinity range However, this high Zr/Y value is likely due to hydrothermal alteration involved in the sulfide mineralization This rhyolite and the Newbec Breccia are considered to be of transitional affinity

Petrographically, the rhyolite is fresh-looking, with large euhedral quartz phenocrysts and occasional albite-oligoclase phenocrysts in a fine grained quartzo-feldspathic matrix (Fig 8a)

Newbec breccia The heterolithic Newbec rhyolite breccia intrudes the Newbec Rhyolite, and is exposed on a ridge south of the mine Unsorted fragments of massive rhyolite, pillow and massive andesites, and quartz diorite occur in a matrix of rhyolite (Fig 8b) The clasts are angular to subrounded, and display a range of weathered colours from white, grey, green, brown, to orange, reflecting their heterolithic nature

One analyzed sample from the rhyolite matrix is chemically identical to the Newbec Rhyolite, with a Zr/Y ratio of 6 5 The Newbec Breccia therefore most likely belongs to the Newbec Rhyolite unit It may be a felsic dike intrusive, related to rhyolites higher in the stratigraphy, such as the North Jevis Rhyolite and the Cléricy Rapids Rhyolite (Tables 4 and 5)

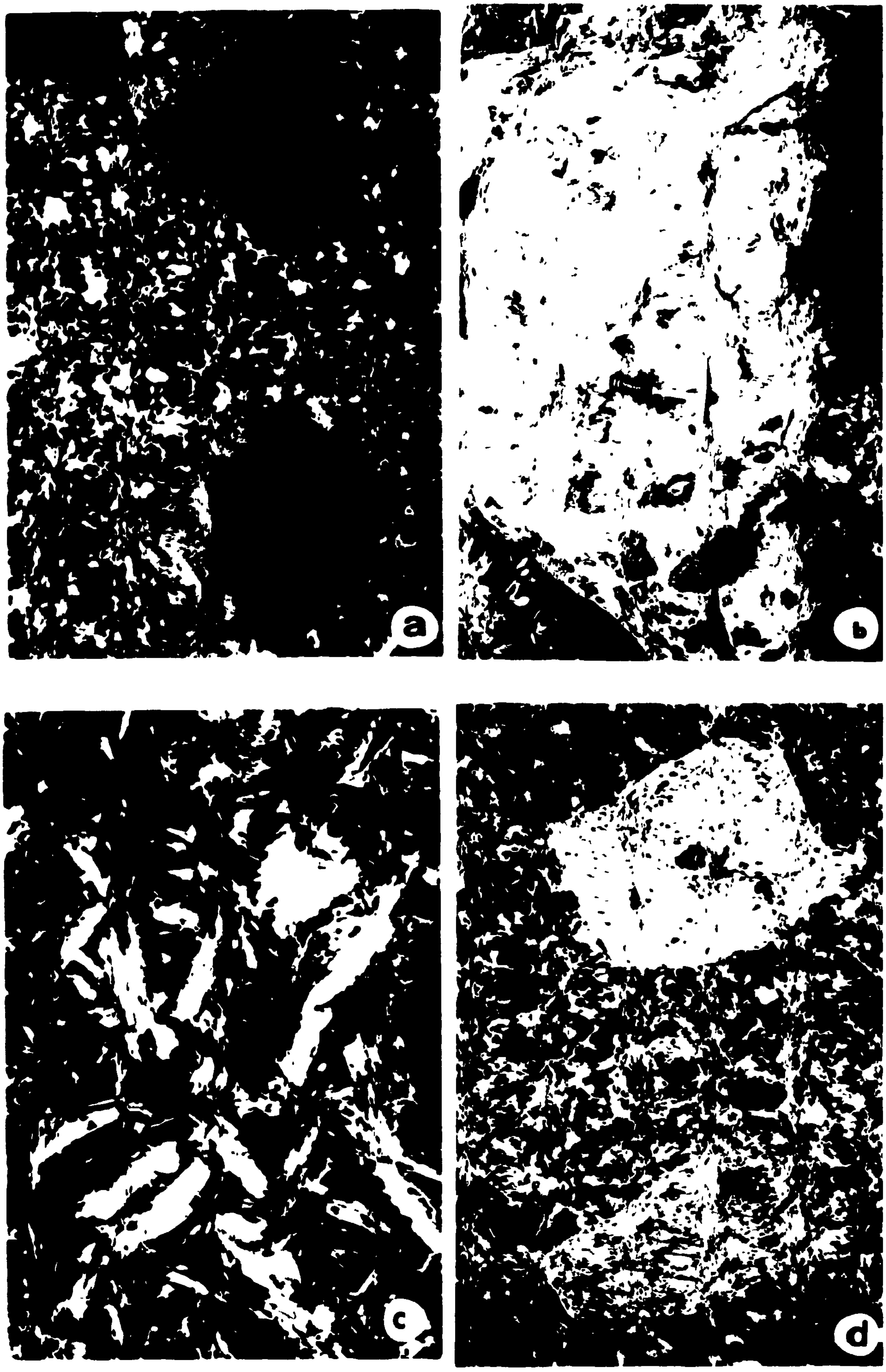
In an earlier report on this unit, Wilson (1941) ascribed an explosive origin to the Newbec Breccia He also suggested that the breccia was late, and may have formed after the intrusion of granodiorite In later geological reports, the Newbec Breccia has been classified as an intrusive 'diatreme breccia' (Spence 1967, Gibson and Watkinson 1990)

Fig. 8a Newbec Rhyolite Photomicrograph of quartz-albite porphyritic rhyolite The albite phenocryst is sericitized, the matrix is quartz, albite, and minor epidote and chlorite. Sample 91-53 Scale bar = 0 5 mm

Fig 8b. Newbec Breccia Field photograph of an outcrop of the heterolithic breccia, the matrix is rhyolitic, and the clasts are diorite, andesite, and massive and porphyritic rhyolite Sample 91-53

Fig 8c Newbec Andesite Photomicrograph of medium grained andesite with intersertal texture of plagioclase laths and a matrix of epidote, actinolite, quartz, plagioclase, chlorite, and opaque oxides Sample 91-52 Scale bar = 0 5 mm

Fig 8d D'Alembert Rhyolite Photomicrograph of albite porphyry rhyolite The albite phenocrysts are largely replaced by carbonate and sericite The felsic matrix is also sericitized and contains minor carbonate and chlorite Sample 91-55 Scale bar = 0 5 mm


a
b
c
d

Newbec Andesite

The Newbec Andesite is a mostly massive, medium grained, plagioclase microporphyritic flow unit that overlies the Newbec Rhyolite It is an andesite of transitional affinity with a Zr/Y ratio of 4 7 (Table 3), and plots in the low-K andesite field (Fig 6) The rock has an intersertal texture with a randomly oriented network of plagioclase laths, and altered mafic matrix of chlorite, epidote, actinolite, sericite, and leucoxene (Fig 8c).

Newbec Deposit The Newbec VMS deposit, located about 500 meters east of Highway 101 (Fig 3), occurs at the contact of Newbec Rhyolite the overlying Newbec Andesite, The deposit is of low tonnage but high grade and was explored in the 1920s Mining records indicated that up to 1930, production was 278 tons of development ore assaying 6.74% Cu (Wilson 1941) The massive sulfide ores contain chalcopyrite, sphalerite, pyrrhotite, and pyrite Altered Newbec Andesite immediately overlies the ore and rhyolite, and is exposed on surface outcrops at the old Newbec mine shaft

D'Alembert Rhyolite

In the field area adjoining the Newbec Andesite, the D'Alembert Rhyolite forms a thin (<10 m) porphyritic unit It contains plagioclase phenocrysts (1 to 3 mm) which are largely replaced by carbonate and to a lesser degree by sericite (Fig 8d) It is a low-K rhyolite of transitional affinity (Table 4 and Appendix Table I), and is possibly to correlate it with the 'Fish-roe Rhyolite', as described by Péloquin and Verpaelst (1989) and Péloquin et al. (1990). The main body of the 'Fish-roe rhyolite' is north of the thesis area near the Hunter Creek fault, where it forms massive rhyolite with plagioclase glomerophenocrysts and a spherulitic texture (Péloquin and Verpaelst 1989) Although it has been mapped as far south as the Cléricy Road, exposures of this rhyolite are scarce in the thesis area

D'Alembert Pluton

This small pluton of albite granite intrudes along the contact of the Newbec Andesite to the west and the Cléricy Road Basalt to the east (Fig. 3) Its eastern margin is taken as the boundary of the Flavrian and East Blake River blocks of Péloquin et al. (1990) The pluton is a coarse grained granitic rock composed of sericitized albite, quartz, chloritized mafic minerals, carbonate, and leucoxene Although in proximity to the Lac Dufault pluton, its genetic relationship is not clear as few comparative lithochemical studies have been made The D'Alembert pluton contains about 70 wt % SiO_2, 14 wt% Al_2O_3, 1 2 wt% K_2O (Table 3) and Zr/Y value of 6 2 suggests a transitional affinity Sericitized albite grains likely account for much of the K_2O in the chemical analysis, which may have been introduced during water-rock interaction. Alteration is also denoted by the high modal carbonate contents and high LOI in the granite

Cléricy Road Basalt

The extensive Cléricy Road Basalt lies between the Newbec Andesite and D'Alembert Pluton to the west and the Cléricy Rhyolite to the east, and includes the previously outlined D'Alembert Andesite as mapped by Wilson (1941) and Paradis et al (1988) This basalt sequence extends over 3 5 km along the Cléricy Road, but its true thickness (perpendicular to strike) is about 2 5 km Two thin felsic volcanic

Table 4. Average chemical analyses of the central volcanic units (least altered samples).

Units Rock Type	D'Alembert Rhyolite	North Jevis And-Dac	South Jevis Rhy-Dac	Cléricy Road Basalt	Cléricy Rhyolite
n	1	3	6	9	1
SiO_2 wt%	68 48	73 68	65 81	49 20	76 88
TiO_2	0 50	0 20	1 04	1 54	0 15
Al_2O_3	12 09	11 72	14 02	15 07	11 84
FeO	4 19	2 89	5 48	12 57	2 63
MnO	0 09	0 07	0 12	0 26	0 05
MgO	1 32	0 24	1 96	4 93	0 68
CaO	3 53	3 78	4 08	8 10	0 28
Na_2O	1 83	3 96	4 30	2 77	5 77
K_2O	2 51	0 49	0 55	0 19	0 83
P_2O_5	0 10	0 03	0 25	0 15	0 02
LOI	4 37	1 37	1 83	3 78	0 59
Total	99 01	98 44	99 43	98 55	99 72
V ppm	49	16	70	320	12
Cr	10	19	99	174	10
Ni	11	13	54	114	18
Ba	379	130	190	66	133
Rb	40	11	13	5	11
Sr	38	192	139	132	30
Y	68	45	31	25	93
Zr	248	249	136	64	314
Nb	15	15	9	7	20
n'	(1)	(3)	(3)	(4)	(4)
Hf	4 4	5 2	3 3	1 2	7 8
Th	3 8	2 6	1 3	0 3	5 7
Ta	1 4	1 3	0 7	0 3	1 9
Sc	9	12	21	37	6 2
La	28	14	13	3 6	39
Ce	64	31	29	10	86
Nd	38	17	16	7	46
Sm	9 6	4 2	4 1	2 2	10 9
Eu	1 44	0 85	1 29	0 75	1 29
Tb	2 10	0 90	0 83	0 55	2 45
Yb	8 21	4 97	3 21	1 93	9 70
Lu	1 25	0 81	0 48	0 30	1.49

n - number of samples

n' - number of samples with REE analyses members, the North Jevis Rhyolite and the South Jevis Felsic Units, are interlayered within this thick basalt sequence (Fig 3) The Cléricy Road Basalt consists of low-K tholeiitic basalt and basaltic-andesite, averaging 51 8 wt % SiO_2 with a Zr/Y value of 2 4 (Table 4)

A number of anticlinal and synclinal folds have been mapped in this thick mafic unit (Trudel, 1978) However, the folds do not appear to continue southward beyond the Cléricy Road, thus the stratigraphic thickness of the Cléricy Road Basalt is not definite Top indicators from pillow lavas (Fig 9a) observed during field work indicate the presence of fold closures in some localities (Fig 3)

The Cléricy Road Basalt is made up of massive and pillow mafic flows These lava flows are locally amygduloidal, and display layering of pillows in some outcrops The rocks dip 70° to 75° E, much steeper than the 35° to 40° for the volcanics of the Amulet Andesite and other units of the Central Mine Sequence The lava flows of this tholeiitic basaltic unit are much thicker and more extensive than those in the transitional Amulet Andesite

The basalts of this unit have intersertal textures, and are composed of altered plagioclase and secondary mafic minerals The matrix and amygdule fillings are mostly chlorite, epidote-zoisite, sericite, and quartz (Fig 9b)

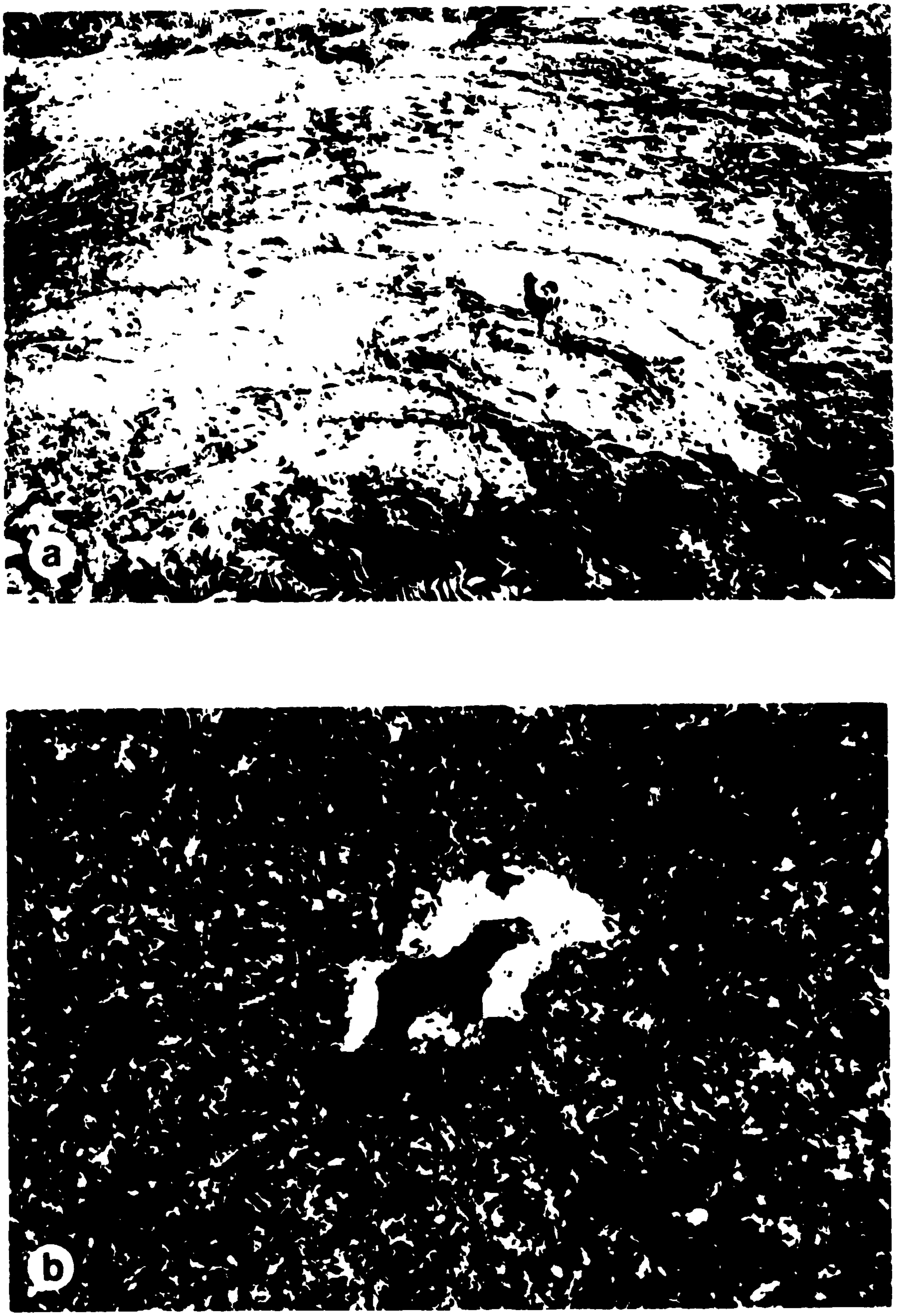
North Jevis Rhyolite

In the field area, this unit occurs as a sequence of foliated rhyolitic flows with lesser amounts of pyroclastic material and rocks of intermediate composition Located north of the Cléricy Road adjacent to the D'Alembert Pluton, the North Jevis unit is contained within the large tholeiitic Cléricy Road Basalt unit (Fig 3) It forms hills and

Fig 9 Clèricy Road Basalt

a. Pillow lava with thin selvages, from a large outcrop 0 5 km north of the Clèricy Road Sample 91-34

b Photomicrograph of spilitized basalt with void-filling blue chlorite in the shape of a bear surrounded by carbonate in vesicle filling Sample 91-9 Scale bar = 0 5 mm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outcrops that rise above the low-lying mafic lava terrain

South of Lac D'Alembert, exposure of layered volcaniclastics containing graded beds and other well-preserved bedding textures (Fig 10a) is interpreted to belong to the North Jevis Rhyolite These graded volcanics are interlayered with mafic lavas of the Cléricy Road Basalt unit The layered volcaniclastic beds comprise a series of graded coarse to fine ash tuff deposits (Fig 10b,c) with tops to the southwest This top direction indicates a reversal in facing of the volcanic sequence, defining one of the second-order folds as documented by Trudel (1978) and Dimroth et al (1982)

Further south, near the road, outcrops of this unit show interlayered rhyolite and andesite flows These rocks exhibit a foliation and strain fabric, with angular cleavage faces, and are locally cut by white quartz-carbonate veins Deformation has also locally formed andesite boudins within the more competent rhyolite The foliation fabric is parallel to bedding, with an average orientation of 295°/dip 80° E

The rhyolites are low-K and transitional, with Zr/Y averaging 5 9 (Table 4) The thin interlayered andesite flows within the North Jevis Rhyolite are also of transitional affinity

South Jevis Andesite-Dacite

This approximately 100 m thick unit of andesite, dacite, and rhyolite occurs on roadside hill outcrops next to farm buildings towards the eastern margin of the Cléricy Road Basalt (Fig 3) On the south side of the road, the most abundant rock type is andesite This andesite forms two fragment-rich pyroclastic flows (Fig 10d), trending northwest-southeast and dipping 76° NE The pyroclastic units are each about 25 m

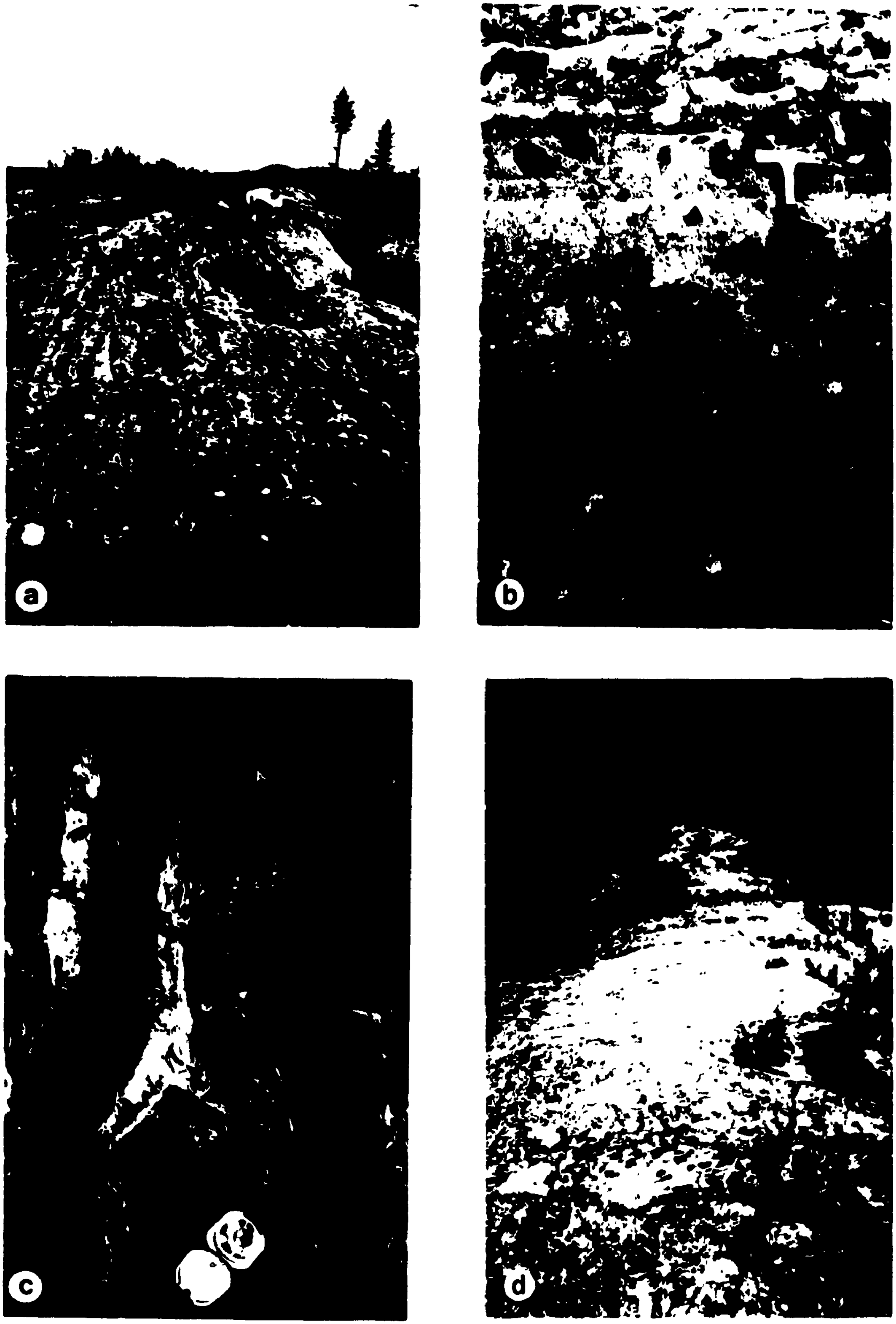
Fig 10a,b,c North Jevis Rhyolite, field photographs, 1 km north of the Cléricy Road.

a Outcrop of layered volcaniclastic beds, tops to the right.

b Detail from (a), repeated graded lapilli tuff beds, fining upwards

c Detail from (a), succession of coarse lapilli tuff, chert, and fine tuff beds, tops to the left

d South Jevis Unit Several units of intermediate volcaniclastic breccia, on a ridge south of the road cut The fragments range up to 15 cm, andesite dike in the foreground Sample 91-32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thick, and contain sorted beds of coarse to fine lapilli clasts, separated by a fine laminated ash tuff bed They fine upward to the northeast, consistent with the overall regional stratigraphic facing

On the north side of the road, a series of thin dacite flows and clastic beds, totalling 50-60 m thick, occur on the western side of the outcrop This unit also includes a thin (few meters) rhyolite bed Some of the interbedded volcaniclastic breccia units contain angular blocks Petrographically, the dacite flows contain plagioclase laths outlining an igneous flow texture with occasional plagioclase phenocrysts and numerous elongated quartz amygdules

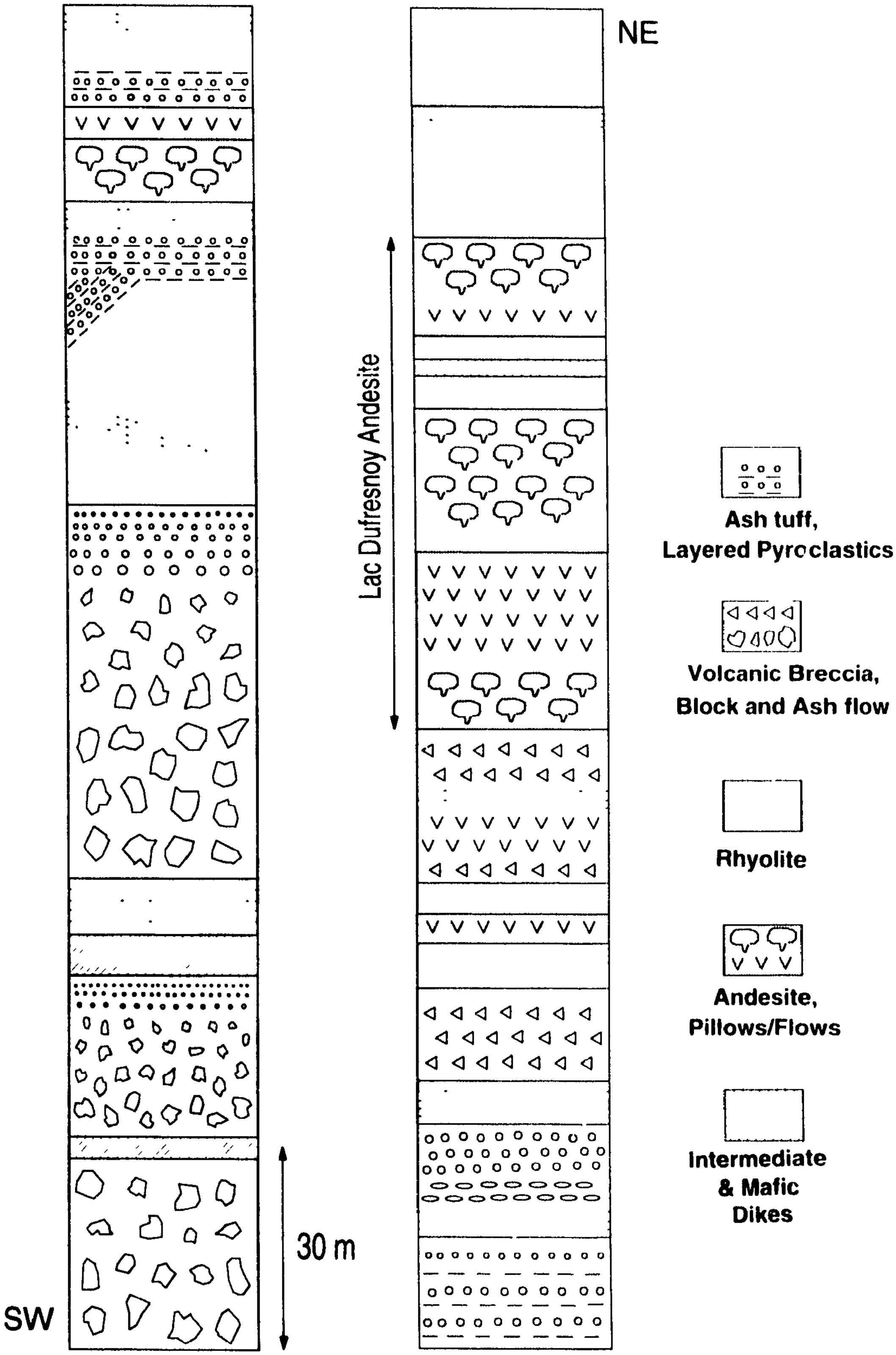
The andesite on the south side of the road is low-K and transitional to calc-alkaline, according to its Zr/Y value of 8 5 (Appendix Table I) Other affinity discriminants, presented in a later chapter, affirm this classification The rhyolite in this unit is also transitional (Zr/Y = 6 2), but the dacite (three samples) is distinctly tholeiitic, according to Zr/Y and other geochemical discriminants (Appendix Table I)

The South Jevis unit has previously been mapped as a rhyolite fragmental volcanic flow This study indicates that it is of mainly andesitic and dacitic composition, and is distinct from the North Jevis Rhyolite, which is mainly rhyolitic

Cléricy Rhyolite

Rocks of Cléricy Rhyolite occur as a wide band of felsic units extending from the south end of Lac Dufresnoy to Lac Savard (Fig 3). They comprise part of the Cléricy Rhyolite complex of Gélinas et al (1978) and Dimroth et al (1982) The type locality is at the southern end of the unit where the Cléricy Road forms a U-shaped loop around the south end of the ridge, near the Kinojevis River (Fig 3)

Fig. 11. Stratigraphic column of volcanic rocks on Rhyolite Hill, Clericy Rhyolite Unit



A succession of rhyolitic volcanics with minor interlayered andesite lava are present on the ridge The volcanic units are presented in a stratigraphic column from southwest to northeast (Fig 11) Parts of this ridge exposure are composed of massive rhyolite lava flows with local flow banding, rhyolite breccia and agglomerate, pyroclastic block and ash deposits, felsic ignimbrite flows, and some graded lapilli ash-tuff beds

The rhyolite units range from 76 to 80 wt% SiO_2, and most are sericitized with high K_2O in the 3 to 4 wt% range (Table 4) They have an average Zr/Y of 3 7 (fresh and altered samples), and are therefore of tholeiitic affinity

Facings in the volcanic sequence on the ridge are to the northeast, and dips are steep from 70° to 85° NE Top directions were determined from graded volcaniclastic deposits, and pillow tops and flow-top breccia in the interlayered andesite lavas As illustrated in the stratigraphic column (Fig 11), the base of the unit is dominated by thick successions of felsic block and ash pyroclastic beds (Fig 12a) and minor ash-tuff beds, both cut by discordant andesitic dikes In the upper section, massive rhyolite, felsic breccia containing rhyolite blocks (Fig 12b), and layered felsic pyroclastic deposits are common Near the top, there are also some interlayered pillow flows of the South Dufresnoy Andesite The fragmental rhyolites in this upper section include massive flows, pyroclastic lapilli ash tuffs (Fig 12c), pyroclastic-phreatic agglomerate breccia, and base-surge ash tuff deposits (Fig 12d) Beds of felsic fine-grained laminated tuff containing pyrite grains, reminiscent of cherty tuff exhalite, are also found on the ridge

Petrographic study shows the flow rhyolites contain pristine quartz and partly altered albite phenocrysts, set in a devitrified fine-grained sericitized quartz-feldspar matrix, some flow samples contain spherulites of felsic composition (Fig 13a) The lapilli-ash tuffs and other pyroclastic beds of the Clérìcy Rhyolite unit are made up of

Fig 12. Cléricy Rhyolite, field photographs

a Outcrop of parts of two block and ash rhyolite flows, the units exhibit well developed coarse to fine grading of volcanic clasts, with tops to the right

b Angular blocks of massive rhyolite embedded in rhyolite ash flow tuff

c Massive rhyolite interbedded with pyroclastic lapilli ash tuff units, hammer for scale (near top of outcrop)

d Finely laminated surge deposits (on right side of the photo) found at the base of a lapilli tuff pyroclastic flow

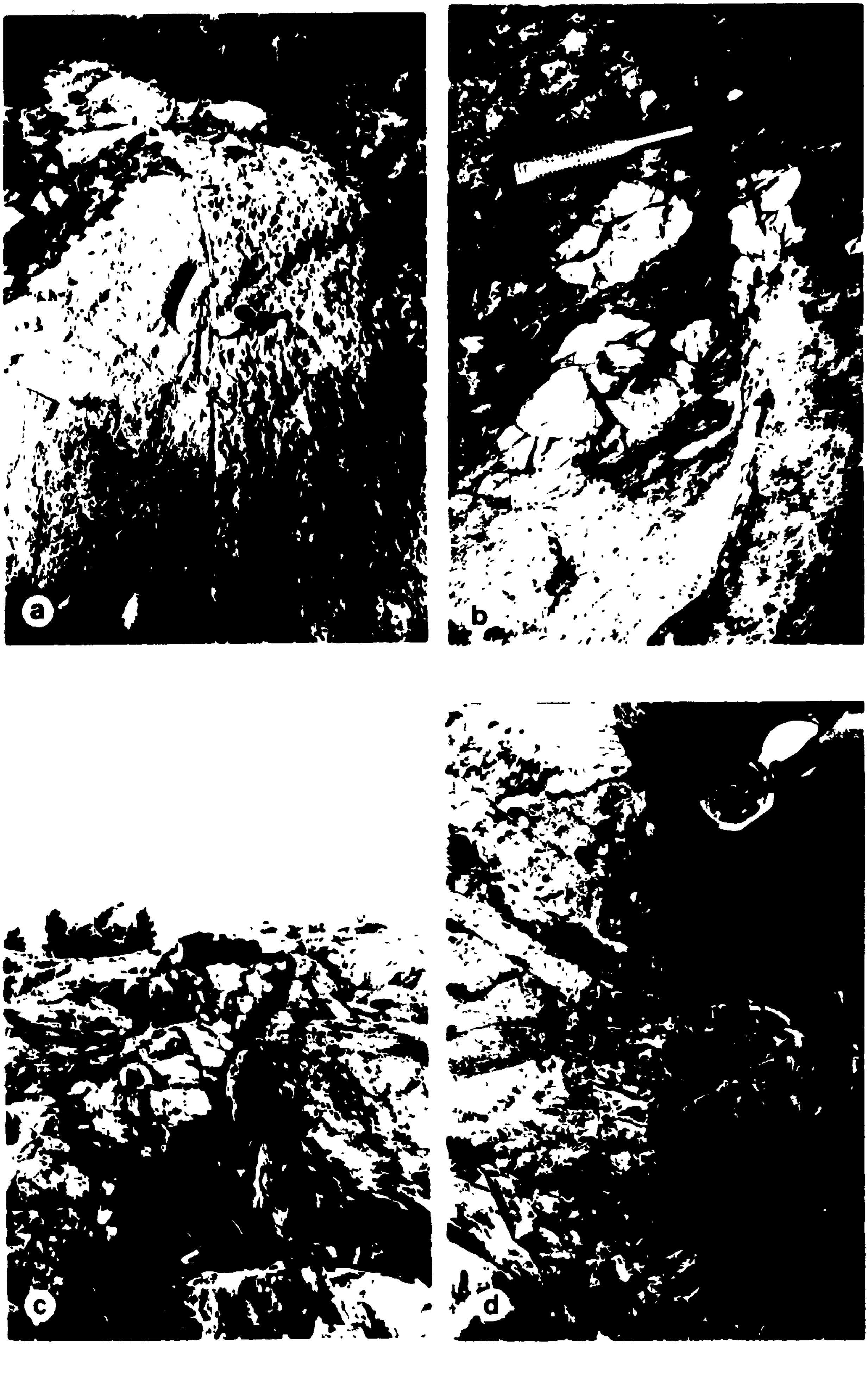

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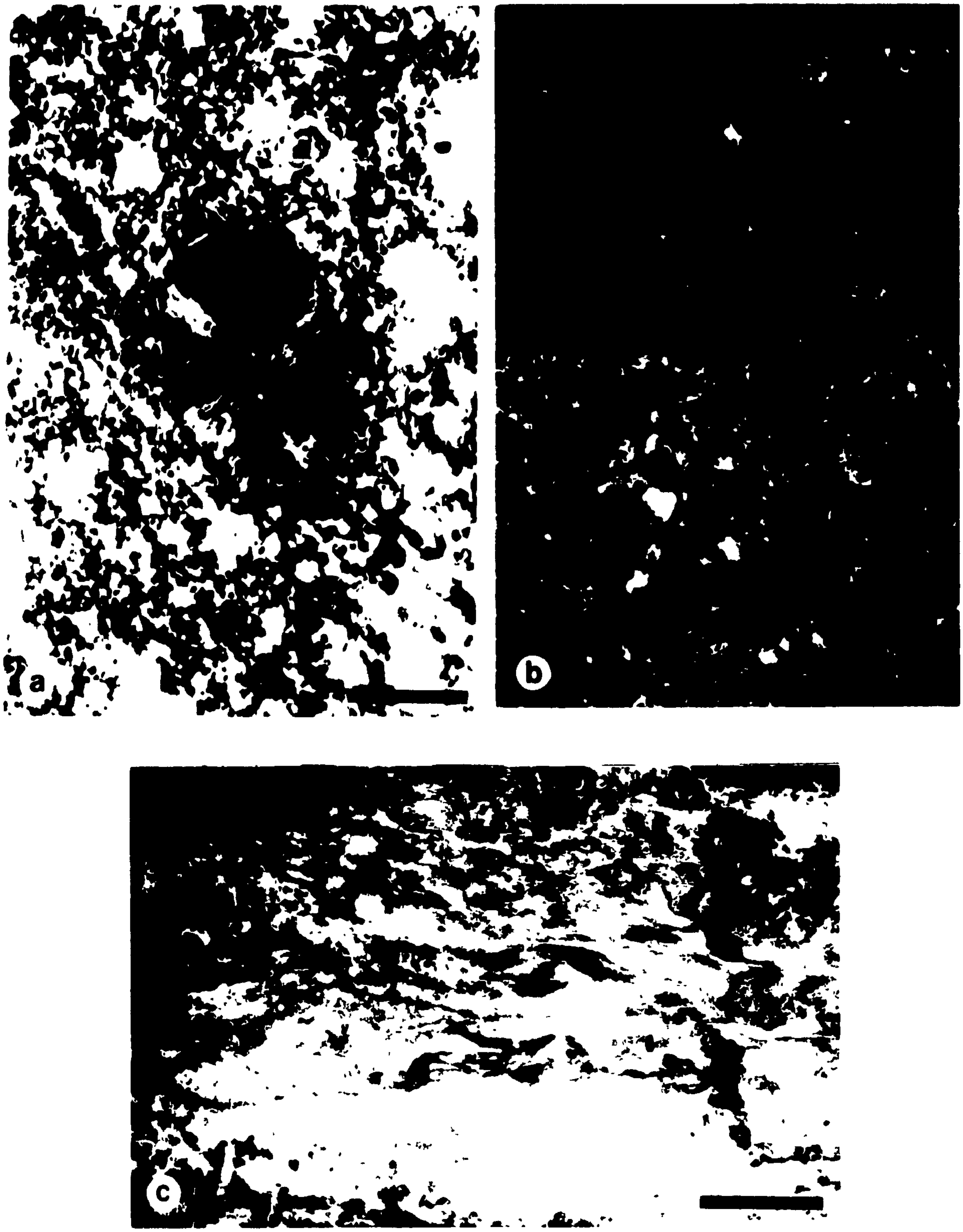
Fig. 13 Cléricy Rhyolite photomicrographs Scale bars = 0.5 mm

a Spherulitic rhyolite, with fine grained devitrified quartz-feldspar groundmass Sample 91-20

b Two graded laminated ash tuff beds, with quartz and albite grains, volcanic ash material and shards Sample 91-16

c Welded texture in block and ash pyroclastic deposit, collapsed shard fragments and ash grains, with large lapilli-pumice material in the lower third of the photo Sample 91-20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volcanic ash of vitric and crystal components, pumiceous lapilli material, and some vesicular lithic fragments Bedded successions and graded textures are well preserved in some of the laminated tuff beds (Fig 13b) The pyroclastic deposits have typical welded textures with collapsed pumice-lapilli material, and flattened shards with compressed and attenuated fluidal fragments (Fig 13c)

This volcanic succession comprises near-vent to proximal facies felsic deposits It formed in the vicinity of hydrothermal vent activity, wherein by accumulation of explosive eruption material and associated slump and debris flow A shallow subaqueous explosive volcanic environment is indicated by the regular intervals of stratified volcaniclastic deposits, and by the low amount of transported and reworked material There are sections within this thick rhyolite unit that are hydrothermally altered Many samples have been sericitized, and show variable degrees of silicification and chloritization Some outcrops of these altered rocks have rusty, bleached, and greyish-yellow colours The field characteristics of these altered rocks and their anomalous geochemistry have been outlined by Trudel (1978)

Cléricy Rapids Rhyolite

The Cléricy Rapids Rhyolite is a mostly massive sequence, separated from the Cléricy Rhyolite to the east by a thin zone of Lac Dufresnoy Andesite The former rhyolite extends south to the Cléricy road, over to the Kinojevis River and around the Cléricy pluton (Fig 3) It differs from the tholeiitic Cléricy Rhyolite in having a transitional affinity, with average Zr/Y = 4 8 (Table 5)

This felsic flow unit ranges from light-green to grey-green to grey-black (Fig 14a) The rhyolite has a fine grained quartzo-feldspathic matrix of devitrified material and phenocrysts of euhedral to subhedral quartz and albite

Table 5. Average chemical analyses of the eastern volcanic units (least altered samples).

Units Rock Type	Clericy Rapids Rhyolite	Lac Dufresnoy And (TR)	Lac Dufresnoy And (TH)	Lac Dufresnoy Rhyolite	Cléricy Rapids Andesite	Mobrun Rhyolite
n	2	3	3	5	2	1
SiO_2 wt%	76.02	56.81	56.29	74.76	56.07	79.96
TiO_2	0.23	0.89	1.45	0.27	1.39	0.20
Al_2O_3	11.76	15.88	13.71	12.02	14.04	9.76
FeO	2.04	6.66	10.14	2.94	10.96	2.46
MnO	0.04	0.09	0.21	0.04	0.15	0.03
MgO	0.42	4.42	3.95	0.46	4.05	0.68
CaO	0.31	8.39	6.99	1.02	6.86	0.47
Na_2O	4.30	4.12	3.60	5.40	2.63	4.36
K_2O	2.83	0.35	0.16	0.72	0.06	0.64
P_2O_5	0.03	0.11	0.15	0.04	0.13	0.03
LOI	0.57	1.67	2.70	1.44	3.04	1.08
Total	98.54	99.39	99.35	99.11	99.36	99.67
V ppm	20	226	340	22	304	28
Cr	91	116	35	11	72	10
Ni	13	60	23	17	12	10
Ba	576	100	94	211	47	166
Rb	41	10	4	14	3	12
Sr	32	170	139	47	129	25
Y	54	17	43	99	32	52
Zr	272	84	124	358	138	242
Nb	16	6	10	23	10	12
n'	(1)	(1)	(1)	(2)	(1)	(1)
Hf	6.6	1.9	4.1	9.7	4.6	5.3
Th	5.8	1.1	1.4	5.6	1.6	5.5
Ta	1.4	0.5	0.6	2.2	0.7	1.2
Sc	7	21	40	6	39	6
La	41	9.0	13	26	18	29
Ce	82	19	31	59	44	61
Nd	37	10	19	35	25	30
Sm	9.0	2.4	6.0	9.5	6.6	7.1
Eu	1.38	0.67	1.68	1.54	1.41	0.99
Tb	1.80	0.50	1.40	2.40	1.40	1.40
Yb	6.54	1.84	5.22	10.05	5.90	6.26
Lu	1.00	0.29	0.84	1.56	0.85	0.94

n - number of samples
n' - number of samples with REE analyses
TR - Transitional subunit
TH - Tholeiitic subunit

The Cléricy Rapids Rhyolite represents a new episode of volcanic activity, producing massive rhyolite flows of transitional affinity distinct from the underlying mainly pyroclastic and tholeiitic Cléricy Rhyolite complex.

Lac Dufresnoy Andesite

The Lac Dufresnoy Andesite is a basaltic-andesite to andesite massive and pillowed flow unit, lying between the Cléricy Rhyolite complex and the Lac Dufresnoy Rhyolite (Fig. 3). Some mafic dikes crosscut the lava. Elsewhere, felsic clasts are incorporated within some pillow breccia. Deformation has produced a weakly developed foliated texture. The pillows have a general elongation trend of 285° and are steeply dipping with tops to the northeast. Epidote and carbonate veinlets are present throughout the flow unit.

The Lac Dufresnoy Andesite is of mixed affinity, with a major transitional subunit having Zr/Y ratios in the 4.4 to 5.4 range, and a smaller tholeiitic subunit with Zr/Y = 2.7 (Table 5).

Lac Dufresnoy Rhyolite

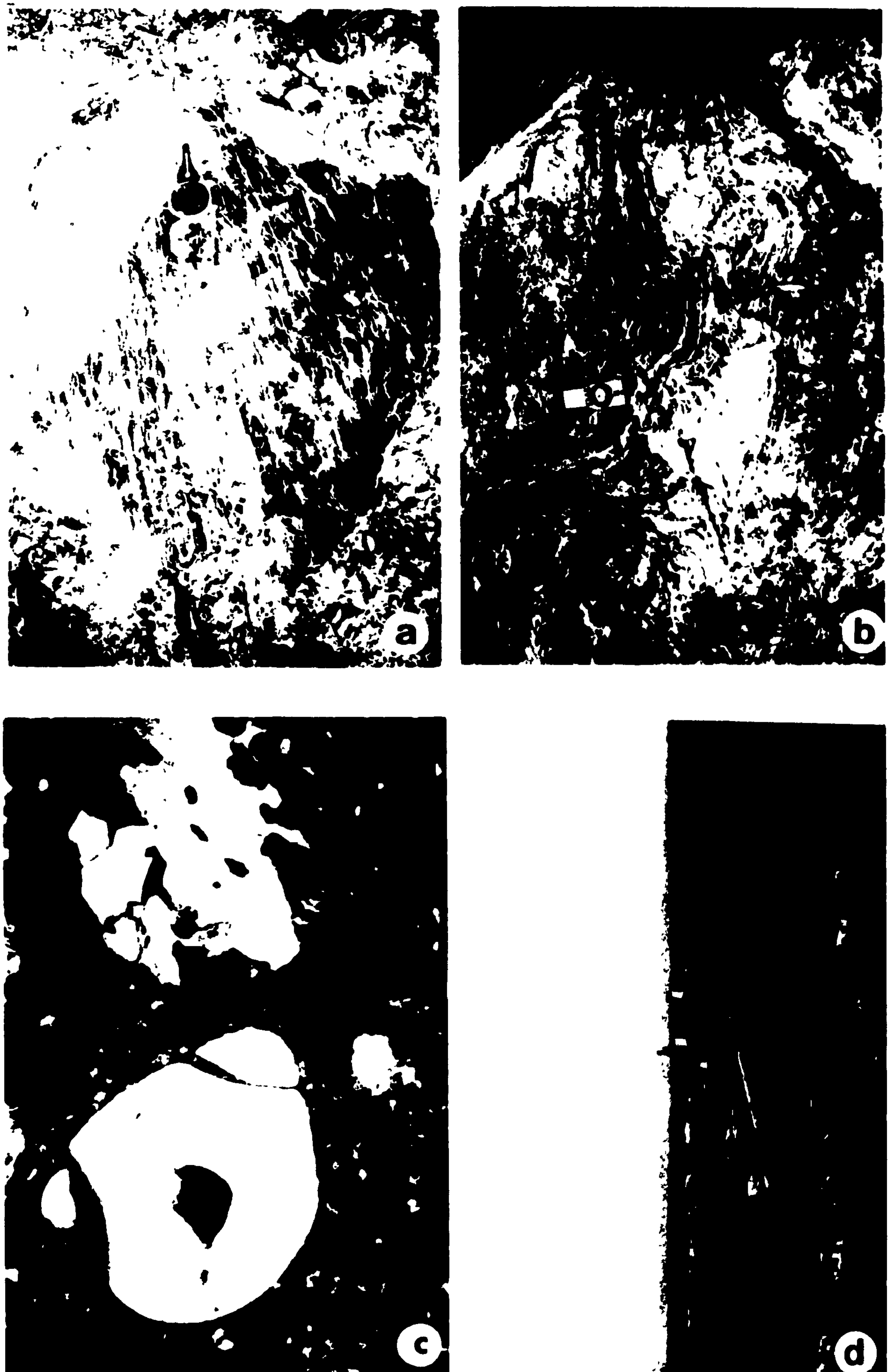
The Lac Dufresnoy Rhyolite forms a broad ridge bounded by topographically lower andesites. The rocks are of tholeiitic affinity, with a group average Zr/Y value of 3.6. Most of the samples are somewhat sericitized with relatively high K_2O, and range from 74 to 80 SiO_2 wt % (indicating silicification in some samples, Table 5).

The rocks of this unit range from greenish-white massive rhyolite, quartz-feldspar porphyry, quartz amygduloidal rhyolite, spherulitic felsic flows, to complex flow banded rhyolite. A foliation fabric is observed with locally developed cleavage faces. The rocks dip steeply, and also exhibit complex igneous flow folding in some outcrops (Fig. 14b). The rhyolites have a slightly sericitized quartzo-feldspathic matrix, Fig 14a Cléricy Rapids Rhyolite. Small roadside outcrop of black massive quartz porphyritic rhyolite, glacial striae trend northerly Sample 91-27

14b Lac Dufresnoy Rhyolite Contorted igneous flow banding in rhyolite

14c Lac Dufresnoy Rhyolite Rounded and embayed quartz phenocryst and a polycrystalline quartz amygdule of the same size in quartz-albite porphyritic rhyolite Sample 91-42 Scale bar = 0.5 mm

14d View looking east of the Mobrun Mine from a ridge of Mobrun Rhyolite.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with rounded and embayed single-crystal quartz phenocrysts and polycrystalline quartz-filled amygdules (Fig. 14c).

Cléricy Rapids Andesite

The Cléricy Rapids Andesite is a massive to pillowed basaltic-andesite. Within the thesis area, this mafic lava unit extends from Lac Dufresnoy to the Cléricy rapids on the Kinojevis River near the bridge at Cléricy. This is a mixed affinity unit, with Zr/Y ratios of about 3.8 and 5.8. It is probably derived from an interlayered sequence of mafic lavas, originating from two separate but coeval sources of differing affinity, each producing bimodal volcanic products.

Mobrun Rhyolite

Geological studies of volcanic stratigraphy around the Mobrun mine area have been made by Caumartin and Caillé (1990), Barrett et al. (1992), Laflèche et al. (1993), and Riopel et al. (in press). The Mobrun Rhyolite (Fig. 14d) is composed of two major rhyolitic units, with minor amounts of interlayered andesite lava flows. The rhyolite is host to the Mobrun VMS deposits. The Copper Hill rhyolite member, which is stratigraphically below the ores, occurs southwest of the mine site. The Main and 1100 complexes occur within a sequence of felsic flows and volcaniclastics (Barrett et al. 1992). The Copper Hill member consists of aphyric felsic flows, with variable degrees of sericitization, silicification, and carbonatization. The Copper Hill rhyolite is overlain by thin units of massive, amygduloidal andesite and minor dacitic volcaniclastic rocks, then the 1100 complex follow by massive rhyolite, the Main Lens complex, and rhyolite volcaniclastics. According to Barrett et al. (1992), the Copper Hill rhyolite member is tholeiitic, whereas the overlying members range from tholeiitic to calc-alkaline (Zr/Y ranges from about 2.5 to 8).

Chapter 4

GREENSCHIST MINERALOGY

INTRODUCTION

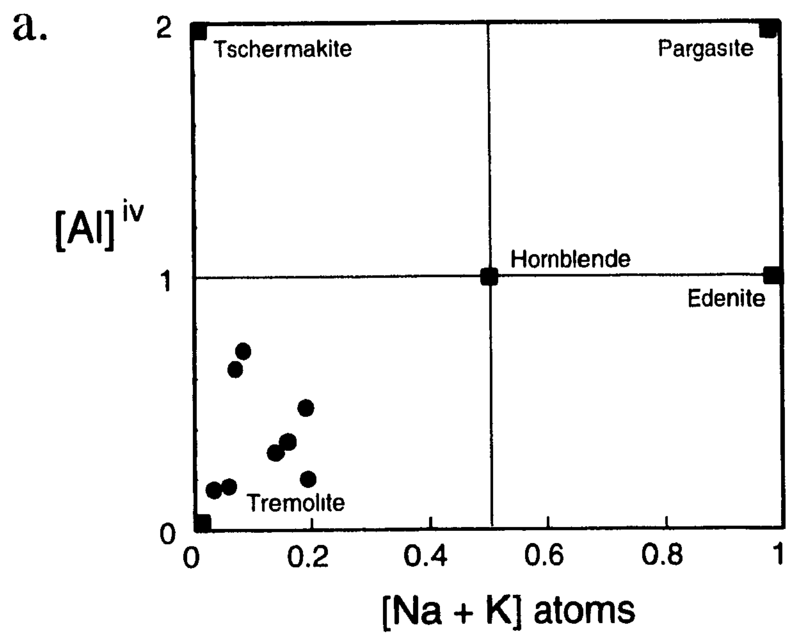
This section documents the low grade greenschist facies minerals found in the volcanic rocks of the thesis area Secondary mineral assemblages have replaced much of the original igneous minerals and glass matrix These greenschist metamorphic assemblages are typical of the rocks in the Noranda district, and of other Archean greenstone belts as well

Each mineral species was analyzed by the electron microprobe wavelength-dispersive technique The compositional variations of the mineral, modes of occurrence, and textures are discussed in the following subsection

Although documentation of greenschist mineralogy is useful, it is commonly neglected in most studies of Archean greenstone terrains Used in conjunction with petrography, lithogeochemistry, and alteration mineral norms, data on mineral chemistry can provide insights into the initial magmatic composition and affinity of the rocks, and assists in the interpretation of lithostratigraphy

Mineral Chemistry Diagrams

Microprobe chemical analyses of a selection of minerals are presented in a series of diagrams in order to document the compositional variations, major cation substitutions, and distributions of the greenschist minerals



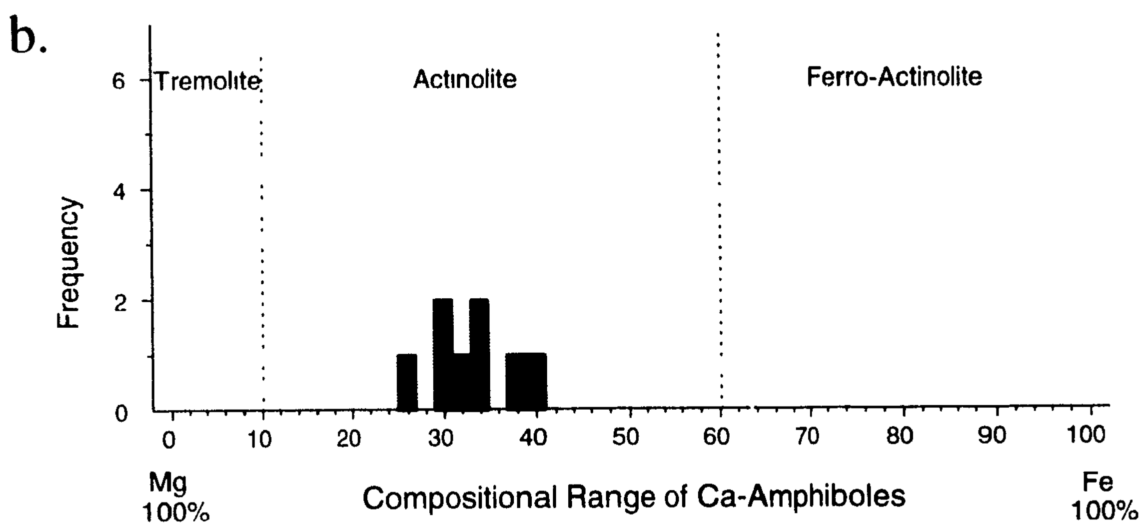


Fig. 15. Amphibole compositional and frequency plots, with bars indicating number of amphibole mineral analyses.
Average microprobe analyases for samples in the thesis area are listed in Appendix Table II.
Diagram (a) is after Deer, Howie, and Zussman (1966), p.168.

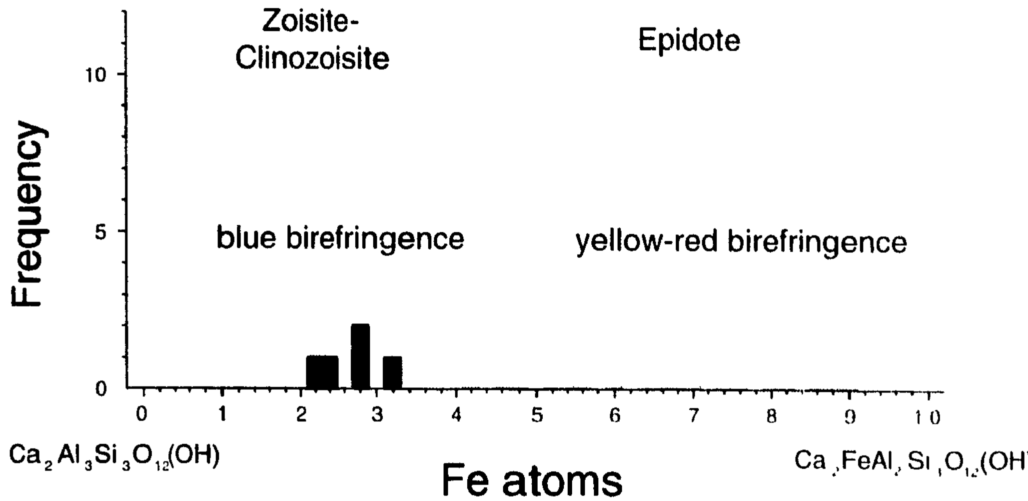


Fig. 16. Epidote-Zoisite frequency diagram with indicated number of analyses for epidote and zoisite-clinozoisite, and distinct relationship between birefringence colours and chemical composition. Average microprobe analyses are listed in Appendix Table II.

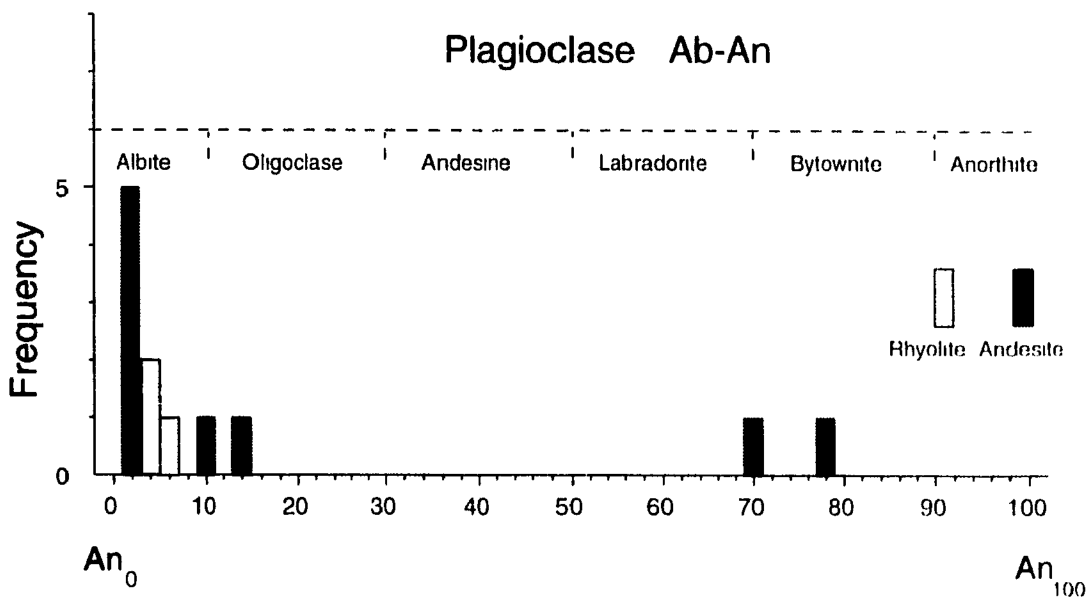


Fig. 17. Plagioclase composition frequency diagram, with bars indicating number of plagioclase analyses Average microprobe chemical analyses are listed in Appendix Table II

Chlorite Diagram

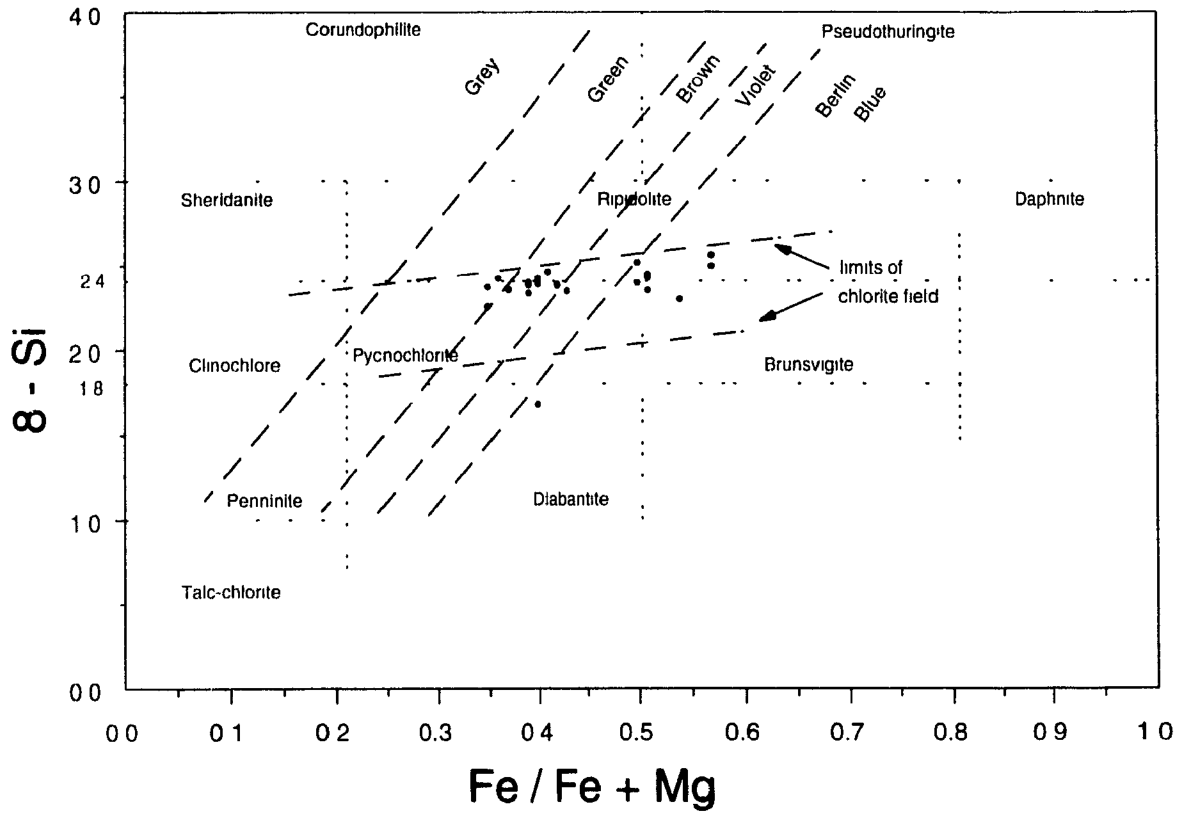


Fig. 18. Chlorite compositional diagram, after Hey (1954), and and Kranidiotis and MacLean (1987), but modified to a rectangular plot for simplification in plotting and interpretation. The limits of chlorite field for samples in the thesis area as shown are approximate. Average chlorite analyses composition of analyzed samples are given in Appendix Table II.

On an Al^4 vs Na+K diagram (Fig 15a), the calcium amphiboles plot as Fig tremolite-actinolite, they outline a narrow range in the actinolite field on an Fe/Fe+Mg frequency diagram (Fig 15b)

The epidote-zoisite frequency plot (Fig 16) reveals a group with high Fe content which are epidotes with yellow-red birefringence, and a group with low Fe are zoisite-clinozoisite with blue birefringence The plagioclase analyses plot as two groups (Fig 17) Two samples are at An_{70} and An_{78} and represent igneous compositions in mafic rocks An albite-oligoclase group represents both primary compositions in rhyolites, and albitized plagioclases in low grade metamorphic mafic rocks

The chlorite diagram (Fig 18) is modified after Hey (1954) by simply plotting 8 - Si^{iv} vs Fe/Fe+Mg which makes it orthogonal and more suitable for plotting The analyzed samples are mainly in the ripidolite and pycnochlore fields, and display a range of birefringence colour from green-brown to Berlin blue Temperature calculations after Cathelineau and Nieva (1985) and Kranidiotis and MacLean (1987) indicate the chlorites formed in the range of 245° to 270°C, based on the distribution of Al and Si

Plagioclase

The feldspars are the most common minerals in many of the pristine volcanic rocks In basalts and andesites they form an intersertal texture of plagioclase laths enclosing mafic minerals and volcanic glass The plagioclase in low grade greenschist rocks has undergone varying degrees of alteration (Fig 19a), having been converted to or replaced by sericite, epidote-zoisite, albite, and carbonates Many of the plagioclases are in the range of An_0 to An_{15} (Fig 17), and may have formed by the albitization reaction

$$CaAl_2Si_2O_8 + 4\,SiO_2 + 2\,Na^+ \Rightarrow 2\,NaAlSi_3O_8 + Ca^{+2}$$

anorthite quartz albite

Under low grade metamorphic conditions, the very mobile Ca is leached from plagioclase and glass, and Na is commonly added from the spilitizing fluid to react with immobile Al to form additional albite The anorthite component of plagioclase is converted to epidote-zoisite, which forms as a replacement phase, and as fine grained saussurite Few plagioclase grains avoid spilitization and hydrothermal alteration Remnant Ca-plagioclase in these mafic rocks is rare in the Noranda district

K-Feldspar

Potassium feldspar has been found in one sample of a mafic pyroclastic tuff lens within the Clericy Rhyolite unit (sample NP-22), as composite grains with sericite in the matrix, and as amygdule fillings (Fig 19b) This crystal and vitric ash tuff is andesite to basaltic-andesite in composition and is surrounded by low-K rhyolite flows and pyroclastic tuffs

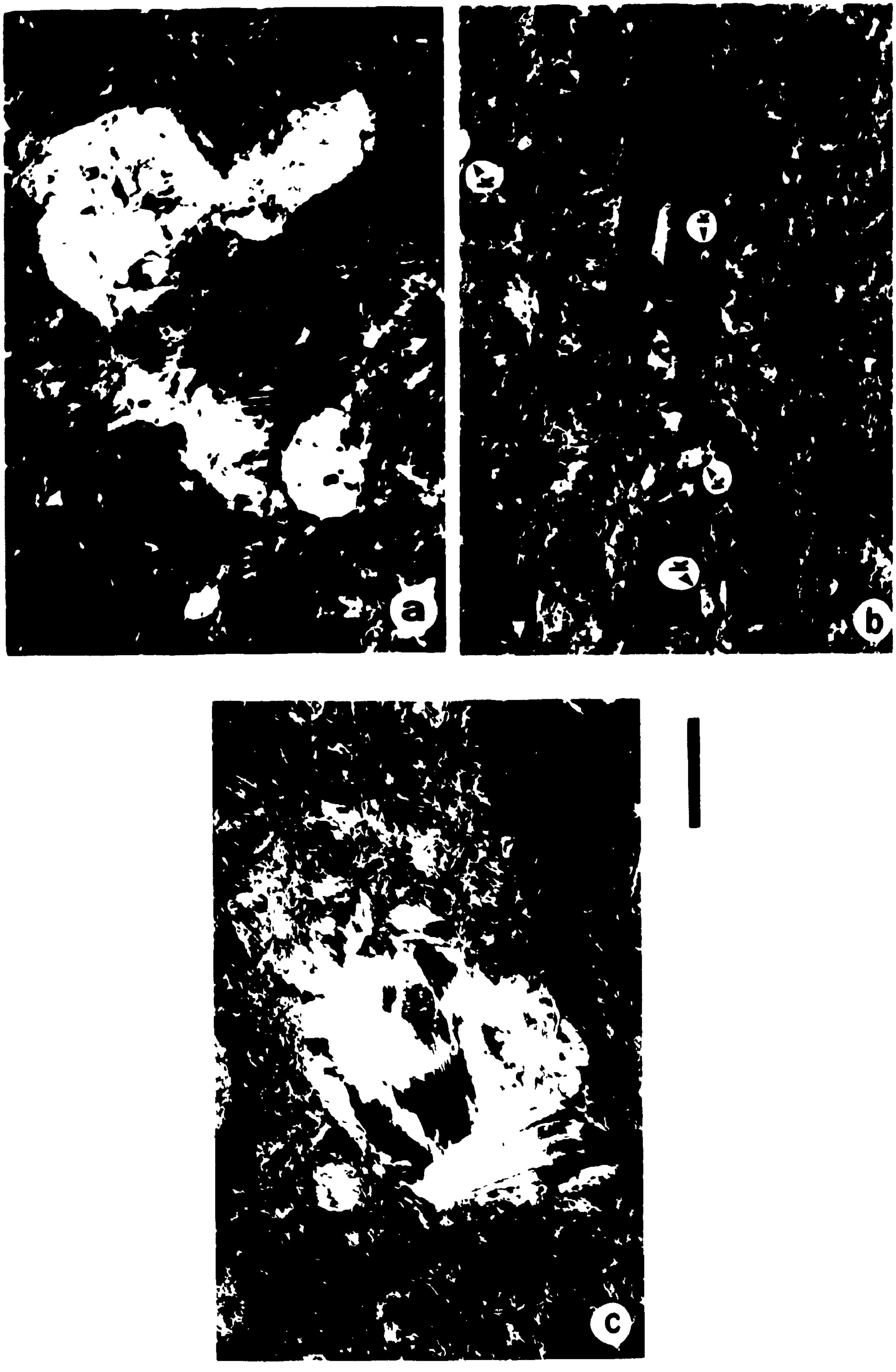
The rock also contains apparently large saussuritized plagioclases that are partly replaced by sericite and lesser K-feldspar, and fragments of devitrified andesitic glass shards (Fig 19b) The amygdules are found in the lithic clasts The devitrified glass

Fig 19 Photomicrographs of mineral textures Scale bar = 0 5 mm

a Plagioclase phenocrysts partially replaced by sericite and carbonate Clericy Rhyolite, Sample 9 1-36

b K-feldspars (k) in an andesitic tuff unit, occurring as an amygdule filling and composite grains with sericite in the groundmass Lac Dufresnoy Andesite, Sample 9 1-22

c Amygdule of coarse grained actinolite Lac Dufresnoy Andesite, Sample 91-29


a
b
c

fragments and the matrix are composed of sericite, chlorite, epidote-zoisite, and K-feldspar. In addition to amygdules that have K-feldspars, many also contain chlorite and epidote, but not sericite.

The K-feldspar appears to an alteration product formed during water-rock interaction which introduced large quantities of potassium. The intergrowth of K-feldspars and sericite in the composite grains indicates high pH conditions at the K-feldspar/sericite boundary. This process is equivalent to the heavy sericitization found in some altered greenstone rocks, but K-feldspar was stable here as well as sericite.

The potassic character of this rock is also indicated by the bulk chemistry (Appendix Table I). The rock contains 4.70 wt% K_2O, but only 1.16 wt% Na_2O. The andesite lens is transitional with a Zr/Y ratio of 5.1. Other HFS element data were not available for this sample. The K-feldspar is very pure, with greater than 99% Or in all the analyzed grains (Appendix Table II).

Potassic feldspar as an alteration phase in pyroclastic flows is an uncommon occurrence in low-K volcanic terrains. This andesitic lens is interlayered with low-K rhyolites in a mainly felsic formation. In the Noranda district, most volcanic rocks are tholeiitic and transitional, and the common feldspar is albite.

Actinolite

Actinolite is a typical greenschist mineral that occurs together with albite, chlorite, sericite, and epidote-zoisite. It is a calcium amphibole with bladed, acicular to fibrous habit that forms as a replacement mineral in the matrix and in amygdules

(Fig 19c) Actinolite replaces pyroxene, hornblende, and other amphiboles under low-grade greenschist conditions A clinopyroxene replacement reaction is possible

$$5Ca(Mg,Fe)Si_2O_6 + 6H^+ \Rightarrow Ca_2(Mg,Fe)_5Si_8O_{22}(OH)_2 + 3Ca^{+2} + 2SiO_2 + 2H_2O$$

clinopyroxene actinolite quartz

Actinolite analyses from the mafic rock samples plot as a narrow cluster between 25 to 40 cation % Fe on the amphibole compositional diagram (Fig 15b)

On the Al^{+4} versus Na+K cation diagram (Fig 15a), the actinolites are in the low Na+K and low Al corner of the diagram, denoting their low metamorphic grade, away from the high-Al hornblende and other amphiboles on the diagram

Epidote

The common epidote group minerals found in low-grade metamorphosed volcanic rocks include epidote, clinozoisite, and zoisite They appear as high relief grains, and are readily distinguished by their birefringence colours second order yellow-red colour for epidote (Fig 20a), first order off-grey to light blue for clinozoisite, and first order anomalous blue colour for zoisite (Fig 20b) Epidote-clinozoisite minerals are monoclinic, whereas zoisite is orthorhombic These are calcium-aluminum-iron sorosilicates, with epidote as the Fe-rich member, and zoisite and clinozoisite as the Fe-poor members (Fig 16) Epidote and zoisite from the collected samples form two groups on the frequency diagram, which is based on the

Fe^{+3} for Al^{+3} substitution The epidote minerals form mainly from the breakdown of plagioclase in the mafic rocks, e g ,

$$3\ CaAl_2Si_2O_8 + Ca^{+2} + 2\ H_2O \Rightarrow 2\ Ca_2Al_3Si_3O_{12}(OH) + 2\ H^+$$

anorthite   zoisite

where the Ca^{+2} could be derived from the albite and actinolite forming reactions given above.

Epidote [$Ca_2FeAl_2Si_3O_{12}(OH)$] tends to form in Fe-rich rocks, while zoisite-clinozoisite minerals [$Ca_2Al_3Si_3O_{12}(OH)$] are more commonly found in Fe-poor rocks The usual modes of occurrence of these minerals are as bladed fans in amygdules and open-space filling (Fig 20a), as granular aggregate replacements of plagioclase and mafic material (Fig 20b), and as a fine grained component of saussuritization

The yellow-red Fe-rich epidotes are usually found in tholeitic rocks in association with Fe-rich Berlin blue chlorite The Al-rich zoisite with its anomalous deep blue colour (and also clinozoisite) is generally found with Mg-rich grey-green to brown chlorite This latter association is more common in transitional and calc-alkaline rocks, which have lower Fe contents than the tholeiites Clinozoisite is not as common as either zoisite or epidote in the rocks of the thesis area

Chlorite

Chlorite is a complex Fe-Mg aluminous phyllosilicate, with different mineral names for the various solid solution ranges of Fe-Mg and Al^{IV}-Si composition The pleochroism and birefringence are due to compositional variations, and are discussed

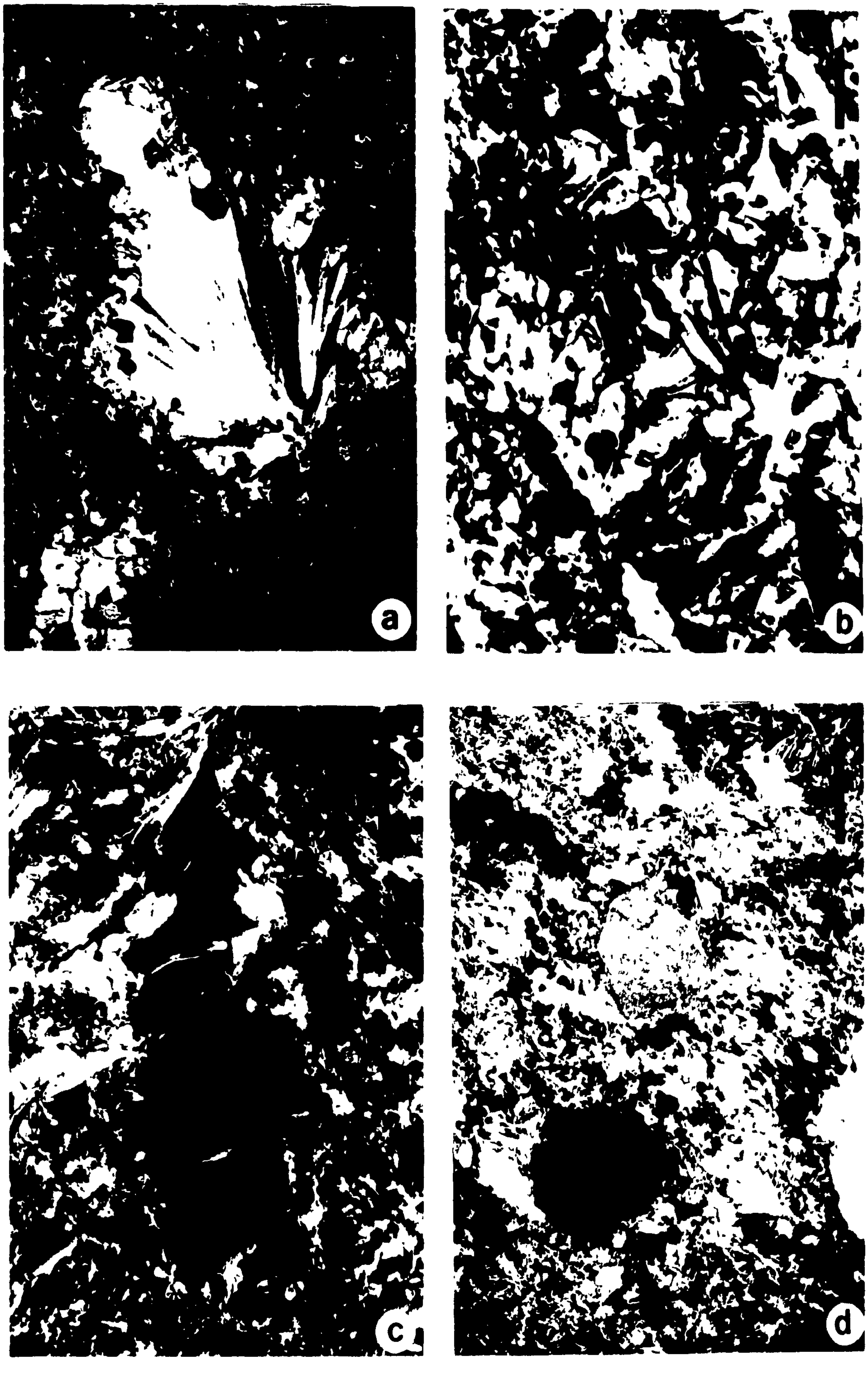
Fig 20 Photomicrographs of mineral textures

a Radiating fan of epidote with red-yellow birefringence in amygdule with quartz Amulet Andesite, Sample NP-25 Scale bar = 0 5 mm

b Blades of zoisite with blue birefringence, occurring with grey-green chlorite and quartz Lac Dufresnoy Andesite, Sample 91-8 Scale bar = 0.1 mm

c Patch of chlorite with Berlin blue birefringence, surrounded by epidote (yellow-red) and quartz (white) Cléricy Road Basalt, Sample 91-29 Scale bar = 0 1 mm

d Sericite-rich matrix in quartz porphyry rhyolite, note the quartz overgrowth in optical continuity with the euhedral phenocrysts Lac Dufresnoy Rhyolite, Sample 91-50 Scale bar = 0 5 mm


a
b
c
d

in detail by Hey (1954), and Kranidiotis and MacLean (1987) The birefringence colours change between Fe-poor and Fe-rich members (based on Fe/Fe+Mg) from grey, green, brown, violet, to Berlin blue These effects are shown on the modified Hey diagram (Fig 18), where the analyzed chlorites from this study are plotted

Chlorite readily takes up Fe, Mg, and Al during alteration of mafic volcanic rocks It replaces other Al-bearing minerals, such as plagioclase, epidote-zoisite, and sericite during spilitization and hydrothermal alteration processes e g ,

$$3CaAl_2Si_2O_8 + 9(Fe,Mg)^{+2} + 14H_2O \Rightarrow (Mg,Fe)_9Al_6Si_5O_{20}(OH)_{16} + SiO_2 + 3Ca^{+2} + 12H^+$$

anorthite chlorite quartz

Fe and Mg cations leached during these processes react with immobile Al to form chlorite As a result, chlorite is the characteristic mineral of alteration pipes below VMS lenses, particularly at the cores of these alteration zones

During spilitization and low-grade metamorphism, replacement of mafic minerals and volcanic glass by chlorite is a common occurrence Chlorite occurs as large blades, irregular masses, and granular aggregates It is also found as large chlorite grains in open-space fillings (Fig 20c) and in amygdules Chlorite, along with epidote and sericite, forms fine grained aggregates replacing plagioclase during saussuritization

The Fe-rich Berlin blue birefringent chlorite is associated with Fe-rich red-yellow epidote in the tholeiitic units The Fe-poor grey-green-brown birefringent chlorite is commonly associated with the Fe-poor blue zoisite or clinozoisite

Sericite

Sericite is very common in the rocks of Noranda district. It is usually found as fine grain aggregates replacing feldspar grains and as an alteration product of glass in the groundmass (Fig. 20d). Sericite forms from the breakdown of feldspar minerals and other Al-bearing material in volcanic rocks as a result of water-rock interaction, e.g.,

$$3NaAlSi_3O_8 + K^+ + 2H^+ \Rightarrow KAl_3Si_3O_{10}(OH)_2 + 6SiO_2 + 3Na^+$$

albite — sericite — quartz

This is a hydrothermal alteration reaction, where both Na and Ca are leached from the host rocks. Unaltered tholeiitic and transitional rocks have low amounts of K_2O (less than 0.5 wt%), whereas calc-alkaline rocks may contain up to 3 to 5 wt% K_2O. Sericitization in tholeiitic and transitional rocks thus requires an external source of potassium and acidic conditions. Seawater and hydrothermal fluids provide the source of K to react with the alumino-silicate phases during the alteration.

Microprobe analyses show sericite has end-member compositional ranges from 76 to 86 % muscovite, 11 to 20 % celadonite, 0.7 to 1.6 % paragonite, and < 0.2 % margarite. The Fe/Fe+Mg ratio for the sericites ranges from 0.33 to 0.53. Sericite is essentially the only K-bearing phyllosilicate formed during alteration. The K_2O/Na_2O+K_2O ratio (Sericitization Index, MacLean and Hoy 1991) can be utilized to indicate the degree of alteration of the albite component of plagioclase to sericite in tholeiitic and transitional rocks. It is an easily calculated index that provide a good means to measure rock alteration.

Sericitization and chloritization are very common and pervasive processes during hydrothermal alteration and other forms of water-rock interaction The reactions use up all the Al available in the rock except for that in epidote-zoisite In more advanced alteration, sericite and chlorite replace all other Al-bearing minerals, including epidote-zoisite As a result, the abundances of these two minerals can be used as general indicators of degrees and intensity of alteration in greenstone volcanic rocks.

Chapter 5

LITHOSTRATIGRAPHY

INTRODUCTION

Hydrothermal water-rock interaction and low-grade metamorphism of volcanic and associated rocks have affected all Archean greenstones. The precursor rock composition and its geochemical make-up are modified by the addition and depletion of mobile components during alteration processes. Lithogeochemical methods using immobile and incompatible elements, as outlined by MacLean and Kranidiotis (1987) and MacLean (1988,1990), can be used to reconstruct original compositions of the altered rocks and to determine the intensity and pattern of alteration. Raw geochemical data can thus be treated to assess alteration conditions, from least to highly altered states. This provides the basis for quantitative evaluation of geochemical changes, leads to better identification of precursor rock types, and assists in lithostratigraphic correlation.

Incompatible Elements

Incompatible elements in magmas are usually defined as having bulk distribution coefficients of $D_{solid/melt} < 0.1$. These elements are concentrated in the melt during igneous fractionation processes as they are not generally incorporated in the rock-forming minerals. In most basaltic rocks, it has been shown that Zr, Nb, Y, a few other high field strength elements (HFSE), and the REE are highly incompatible (Pearce and Cann 1973, Pearce and Norry 1979, Wood et al. 1979). This also holds true for rocks in the andesite-dacite-rhyolite range in tholeiite suites, but not in the majority of alkaline and calc-alkaline suites where the HFSE are compatible. These elements are tested on binary plots for incompatibility in a rock suite before proceeding with the lithogeochemical treatment. When they remain incompatible throughout fractionation, these elements plot as a single straight line.

The incompatible HFSE pair, Zr and Y, is especially useful for providing a discriminant ratio that changes with rock affinity (Pearce and Norry 1979, Lesher et al. 1986, MacLean 1990, MacLean and Barrett 1993). This pair exhibits different enrichment ratios for rocks of different magmatic affinity. Tholeiite rocks range from about 2 to 4.5, and calc-alkaline and alkaline rocks from about 7 to 20. Rocks with the Zr/Y ratios intermediate between tholeiite and calc-alkaline are designated **transitional**. In transitional rocks the HFSE are still incompatible (linear enrichment trends), but with slightly steeper REE profiles than the tholeiites.

Major element discriminants, such as AFM, Miyashiro, Al_2O_3-Zr, and TiO_2-Zr diagrams, have been used to differentiate the rock types. As well, the magmatic affinity can be verified with La_N/Yb_N, Th/Yb, Zr/Yb, and other HFSE ratios. The variable compatibility of Zr, Y, and other HFSE in alkaline and calc-alkaline rock suites produce a range of trends; for example, a higher depletion of Y relative to Zr in these rocks accounts for their higher Zr/Y values than in tholeiites.

Immobile Elements and Single Precursor System

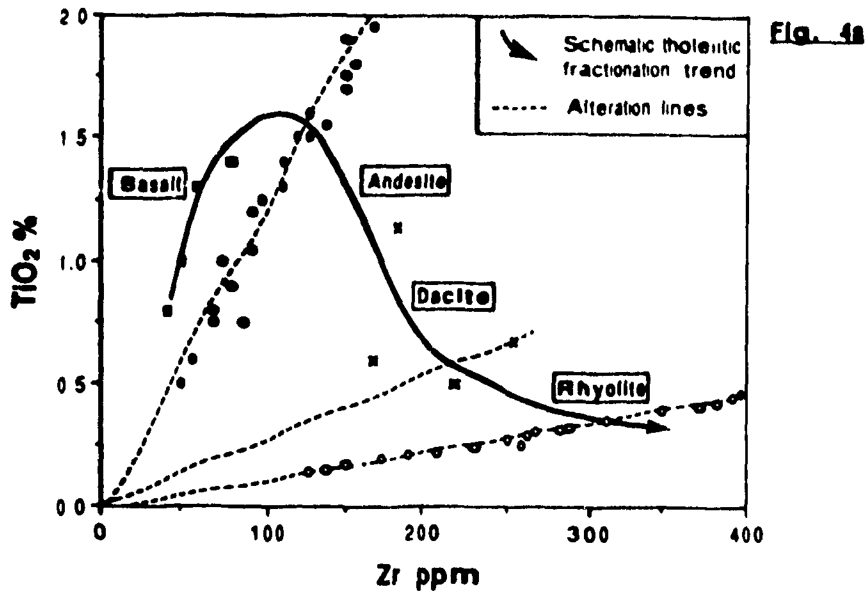
Some elements are immobile, that is they are not generally leached from or added to the rock material during alteration processes. Testing for immobility is done with pairs of elements from a specific volcanic unit. A highly correlated binary plot of a pair of elements, with a correlation coefficient of around 0 90 to 0 99, is indicative of high immobility It is important to note that elements of closely related chemical affinity, such as K-Rb, Ca-Sr, and Zr-Hf, can also produce similarly high correlations and must be excluded from these immobility element tests

During alteration, sample points move along the primary fractionation line defined by an immobile and incompatible element pair Altered samples shift towards the origin when large amounts of mobile material such as silica, carbonate, and sulfide have been added to the rock unit At the other end, mass loss from leaching of mobile material, such as silica, Ca. Na, and K, results in concentrated amounts of immobile material It has been shown that Al, Ti, HFSE, Zr, Nb, Y, and the REE are commonly immobile in altered volcanic rocks around VMS deposits (MacLean and Kranidiotis 1987, MacLean 1988)

Multiple Precursors

In greenstone belts, a range of fractionated volcanic rock compositions can be viewed as a multiple precursor sequence Fractionation trends are first constructed using binary plots of TiO_2-Zr and Al_2O_3-Zr Because these elements are also immobile, they are used to assess mass changes during alteration, as in a single precursor system.

Least altered samples from basaltic-andesite to rhyolite form concave fractionation curves for TiO_2-Zr (Fig 21a), FeO-Zr, MnO-Zr, MgO-Zr, and CaO-Zr, whereas Al_2O_3-Zr plots (Fig 21b) as a linear trend with a slightly negative slope Altered samples form a series of divergent alteration lines that result from mass changes of the mobile components The intersection of an alteration line and the fractionation curve defines the precursor composition of each altered sample (Fig. 21a,b).



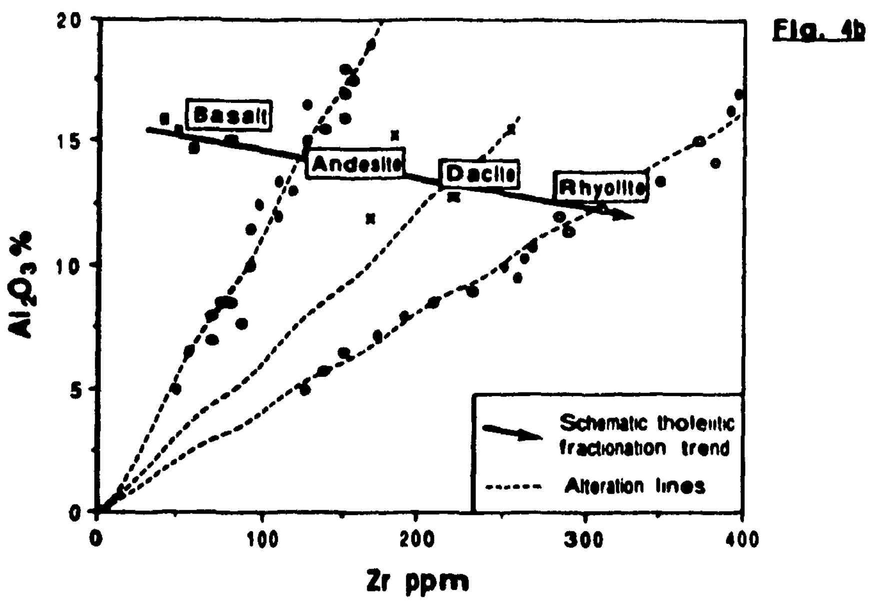


Fig. 21. Demonstration diagram showing idealized fractionation lines for a tholeiitic volcanic suite with superimposed plots of idealized data for altered rocks. The two well defined alteration lines represent initially homogeneous units within the stratigraphy Their intersection with the fractionation lines identifies the precursors to the altered rocks as an andesite and a rhyolite
a) TiO2-Zr: The fractionation line exhibits strong Ti enrichment in basalts (paralleling iron-enrichment in tholeiites), followed by strong Ti depletion from andesite to rhyolite
b) Al2O3-Zr: The fractionation line is near linear Plagioclase accumulation may produce anomalously high Al values (After MacLean and Barrett, 1993).

The multiple-precursor analysis is particularly useful in detailed studies around mineral deposits where the immediate surrounding volcanic rocks consist of a few well-defined units In these cases, analysis of numerous outcrop and drill-hole samples enables good lithostratigraphic correlation and delineation of host rock types even under extreme alteration

In a larger regional survey with widely spaced samples, such as this thesis project, a detailed assessment of each unit based on precursor identification and well-defined alteration lines was not possible Each unit has less than 10 samples, even for the 500 m thick Cléricy Rhyolite

On the TiO_2-Zr and Al_2O_3-Zr plots of least altered samples from the thesis area (Fig 22a,b), several separate fractionation trends can be inferred in mafic rocks and rhyolites The least altered samples define the fractionation trends On this regional scale of stratigraphic interpretation, these trends may represent several batches of magma These batches are probably derived from various stages of partial melting, magma mixing, or assimilation of wall rock Each of the magmas formed by these processes would be then affected by fractional crystallization

The volcanic rocks in this 6 km transect likely represent several different batches of magma and will not plot on one or two specific fractionation trends. Where there are many samples from one or several adjoining stratigraphic units of the same affinity, such as the Clericy Road Basalt and Cléricy Rhyolite, a single igneous fractionation trend could be defined When many stratigraphic units (as in the thesis area) are plotted together on one diagram, they form, as expected, a continuous series of fractionation trends (Fig 22a,b)

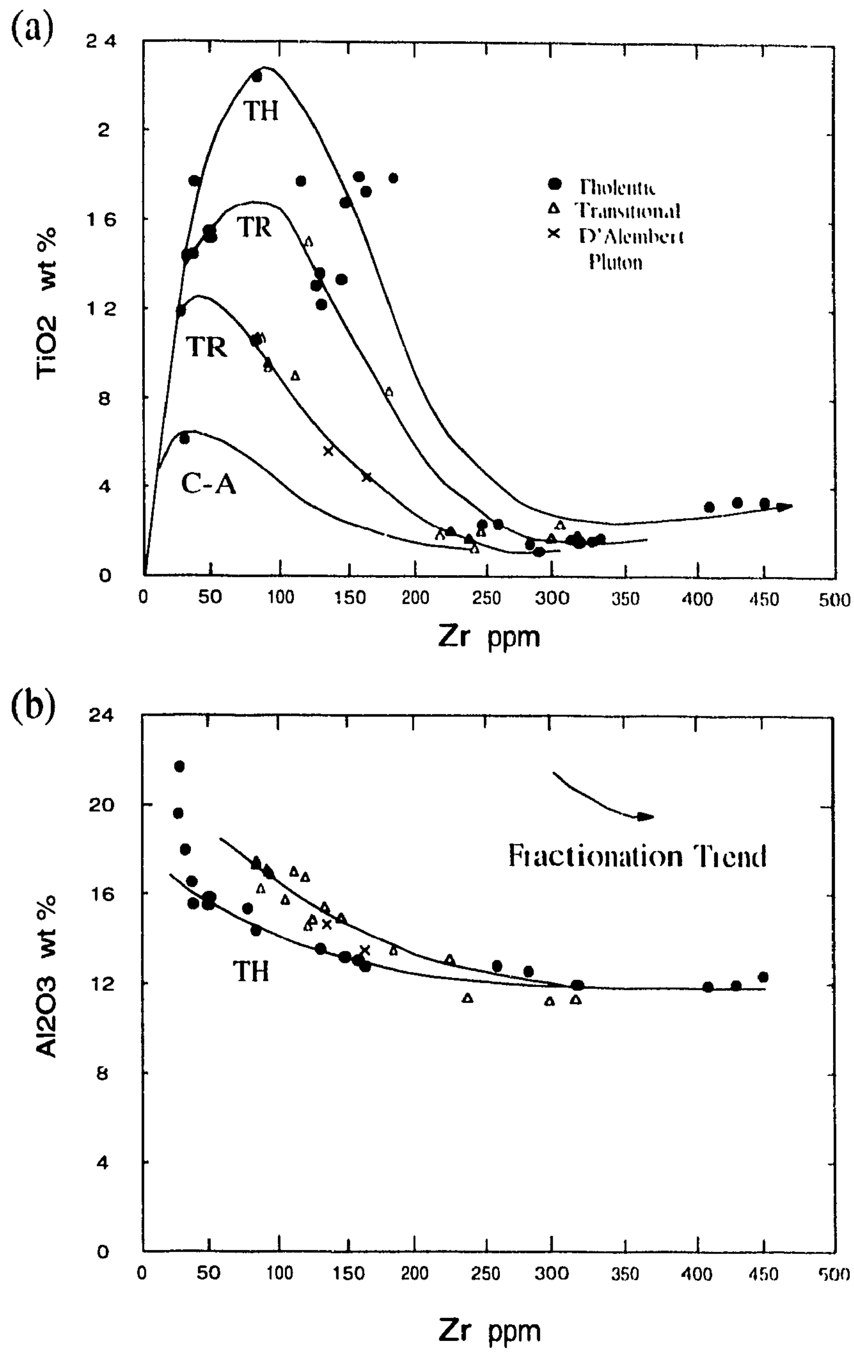


Fig. 22. Harker-type plots for D'Alembert-Cléricy samples with Zr as the fractionation monitor.

In (a) the TH trend follows the high enrichment in TiO_2 typical of tholeiitic fractionation. Calc-alkaline rocks have little TiO_2 enrichment. The transitional trends are intermediate.

In (b) only two fractionation trends are discernable in the data

DEFINITION OF LITHOSTRATIGRAPHIC UNITS

In previous studies, the volcanic rocks in the area have been subdivided into broad lithological units based initially on their stratigraphic relationships and subsequently on geochemical characteristics Some existing regional lithostratigraphic classification schemes cover all or parts of the volcanic succession in the thesis area (Spence and de Rosen-Spence 1975, Gélinas et al. 1977, 1984, Dimroth et al 1982; Gibson and Watkinson 1990, Laflèche et al 1992)

For this study, subdivision of the volcanic stratigraphy utilizes lithogeochemical evaluation of the major and HFS trace elements, as well as the REE, to determine the geochemical affinity The ratios of the immobile and incompatible trace elements and various geochemical plots of the rock units are used for the classification

Based on individual chemical analyses and group averages of the respective members, the rocks in the study area are divided into lithostratigraphic units and three overall lithological series (Table 6, Fig 23)

The Lower Transitional Series forms the upper part of the Central Mine Sequence It is overlain by the thick Middle Tholeiitic Series to the east The Upper Series, further to the east, is a mixed group of alternating transitional and tholeiitic units

The lithogeochemical subdivision uses Zr/Y ratios of 1 to 4 5 to distinguish tholeiitic rocks, and 7 to 30 for calc-alkaline rocks Ratios between these two ranges, from 4 5 to 7, are designated as transitional rocks. On the basis of La_N/Yb_N values, tholeiitic rocks have values from 1 to 3, and calc-alkaline rocks from 5 to 40 Transitional rocks are taken as having from La_N/Yb_N from 3 to 5, between the two major groups

TABLE 6. Volcanic Stratigraphy along the D'Alembert-Cléricy Transect

Upper Mixed Transitional-Tholeiitic Series

Mobrun Rhyolites (tholeiitic and transitional)

Cléricy Rapids andesite (tholeiitic)

Lac Dufresnoy Rhyolite (tholeiitic)

Lac Dufresnoy Andesite (transitional)

Cléricy Rapids Rhyolite (transitional)

Middle Tholeiitic Series

Cléricy Rhyolite

South Jevis Andesite-Dacite

- contains minor felsic volcanics

Cléricy Road Basalt

Lower Transitional Series

North Jevis Rhyolite

D'Alembert Rhyolite

Newbec Rhyolite

Newbec Andesite

Amulet Andesite

Lithological Units and Series of the Thesis Area

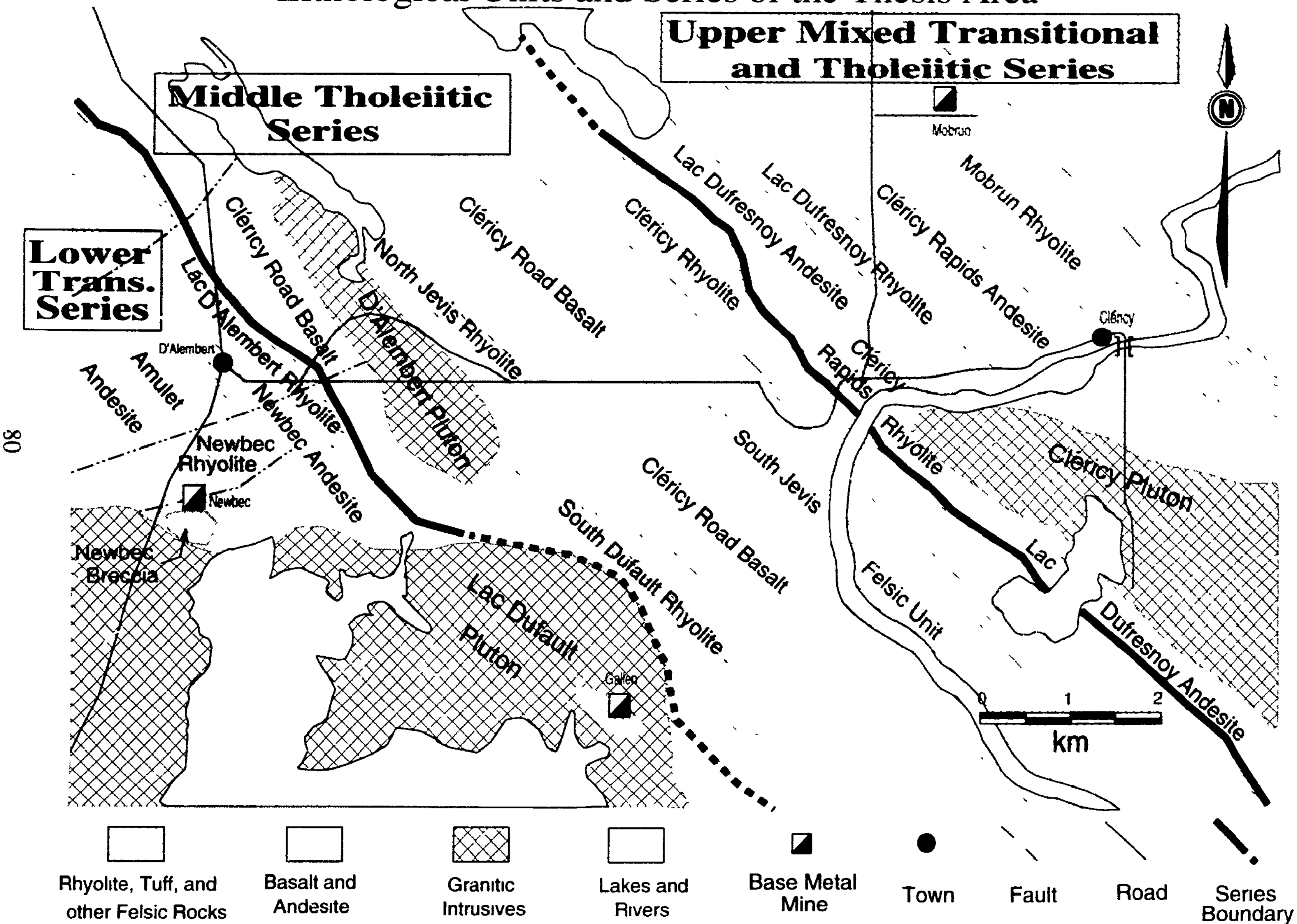


Fig. 23. **Map of the volcanic stratigraphy along the D'Alembert-Clericy transect.**

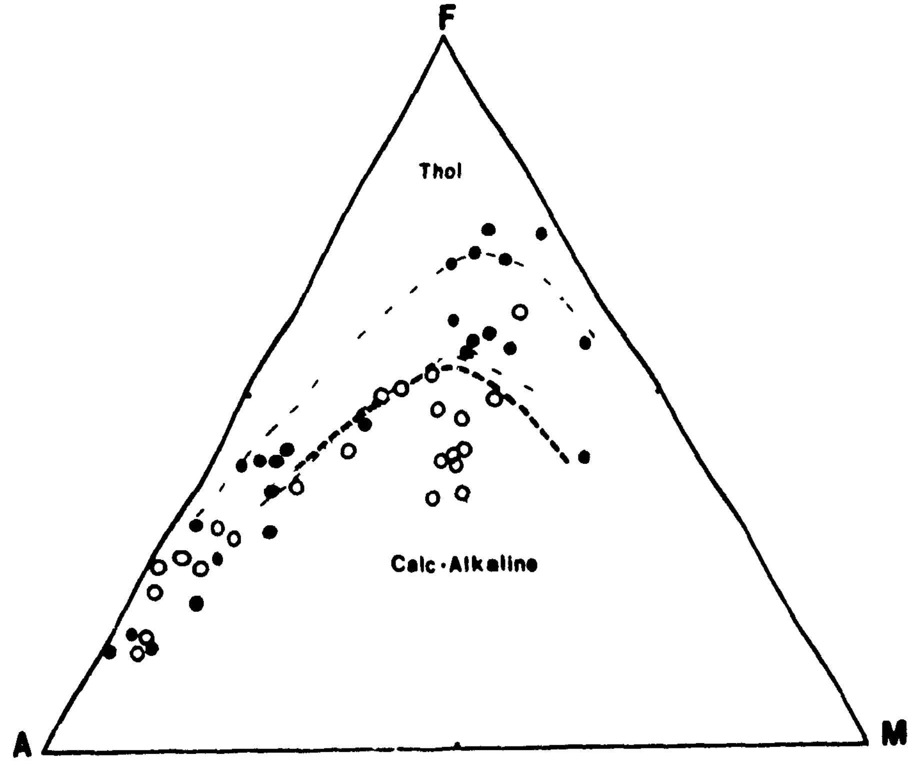


Fig. 24. AFM diagram for D'Alembert-Clericy samples, showing fields of tholeiitic (filled circle and double-dotted boundaries), and transitional (open circle and fine-dotted boundaries) samples. The heavy dashed line is the boundary between the tholeiitic and calc-alkaline fields according to Irvine and Baragar (1971).
The samples were designated as tholeiitic or transitional using Zr/Y, La_N/Yb_N, and other HFSE ratios.

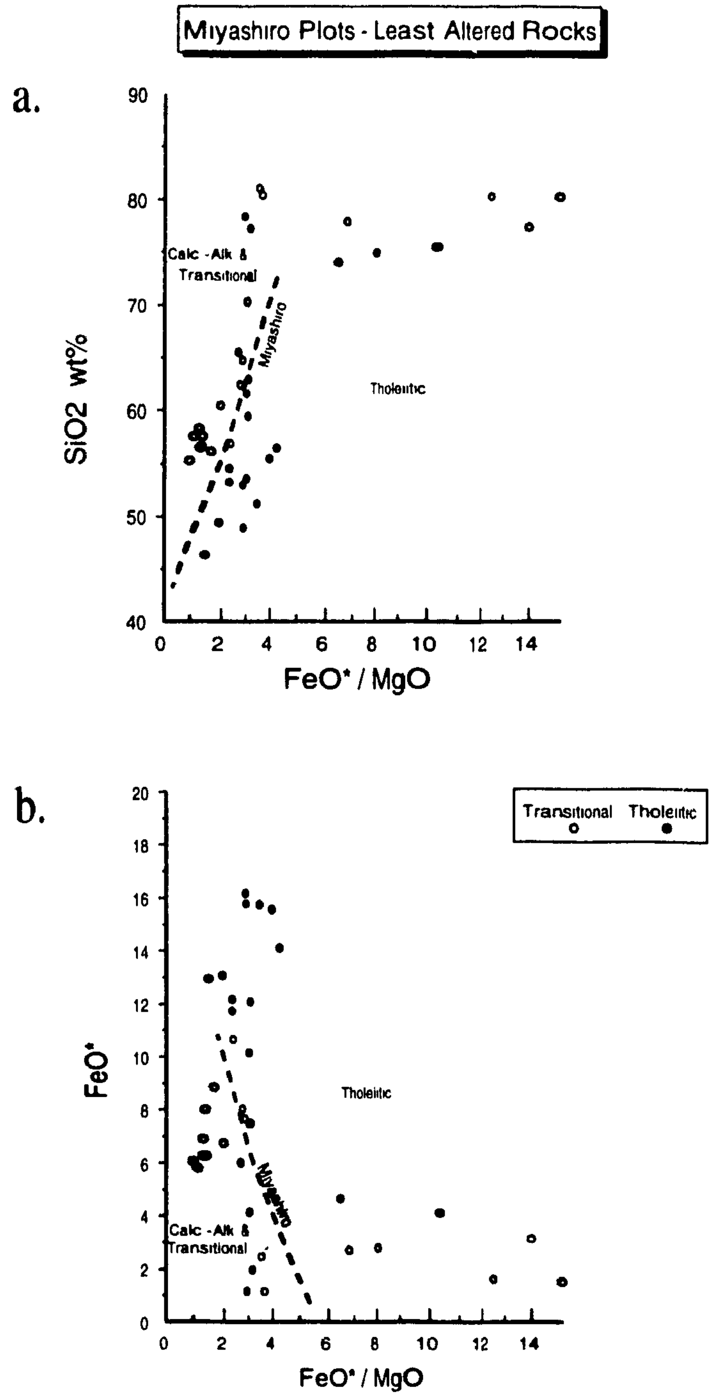


Fig. 25. Miyashiro Diagrams, least altered rocks only, after Miyashiro (1974).
The grey area is the field occupied by the majority of transitional rocks in the transect area.
Felsic rocks change to constant SiO2 and FeO* with extreme fractionation,
and deviate from Miyashiro's boundary lines (see Ichang'i and MacLean 1991).

Since major element differences are more reflective of lithological and mineralogical characteristics than are trace elements, the HFSE-based classifications are compared with major element AFM plot (Fig 24) and the Miyashiro (1974) diagrams (Fig 25a,b) On the AFM diagram, the rocks designated as tholeitic using the HFSE classifications plot in the tholeitic field as outlined by Irvine and Baragar (1971) The transitional samples plot in the calc-alkaline field Thus the transitional and true calc-alkaline rocks are not distinguished the major element AFM plot For the Miyashiro diagrams, the two major affinity groups are separated, except for a few tholeitic samples which fall in the calc-alkaline/transitional field The deflection and flattening of the trends for rhyolites of all affinities are caused by fractionation of quartz and feldspars at the granite eutectic, as discussed by Lchang'i and MacLean (1991) The HFS trace elements are preferred because they are incompatible (and also not affected by alteration) and provide an affinity determination on a single sample basis which is very useful in stratigraphic correlation

LOWER TRANSITIONAL SERIES

This transitional group includes the Amulet and Newbec Andesites, and the Newbec and D'Alembert Rhyolites The Amulet mafic lavas have an average Zr/Y ratio of 4 7, the Newbec Andesite 4 3, and the Newbec Rhyolite ranges from 6 5 to 13.5 The D'Alembert Rhyolite is of transitional affinity as indicated by La_N/Yb_N, Th/Hf, Th/Yb, and Zr/Th ratios (Appendix Table I), but has a low Zr/Y value of 3 6

The REE plots of these rocks have slightly negatively sloping profiles (Fig 26a, 27a) with La_N/Yb_N ratios of 4 0 for Amulet Andesite, and 2 5 and 3 5 for Newbec Rhyolite

The Zr/Y ratios from the Newbec Rhyolite are high, and one is in the calc-alkaline range, however, the REE profiles have moderate slopes in the range of transitional rocks Other HFSE ratios, Zr/Th and Yb/Th (Appendix Table I), also indicate a transitional affinity This rhyolite is host to a small VMS deposit at the old Newbec mine The high Zr/Y value could have been caused by loss of Y during strong hydrothermal alteration

MIDDLE THOLEIITIC SERIES

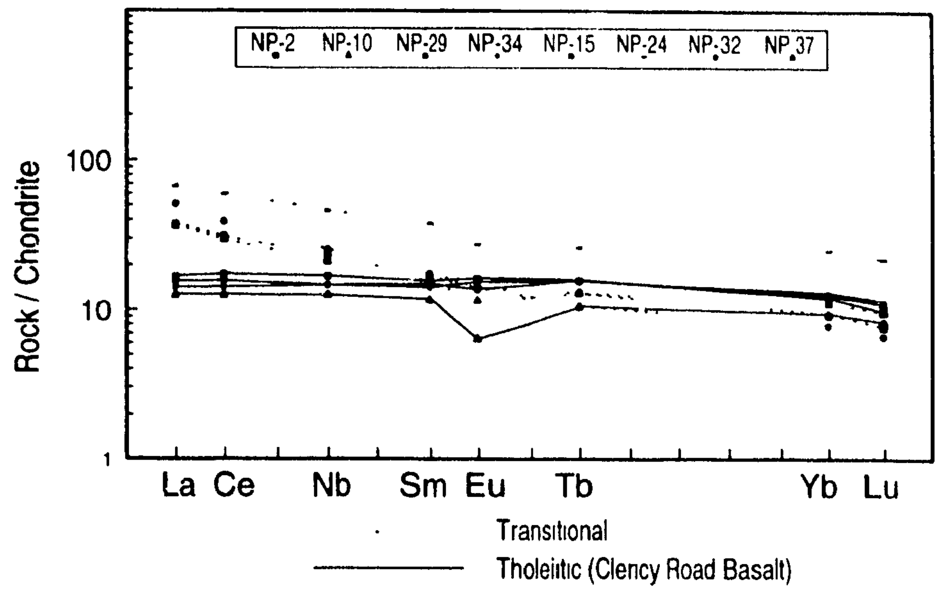
This middle tholeiitic series is composed of thick mafic and rhyolitic units which occupy the central portion of the study area It includes the thin D'Alembert Andesite, as described by Wilson (1941) and Paradis et al (1990), located on the traverse to the west of the D'Alembert pluton at the base of this tholeiitic series

Cléricy Road Basalt

This unit ranges from mainly basalt to lesser basaltic-andesite. The tholeiitic nature of these rocks is indicated by the group average of Zr/Y ratio of 2 6, and the characteristic flat REE profiles (Fig 26a) with an average La_N/Yb_N of 1 3

This mafic sequence has a distinctly different geochemical affinity from the bordering transitional units, and probably is from a more primitive source The massive to pillow flows were the products of tholeiitic volcanism on an Archean ocean floor The more evolved transitional and calc-alkaline rocks are composed largely of intermediate and felsic massive to pyroclastic material, and may have formed as a volcanic arc complex on top of this tholeiitic ocean floor

a. Tholeiitic and Transitional Mafic Rocks



b. Clericy Rhyolite Unit

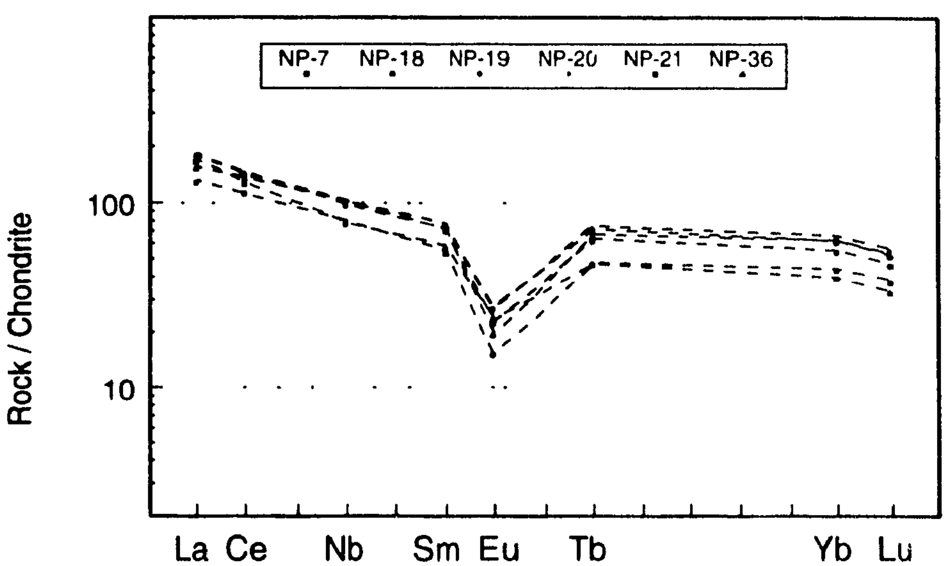
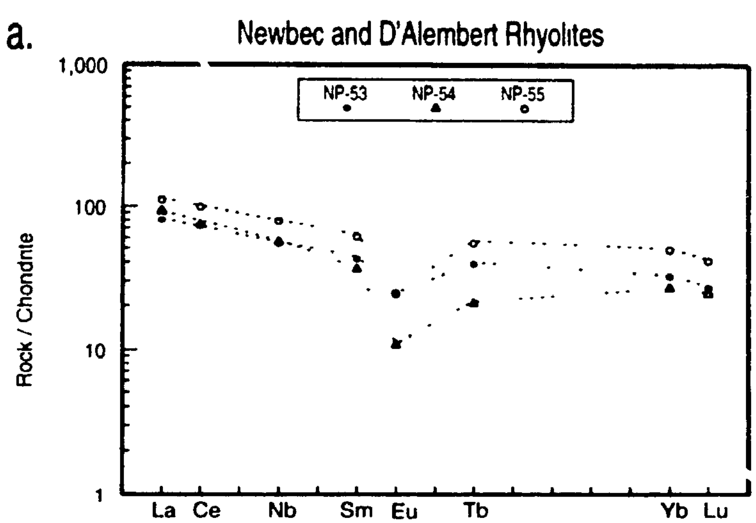


Fig. 26. REE Plots. Normalized to chondrite values of Evensen et al. (1978).



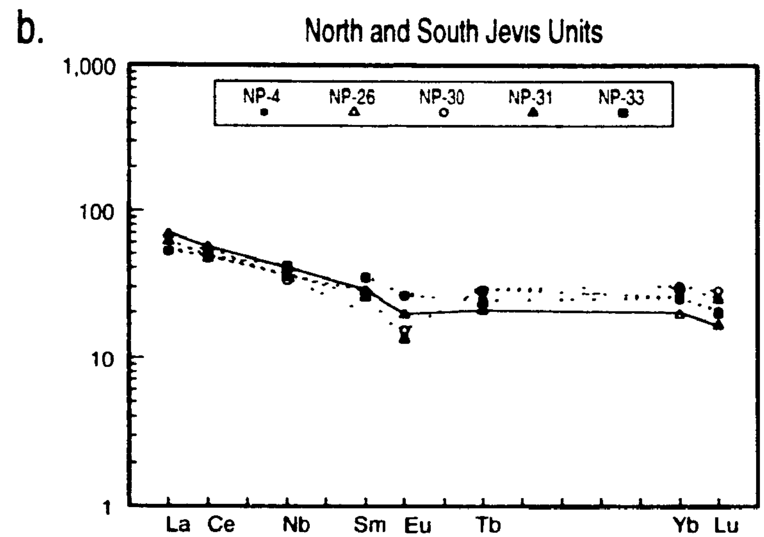
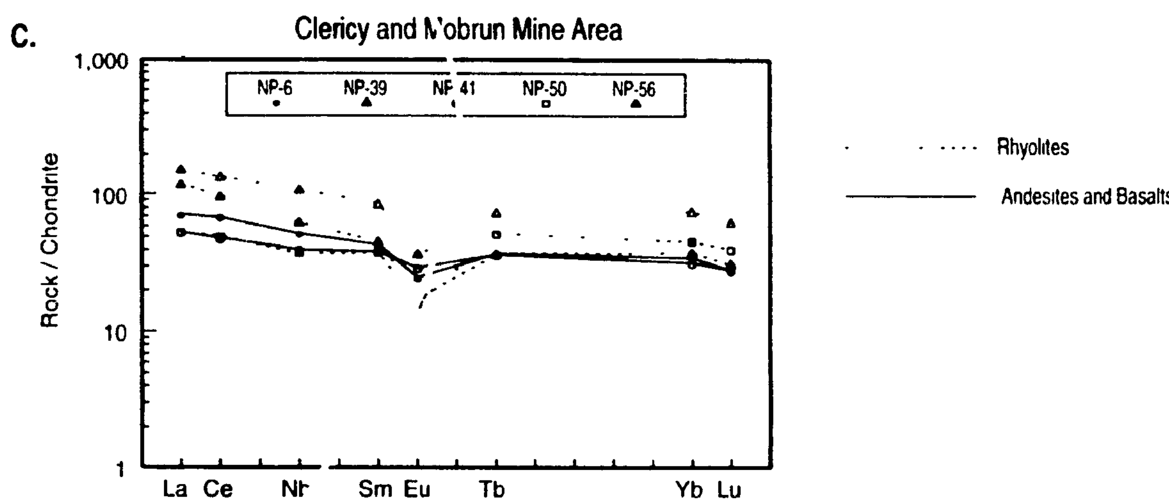


Fig. 27. REE Plots.
Chondrite normalized REE pattern
for felsic and mafic units in the transect



North and South Jevis Felsic Units

The North Jevis and South Jevis units occur within the thick tholeiitic Cléricy Road Basalt. They are massive to pyroclastic rhyolite, dacite, and andesite rocks. The felsic rocks of both units have mostly transitional REE profiles (Fig. 27b). The North Jevis unit is transitional, with Zr/Y = 5.8, and La_N/Yb_N = 2.4, while the South Jevis unit has both transitional and tholeiitic members (Appendix Table I).

These two felsic-intermediate volcanic units likely represent fractionated members of an arc sequence. The large proportions of volcanic breccias, lapilli tuffs, and ash tuffs indicate they are distal from their volcanic sources. It was not possible to determine the source of the pyroclastic rocks of the North Jevis Rhyolite, but the sorting of the volcanic clasts in the South Jevis Rhyolite indicate it is derived from a volcanic source to the south.

Cléricy Rhyolite

This thick group of rhyolites is defined as tholeiitic based on their average Zr/Y value of 3.5 and La_N/Yb_N of 2.8 (Appendix Table I). The tholeiitic magmatic affinity of the rhyolites suggests that they are related to the Cléricy Road Basalt, together forming a tholeiitic basalt-rhyolite bimodal suite. The Cléricy Rhyolite is different from the major rhyolite formations in the Mine Sequence to the west and the Mobrun Rhyolites to the east, which are mostly of transitional affinity. The Cléricy Rhyolite complex represents an episode of major felsic magmatic activity, built upon related Cléricy Road ocean floor basalts.

UPPER MIXED TRANSITIONAL AND THOLEIITIC SERIES

The appearance of alternating transitional and tholeiitic volcanic sequences defines the Upper Mixed Series, contrasting with the thick Tholeiitic Series to the west This section of volcanic stratigraphy contains several paired andesite-rhyolite units of either tholeiitic and transitional affinity The mafic rocks in the Upper Mixed Series are mostly andesitic, distinct from the basaltic mafic rocks in the Middle Tholeiitic Series The Upper Mixed Series includes the voluminous Mobrun Rhyolite formation on its eastern side, which hosts the VMS deposits at the Mobrun mine

The advent of volcanic eruptions of alternating lithogeochemical affinities indicate additional sources of transitional magma in the Upper Mixed Series relative to the Tholeiitic Series It is likely that new melt material from assimilation or mixing contributed to the generation of the Upper Mixed Series

Cléricy Rapids Rhyolite

The transitional Cléricy Rapids Rhyolite, has an average Zr/Y ratio of 5 0 (Appendix Table I) The REE plot of a sample from this unit has a slightly steeper profile (Fig 27c) than those of the adjacent tholeiitic Cléricy Rhyolite It has an La_N/Yb_N ratio of 4 2, higher than its tholeiitic rhyolite counterpart which averages 2.8 (Appendix Table I)

Lac Dufresnoy Andesite

Six out of eight samples of this andesitic unit are transitional (avg Zr/Y = 4 9), whereas two are tholeiitic (avg Zr/Y = 2 7) (Appendix Table I) The tholeiitic subunit is at the northwest margin, which borders the tholeiitic Lac Dufresnoy Rhyolite unit.

The REE plots (Fig 27c) also demonstrate the contrasting lithogeochemical affinities, with the tholeiitic sample having a flatter profile (La_N/Yb_N = 1 7) than the transitional one (La_N/Yb_N = 3 3)

Lac Dufresnoy Rhyolite

This unit of tholeiitic rhyolite has an average Zr/Y = 3 9 Two samples from this unit have characteristic flat REE patterns of tholeiitic rocks, with La_N/Yb_N values of 2 1 and 1 2 (Appendix Table I)

Cléricy Rapids Andesite

A sample taken at the bridge at the town of Cléricy with Zr/Y = 3 8 and a flat REE profile with La_N/Yb_N = 2 0 (Appendix Table I) is of tholeiitic affinity The other sample was to the south near Lac Savard, and had a transitional Zr/Y value of 5 8 Further field mapping and sampling is required to determine the distribution of magmatic types

Like the Mobrun Rhyolite formation to the east, the mixed affinity indicates that successive eruptions of volcanic material were derived from different magmatic sources

Mobrun Rhyolite

The rhyolite sequence around the Mobrun orebodies includes the Copper Hill rhyolite and the rhyolites hosting the Mobrun orebodies Some of the rhyolites are tholeiitic, and others are transitional with Zr/Y ratios ranging from 2 5 to over 7 0, and La_N/Yb_N values ranging from 1 9 to 6 4 (Barrett et al 1992) The hangingwall of the Main complex is tholeiitic, and the footwall is transitional, for the 1100 complex, the footwall rhyolite is tholeiitic, while the hangingwall rhyolite is transitional (Barrett et al 1992) The contrasting geochemical affinities of the rhyolites indicate that somewhat varied magmatic sources were tapped during successive eruptive phases

OTHER CHEMOSTRATIGRAPHIC CLASSIFICATIONS

This thesis project is part of the continuing scientific study into this section of the Noranda district stratigraphy This study provides a more detailed geochemical contribution to the classification of the volcanic units in the D'Alembert-Cléricy area With the application of incompatible HFSE, it is shown that the rocks are mainly of transitional and tholeiitic affinity Using lithogeochemical data to assist in reconstructing the tectono-volcanic setting of the stratigraphy, the successive active volcanic phases and their magmatic products can be improved

The volcanic rocks in the thesis area have been classified into chemostratigraphic units using major elements and other discrimination criteria by Gélinas et al (1977, 1984) and modified by Trudel (1978, 1979) These authors subdivided the mafic rocks into a succession of tholeiitic and calc-alkaline members From west to east in the field area, they are the calc-alkaline Dufault unit, the tholeiitic Trémoy unit, the calc-alkaline Cléricy unit, the tholeiitic Destor unit, and the calc-alkaline Reneault unit

Relative to the subdivision of Gélinas et al (1984), the Lower Transitional Series is mostly equivalent to the Dufault and Trémoy units, while the Middle Tholeiitic Series corresponds to the Cléricy and parts of the Trémoy units The Upper Mixed Transitional and Tholeiitic Series generally are the volcanics of Destor and Reneault units The study of the rocks in the eastern part of the area by Laflèche et al (1992) also established a chemostratigraphic division of the mafic volcanic rocks, similar to the one presented in this thesis A significant difference is that the present thesis study recognizes the transitional affinity of the Upper Mixed Series, rather than calc-alkaline as designated by Laflèche et al (1992), and that some of the units are mixed tholeiitic-transitional in affinity The present thesis study incorporates the rhyolitic as well as the mafic rocks in this part of the district, and utilizes their geochemical characteristics in the chemostratigraphic classification

COMPARISON OF CHEMICAL DISCRIMINANTS

The HFSE plots and trace element discrimination diagrams are utilized for distinguishing rock suites and assisting in the definition of the lithostratigraphic units in this project They are shown to be useful and have good correlation with major element discrimination plots The Zr/Y ratio, in particular, is an easy and readily applied first-step indicator of the rock affinities It should be compared with other geochemical discriminants, such as the La_N/Yb_N ratio, which approximates the slope of the REE pattern In this study, the REE data correlate with the Zr/Y ratios for most samples, but yields a different affinity determination for some samples The LREE are found to be mobile under some strong alteration conditions (MacLean 1988) and this should be taken into account Nevertheless, REE plots for transitional rocks in the thesis area generally have steeper profiles than tholeiitic rocks

The Miyashiro and AFM diagrams serve to compare and contrast the chemical affinities deduced from immobile and incompatible lithogeochemical plots Both the AFM and Miyashiro graphs reasonably discriminate between the tholeiitic and transitional fields for most of the least altered samples However, a few of the samples lie in different fields relative to their affinity as first established using HFSE ratios, mostly Zr/Y The "wayward" samples may be somewhat altered rocks The scatter on the Miyashiro and AFM diagrams is due in part to the mobility of FeO, MgO, SiO_2 and alkalies during alteration The AFM plot is not a positive identifier on a single sample basis, but in general there is good agreement when only fresh rocks are used The immobile trace elements are more specific, and affected to a much lesser degree during hydrothermal water-rock alteration processes

TECTONIC SETTINGS

Trace element plots utilizing HFSE can be used to help in discerning their tectonic environments of Archean volcanic rocks The HFSE ratios vary according to magma source and provide discrimination fields for different volcanic rock types For this purpose, only the least altered mafic rocks are used

Ternary discrimination diagrams, (Hf/3-Th-Ta after Wood et al 1979 and Nb*2-Zr/4-Y after Meschede 1986) indicate that the mafic rocks in the thesis area include enriched MORBs, and within-plate tholeiites, and volcanic arc material for the mafic lavas (Fig 28a,b) On binary plots of Nb-Y and Rb-Y+Nb (after Pearce et al 1984), the mafic rocks are mainly volcanic arc basalts with some ocean ridge tholeiites (Fig 29a,b) These are in general agreement with the paleotectonic interpretations of the other workers in the area (e g Dimroth et al 1982, Laflèche et al 1992)

Other trace element diagrams have been applied to petrogenetic studies of magma generation and fractionation modelling of the volcanic rocks The Nb/Th versus Zr binary plot shows a progressive decrease in Nb/Th with Zr, or in general, with advanced fractionation (Fig 30) This is mainly a result of the enrichment of Th in transitional and calc-alkaline rocks relative to tholeiites, which causes the Nb/Th ratio to decrease towards the calc-alkaline rocks The trend may also represent continuous batch melting of magma in the mantle, magma mixing, or contamination by crustal rocks (Pearce and Norry 1979, Laflèche et al 1992) The presence of both tholeiitic and transitional rocks along the Nb/Th versus Zr curve shows a continuous range of magmatic affinity for the rock units in this thick section of volcanic stratigraphy along the D'Alembert-Cléricy transect

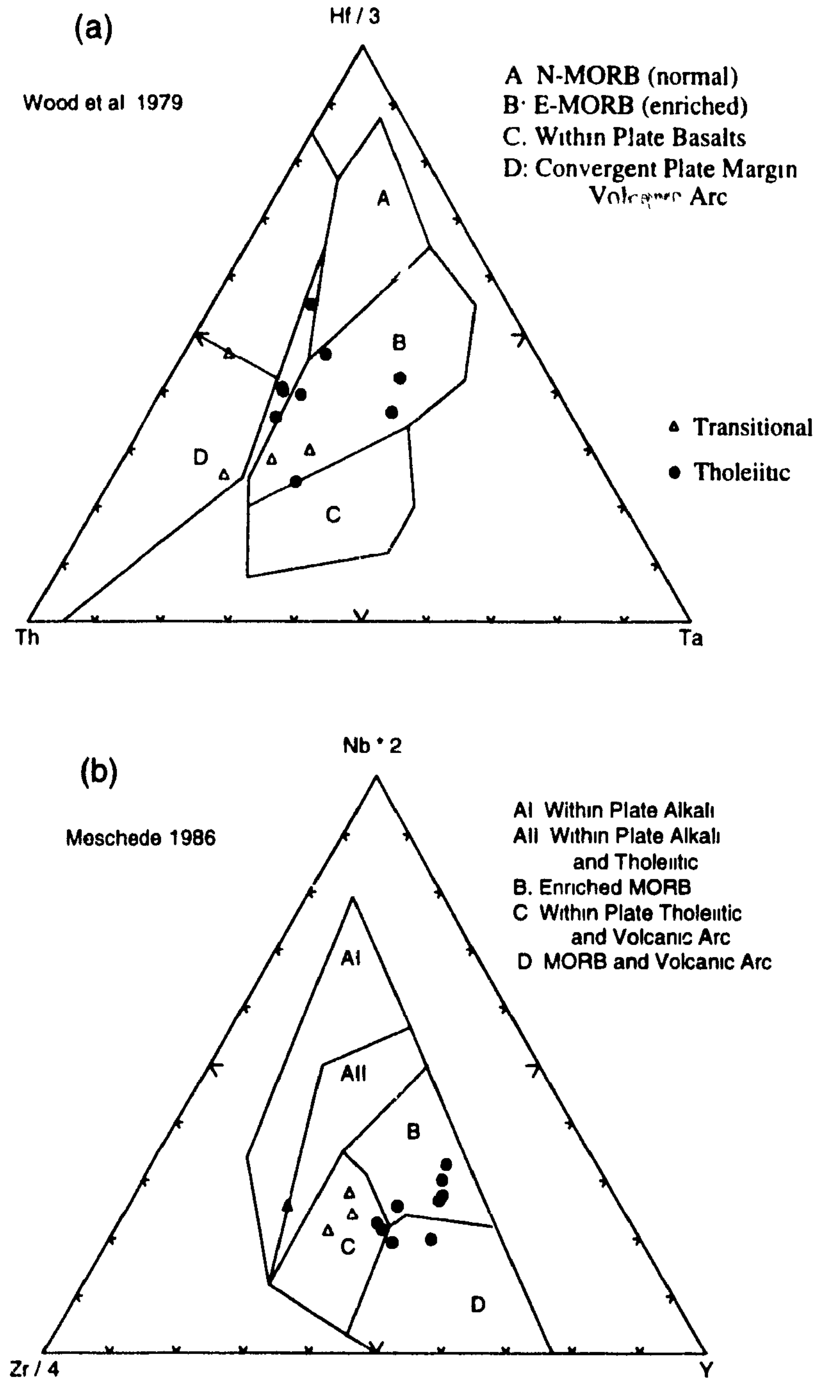
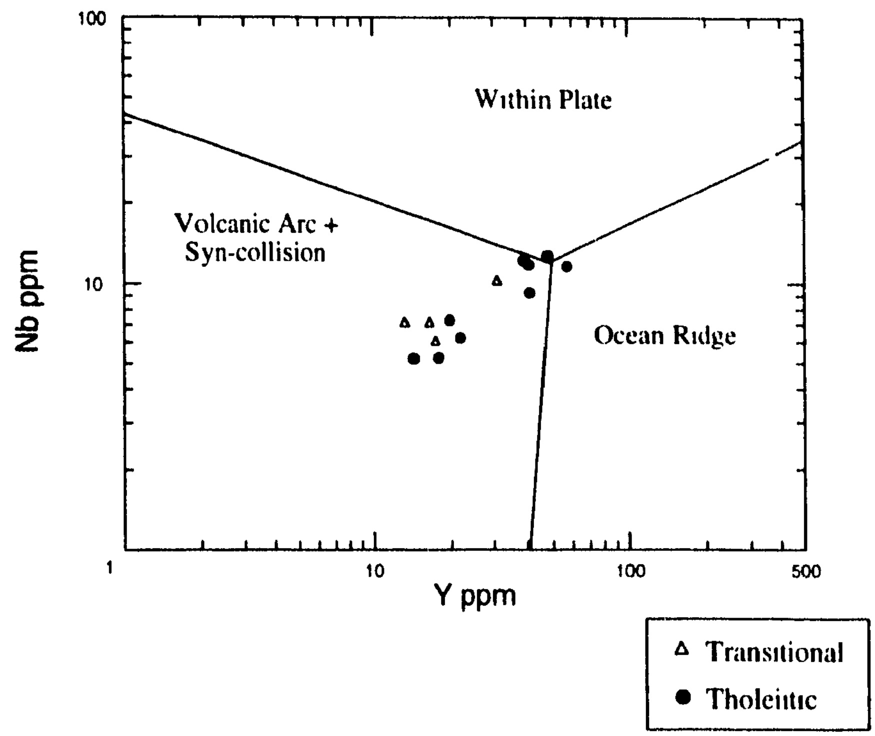


Fig. 28. Discrimination diagrams for tectonic settings (mafic lavas only). Both indicate a mixture of enriched ocean ridge and convergent plate volcanic arc basalts.

(a)



(b)

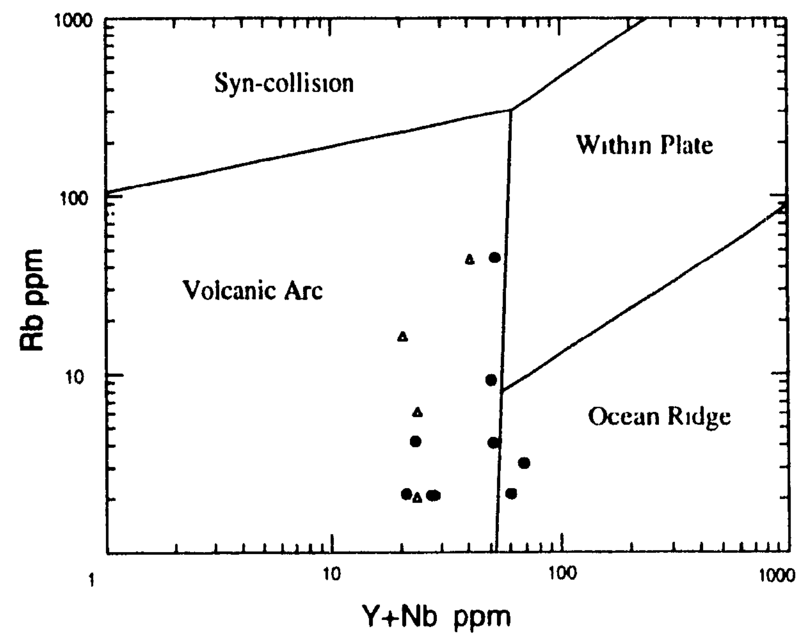


Fig. 29. Discrimination diagrams for tectonic setting (least altered mafic lavas only) after Pearce et al. (1984).
The tectonic setting for the volcanism in the thesis area is limited to a volcanic arc environment by these plots.

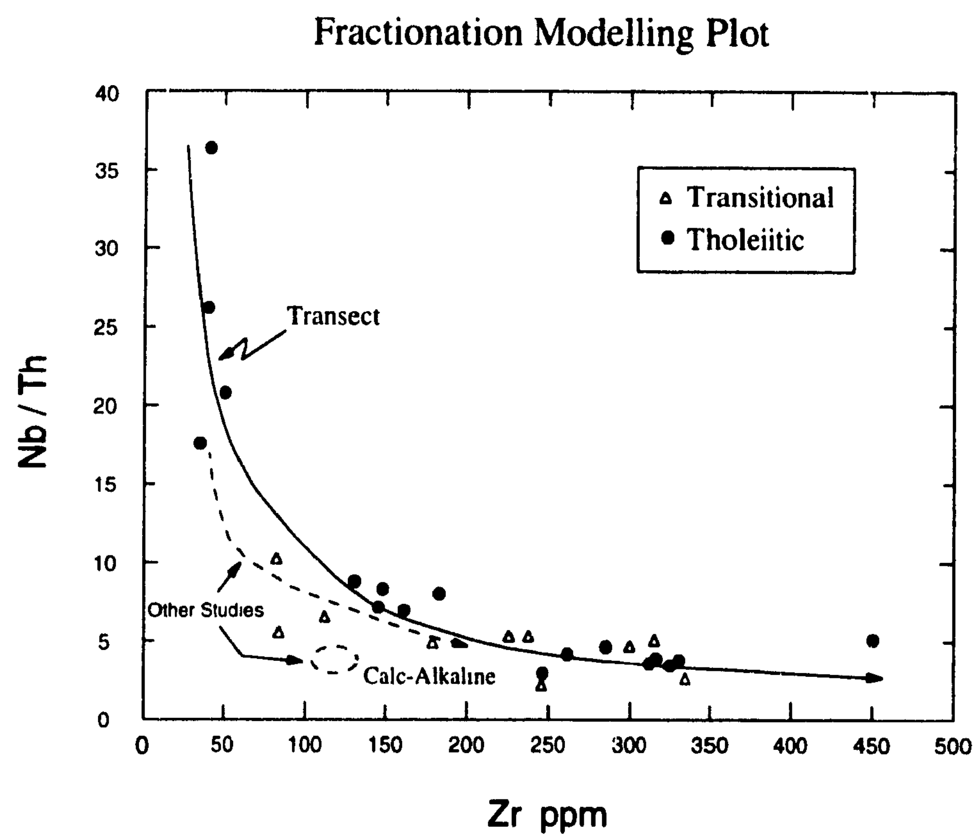


Fig. 30. Nb/Th vs. Zr diagram showing compositional trends for the tholeiitic and transitional rocks in the transect (After Laflèche et al. 1992).

Chapter 5

SUMMARY AND CONCLUSIONS

This research project produces a regional geological synthesis of the volcanic stratigraphy along a transect in the D'Alembert-Cléricy area. The volcanic succession along the transect consists of low-K basalts, basaltic-andesites, andesites, and rhyolites. The rocks belong to two major lithogeochemical affinities: tholeiitic and transitional, the latter having geochemical characteristics intermediate between tholeiitic and calc-alkaline suites. The volcanic sequences can be subdivided into three broad lithogeochemical-stratigraphic groups: a Lower Transitional Series, a Middle Tholeiitic Series, and an Upper Mixed Tholeiitic-Transitional Series.

The geochemical characteristics and alteration conditions of the volcanic units provide useful information to help to assess the potential for volcanogenic massive sulfide (VMS) deposits in the area. The approach in this study integrates lithogeochemical techniques with field mapping, volcanic facies interpretation, alteration mineral geochemistry, and petrographic studies.

Lithogeochemical techniques provide a means for stratigraphic correlation, and as such, are especially suitable for mineral exploration. The necessary major and trace element data are available from standard analytical packages and are readily adapted to exploration programs. Fractionation and alteration trends can be identified, and the intensity of alteration processes such as silicification, sericitization, and chloritization, can be quantified.

The volcanic stratigraphy in the field area has characteristics similar to that of the Central Mine Sequence (CMS) a thick assemblage of bimodal volcanic stratigraphy, tholeiitic basalt-rhyolite and transitional andesite-rhyolite suites, substantial amounts of rhyolitic rocks, presence of felsic breccia and pyroclastic rocks, and local successions containing both tholeiitic and transitional lithologies

There are also distinct differences relative to the Central Mine Sequence volcanic terrain In most of the thesis area, the rocks are steeply dipping, from 75° to 90° NE, whereas in the central part of the Noranda district, the sequence is shallowly dipping at 30°-35° NE There are tholeiitic as well as transitional rocks in the thesis area, whereas rocks in the CMS are essentially transitional with only the Flavrian Andesite containing tholeiitic units The rocks of transitional affinity in the thesis area and in the CMS are mostly andesite-rhyolite suites Overall, a greater proportion of the mafic rocks in the thesis area are basalts There is also a higher proportion of lapilli-ash tuffs and fine grained volcaniclastic rocks in the thesis area than in the CMS

The analysis and results of this study indicate the D'Alembert-Cléricy area has favourable attributes for the occurrence of massive sulfide mineralization The bimodal volcanic stratigraphy, high amount of tholeiitic to transitional rocks, and significant proportion of rhyolitic units are the key features of this promising terrain The geological and lithogeochemical characteristics are shared by the historically productive Central Mine Sequence

This research project indicates some specific localities for targets of massive sulfide exploration The Cléricy Rhyolite ridge, lying above a tholeiitic mafic-felsic transition, warrants more exploration assessment Geochemical alteration anomalies in this unit have been outlined in this thesis and by Trudel (1978) These anomalies along with the presence of a laminated pyritic tuff unit are evidence that hydrothermal systems were active in this terrain The occurrence of fragmental rhyolite material in the Cléricy Rhyolite is also a favourable characteristic for VMS mineralization

The area around the Newbec Rhyolite, and the associated Newbec VMS deposit, merits more exploration work At this locality, the geological and geochemical environment is favourable for hosting additional massive sulfide orebodies The area around the North Jevis Rhyolite just south of Lac D'Alembert also has potential for base metal mineralization Here the transitional rhyolitic rocks are interlayered within a tholeiitic mafic volcanic package As well, the presence of felsic volcaniclastics and alteration along a nearby fault zone indicate potential for mineralization

New historical perspectives are gained with a review of the evolution and development of the geological concepts of the Noranda district As such, it is important to recognize the pioneering work and valuable contributions by the early prospectors and geologists The geochemical and ore deposit models from the early years to the present have influenced industry exploration strategies and research interests, and will continue to do so as new techniques and approaches are developed This thesis work represents a regional geological synthesis based on stratigraphy and lithogeochemistry, and provides an improved framework for VMS exploration in the eastern Noranda district

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Péloquin, A S and Verpaelst, P 1989 Groupe de Blake River, Region de Rouyn-Noranda, Quebec Correlation au nord et au sud de la faille de Hunter-Creek GAC/MAC annual meeting, Montreal, Program with Abstracts, v 14, p A37

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Riverin, G , and Hodgson, C J 1980 Wall rock alteration at the Millenbach Cu-Zn mine, Noranda, Quebec Economic Geology, 75 424-444

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Shriver, N A, and MacLean, W H 1993 Mass, volume and chemical changes in the alteration zone at the Norbec mine, Noranda, Quebec Mineralium Deposita, 28 157-166

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Spence, C D 1975 Volcanogenic features of the Vauze sulfide mineralization in the volcanic sequence at Noranda, Quebec Economic Geology, 70 102-114

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Tasse, N, Lajoie, J, and Dimroth, E 1978 The anatomy and interpretation of an Archean volcaniclastic sequence, Noranda region, Quebec Canadian Journal of Earth Sciences, 15 874-888

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Trudel, P 1978 Geologie de la Region de Cléricy Ministère de l'Energie et des Ressources du Québec, Rapport Final, DP-598, pp 150

Trudel, P 1979 Le volcanisme archéen et la géologie structurale de la région de Clericy, Abitibi, Québec Thèse D Sc A, Ecole Polytechnique de Montréal, Montréal, Que

Watkinson, D H, McEwen, J, and Jonasson, I R 1990 Mine Gallen, Noranda, Quebec Geology of an Archean massive sulphide mound In The Northwestern Quebec Polymetallic Belt Edited by M Rive, P Verpaelst, Y Gagnon, J M Lulin, G Riverin, and A Simard Canadian Institute of Mining and Metallurgy, Special Volume 43, pp 167-174

Wilson, M E 1912 Kewagama Lake Map-Area, Pontiac and Abitibi Counties, Quebec Geological Survey of Canada Summary Report, 1911, pp 273-279

Wilson, M E 1939 Dufault Area, Dufresnoy and Rouyn Townships, Abitibi and

Temiscamingue Counties, Quebec Geological Survey of Canada, Map 457A

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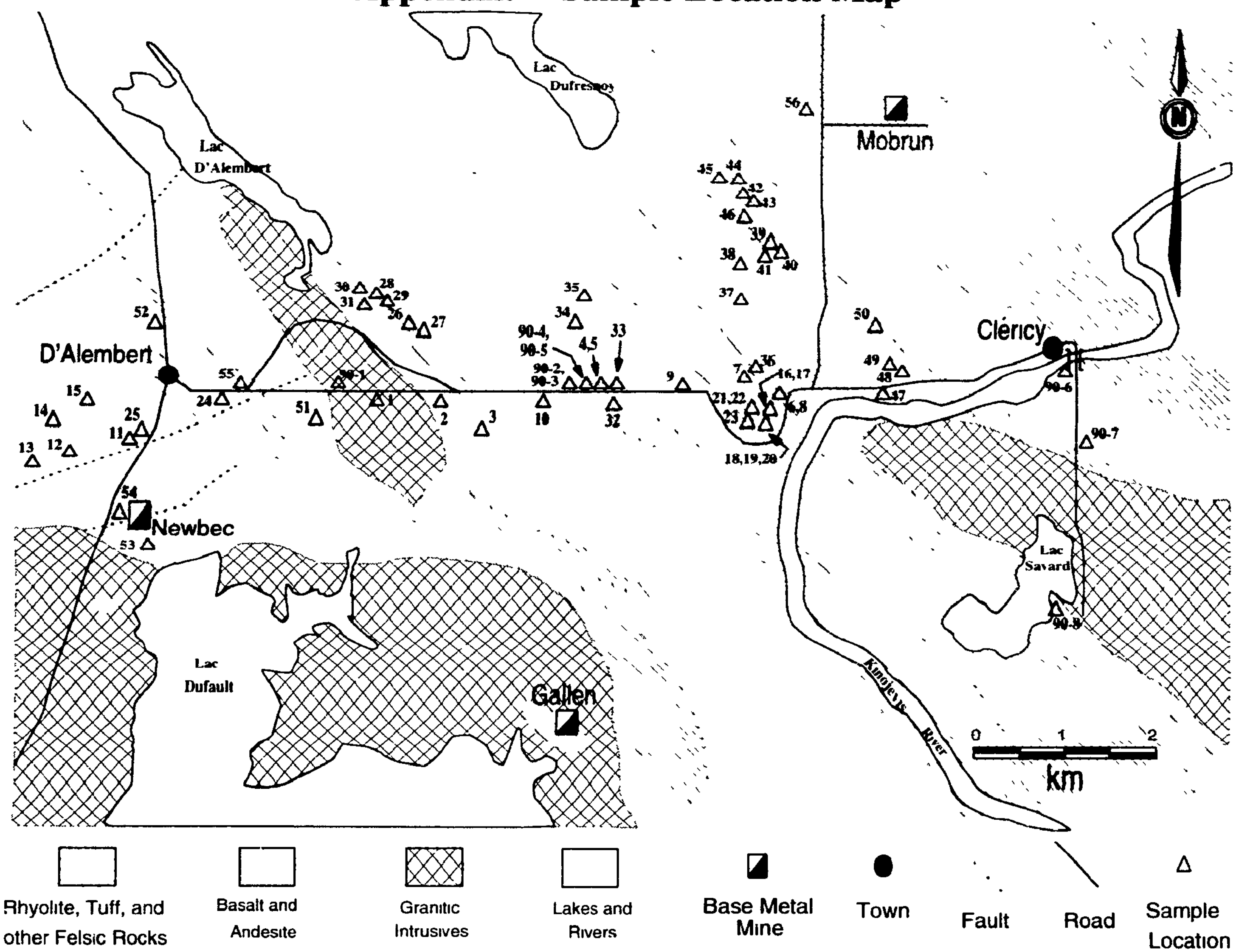
Wilson, M E 1962. Rouyn-Beauchastel Map-Area, Quebec Geological Survey of Canada, Memoir 315

Wood, D A, Joron, J-L, and Treuil, M 1979 A re-appraisal of the use of trace elements to classify and discriminate between magma series erupted in different tectonic settings Earth and Planetary Science Letters, 45 326-336

Appendix: Sample Location Map



Appendix Fig.1 Location of samples in the D'Alembert-Cléricy transect.

* Note: Samples from 1991 thesis field work are from numbered 1 to 56, eight samples available from other work are numbered 90-1 to 90-8.

APPENDIX: List of Theses

The following list of university research theses are relevant to the geology, volcanic stratigraphy, and massive sulfide deposits in the Noranda district. This list is for reference purposes only, and individual entries may not have been cited in this thesis.

A. Non-McGill Theses

Camiré, G. 1989 Volcanic stratigraphy in the Hunter Creek Fault area, east of the Flavrian Pluton, Rouyn-Noranda, Quebec M Sc thesis, Carleton University, Ottawa, Ontario, 213 p

Comba, C D A 1975 Copper-zinc zonation in tuffaceous exhalites, Millenbach Mine, Noranda, Quebec M Sc thesis, Queen's University, Kingston, Ontario, 107 p

De Rosen-Spence, A F 1976 Stratigraphy, development and petrogenesis of the central Noranda volcanic pile, Noranda, Quebec Ph D thesis, University of Toronto, Toronto, Ontario, 166 p

Fisher, D F 1970 The origin of the Number Five Zone, Horne mine, Noranda, Quebec M Sc thesis, University of Western Ontario, London, Ontario

Gibson, H L 1979 Geology of the Amulet Rhyolite formation, Turcotte Lake section, Noranda area, Quebec M Sc thesis, Carleton University, Ottawa, Ontario

Gibson, H L 1989 The Mine Sequence of the Central Noranda Volcanic Complex geology, alteration, massive sulphide deposits and volcanological reconstruction Ph D thesis, Carleton University, Ottawa, Ontario, 715 p

Goldie, R J 1976 The Flavrian and Powell plutons, Noranda Area, Quebec Ph D thesis, Queen's University, Kingston, Ontario, 356 p

Kennedy, L P 1985 The geology and geochemistry of the Archean Flavrian pluton, Noranda, Québec Ph D thesis, University of Western Ontario, London, Ontario

Laflèche, M R 1991 Pétrologie et géochimie des éléments traces du magmatisme Archéen de la partie sud de la ceinture volcano-plutonique de L'Abitibi, Québec Ph D thesis, Université de Montpellier II, Montpellier, France

Larouche, M 1974 Etude stratigraphique, volcanologique et structurale de la région de Destor-Cléricy-Montbrun, Abitibi-ouest M Sc Université Laval, Québec, Québec, 67p

MacRobbie, P A 1986 Stratigraphy, hydrothermal alteration and structure of the Mobrun massive sulfide deposit, Rouyn-Noranda, Québec B Sc thesis, Carleton University, Ottawa, Ontario, 46 p

Price, P 1933 The geology and ore deposits of the Horne Mine, Noranda, Quebec Ph D thesis, McGill University, Montreal, Que

Paradis, S 1984 Le pluton de Flavrian, évolution pétrologique et relation avec les roches volcaniques du Groupe de Blake River, Abitibi, P Q M Sc thesis, Université de Montréal, Québec

Paradis, S , 1992 Stratigraphy, volcanology and geochemistry of the New Vauze-Norbec area, Central Noranda Volcanic Complex, Quebec Ph D thesis, Carleton University, Ottawa, Ontario

Riverin, G 1977 Wall-rock alteration at the Millenbach Mine, Noranda Area, Quebec Ph D thesis, Queen's University, Kingston, Ontario

Sinclair, W D 1970 Geology of the No 5 Zone, Noranda, Quebec, Canada M Sc. thesis, University of Wisconsin, Madison, Wisconsin

Setterfield, T 1984 Nature and significance of the McDougall-Despina fault set, Noranda, Quebec M Sc thesis, University of Western Ontario, London, Ontario

Trudel, P 1979 Le volcanisme archéen et la géologie structurale de la région de Cléricy, Abitibi, Québec Thèse D Sc A , Ecole Polytechnique de Montréal, Montréal, Qué 307 p

Watkins, J J 1980 The geology of the Corbet Cu-Zn deposit and the environment of ore deposition in the Central Noranda area M Sc thesis, Queen's University, Kingston, Ontario

B. McGill Theses

Index of Geological Research Thesis of the Noranda District at McGill University, Montreal, Quebec, Canada

In Chronological Order:

Holbrooke, G L 1928 A petrographic study of the Aldermac Mine M Sc thesis

Bray, A C 1929 A petrographic study of certain cordierite-bearing rocks M Sc thesis

Denis, F T 1933 An investigation of the mineral composition of the ores of Noranda Mines Ltd M Sc thesis

Schindler, N R 1933 Geology of the Waite-Ackerman-Montgomery property, Duprat and Dufresnoy Townships, Quebec M Sc thesis

Price, P 1933 The geology and ore deposits of the Horne Mine, Noranda, Quebec Ph D thesis

Schindler, N R 1934 Igneous rocks of the Duprat Lake and Rouyn Lake Areas, Quebec Ph D thesis

MacDonald, W V 1938 The Aldermac syenite porphyry stock, Quebec M Sc thesis

Riodan, P H 1938 The Geology of a section of Beauchastel Township, Quebec M Sc thesis

Robinson, R F 1938 The geology of the Orland Property, Beauchastel Township, Province of Quebec M Sc thesis

Hall, J D 1939 The geology of he lower 'A' ore-body, Waite-Amulet M Sc thesis

Bray, R C E 1940 A comparison of the non-opaque minerals of certain parts of the Waite-Amulet area, Quebec M Sc thesis

Asbury, W N 1941 Faulting and ore deposition in the Rouyn-Bell River Region M Sc thesis

Malouf, S E 1941 The geology of the Francoeur-Arntfield District, Beauchastel Township, Quebec Ph D thesis

Robinson, W G 1941 The Flavrian Lake map area and the structural geology of the surrounding district Ph D thesis

Buck, W K 1951 The geology of the Lake Wasa property, Beauchastel Township, Quebec M Sc thesis

L'Esperance, R L 1951 The geology of Duprat Township and some adjacent areas, Northwestern Quebec, and the structure of the Noranda District Ph D thesis

Riddell, J E 1953 Wall rock alteration around base metal sulphide deposit of Northwestern Quebec Ph D thesis

Lickus, R J 1965 Geology and geochemistry of the ore deposits at the Vauze Mine, Noranda District, Quebec Ph D thesis

Sakrison, H C 1967 Studies of the host rocks of the Lake Dufault Mine, Quebec Ph D thesis

Beaton, W D 1970 Trace element partition in sulphides, Noranda, Quebec Ph D thesis

Umar, P 1978 Mineral resource potential Rouyn-Noranda Region, Quebec Ph D thesis

MacGeehan, P 1979 An investigation of the geochemistry of hydrothermally altered volcanic rocks and a proposed new geothermal model for massive sulphide genesis Ph D thesis 414 p

Meyers, R 1980 The geology and origin of New Insco copper deposit, Noranda District, Quebec M Sc thesis 134 p

Liaghat, S 1990 Use of immobile elements to determine mass changes and origin of hydrothermally altered rocks Key Tuffite, Matagami, and New Insco Mine, Noranda M Sc thesis 112 p

Shriver, N 1992 A geochemical evaluation of the alteration zone at the Norbec Mine, Noranda, Quebec bulk chemical composition, mass change, flux of elements M Sc thesis 101 p

APPENDIX Table 1

	Amulet Andesite						Newbec Rhyolite		Newbec Andesite		Lac D'Alembert Rhy
Sample #	91-15	91-13	91-12	91-14	91-11	91-25	91-54	91-53	91-52	91-24	91-55
Rock Type	AND-F	AND-F	AND-A	AND-A	AND-F	B-A-A	RHY-F	RHY-F	AND-F	AND-A	RHY-A
SiO_2 wt%	56.25	56.87	53.22	55.87	54.23	53.53	79.25	79.57	54.99	56.41	68.48
TiO_2	1.04	0.96	1.39	1.18	1.37	0.92	0.18	0.17	0.64	1.33	0.50
Al_2O_3	16.94	16.33	13.49	15.72	14.79	16.81	11.15	11.13	16.48	15.75	12.09
FeO	6.14	6.74	6.94	6.23	8.57	6.42	1.15	1.63	7.78	7.96	4.19
MnO	0.12	0.11	0.16	0.15	0.25	0.13	0.01	0.01	0.13	0.12	0.09
MgO	4.32	5.05	4.11	3.01	5.11	3.94	0.31	0.13	5.61	3.69	1.32
CaO	7.96	6.17	10.18	14.83	7.22	13.35	0.43	0.96	5.88	2.72	3.53
Na_2O	4.45	4.55	1.93	0.38	4.59	1.66	5.57	5.27	5.28	2.57	1.83
K_2O	0.23	0.50	0.87	0.9	0.18	1.08	0.4	0.17	0.04	2.45	2.51
P_2O_5	0.17	0.17	0.26	0.25	0.16	0.15	0.03	0.02	0.09	0.36	0.10
LOI	1.90	1.90	1.49	1.69	1.19	1.43	0.73	0.47	2.76	5.96	4.37
Total	99.52	99.35	94.04	100.21	97.66	99.42	99.21	99.53	99.68	99.32	99.01
V ppm	211	187	240	192	264	198	21	14	165	175	49
Cr	127	55	113	83	98	138	106	10	127	21	10
Ni	54	58	57	33	36	63	17	11	60	30	11
Ba	65	92	262	409	13	386	51	81	154	253	379
Rb	6	11	30	28	4	26	8	3	0	42	40
Sr	92	123	234	265	77	101	17	64	204	29	38
Y	16	22	24	21	19	20	23	46	19	38	68
Zr	80	118	114	98	73	89	311	297	89	151	248
Nb	7	11	8	9	7	7	16	13	7	12	15
Hf	2.1						8	7.3		2.6	4.4
Th	0.7						3.2	2.8		1.7	3.8
Ta	0.3						3	1.7		1	1.4
Sc	25						6.3	5.5		26	9.1
La	9.2						23	20		16.5	27.6
Ce	20						48	47		38	64
Nd	11						27	26		22	38
Sm	2.6						5.6	6.6		5.9	9.6
Eu	0.82						0.56	1.43		1.6	1.44
Tb	0.5						0.8	1.5		1.0	2.1
Yb	1.53						4.45	5.39		4.14	8.21
Lu	0.23						0.74	0.82		0.66	1.25
Sericit Index	5	10	31	70	4	39	7	3	1	49	58
Zr/Y	5.0 TR	5.4 TR	4.8 TR	4.7 TR	3.8 TH	4.5 TR	13.5 CA	6.5 TR	4.7 TR	4.0 TH	3.6 TH
La_N/Yb_N	4.1 TR						3.5 TR	2.5 TH		2.7 TH	2.3 TH
Zr/Yb	54 TR						71 TR	56 TR		39 TH	32 TH
Th/Hf	0.33 TH						0.4 TH	0.38 TH		0.65 TR	0.86 CA
Th/Yb	0.46 TR						0.72 TR	0.52 TR		0.41 TR	0.46 TR
Zr/Th	117 TH						99 TH	107 TH		95 TH	69 TR
AFM	CA	CA			CA		nd	nd	CA		
Miyashiro	CA	CA			CA		CA	nd	CA		

** Note CA = calc-alkaline TH = tholeiitic TR = transitional nd = not determinable affinity discrimination based on above trace and major element ratios

APPENDIX Table 1

	D Alembert Pluton		North Jevis Rhyolite				South Jevis Unit					
Sample #	91-1	90-1	91-31	91-30	91-27	91-26	90-4	91-5	90-5	91-4	91-32	91-33
Rock Type	GRAN-F	GRAN-F	RHY-F	RHY-F	RHY-A	AND-A	RHY-F	RHY-F	DAC-F	DAC-F	AND-F	DAC-F
SiO_2 wt%	64 84	67 14	73 63	73 44	73 96	59 3	78 43	68 75	63 08	63 93	59 11	61 58
TiO_2	0 53	0 42	0 16	0 20	0 23	0 81	0 28	1 19	1 27	1 3	0 88	1 33
Al_2O_3	13 83	12 75	10 75	13 00	11 42	16 23	10 28	13 21	1- 40	14 43	16 64	15 13
FeO	4 55	3 93	2 59	2 75	3 33	6 96	1 48	4 07	' 49	5 88	6 61	7 34
MnO	0 06	0 22	0 07	0 05	0 09	0 15	0 04	0 09	0 18	0 13	0 11	0 16
MgO	1 48	1 65	0 38	0 34	0 01	3 19	0 05	1 31	2 60	2 19	3 29	2 33
CaO	3 19	3 35	1 51	1 19	8 64	6 72	2 77	3 13	3 46	3 56	7 04	4 49
Na_2O	4 67	3 94	4 52	6 51	0 86	2 5	3 63	4 96	4 17	5 13	3 18	4 70
K_2O	1 19	1 10	0 78	0 46	0 23	1 16	0 64	0 76	0 32	0 65	0 71	0 23
P_2O_5	0 14	0 10	0 02	0 04	0 04	0 14	0 05	0 24	0 38	0 26	0 15	0 44
LOI	4 45	4 83	1 8	1 41	0 90	2 29	0 95	1 66	1 99	1 99	2 41	1 98
Total	98 94	99 43	96 21	99 39	99 71	99 45	98 60	99 37	99 34	99 45	100 13	99 71
V ppm	72	40	16	10	21	153	10	75	42	59	173	61
Cr	61	120	36	10	10	10	250	10	91	151	80	10
Ni	51	10	16	10	14	39	31	32	10	190	48	10
Ba	318	480	176	155	61	265	190	297	201	188	149	117
Rb	39	23	21	9	4	43	24	17	6	9	16	4
Sr	134	72	47	52	476	182	93	123	122	141	172	184
Y	20	26	35	33	67	30	29	33	32	40	13	38
Zr	129	153	224	221	302	174	179	129	125	142	110	128
Nb	8	10	13	13	18	10	10	8	9	9	7	12
Hf			5	5 4		2 8				3 9	2 6	3 3
Th			2 6	2 5		2 1				1 3	1 1	1 4
Ta			1 5	1		0 6				0 7	0 9	0 6
Sc			11	13		17				23	16	24
La			15 1	12 9		17				13 2	12.5	13
Ce			30	32		36				30	25	31
Nd			17	16		19				17	12	20
Sm			4	4 3		4 4				4 3	2 7	5 4
Eu			0 79	0 91		1 14				1 52	0 82	1.54
Tb			0 9	0 9		0 8				1	0 4	1 1
Yb			4 88	5 06		3 24				4 07	1 3	4 25
Lu			0 75	0 86		0 5				0 64	0 2	0 6
Sericit Index	20	22	15	7	21	32	15	13	7	11	18	5
Zr/Y	6 5 TR	5 9 TR	6 4 TR	6 7 TR	4 5 TR	5 8 TR	6 2 TR	3 9 TH	3 9 TH	3 6 TH	8 5 CA	3 4 TH
La_N/Yb_N			2 1 TH	1 7 TH		3.5 TR				2 2 TH	6 5 CA	2 1 TH
Zr/Yb			49 TR	45 TR		55 TR				36 TH	87 CA	31 TH
Th/Hf			0 52 TR	0 46 TH		0 75 TR				0 33 TH	0 42 TH	0 42 TH
Th/Yb			0 53 TR	0 49 TR		0 65 TR				0 32 TH	0 85 CA	0 33 TH
Zr/Th			91 TH	90 TH		85 TH				112 TH	103 TH	94 TH
AFM	CA	CA	nd	nd			nd	TH	TH	CA	CA	TH
Miyashiro	CA	CA	TH	TH			nd	CA	CA	CA	CA	TH

** Note CA = calc-alkaline, TH = tholeiitic, TR = transitional, nd = not determinable, affinity discrimination based on above trace and major element ratios

APPENDIX Table 1

Cléricy Road Basalt

Sample #	91-51	90-2	91-2	91-3	91-28	91-29	91-10	90-3	91-34	91-9
Rock Type	BAS-F	BAS-A	BAS-F	B-A-F	BAS-F	BAS-F	B-A-F	B-A-F	BAS-F	B-A-F
SiO_2 wt%	47.1	45.42	44.02	50.69	49.20	47.65	52.22	50.98	47.14	53.76
TiO_2	1.57	0.59	1.36	1.12	2.15	1.46	1.38	1.48	1.7	1.64
Al_2O_3	11.39	18.66	17.03	20.47	13.79	15.24	15.79	14.81	14.94	12.13
FeO	14.38	8.62	12.31	7.09	15.15	12.62	11.64	11.25	15.22	13.43
MnO	0.38	0.16	0.21	0.14	0.26	0.19	0.26	0.22	0.29	0.35
MgO	4.94	9.88	8.23	2.31	4.31	6.44	4.99	4.82	5.2	3.12
CaO	6.9	10.54	10.42	6.68	8.25	9.28	5.06	8.14	10.96	7.24
Na_2O	1.9	1.94	1.12	5.51	2.47	3.18	3.89	3.51	0.6	2.79
K_2O	0.06	0.77	0.03	0.36	0.18	0.13	0.16	0.28	0.06	0.48
P_2O_5	0.12	0.10	0.14	0.09	0.25	0.15	0.15	0.14	0.16	0.14
LOI	7.36	3.63	4.23	2.53	2.85	2.72	3.71	3.58	3.47	3.53
Total	96.10	100.31	99.10	96.99	98.86	99.06	99.25	99.21	99.74	98.61
V ppm	380	132	265	272	409	254	246	270	384	404
Cr	48	262	270	160	16	138	339	476	96	27
Ni	40	296	225	112	30	74	183	222	78	60
Ba	9	147	9	234	18	19	121	56	74	51
Rb	2	20	2	11	5	2	4	5	2	11
Sr	53	85	305	138	144	122	35	71	185	132
Y	40	9	15	13	31	21	17	16	19	56
Zr	104	32	33	29	79	49	38	48	39	154
Nb	8	4	5	5	8	6	5	6	7	12
Hf			1.3			1.2	1.1		1.1	
Th			0.3			0.3	0.2		0.2	
Ta			0.3			0.4	0.3		0.3	
Sc			41			34	33		41	
La			4.1			3.8	3.1		3.5	
Ce			11			10	8		9	
Nd			8			7	6		7	
Sm			2.3			2.3	1.8		2.2	
Eu			0.94			0.8	0.37		0.89	
Tb			0.6			0.6	0.4		0.6	
Yb			1.97			2.1	1.54		2.12	
Lu			0.29			0.32	0.25		0.34	
Sericit Index	3	28	3	6	7	4	4	7	9	15
Zr/Y	2.6 TH	3.6 TH	2.2 TH	2.2 TH	2.5 TH	2.3 TH	2.2 TH	3.0 TH	2.1 TH	2.8 TH
La_N/Yb_N			1.4 TH			1.2 TH	1.4 TH		1.1 TH	
Zr/Yb			18 TH			24 TH	26 TH		19 TH	
Th/Hf			0.23 TH			0.25 TH	0.18 TH		0.18 TH	
Th/Yb			0.15 TH			0.14 TH	0.13 TH		0.09 TH	
Zr/Th			117 TH			170 TH	200 TH		205 TH	
AFM	TH		TH	CA	TH	TH	TH	TH	TH	TH
Miyashiro	TH		TH	TH	TH	TH	TH	TH	TH	TH

** Note CA = calc-alkaline TH = tholeiitic TR = transitional nd = not determinable affinity discrimination based on above trace and major element ratios

APPENDIX Table 1

Clérícy Rhyolite								
Sample #	91-23	91-21	91-18	91-19	91-20	91-16	91-17	91-7
Rock Type	RHY-A	RHY-F	RHY-A	RHY-A	RHY-A	RHY-A	RHY-A	RHY-A
SiO_2 wt%	77 96	76 88	75 03	70 79	75 63	71 08	73 55	79 44
TiO_2	0 11	0 15	0 15	0 16	0 16	0 48	0 27	0 23
Al_2O_3	11 35	11 84	11 82	11 1	11 97	11 81	11 61	10 44
FeO	1 47	2 63	2 74	2 93	2 78	4 49	2 74	1 37
MnO	0 01	0 05	0 06	0 06	0 06	0 07	0 07	0 02
MgO	0 04	0 68	1 08	0 72	0 5	0 79	0 89	0 16
CaO	0 33	0 28	0 80	2 96	4 45	2 17	1 57	0 62
Na_2O	3 72	5 77	0 59	1 13	1 65	3 29	1 23	4 56
K_2O	4 41	0 83	4 52	3 2	1 65	2 37	3 32	1 76
P_2O_5	0 01	0 02	0 02	0 01	0 02	0 07	0 05	0 04
LOI	0 23	0 59	1 98	2 12	1 19	2 46	1 89	0 46
Total	99 64	99 72	98 79	95 18	100 06	99 08	97 19	99 10
V ppm	20	12	24	27	30	46	29	26
Cr	10	10	14	10	10	10	62	10
Ni	11	18	13	32	19	11	15	11
Ba	391	133	936	745	344	493	495	597
Rb	60	11	116	83	42	61	103	21
Sr	27	30	35	65	123	25	52	28
Y	94	93	83	91	97	39	76	66
Zr	290	314	315	308	309	158	270	243
Nb	21	20	20	20	20	8	15	15
Hf		7 5	8 2	7 3	7 3			8 3
Th		5 2	6	5 7	5 7			5 2
Ta		2 1	1 6	2	2 2			1 6
Sc		6 2	6 4	6 4	6 5			5 6
La		44 7	37 9	42 6	41 8			32
Ce		91	87	92	90			73
Nd		47	48	48	49			37
Sm		11	11	12	12			8 4
Eu		1 32	1 14	1 58	1 56			0 89
Tb		2 4	2 5	2 7	2 8			1 8
Yb		9 09	10 30	10 3	10 9			7 3
Lu		1 40	1 58	1 56	1 69			1 14
Sericit Index	54	13	88	74	50	42	73	28
Zr/Y	3 1 TH	3 4 TH	3 8 TH	3 4 TH	3 2 TH	4 1 TH	3 6 TH	3 7 TH
La_N/Yb_N		3 3 TR	2 5 TH	2 8 TH	2 6 TH			3 0 TR
Zr/Yb		35 TH	32 TH	32 TH	29 TH			34 TH
Th/Hf		0 69 TR	0 73 TR	0 78 TR	0 78 TR			0 63 TR
Th/Yb		0 57 TR	0 58 TR	0 55 TR	0 52 TR			0 71 TR
Zr/Th		61 TR	54 TR	58 TR	55 TR			47 CA
AFM		nd						
Miyashiro		CA						

** Note CA = calc-alkaline, TH = tholeiitic, TR = transitional, nd = not determinable, affinity discrimination based on above trace and major element ratios

APPENDIX Table 1

	Clericy Rapids Rhyolite			Lac Dufresnoy Andesite							
Sample #	91-36	91-47	90-8	91-22	91-6	91-8	91-37	91-49	91-48	91-38	91-41
Rock Type	RHY-A	RHY-A	RHY-A	AND-A	AND-F	B-A-F	AND-F	B-A-A	AND-F	B-A-F	AND-F
SiO_2 wt%	75 31	75 93	76 73	59 46	54 79	54 22	61 43	51 14	57 09	53 3	58 48
TiO_2	0 28	0 12	0 18	0 44	0 93	1 05	0 68	1 01	1 05	1 72	1 59
Al_2O_3	12 16	10 97	11 36	16 36	17 50	17 12	13 02	15 28	16 13	12 51	12 49
FeO	2 68	4 98	1 40	4 98	6 09	5 95	7 93	15 85	5 79	14 96	9 66
MnO	0 04	0 02	0 03	0 11	0 09	0 07	0 12	0 29	0 11	0 32	0 19
MgO	0 49	0 71	0 35	5 25	4 55	5 85	2 85	8 29	4 97	3 73	3 15
CaO	0 33	0 01	0 29	4 53	8 58	8 24	8 36	0 76	8 07	7 5	5 39
Na_2O	4 57	0 47	4 02	1 12	3 36	5 28	3 71	0 85	5 68	1 55	3 58
K_2O	2 62	2 65	3 04	4 55	0 89	0 07	0 1	0 53	0 12	0 23	0 14
P_2O_5	0 04	0 02	0 01	0 08	0 12	0 1	0 11	0 1	0 1	0 15	0 19
LOI	0 65	2 60	0 49	2 69	2 21	1 68	1 13	5 19	0 99	3	4 12
Total	99 17	98 48	97 90	99 57	99 11	99 63	99 44	99 29	100 10	98 97	98 98
V ppm	25	10	14	100	219	279	179	263	274	424	323
Cr	10	10	172	55	94	179	76	34	77	14	14
Ni	10	15	15	62	80	45	55	23	28	24	16
Ba	582	768	570	747	183	109	9	184	106	87	90
Rb	44	42	38	112	27	2	2	9	3	6	3
Sr	36	7	27	137	208	123	179	6	198	117	102
Y	60	47	47	18	18	17	17	15	18	56	54
Zr	330	231	213	91	88	81	82	81	80	151	141
Nb	15	33	16	7	6	7	6	8	7	12	11
Hf	6 6						1 9				4 1
Th	5 8						1 1				1 4
Ta	1 4						0 5				0 6
Sc	7 1						21				40
La	41 3						9				13 2
Ce	82						19				31
Nd	37						10				19
Sm	9						2 4				6
Eu	1 38						0 67				1 68
Tb	1 8						0 5				1 4
Yb	6 54						1 84				5 22
Lu	1 00						0 29				0 84
Sericit Index	36	85	43	80	21	1	3	38	2	13	4
Zr Y	5 5 TR	4 9 TR	4 5 TR	5 1 TR	4 9 TR	4 8 TR	4 8 TR	5 4 TR	4 4 TH	2 7 TH	2 6 TH
La_N Yb_N	4 3 TR						3 3 TR				1 7 TH
Zr Yb	51 TR						45 TR				28 TH
Th Hf	0 88 CA						0 58 TR				0 34 TH
Th Yb	0 89 CA						0 60 TR				0 27 TH
Zr Th	58 TR						75 TR				106 TH
AFM					CA	CA	TH		CA	TH	TH
Miyashiro					CA	CA	CA		CA	TH	TH

** Note CA = calc-alkaline TH = tholeiitic TR = transitional nd = not determinable affinity discrimination based on above trace and major element ratios

APPENDIX Table 1

	Lac Dufresnoy Rhyolite								Clericy Rapids Rhyolite		Mobrun Rhyolite
Sample #	91-46	91-40	91-42	91-39	91-43	91-44	91-45	91-50	90-6	90-7	91-56
Rock Type	RHY-A	RHY-A	RHY-A	RHY-F	RHY-F	RHY-F	RHY-F	RHY-F	AND-F	AND-F	RHY-F
SiO_2 wt%	75 81	74 23	75 90	70 83	73 72	76 32	75 9	77 03	55 97	56 16	79 96
TiO_2	0 19	0 3	0 27	0 32	0 33	0 23	0 31	0 14	1 68	1 09	0 20
Al_2O_3	10 14	12 87	10 09	11 80	11 68	12 62	11 68	12 32	12 56	15 52	9 76
FeO	1 75	3 45	3 33	4 46	4 04	1 96	3 09	1 16	11 39	10 53	2 46
MnO	0 04	0 02	0 08	0 08	0 09	0 02	0 02	0 01	0 20	0 10	0 03
MgO	1 02	0 72	0 40	0 69	0 39	0 61	0 22	0 39	3 65	4 44	0 68
CaO	0 69	0 59	2 18	1 81	1 71	0 20	0 6	0 76	4 95	8 77	0 47
Na_2O	3 35	2 71	2 87	4 95	4 88	5 57	5 86	5 76	3 46	1 79	4 36
K_2O	1 43	3 33	1 71	0 66	0 77	1 17	0 37	0 61	0 03	0 09	0 64
P_2O_5	0 02	0 04	0 05	0 05	0 05	0 03	0 05	0 01	0 14	0 11	0 03
LOI	1 03	1 65	2 78	2 32	2 01	0 93	0 72	1 22	4 88	1 20	1 08
Total	95 47	99 91	99 66	97 97	99 67	99 66	98 82	99 41	98 91	99 80	99 67
V ppm	23	35	20	24	22	26	21	17	312	295	28
Cr	10	10	36	13	10	14	10	10	27	116	10
Ni	14	22	13	25	22	11	17	10	10	14	10
Ba	425	974	417	274	323	327	102	30	60	33	166
Rb	32	69	35	12	13	25	7	13	2	3	12
Sr	34	23	54	51	59	35	50	38	46	212	25
Y	68	79	99	118	114	90	97	74	45	18	52
Zr	163	357	358	431	420	256	401	280	172	104	242
Nb	12	17	18	22	21	20	21	30	12	8	12
Hf				11				8 3	4 6		5 3
Th				4 5				6 6	1 6		5 5
Ta				1 7				2 7	0 7		1 2
Sc				6 4				4 8	39		6 4
La				37 7				13 3	17 5		28 9
Ce				86				32	44		61
Nd				51				18	25		30
Sm				13				5 9	6 6		7 1
Eu				2.15				0 93	1 41		0 99
Tb				2 8				2	1 4		1 4
Yb				12 4				7 7	5 9		6 26
Lu				1 9				1 21	0 85		0 94
Sericit Index	30	55	37	12	14	17	6	10	1	5	13
Zr/Y	2 4 TH	4 5 TR	3 6 TH	3 7 TH	3 7 TH	2 8 TH	4 1 TH	3 8 TH	3 8 TH	5 8 TR	4 7 TR
La_N/Yb_N				2 1 TH				1 2 TH	2 0 TH		3 1 TR
Zr/Yb				36 TH				37 TH	31 TH		39 TH
Th/Hf				0 41 TH				0 80 TR	0 35 TH		1 04 CA
Th/Yb				0 36 TR				0 86 CA	0 27 TH		0 88 CA
Zr/Th				100 TH				43 CA	114 TH		45 CA
AFM				TH	TH	nd	TH	nd	TH	TH	CA
Miyashiro				TH	nd	CA	nd	CA	TH	TH	CA

** Note CA = calc-alkaline, TH = tholeiitic, TR = transitional, nd = not determinable, affinity discrimination based on above trace and major element ratios

Appendix Table II

Average Mineral Microprobe Analyses

Sample 91-2   Clericy Road Basalt

Mineral	Chlorite n=5	Tremolite n=1	Epidote n=3	Zoisite n=1
Wt% Oxide				
SiO2	28.10	54.90	38.34	46.69
AlO iv	8.97	0.92	0.00	0.00
AlO vi	10.00	0.00	24.07	23.61
TiO2	0.02	0.00	1.84	0.02
FeO	21.94	10.94	10.34	6.14
MnO	0.39	0.49	0.00	0.00
MgO	17.91	17.84	0.27	0.01
CaO	0.17	12.39	22.90	17.96
NaO.5	0.02	0.10	0.02	3.15
KO.5	0.00	0.01	0.12	0.01
OH	11.58	2.10	1.87	1.95
Total	99.10	99.69	99.76	99.53
MINERAL COMPOSITION				
Si	5.8131	7.8449	3.0774	3.5881
Al iv	2.1869	0.1551	0.0000	0.0000
Al vi	2.4383	0.0000	2.2770	2.1384
Ti	0.0031	0.0000	0.1111	0.0012
Fe	3.7956	1.3071	0.6941	0.3946
Mn	0.0683	0.0593	0.0000	0.0000
Mg	5.5242	3.8001	0.0323	0.0011
Ca	0.0377	1.8966	1.9694	1.4788
Na	0.0080	0.0277	0.0031	0.4695
K	0.0000	0.0018	0.0123	0.0010
OH	16.0000	2.0000	1.0000	1.0000

Average Mineral Microprobe Analyses

Sample 91-8		Lac Dufresnoy Andesite				
Mineral	Chlorite	Tremolite	Epidote	Zoisite		Albite
	n=7	n=4	n=1	n=9		n=3
Wt% Oxide						Wt% Oxide
SiO2	27 64	52 32	41 08	39 23	SiO2	68 96
AlO iv	9 62	2 55	0 00	0 00	Al2O3	20 05
AlO vi	10 07	0 83	23 11	29 39	TiO2	0 00
TiO2	0 02	0 25	0 10	0 08	FeO	0 14
FeO	19 53	13 25	6 11	4 20	MnO	0 00
MnO	0 19	0 16	0 22	0 31	MgO	0 00
MgO	19 92	16 17	2 33	0 08	CaO	0 69
CaO	0 08	11 45	22 29	24 28	Na2O	11 07
NaO 5	0 03	0 47	0 03	0 01	K2O	0.04
KO 5	0 01	0 05	0 02	0 01	Total	100 95
OH	11 68	2 07	1 87	1 92		
Total	98 79	99 57	97 17	99 50		
MINERAL COMPOSITION						
Si	5 6736	7 5642	3 2945	3 0594	Si	2 9822
Al iv	2 3264	0 4358	0 0000	0 0000	Al	1 0222
Al vi	2 4351	0 1417	2 1843	2 7008	Ti	0 0001
Ti	0 0024	0 0269	0 0063	0 0046	Fe	0 0049
Fe	3 3509	1 6025	0 4099	0 2742	Mn	0 0000
Mn	0 0330	0 0196	0 0150	0 0204	Mg	0.0002
Mg	6 0962	3 4865	0 2785	0 0094	Ca	0 0319
Ca	0 0179	1 7728	1 9153	2 0285	Na	0 9278
Na	0 0114	0 1304	0 0045	0 0007	K	0 0024
K	0 0037	0 0088	0 0019	0 0006		
OH	16 0000	2 0000	1 0000	1 0000		

Average Mineral Microprobe Analyses

Sample 91-22 — Lac Dufresnoy Andesite

Mineral	Sericite n=3	Zoisite n=2	Chlorite n=5
Wt% Oxide			
SiO2	48.36	38 37	26 89
AlO iv	10 24	0 00	10 18
AlO vi	22 93	24 72	9 45
TiO2	0 01	0 03	0 02
FeO	1 58	9 69	21.25
MnO	0.03	0 19	0 51
MgO	1.38	0 07	18 54
CaO	0 01	23.17	0 04
Na2O	0 10	0 01	0 03
K2O	11 43	0 03	0 03
OH	4.53	1 84	11 51
Total	100 59	98 10	98.43
MINERAL COMPOSITION			
Si	6 4023	3 1210	5 6009
Al iv	1 5977	0 0000	2 3991
Al vi	3 5778	2 3693	2 4185
Ti	0 0010	0 0018	0 0031
Fe	0 1749	0 6589	3 7005
Mn	0 0034	0 0000	0 0896
Mg	0 2724	0 0079	5 7560
Ca	0 0014	2 0186	0 0094
Na	0 0257	0 0016	0 0129
K	1.9305	0 0026	0 0070
OH	4.0000	1 0000	16 0000

	K-Feldspar n 10	Plagioclase n 1
SiO2	64 99	54 49
Al2O3	18 08	26 49
TiO2	0 00	0 00
FeO	0 01	1 60
MnO	0 01	0 05
MgO	0 01	0 09
CaO	0 01	14 76
Na2O	0 14	1 20
K2O	17 28	0 60
Total	100 56	99 28
Si	3 0117	2 4006
Al	0 9746	1 1556
Ti	0 0006	0 0000
Fe	0 0010	0 0624
Mn	0 0002	0 0020
Mg	0 0022	0 0063
Ca	0 0010	0 7373
Na	0 0105	0 3797
K	1 0078	0 0357

Average Mineral Microprobe Analyses

Sample 91-25	Amulet Andesite		
Mineral	Tremolite n=1	Epidote n=2	Zoisite n=4
Wt% Oxide			
SiO2	49.44	37.32	38.00
AlO iv	3.99	0.00	0.00
AlO vi	2.94	22.69	25.77
TiO2	0.09	0.18	0.14
FeO	12.48	11.37	8.43
MnO	0.18	0.00	0.00
MgO	11.79	0.07	0.08
CaO	14.90	23.23	23.73
NaO 5	0.22	0.00	0.00
KO 5	0.10	0.00	0.00
OH	2.03	1.79	1.85
Total	98.15	96.65	98.00
MINERAL COMPOSITION			
Si	7.3044	3.1185	3.0745
Al	0.69[illegible]	0.0000	0.0000
Al	0.5111	2.2345	2.4573
Ti	0.0100	0.0113	0.0085
Fe	1.5419	0.7945	0.5704
Mn	0.0225	0.0000	0.0000
Mg	2.5971	0.0087	0.0097
Ca	2.3586	2.0798	2.0571
Na	0.0630	0.0000	0.0000
K	0.0188	0.0000	0.0000
OH	2.0000	1.0000	1.0000

Average Mineral Microprobe Analyses

Sample 91-27 North Jevis Rhyolite

Mineral	Epidote n=5		Albite n=3
Wt% Oxide			Wt% Oxide
SiO_2	38.07	SiO_2	69.31
AlO iv	0.00	Al_2O_3	18.95
AlO vi	26.32	TiO_2	0.12
TiO_2	0.13	FeO	0.08
FeO	7.72	MnO	0.00
MnO	0.00	MgO	0.02
MgO	0.01	CaO	0.52
CaO	23.62	Na_2O	10.60
NaO 5	0.03	K_2O	0.30
KO 5	0.05	Total	99.90
OH	1.86		
Total	97.80		

MINERAL COMPOSITION			
Si	3.0725	Si	3.0230
Al iv	0.0000	Al	0.9741
Al vi	2.5035	Ti	0.0039
Ti	0.0079	Fe	0.0029
Fe	0.5210	Mn	0.0000
Mn	0.0000	Mg	0.0013
Mg	0.0012	Ca	0.0243
Ca	2.0425	Na	0.8964
Na	0.0051	K	0.0167
K	0.0060		
OH	1.0000		

Average Mineral Microprobe Analyses

Sample 91-29 — Clericy Road Basalt

Mineral	Chlorite n=7	Tremolite n=2	Epidote n=3
Wt% Oxide			
SiO2	26.44	53.93	50.27
AlO iv	9.39	1.04	0.00
AlO vi	9.60	0.64	8.00
TiO2	0.02	0.02	0.03
FeO	26.62	14.78	13.46
MnO	0.39	0.27	0.21
MgO	14.81	14.17	9.46
CaO	0.12	12.68	15.75
NaO.5	0.01	0.40	0.27
KO.5	0.01	0.06	0.04
OH	11.24	2.07	1.89
Total	98.63	100.06	99.38
MINERAL COMPOSITION			
Si	5.6398	7.8219	3.9918
Al iv	2.3602	0.1781	0.0000
Al vi	2.4142	0.1091	0.7485
Ti	0.0024	0.0022	0.0018
Fe	4.7468	1.7924	0.8936
Mn	0.0696	0.0332	0.0141
Mg	4.7084	3.0632	1.1198
Ca	0.0263	1.9701	1.3397
Na	0.0031	0.1125	0.0416
K	0.0027	0.0111	0.0041
OH	16.0000	2.0000	1.0000

	Albite n=2
	Wt% Oxide
SiO2	69.40
Al2O3	19.56
TiO2	0.01
FeO	0.25
MnO	0.00
MgO	0.01
CaO	0.16
Na2O	11.71
K2O	0.05
Total	101.15
Si	2.9983
Al	0.9959
Ti	0.0003
Fe	0.0090
Mn	0.0000
Mg	0.0006
Ca	0.0074
Na	0.9809
K	0.0028

Average Mineral Microprobe Analyses

Sample 91-33 — <u>South Jevis Unit</u>

Mineral	Chlorite n=3	Epidote n=1	Zoisite n=1		Albite n=1
Wt% Oxide					Wt% Oxide
SiO2	27.16	37.82	38.38	SiO2	68.15
AlO iv	8.89	0.00	0.00	Al2O3	20.11
AlO vi	10.87	22.82	26.58	TiO2	0.00
TiO2	0.00	0.06	0.05	FeO	0.17
FeO	26.92	11.51	8.38	MnO	0.03
MnO	0.72	0.00	0.00	MgO	0.02
MgO	12.25	0.03	0.01	CaO	1.33
CaO	0.07	23.16	23.50	Na2O	10.83
NaO.5	1.02	0.02	0.06	K2O	0.06
KO.5	0.03	0.00	0.04	Total	101.33
OH	11.27	1.81	1.87		
Total	99.20	97.22	98.87		

MINERAL COMPOSITION

Si	5.7733	3.1373	3.0710	Si	2.9195
Al iv	2.2267	0.0000	0.0000	Al	1.0126
Al vi	2.7237	2.2310	2.5066	Ti	0.0000
Ti	0.0000	0.0037	0.0030	Fe	0.0170
Fe	4.7854	0.7985	0.5607	Mn	0.0011
Mn	0.1297	0.0000	0.0000	Mg	0.0013
Mg	3.8824	0.0037	0.0012	Ca	0.0617
Ca	0.0159	2.0584	2.0147	Na	0.9088
Na	0.4205	0.0032	0.0093	K	0.0033
K	0.0081	0.0000	0.0041		
OH	16.0000	1.0000	1.0000		