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**STRATIGRAPHY, VOLCANOLOGY AND GEOCHEMISTRY OF THE
NEW VAUZE - NORBEC AREA, CENTRAL NORANDA VOLCANIC COMPLEX,
QUEBEC, CANADA**

by

Suzanne Paradis, B.Sc., M.Sc.

Thesis submitted to
the Faculty of Graduate Studies and Research
in partial fulfilment of
the requirements for the degree of
Doctor of Philosophy

Department of Earth Sciences
Carleton University
Ottawa, Ontario
March 1990

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**Stratigraphy, volcanology and geochemistry of the
New Vauze-Norbec area, Central Noranda Volcanic Complex,
Quebec**

Suzanne Paradis, B.Sc., M.Sc.
in partial fulfilment of the requirements
for the degree of Doctor of Philosophy

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May 1996

ABSTRACT

The Archean volcanic sequence of the New Vauze-Norbec area consists of subaqueous andesitic and rhyolitic flows with minor dacitic flows and pyroclastic rocks. The volcanic rocks are relatively undeformed, metamorphosed to low-greenschist facies and intruded by dioritic dykes. Volcanic rocks were emplaced at the end of a period of cauldron subsidence or extensional rifting within the upper parts of the Noranda Shield Volcanic Complex. Detailed stratigraphic correlations show that local zones of subsidence accommodated along synvolcanic faults accompanied the voluminous andesitic and rhyolitic eruptions and prevented the emergence of the volcanic pile.

Andesitic flows of the Waite Andesite, Amulet Andesite, Newbec Andesite, and D'Alembert Andesite formations are, for the most part, pillowed and brecciated. They erupted from fissures and formed extensive and sheet-like structures up to 10 km long that flooded large areas, accumulated in topographic depressions, and buried the irregular relief created by the underlying rhyolitic flows and domes.

Rhyolitic flows of the Waite Rhyolite, Amulet formations, and Splinter member erupted from local vents as quiet effusions that formed large tabular flows 0.5 to 5 km long, characterized by low slope ($\leq 20^\circ$). Individual massive, flow-banded, and lobe-flow breccia flows overlap and coalesce to form low relief shields. Local massive and low relief domes and elongated dyke-like features mark the sites of felsic volcanic vents.

Spherulitic dacitic flow of the Fish Roe formation formed an extensive sheet-like structure that is several

km long. Pyroclastic rocks are restricted to the felsic ash and lapilli tuffs of the Fish Roe formation and to the plane bedded andesitic tuffs of the uppermost flows of the Amulet Andesite, Newbec Andesite, and D'Alembert Andesite formations.

The volcanic rocks have been chemically altered by synvolcanic, alteration processes; initial devitrification was followed by spilitization, epidote-quartz alteration and silicification which are interpreted as the products of alteration within a shallow, subseafloor hydrothermal system. Widespread and pervasive spilitization uniformly affected all the volcanic rocks. It is interpreted to result from subaqueous hydrothermal metamorphism that occurred shortly after burial. Epidote-quartz alteration is imposed on spilitized rocks and is restricted to the upper member of the Waite Andesite formation. It is interpreted to result from the interaction of evolved seawater with previously devitrified and spilitized rocks. Silicification is essentially confined to the upper member of Waite Andesite formation, the uppermost flows of the Waite Rhyolite formation and local zones in proximity to synvolcanic faults and feeder dykes. Silicification is interpreted to result from the interaction of silica-saturated solutions with volcanic rocks at relatively low temperatures and low pH conditions.

The whole-rock $\delta^{18}\text{O}$ values of volcanic rocks increase with stratigraphic height, from 5.2 to 12.7. It reflects a gradient in temperature and water:rock ratio in the hydrothermal system.

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CHAPTER 1. INTRODUCTION

1.1 PURPOSE OF THE STUDY

The lithology of the poorly known New Vauze-Norbec (NV-N) area (Figs. 1.1, 1.2), within the NE sector of the Central Noranda Volcanic Complex (CNVC) is dominated by rhyolitic rocks, mainly the Waite Rhyolite formation.

This study centred on the volcanic stratigraphy of the NV-N area was undertaken with the cooperation of Minnova Inc. (formerly Corporation Falconbridge Copper) for six main reasons:

- 1) to provide detailed lithologic mapping and stratigraphic interpretation, and volcanological model for the area,
- 2) to establish the relationship of volcanogenic massive sulphide (VMS) deposits to synvolcanic structures,
- 3) to determine the relationship of VMS to rhyolite domes, flows and feeder dykes,
- 4) to determine the relationship of VMS to synvolcanic growth faults and feeding fissures,
- 5) to determine the relationship of VMS to zones of hydrothermal alteration, both semiconformable and discordant, and
- 6) to establish a geochemical model for the hydrothermal alteration of rhyolites in the Noranda area.

The main objective of this study was to establish the volcanic stratigraphy of the NV-N area (Fig. 1.2). A clear understanding of the volcanic stratigraphy in the southern and central parts of the Noranda Volcanic Complex has proved to be an important tool in the search for volcanogenic massive sulphide deposits (de Rosen Spence 1976, Gibson 1989) and may well be as effective in this lesser known sector of the Noranda mining camp.

Detailed studies of Archean subaqueous rhyolite flows are rare; most studies on rhyolites have concentrated on young subaerial rhyolite flows (Cole 1970, Christiansen and Lipman 1966, Furnes et al. 1980, Manley and Fink 1987, Bonnichsen and Kauffman 1987). The remarkably well exposed and continuous succession of Archean rhyolites in the NV-N area and preservation of their primary volcanic textures and structures present a unique opportunity to study the morphology, flow mechanism and emplacement of subaqueous rhyolitic flows.

Because these rocks are variably altered, it was essential to describe the petrography and chemical composition, including oxygen isotopic data of altered volcanic rocks, to determine the relationship of alteration to volcanic stratigraphy, and to evaluate its use as a tool in exploration for massive sulphide deposits.

Finally, a volcanological model for the NV-N area was established and incorporated into the more regional perspective of a large submarine volcanic cauldron, viz., the

Central Noranda Volcanic Complex (CNVC) defined by Gibson (1989).

1.2 LOCATION

The NV-N area is located in the NE sector of the CNVC, approximately 16 km NW of the town of Rouyn-Noranda, Quebec. The 55 km² area is mostly in Dufresnoy Township and is bounded geologically to the west, north, and south by the Dufresnoy Diorite, the Hunter Creek Fault (HCF) and the Lake Dufault Pluton, respectively.

1.3 PREVIOUS WORK

The Noranda area contains a remarkably well exposed and preserved succession of Archean volcanic rocks and the classical examples of Archean Cu-Zn volcanogenic massive sulphide deposits. It is one of the most intensely explored geological areas in Canada. Discovery of copper and gold in 1923 (Horne Mine) initiated extensive exploration work which is continuing today.

Although many geologists have worked in the Noranda area, relatively little has been published on the volcanic stratigraphy, the main interest having been the study of the Cu-Zn massive sulphide deposits.

The earliest recorded geological investigation in the area is that of Wilson (1913). James (1924) and Cooke et al. (1931) continued the geological reconnaissance work. Wilson

(1941, 1962) provided excellent lithological maps and reports on the Noranda district and was the first to publish detailed maps showing the regional volcanic stratigraphy.

More recently, de Rosen Spence (1976) correlated the stratigraphic succession throughout the Noranda area and established the local stratigraphic framework. Cousineau (1980) mapped the Amulet Andesite formation in the Norbec area of the CNVC. Dimroth et al. (1982, 1983a, b) and Goodwin (1977, 1982) discussed the volcanology and the tectonic evolution of the southwestern Abitibi Belt. Gibson (1989) produced a detailed volcanological reconstruction of the Mine Sequence of the Central Noranda Volcanic Complex, west of the Dufresnoy Diorite. The geology of an extensive sector north of the HCF has been studied by Camiré (1989).

Other studies have centred on the relationship of mineralization to stratigraphy (Gilmour 1965, Dugas 1966, Spence and de Rosen Spence 1975), the geochemistry of volcanic rocks (Baragar 1968, Gelinas et al. 1977, 1982, 1984, Jolly 1980, Ludden et al. 1982, Gelinas and Ludden 1984), and the hydrothermal alteration processes which accompanied the formation of massive sulphide deposits (Wilson 1935, Riverin 1977, Riverin and Hodgson 1980, Gibson et al. 1983).

Compilation maps at 1:125,000 have been published and periodically revised by the Ministère de l'Energie et des Ressources (MER) of Québec.

The Noranda area has also been intensively mapped by geologists of mining and exploration companies. A brief list of geological maps specific to parts of the NE sector of the CNVC (the study area) is outlined below.

1964	C.D. Spence mapped parts of the NV-N area at a scale of 1"=400' for Consolidated Vauze and Waite Lake Mines Limited.
1977	U. Abolins did reconnaissance mapping of parts of the NV-N area (scale of 1"=200') for Asarco Exploration Limited.
1980	J.G. Barrette remapped the same area as Abolins at a scale of 1"=400' for Corporation Falconbridge Copper.

Some of these maps are available at the regional office of the Ministere Energie et Ressources du Quebec, along with the results of the vast amount of drilling carried out by exploration companies in the Noranda area.

1.4 METHODS

Preliminary investigation of the NV-N area was made during the summer of 1984 and detailed mapping was carried out at scales of 1:500 and 1:2,000, during the summers of 1985, 1986, and 1987. Eight maps at a scale of 1:2,000 containing field observations and notes provided the basis

for all descriptions and interpretations and the basis for a compilation map at a scale of 1:5,000 (Fig. 1.3; in pocket). Selected areas outlined on Figure 1.3 were mapped at a scale of 1:500 (Figs. 1.4, 1.5, 1.6; in pocket). The 1:2,000 scale maps are available at the discretion of Minnova Inc. at their Exploration Office in Noranda. In order to understand and reconstruct the paleovolcanology of the NV-N area, reconnaissance traverses were done north of the HCF in the Waite Lake area and in sectors of the Amulet Andesite formation mapped by Cousineau (1980) (Fig. 1.8).

Sampling of outcrops and diamond drill core was carried out for petrographic and geochemical studies. Location of samples are given on Figure 1.7. Construction of detailed geological sections using available drill hole data and geological mapping information were also done to understand the volcanological setting.

The sample numbers consist of two parts (e.g. 282-86). The first number refers to the sample number and the last number indicates the year of sampling. Sample numbers 200-86 to 302-86 are drill core samples from hole NV-8. Sample series XX-84 and XX-85 were analyzed for most of the major and trace elements at the geochemical laboratory of Minnova Inc. (formerly Corporation Falconbridge Copper). Si, Al, and Ti analyses of XX-84 and XX-85 were done at Metric Lab, Quebec. Samples XX-86 and XX-87 were analyzed for 10 major elements and 6 trace elements at X-Ray Assay Laboratories, Toronto.

Selected XX-86 and XX-87 samples were analyzed for major, trace and REE elements by the Analytical Chemistry Section of the Geological Survey of Canada (GSC), Ottawa. Oxygen isotopic analyses and recent experimental and theoretical studies of hydrothermal alteration are used to evaluate the origin of the alteration associated with the volcanic rocks of the NV-N area. Oxygen isotope analyses were carried out on selected whole-rock samples and silicate mineral separates at the stable-isotope geochemical laboratory of B.E. Taylor, Geological Survey of Canada (GSC).

Details of sample preparation, analytical methods, precision and accuracy are given in Appendix I and the results of geochemical analyses are tabulated in Appendices II and III.

1.5 NOMENCLATURE

Mafic to intermediate volcanic rocks in the Noranda area have generally been called "andesite" and felsic rocks have been called "rhyolite" as a result of geochemical classifications (Spence and de Rosen Spence 1975, de Rosen Spence 1976). However, most so-called andesite is in fact silicified basalt or basaltic andesite (Gibson et al. 1983, Gibson 1989), and most so-called rhyolite varies from dacite to rhyolite (de Rosen Spence 1976). In the field, flows were classified as andesite, dacite, and rhyolite. Andesitic flows are identified by their brownish weathered surface and dark

green to gray-green fresh surface. They are massive, pillowed, and brecciated. They are often fine-grained, aphanitic and amygdaloidal and sometimes feldspar porphyritic. Microscopically, andesites have hyalopilitic and pilotaxitic to intersertal textures. Rhyolitic flows are recognized by their light gray to white weathered surface and dark gray to light gray fresh surface. Rhyolites are feldspar porphyritic (FP), quartz-feldspar porphyritic (QFP), and commonly spherulitic. Microscopically, rhyolites are characterized by microspherulitic and/or felsitic textures. Dacitic flows are difficult to recognize in the field because they share characteristics of both andesitic and rhyolitic flows. The only true dacitic flow recognized is the spherulitic massive flow of the Fish Roe formation. Other rocks called dacite in the field were in fact altered andesite or altered rhyolite. Those rocks have brown to white weathered surfaces, light gray to green fresh surface and may have a white mottling. In the field, rocks called andesite generally are found to have intermediate silica contents (52-64% SiO_2), whereas dacite contains 64-68% SiO_2 , and rhyolite has more than 68% SiO_2 . These SiO_2 class limits correspond to those used by de Rosen Spence (1976) and Gibson (1989).

The rocks have retained many of their primary textural and structural features since deformation has not been penetrative. However, many of the volcanic rocks have been altered and their primary mineralogy and chemistry have

changed. Therefore by using field and petrographic observations together with some chemical classification (Jensen 1976), rock names were assigned.

The prefix "meta" will not be used in this study, although the rocks have been extensively spilitized and regionally metamorphosed to lower greenschist facies (de Rosen Spence 1976, Jolly 1980).

According to the North American Stratigraphic Code, strata were subdivided from smallest to largest units by lava flow, member and formation. A single flow or series of flows that can be distinguished texturally and structurally in the field is referred to here as a flow unit. A flow is the smallest stratigraphic unit identified in the field and corresponds to a single pulse of lava that cooled individually. Flows are further subdivided into different facies which refer to a segment of a flow that differs from another by its appearance and structure (Dimroth et al. 1978, 1979). Members are distinct lithostratigraphic units within a formation. They may consist of one or several flow units. Formations consist generally of lithologically homogeneous units of andesite or rhyolite, but some formations have members of different lithologies. The formations have been informally named by de Rosen Spence (1976), Gibson (1989) and Paradis et al. (1989).

Fig. 1.1. General geology and location of the Central Noranda Volcanic complex (CNVC), modified from de Rosen Spence (1976). Rectangle outlines the New Vauze-Norbec area of Figure 1.2.

Fig. 1.2. General geology of the New Vauze-Norbec area. A, B, C D, and E represent the location of the stratigraphic columns of Figure 2.2.

Fig. 1.8. General geology of the Central Noranda Volcanic Complex (CNVC), modified from de Rosen Spence (1976), and location of mapped area (yellow) and reconnaissance traverses.

CHAPTER 2. GENERAL GEOLOGY

2.1 REGIONAL GEOLOGY

The New Vauze-Norbec (NV-N) area is located in the southern part of the Abitibi greenstone belt of the Archean, Superior structural geologic province of the Canadian Shield. The Abitibi greenstone belt is predominantly composed of mafic, submarine volcanic rocks with lesser clastic and chemical sedimentary rocks (Fig. 2.1).

The south-central Abitibi belt has an apparent stratigraphic thickness estimated at 18 to 21 km (Goodwin 1982). The Blake River Group (BRG) which includes the Central Noranda Volcanic Complex (CNVC) has an estimated thickness of about 7.5 to 9 km (Gibson 1989) and predominates volumetrically in the south-central part of the Abitibi belt. Dimroth et al. (1982) subdivided the southern part of the Abitibi belt into two major volcanic cycles. Cycle I is composed of the Hunter Group and cycle II included the Malartic, Kinojevis, Kewagama, and Blake River Groups. The BRG is predominantly composed of a subaqueous assemblage of basalt, andesite, dacite, and rhyolite flows and minor pyroclastic rocks. Various subdivisions of the BRG based on lithology and geochemistry have been proposed. Goodwin (1972, 1982) divided it into four successive subgroups from base to top: Bowman (Mg-tholeiite), Garrison (Fe-tholeiite), Misema (calc-alkaline), and Noranda (tholeiitic-calc-alkaline). The

change in the composition of volcanism coincided with an eastward migration of volcanic activity, resulting in a west to east distribution of the above-mentioned subgroups. Gelinas et al. (1977, 1982, 1984) divided the BRG into a basal Mg-tholeiite, a middle Fe-tholeiite and tholeiitic andesite and an upper calc-alkaline andesite.

Numerous granitoid stocks, dykes, and sills intruded this succession. Some of these intrusions are concordant with the stratigraphy and are thought to be coeval with the BRG volcanic rocks (Goldie 1976, Kennedy 1984, Paradis et al. 1988).

Several felsic volcanic centres, which include the CNVC have been recognized within the BRG. They are characterized by anomalous accumulations of felsic flows and pyroclastic rocks that may be as much as 50 km in diameter. The CNVC is one of such centres and is considered as a large shield-like volcano on the larger Blake River shield volcano (de Rosen Spence 1976).

Volcanic rocks of the Noranda area are in contact to the south with the sedimentary rocks of the Pontiac, Cadillac, and Timiskaming Groups (Dimroth et al. 1982). The Larder Lake-Cadillac Fault, interpreted to be a reactivated synvolcanic fault, separates the sedimentary basin to the south from the volcanic rocks of the CNVC to the north. The sedimentary rocks which are greywacke, argillite, and conglomerate are interpreted as having been derived from the erosion of the

adjacent volcanic edifice to the north and to a lesser extent from pyroclastic volcanic activity (Dimroth and Rocheleau 1979, Dimroth et al. 1982).

2.2 STRUCTURE AND METAMORPHISM

The Archean succession in the south-central Abitibi belt was successively affected by synvolcanic deformation and by folding and faulting related to the Kenoran orogeny. The rocks were folded into an open east-trending syncline with steeply-dipping north and south limbs (Dimroth et al. 1982). Dimroth et al. (1983a) and Gibson (1989) consider the CNVC to be an homoclinal sequence which occupies the central part of the syncline. Volcanic formations generally strike NW to NE and young easterly. The variation in the direction of the volcanic formations in the CNVC is due to displacement along numerous NE- and NW-trending faults, rather than the presence of east-trending and plunging fold axes as suggested by de Rosen Spence (1976). The CNVC is an area that has escaped severe Kenoran deformation possibly because it was consolidated by synvolcanic granitoid plutons.

Numerous faults and shear zones with varied ages, orientations, and displacements occur in the CNVC. Some of these faults are synvolcanic structures formed due to volcano-tectonic subsidence during the development of the volcanic complex and that were reactivated during the orogeny. Many of these faults have been filled by synvolcanic mafic and felsic

dykes, and are the sites of abrupt changes in thickness and facies of volcanic units (de Rosen Spence 1976, Cousineau and Dimroth 1982, Dimroth et al. 1982). According to Gibson (1989), two major steeply dipping synvolcanic faults, the Hunter Creek (HCF) and Horne Creek faults form the respective northern and southern boundaries of the CNVC.

Volcanic rocks of the CNVC have a complex hydrothermal-metamorphic history. Semiconformable alteration types, which consists of initial devitrification, followed by spilitization, chloritization, silicification, and epidote-quartz alteration variably altered all the volcanic rocks. Sericitic-carbonate alteration is a discordant, postvolcanic process that affected the volcanic rocks and the late intrusions.

Metamorphic facies in the Abitibi belt vary from prehnite-pumpellyite to amphibolite (Goodwin 1982). Low to mid-greenschist facies assemblages are most common in the BRG. In the Noranda area, metamorphic grade is predominantly lower greenschist facies and primary volcanic textures are for the most part extremely well preserved. Upper greenschist and amphibolite facies metamorphisms are restricted to contact aureoles of the Lac Dufault pluton (de Rosen Spence 1969) and the Flavrian pluton (Jolly 1980, Kennedy 1984). Jolly (1980), Gelinas et al. (1982), Ludden and Hubert (1986) and Ludden et al. (1986) observed that the metamorphic grade generally increases from prehnite-pumpellyite assemblage in the area

massive andesite grading to flow breccia at the top. The lateral continuity of these flows is not known. The flow breccias of the upper member are distinct from the brecciated flows of the lower member in that they (flow breccias of the upper member) are ribbed, extremely silicified, and contain from 1% to 10% of elongate quartz-epidote amygdules up to 15 cm in diameter (average 1 cm). Also, there is a higher proportion of metre-sized, silicified ribbon-like forms and lobes. The flow breccias consist of ribbon-like forms (Fig. 3.1b), "lobes", and amoeboid-shape fragments of massive white silicified amygdaloidal andesite (Fig. 3.1c) in a matrix of hyaloclastite and massive flow-banded chloritic andesite. The "fragments" are called ribbons or lobes depending on their shape. "Lobes" resemble massive rhyolitic lobes of the Waite Rhyolite formation, except that they are silicified, ribbed, and amygdaloidal. Many of the ribbons resemble elongate amoeboid-shaped pillows with distinctly silicified, chilled contacts. The ribbon-like forms may be totally silicified, silicified only at their margins, or variably silicified along amygdules and flow banding which gives a mottled and frayed appearance (Fig. 3.1e). In general, regular and contorted siliceous ribbon-like forms reflect silicification along trains of amygdules. Ribbon-like forms are aligned and define a "flow foliation" which varies between N265° and N360°. The apparent length of the ribbon-like forms ranges from less than 0.5 m to a few metres and thicknesses are usually only a few

strata within the Mine Sequence comprise alternating subaqueous andesitic and rhyolitic flows with less than 5% pyroclastic and epiclastic rocks (Gibson et al. 1984). From oldest to youngest, volcanic formations are: Flavrian Andesite, Northwest Rhyolite, Rusty Ridge Andesite, Amulet, Millenbach - Waite Andesite, Millenbach QFP Rhyolite - Waite Rhyolite, Amulet Andesite, Newbec Rhyolite, Newbec Andesite, Fish Roe, and D'Alembert Andesite. The Amulet formation, formerly known as the Amulet Rhyolite formation, was recently renamed by Gibson (1989). The Fish Roe formation was formerly known as the Fish Roe Rhyolite formation and is renamed in this study. Formations strike NNE and dip from 5° to 65° to the east (Gibson et al. 1984). Volcanogenic massive sulphide (VMS) deposits are scattered throughout the succession although 11 of the 15 deposits are clustered stratigraphically just above the Amulet formation. VMS deposits are of the proximal type and are located near both rhyolitic and andesitic vent areas that are localized along synvolcanic faults. The synvolcanic faults were active during the volcanism and were reactivated during the Kenoran Orogeny.

The NV-N area is subdivided into two blocks: New Vauze and Norbec (Fig. 1.2) and is referred to here as the New Vauze and the Norbec areas. The volcanic strata of the NV-N area consist of alternating subaqueous rhyolite and andesite flows with less than 2% pyroclastic rocks. The volcanic sequence forms a rather simple homocline with formations striking NW-

SE and dipping eastward 35° to 60° . Volcanic formations are cut and offset by $N20^{\circ}W$ and $N45^{\circ}W$, steeply NE dipping diorite dykes and sills and $N240^{\circ}$ - 250° -trending synvolcanic faults.

The Norbec area contains three mined-out massive sulphide deposits: Vauze, Norbec and D-zone, and Newbec. The New Vauze area as yet does not have any known economic massive sulphide deposits, but remains an important target area in the exploration for such deposits.

Detailed mapping (Fig. 1.3; in pocket) and correlation of volcanic rocks of the NV-N area with those west of the Dufresnoy Diorite and across synvolcanic faults permits definition of the stratigraphic succession illustrated in Figure 2.2 and outlined in chapter 3.

Fig.2.1 General geology of the Archean Abitibi greenstone belt (after Gellinas and Ludden 1984).

CHAPTER 3. STRATIGRAPHY AND VOLCANOLOGY OF THE NEW VAUZE-NORBEC AREA

3.1 GENERAL STATEMENTS

This chapter outlines the stratigraphy of the New Vauze-Norbec (NV-N) area (Fig. 1.3, in pocket) which consists of 17 alternating subaqueous andesitic and rhyolitic flow units with less than 2% pyroclastic rocks. Volcanic formations, members, and the corresponding lithologies are listed in chronological order in Table 3.1. One-third of the volcanic rocks are rhyolitic flows and most of them belong to the Waite Rhyolite formation. Rhyolitic flows are characteristically heterogeneous with abundant altered flow breccias containing massive lava-lobes. They formed large tabular bodies 0.5 to 5 km long. Two-thirds of the volcanic rocks are andesitic flows and most of them belong to the Waite Andesite and Amulet Andesite formations. Most andesitic flows are homogeneous, several kilometres long and are pillowed and brecciated.

3.2 STRATIGRAPHY AND PETROGRAPHY

3.2.1 Rusty Ridge Andesite formation

The Rusty Ridge Andesite formation conformably overlies the Northwest Rhyolite formation and is overlain by a pyroclastic unit, the Beecham tuff-breccia. The brown-weathering Rusty Ridge Andesite in the Turcotte Lake area has been described by Gibson (1979) as a mixed succession of

basaltic and andesitic lava flows. The succession of pillowed and massive andesite-basalt flow units have well-preserved primary volcanic textures, such as concentric cooling laminations, flow laminations, imbricate structures in hyaloclastite flow-top breccias, columnar joints in massive flows, quartz amygdules elongated parallel to the flow laminations and various pillow types (Gibson 1979). Several local vents and feeder dykes to the formation may be recognized (Comba 1977).

The Rusty Ridge Andesite formation does not crop out in the NV-N area but has been encountered in drill holes. The andesite is massive or pillowed, aphanitic and amygdular (quartz and calcite; 5% to 30%; 2-5mm in diameter). In thin section, the Rusty Ridge Andesite contains abundant, randomly oriented, acicular, albite microlites and minor albite phenocrysts in a groundmass now composed of fine-grained chlorite and quartz.

According to Gibson (1989), the main vent area for andesitic flows of the Rusty Ridge formation lies within the NE striking Old Waite Dyke Swarm in the Duprat Lake area located 2.5 km west of the Lake Dufault Pluton (see Fig. 1.1).

3.2.2 Amulet formation, lower member

The Amulet formation, formerly known as the Amulet Rhyolite formation, was recently renamed by Gibson (1989)

because it contains less than 30% of rocks which originally were of rhyolitic composition (Gibson et al. 1983).

The Amulet formation extends from the Beauchastel Fault in the south to the Hunter Creek Fault (HCF) in the north. It overlies the Rusty Ridge Andesite formation. The Amulet formation has a total thickness of approximately 600 metres (Knuckey et al. 1982) and is composed of a complex sequence of interfingering rhyolitic, andesitic and basaltic submarine flows and flow breccias. In the central part of the Noranda Volcanic Complex, the Amulet formation has been divided into lower and upper members (Gibson 1979, Gibson et al. 1983, Gibson 1989). The lower member consists of massive and flow-banded rhyolite and small domal rhyolitic structures. The upper member consists of variably silicified andesitic flows. The silicic nature of these andesites was interpreted to result from a silicification process by widespread synvolcanic and submarine hydrothermal hot-springs. This regional hydrothermal activity also resulted in the deposition of an extensive, sulphidic siliceous "tuffaceous exhalite", known as the "C" Contact Tuff described in section 3.2.3. "Tuffaceous exhalite" as used in this study refers to a rock made up of variable proportions of volcanoclastic debris and chemically precipitated sulphides and silicates.

In the NV-N area, the Amulet formation consists of a massive rhyolitic flow and flow-banded breccia facies; the upper member silicified andesite is absent. The rhyolite forms

a domal structure capped by a bedded, siliceous, pyritic, ash-sized sediment, the "C" Contact Tuff. The rhyolite commonly weathers white to light gray and has a bluish tinge on fresh surface. It is amygdaloidal, lacks macroscopic quartz or feldspar phenocrysts and is weakly spherulitic; spherulites display advanced stages of recrystallization and replacement by quartz. Few plagioclase microphenocrysts are present in a groundmass now composed of a mosaic of fine-grained granular quartz and interstitial chlorite and sericite. The plagioclase is generally almost pure albite, with a mean composition of $Ab_{99}An_1Or_0$ (appendix II; Table II.2). Primary potassic feldspar (appendix II; Table II.2) showing some stage of replacement by albite occurs in rhyolitic flow breccias. Fine sericite flakes are trace alteration products of plagioclase. The rhyolite has been moderately chloritized and silicified; this is expressed as a network of 1-2 mm quartz veinlets which give the weathered surfaces a brecciated and pseudo-scoriaceous texture.

No vent areas are known in the NV-N area for the Amulet formation, but its increase in thickness toward the HCF suggests a possible vent around or beyond the fault.

3.2.3 "C" Contact Tuff

The "C" Contact Tuff is a regionally extensive unit that defines the contact between the Amulet formation and the overlying andesitic formation which is the Waite Andesite in

the New Vauze area. West of the Dufresnoy Diorite, numerous small lenses of massive sulphide (Amulet C-orebody, Moosehead deposit, Lac Dufault Zinc deposit, and Amulet F-orebody) occur at this contact. It is a very useful time-stratigraphic marker.

The "C" Contact Tuff in the New Vauze area is a few centimetres to 1.5 m thick and was deposited on the irregular surface of the lower member of the Amulet formation. The tuff outcrops at only one locality in the NW corner of the New Vauze area (Figs. 1.3, 1.5, in pocket), but was observed in several drill holes from this area. The tuff is plane bedded and dips 60° to the east. It is well bedded to laminated and consists of andesitic lapilli-ash and siliceous bands or chert interlayered with thin pyritic bands parallel to bedding planes (Fig. 3.1a). The andesitic lapilli-ash is composed of chloritized shards (< 3 mm) in fine-grained granular quartz, chlorite, epidote and sulphides and has normal grading. The chert-rich bands (1.5 mm to 1 cm thick) consist of a microcrystalline mosaic of quartz (interpreted as recrystallized chert) with disseminated, trace amounts of pyrite, chalcopyrite, sphalerite, and rutile. Some quartz-rich layers contain strongly chloritized and quartzose angular fragments. The pyritic bands (2.5 mm to 3 cm thick) consist of massive to finely bedded pyrite with traces of chalcopyrite, sphalerite, and pyrrhotite. The physical

characteristics of the "C" Contact Tuff and its sulphide minerals are summarized in Tables 3.2 and 3.3, respectively.

The pyrite crystals contain inclusions of chalcopyrite and pyrrhotite. Chalcopyrite and sphalerite occupy spaces between pyrite crystals and are present as fracture fillings in pyrite. Sphalerite and chalcopyrite are closely associated as grains in contact with each other and as chalcopyrite blebs in sphalerite grains. The latter texture has been variously interpreted as products of exsolution (Ramdohr 1980, Shimazaki 1980), epitaxial growth or replacement (Hutchinson and Scott 1981, Wiggins and Craig 1980, Kojima and Sugaki 1985) including so-called "chalcopyrite disease" (Barton 1978, Eldridge et al. 1983) and mechanical mixing (Roberts 1965). This texture has also be interpreted as primary quench deposition of sulphides as in plume smoke of recent seafloor hydrothermal systems (Normark et al. 1982, 1983, Goldfarb et al. 1983, Koski et al. 1984, Peter and Scott 1988). The abundance of chalcopyrite and sphalerite in the pyritic bands is less than 2% and pyrrhotite less than 0.2%.

All the sulphides are recrystallized. Pyrite grains have well developed 120° grain boundary junctions, are coarse-grained and have numerous inclusions of chalcopyrite, pyrrhotite and silicates. All the pyrrhotite and some chalcopyrite inclusions in pyrite are round.

The "C" Contact Tuff is composed of two main components, a clastic or tuffaceous component and a chert/sulphide

component. It is the product of early unfocussed, widespread seawater circulation through highly permeable rocks and deposition of fine ash, chert and sulphides on the seafloor during a hiatus in volcanic activity. The tuffaceous or clastic component of the "C" Contact Tuff consists of a waterlain ash that originated from mild phreatic explosion whereas the chert/sulphide component is a chemical constituent introduced through discharge of submarine hot springs (Kalogeropoulos and Scott 1989; Gibson 1989).

Ascent and discharge of silica-saturated hydrothermal fluid were probably channelled along the same synvolcanic fault which served later as a conduit for the intrusion of a rhyolitic dyke (Fig. 1.5, in pocket).

3.2.4 Waite Andesite formation

Distribution and thickness

The Waite Andesite formation stratigraphically overlies the "C" Contact Tuff and is, in turn, overlain by the Waite Rhyolite formation. It has been interpreted as the stratigraphic equivalent of the Millenbach Andesite formation of the Amulet-Millenbach area (Gibson et al. 1984; Gibson 1989).

The Waite Andesite formation has been divided into lower and upper members. In the New Vauze area, a felsic unit, the **Splinter member**, separates the lower and upper members (Fig. 1.3, in pocket). Locally, a thin cherty tuff separates

underlying non-silicified pillowed andesite from its uppermost silicified andesitic member. In the Norbec area, a stratigraphically equivalent felsic unit called the Norbec Rhyolite member locally separates the lower and the upper members (Fig. 2.2); the upper member was called the Norbec Andesite by previous workers. In the New Vauze area, the formation has minimum and maximum exposed thicknesses of 320 m and 560 m in the NW and central parts, respectively; the flows thin to the NW. The thickness of the Waite Andesite formation in the Norbec area is not known precisely but is estimated to be more than 600 m (Lefebure 1983). In the Ansil area, Gibson (1989) estimated the maximum thickness of the Waite Andesite formation to be 1200 m.

Lithology

In the New Vauze area, the lower member of the Waite Andesite formation is composed of at least three flow units (Fig. 1.3, in pocket). The first consists of amygdaloidal massive andesite (quartz amygdules < 10 cm in diameter), overlain by pillowed andesite and silicified amygdaloidal flow-top breccia. The second flow unit consists of silicified amygdaloidal massive lava and flow-top breccia. The massive facies is characterized by abundant quartz amygdules and large scale siliceous flow laminae. The width of the laminae or bands is in the decimetre range. They are laterally continuous over several metres, and are irregularly spaced from 10 cm to

1 m apart. The flow-top breccia is composed of silicified amygdaloidal fragments in a fine-grained chloritized, hyaloclastite matrix. The fragments are angular to amoeboid in shape and range from a few centimetres to block size (average: a few cm). The third flow unit is a remarkably uniform non-silicified pillowed andesite that weathers grayish orange to light brown. Quartz-filled and calcite-filled millimetre-sized amygdules are concentrated in a radial pattern near pillow rims. The centres of pillows are sometimes epidotized. Pillows are poorly to well formed with little interpillow hyaloclastite. They range in size from 0.25 m to 1 m; large irregular megapillows (> 2 m) and channels of massive lava flows also exist. The pillowed flows are interlayered with small and discontinuous flow breccia beds.

The upper member of the Waite Andesite formation has been previously interpreted as dacite, forming the base of the Waite Rhyolite formation (flow #2; de Rosen Spence 1976); it is now known to consist of silicified andesitic flows. The silicified andesitic flow breccias of the upper member are very similar to the silicified andesitic flows of the upper member of the Amulet formation described by Gibson (1979) and Gibson et al. (1983). It consists of more than 75% silicified flow breccia of andesitic composition (Fig. 1.3, in pocket). Few massive lava flows are interlayered with the flow breccias. Drill hole information shows that the upper member of the Waite Andesite formation consists of several flows of

massive andesite grading to flow breccia at the top. The lateral continuity of these flows is not known. The flow breccias of the upper member are distinct from the brecciated flows of the lower member in that they (flow breccias of the upper member) are ribbed, extremely silicified, and contain from 1% to 10% of elongate quartz-epidote amygdules up to 15 cm in diameter (average 1 cm). Also, there is a higher proportion of metre-sized, silicified ribbon-like forms and lobes. The flow breccias consist of ribbon-like forms (Fig. 3.1b), "lobes", and amoeboid-shape fragments of massive white silicified amygdaloidal andesite (Fig. 3.1c) in a matrix of hyaloclastite and massive flow-banded chloritic andesite. The "fragments" are called ribbons or lobes depending on their shape. "Lobes" resemble massive rhyolitic lobes of the Waite Rhyolite formation, except that they are silicified, ribbed, and amygdaloidal. Many of the ribbons resemble elongate amoeboid-shaped pillows with distinctly silicified, chilled contacts. The ribbon-like forms may be totally silicified, silicified only at their margins, or variably silicified along amygdules and flow banding which gives a mottled and frayed appearance (Fig. 3.1e). In general, regular and contorted siliceous ribbon-like forms reflect silicification along trains of amygdules. Ribbon-like forms are aligned and define a "flow foliation" which varies between N265° and N360°. The apparent length of the ribbon-like forms ranges from less than 0.5 m to a few metres and thicknesses are usually only a few

centimetres. The amoeboid-shaped fragments are stretched, folded, rolled, or broken (Fig. 3.1f). The ribbon-like and amoeboid-shaped fragments are framework supported in a matrix, sometimes flow-banded and composed of chloritized-epidotized hyaloclastite and small (< 1-2 cm) silicified andesitic fragments. The outline of fragments is usually sharp but may be diffuse.

The ribbon-like fragments are silicified amygdaloidal massive andesite that may have originated from underlying massive andesite and extended upward into the overlying flow breccia. The prolongation of the ribbon-like fragments into the underlying flow has not been observed in the NV-N area, but has been observed by Gibson (1989) SW of Waite Lake.

The fragments contain as much as 82% SiO_2 , whereas the chloritic aphyric matrix contains less than 58% SiO_2 . The mean composition of silicified fragments and chloritized breccia matrix is given in Table III.2 of appendix III. The chemical composition of these rocks is discussed in chapter 5. The fragments contain glomeroporphyritic plagioclase microphenocrysts in a pilotaxitic groundmass of plagioclase microlites with interstitial chlorite, epidote, and carbonate. Micropoikilitic quartz forms the bulk of the groundmass and encloses microlites which are ragged and partially replaced by quartz. The andesitic matrix is aphyric or weakly glomeroporphyritic, with albite microphenocrysts and rare

microlites in a fine-grained groundmass of quartz, chlorite-actinolite, and epidote.

Paleotopography

The Waite Andesite formation in the NV-N area was extruded on an faulted paleotopography dominated by the rhyolitic dome and plateau of the Amulet formation. The lateral continuity of certain flows within the Waite Andesite formation suggests that the paleotopography after its extrusion was relatively flat and horizontal.

Feeders

The main effusive vent area for the Waite Andesite formation is located in the Duprat Lake area within the N070°-trending Old Waite Dyke Swarm (Gibson 1989). No vent has been identified within the NV-N area where paleo-flow directions obtained from pillowed flows and flow breccias suggest a north to south flow direction.

Splinter member

The Splinter member of the Waite Andesite formation is 70 to 100 m thick and may be traced for at least 1.5 km within the New Vauze area (Fig. 1.3, in pocket). It has not been identified north of the HCF and it may be the stratigraphic equivalent of the Norbec Rhyolite south of the VCF. The Splinter member is characterized by facies heterogeneity,

strong alteration, and intermediate chemical composition. It consists of chloritized, carbonatized and sericitized rocks of rhyolitic composition.

Facies are massive, flow-banded, lobate, and brecciated (Fig. 1.6, in pocket). They are also amygdaloidal (5-15%) and feldspar-phyric (3-5%). Massive rhyolite forms the base of the Splinter member and is gradational into flow-banded facies which may be locally brecciated and may incorporate large lobes. Large rhyolitic lobes surrounded by flow-banded rhyolite occur at the periphery of the massive facies or within the massive facies (Fig. 1.6, in pocket). They possibly represent multiple internal flows of lava separated by margins of flow-banded lava. Rocks of the massive facies are feldspar-phyric, columnar-jointed, possess a sugary texture and have yellow-gray weathered surfaces. The flow-banded facies is characterized by alternating siliceous and chloritic laminae and elongated quartz amygdules. It is generally regular over a few metres or tens of cm and is folded to highly contorted with pinch and swell features (Fig. 3.2a). Irregular, diffuse, white patches give a heterogeneous and brecciated aspect to the flow-banded facies (Fig. 3.2b). Overlying this flow is a highly amygdaloidal flow composed of massive siliceous rhyolitic lobes and lobe fragments, enclosed in chloritized, carbonatized and sericitized flow-banded breccias. Numerous small synvolcanic chloritic dykes cross-cut this flow, which could be mistaken for chloritic zones bordering lobe margins.

The siliceous lobes and pods of the Splinter member rarely have chloritic hyaloclastite selvages so common to the Waite Rhyolite flows. The siliceous lobes are in sharp contact with the surrounding breccias (Fig. 3.2c). In-situ brecciation of lobes is often recognized. This flow is "gradational" into amygdaloidal, locally flow-banded flow breccia. The flow breccia consists of silicified and epidotized lapilli-sized fragments in variably silicified or chloritized microbreccia (Fig. 3.2d). The flow breccia is relatively well sorted and matrix-supported.

In thin section, massive and flow-banded rhyolites are feldspar-phyric (3-5%) in a groundmass of plagioclase microlites and anhedral quartz grains showing consertal texture. Some massive rhyolites are entirely composed of interconnected networks of spherical domains outlined by chlorite and composed of a mosaic of quartz and plagioclase microlites, referred to as orb textures (Lofgren 1971a) and represent quenched features. The flow breccia is characterized by oriented subangular chloritic fragments (lapilli-sized), elongated quartz and chlorite amygdules (5%), and oriented plagioclase microphenocrysts in a felted groundmass of plagioclase microlites and interstitial quartz and chlorite. Perlitic cracks outlined by chlorite filling the cracks and hyaloclastite granules are common.

Norbec Andesite member

The Norbec Andesite was recognized by Simmons (1971) as an andesitic unit underlying the Waite Rhyolite formation in the Norbec area (Fig. 2.2). This unit is interpreted to be the stratigraphic equivalent to the upper member of the Waite Andesite formation in the New Vauze area, but in contrast to the latter, it is not a flow-top breccia showing the distinctive siliceous ribbon fragments. The Norbec Andesite has been described as a massive and pillowed amygdaloidal andesite to dacite, lithologically and chemically indistinguishable from the underlying lower member of the Waite Andesite formation (Simmons 1971).

Norbec Rhyolite member

The Norbec Rhyolite member was recognized in the Norbec area stratigraphically underlying the Norbec Andesite member and overlying the Waite Andesite formation (Fig. 2.2). This unit could be the stratigraphic equivalent of the Splinter member in the New Vauze area.

Simmons (1971) noted that there is commonly a thin tuff at the top of the Norbec Rhyolite. The Norbec Rhyolite is an aphyric rhyolite flow breccia with intercalated dacitic and possibly andesitic flows.

3.2.5 Waite Rhyolite formation

Geology

The Waite Rhyolite formation overlies the Waite Andesite formation and underlies the Newbec Andesite formation. South of the VCF, it underlies the Amulet Andesite formation (Fig. 1.3, in pocket). The Waite Rhyolite consists of extensive felsic lava flows. Remnants of the flows occur in a 4.5 km long by 1.5 km large shield. In the central part of the New Vauze area, the exposed thickness of the Waite Rhyolite is about 850 m, excluding dilation by diorite dykes and it thins to 460 m toward the HCF. North of the HCF and south of the VCF thicknesses are 120-250 m and 140-210 m respectively. West of the Dufresnoy Diorite in the Waite Lake area, the Waite Rhyolite formation is approximately 250 m thick.

In the Norbec sector, a few cm thick "tuffaceous exhalite", called the Norbec Tuff, occurs at the contact between the Waite Rhyolite and the overlying Amulet Andesite. This extensive, massive to thinly bedded unit is composed of ash-sediment, chert, and sulphides (mostly pyrite). This unit is the time-stratigraphic equivalent of the Main Contact Tuff where the Norbec, D-zone, East Waite, and Vauze massive sulphide deposits occur. In the New Vauze sector, the same tuffaceous exhalite occurs at the contact between the Waite Rhyolite and the overlying Newbec Andesite.

General description of the flows

The Waite Rhyolite generally weathers dark greenish gray to yellowish brown. It is characterized by peculiar facies heterogeneity. The size range of phenocrysts and their relative abundance are diagnostic features in the recognition of the various rhyolite flows. The type and relative abundance of phenocrysts are constant vertically and laterally within a flow. The flows may be highly to weakly spherulitic, weakly (1-2%) to moderately (5-10%) amygdaloidal, quartz-feldspar porphyritic (QFP; 1-2% phenocrysts and QFP; > 5% phenocrysts), and feldspar porphyritic (FP; 1-5% phenocrysts). In general, all rocks are slightly feldspar-phyric (1-2%) to glomeroporphyritic in a variably recrystallized mosaic of quartz and feldspar with disseminated chlorite, sericite, calcite and opaques. Quartz phenocrysts are < 2 mm in diameter, vary from embayed and subhedral to broken and angular, whereas feldspar phenocrysts are usually smaller (< 2mm) and recrystallized to euhedral crystals. No internal textural or compositional zonation has been detected within individual flows, except that phenocrysts are sometimes more abundant in the chilled margins of the lobes than at their centres. Some characteristics of the rhyolitic flows are given in Table 3.4.

Ten flow units have been recognized in the surface exposures of the NV area of which nine are rhyolitic in composition and one is andesitic (flow unit #4). This

andesitic unit is the **NEW VAUZE ANDESITE MEMBER** described below.

Organization of flows

The rhyolitic flows consist of four distinct facies: massive, flow-banded, lobe-flow breccia, and flow breccia. The most voluminous type of rhyolitic flows exposed is feldspar-phyric and lobate-flow brecciated. The rhyolitic facies are mutually gradational and spatially organized. The flows show distinct facies change from the feeding vent to the flow front (Fig. 3.3). Individual flows generally form large tabular body that may be up to 5 km long. The proximal facies of an individual flow is heterogeneous, consisting of massive to flow-banded rhyolite that grades radially into a facies composed of numerous, large, massive lobes enclosed in flow-banded, locally flow-brecciated rhyolite. The distal facies are more homogeneous and consist of fewer and smaller isolated rhyolitic lobes which are randomly and sporadically distributed and enclosed in flow breccias. Rhyolitic microbreccias (or hyaloclastite breccias) form a carapace on certain flows and are abundant within the distal facies. The proportion of breccias generally increases toward the top of the flows.

Within the general framework outlined above, the organization of the flow facies may show some variations. From

flow to flow, the proportion of lobe versus flow-banded and flow breccia facies varies.

The direction of flow folds in lobes and flow-banded rhyolite, the organization of lobes, and the geometry of in-situ breccia may permit the deduction of the flow direction. Flow lobes branch in the same direction as advancing pillows in mafic flows, by successive emplacement of lobes nearer the flow front (de Rosen Spence et al. 1980). Within flow unit #8, interconnected large lobes display foreset structures which give some indication of flow direction. Flow direction of the various flow units within the NV-N area are illustrated in Figure 3.8.

Detailed textural studies of the Obsidian Dome rhyolite flow in California have provided knowledge of the mode of emplacement of rhyolite flows and domes. Fink and Manley (1987) have shown that the attitude of flow banding in a flow reflects how the lava moved during emplacement. Dissected flows contain a zone of subhorizontal foliations extending from the base to within several metres of the upper surface. Near the vent areas, flow layering is subvertical. These features have been interpreted (e.g., Fink 1983) as being the combined results of flow through a conduit and along the ground. As the magma rises through a conduit, it develops vertical foliation in response to shear stresses along the walls. Emerging lava rises vertically above the vent, rifts, and then spreads laterally, inheriting nearly vertical

layering. As the lava moves outward, shear stresses at the flow base can cause the flow layering to rotate to horizontal and, as a consequence, a zone of horizontal layers propagates upward through the flow as it advances.

Description of flow facies and flow morphology

Massive facies is homogeneous and may be structureless or weakly flow-banded. Columnar joints are locally observed (Fig. 3.2e). Massive facies occurs in forms of tabular and sheet-like flows and low-relief domes. Large lobes of massive rhyolite that are recognizable by their flow-banded margin may be present and they represent multiple internal flows. A conformable, low-relief dome rising ≈ 50 m and 175 m x 250 m in diameter occurs in the central part of the New Vauze area (flow unit #2; Figs. 1.3, in pocket, and 3.4). The original slope of the dome is unknown. This dome consists of feldspar-phyric (< 1% phenocrysts) rhyolite and grades radially into flow-banded and lobe facies. Smaller rhyolitic domes may occur in the NV-N area but because of poor exposure are difficult to distinguish from large massive flows and humps of large lobes. Other rhyolitic domes such as the "Vauze dome" (Spence 1975), "Millenbach domes" (Riverin 1977, Knuckey et al. 1982) and "East Waite dome" (Spence and de Rosen Spence, 1975) have been identified in the southern and central parts of the Noranda Volcanic Complex. They consist of a quartz-feldspar-phyric flow and have steep slopes in the range of 10-70°

(Gibson and Lichtblau 1986). They may have associated massive sulphide deposits.

Outcrop surfaces of the massive facies weather gray-white to medium gray and fresh surfaces are medium gray to blue-black. The massive rhyolite has sometimes a granular texture that reflects the presence of microspherulites. These are well developed fibrous microspherulites with anhedral quartz grains forming patches in a randomly fibrous to micropoikilitic groundmass.

Flow-banded facies is morphologically very similar to the preceding facies, the main difference being weak to strong, regular to contorted, flow-banding and a much more heterogeneous appearance (Fig. 3.2f). The weathered surface is a mottled yellowish gray. Flow-banding may be regular over tens of metres but more often is regular and continuous only over short distances (less than tens of cm) and may be broken up during flowage, resulting in the flow breccia facies (Fig. 3.5a). Flow-banding is marked by thin (less than 2 mm) white, siliceous devitrified bands alternating with chlorite-epidote-rich bands. Thickness of flow-bands is usually in the millimetre range. The flow-banded facies is not as well defined microscopically as macroscopically, but diffuse laminae, oriented feldspar phenocrysts and elongated amygdules may be observed. White bands defined by variably recrystallized spherulites alternate with coarser-grained chlorite-rich bands.

The lobe facies consists of distinct lobes or tongues of massive homogeneous devitrified rhyolite, variably silicified, enveloped by flow-banded, flow-brecciated rhyolite and hyaloclastite (Fig. 3.5b). Lobes range in size from less than 1 m to hundreds of metres (in longest apparent dimension), the most common size being on the order of a few metres. Apparent widths of lobes range from less than 1 m to approximately 50 m, so in the field, they appear as finger-shaped bodies. Tongues are smaller than lobes; their apparent length ranges from a few metres to tens of metres, and their width is less than a few metres. They form long, narrow, regular to irregular bands subparallel to flow direction. In general, apparent width of lobes and tongues is 1/10 of their length. Lobe sections may be subspherical to elliptical to dyke-like. Their apparent longest dimension is subparallel to flow direction. Many lobes have their longest dimension striking N290-320°; they plunge 40-70°NW and their dip varies between 40° and 65°NE. Some large lobes are discordant to the bedding and may have acted as feeders supplying magma to overlying parts of the volcanic pile. The lobes weather cream to white, whereas the surrounding flow breccias weather gray to yellowish gray, so they usually contrast sharply with the surrounding darker breccias. Contact between lobes or tongues and the surrounding breccia is sharp. Brecciation of the margins of lobes into coarse angular white siliceous fragments (1 cm to 30 cm in size) and their dispersion in the brecciated

rhyolite are locally observed and become abundant toward the top of individual flows and the top of the formation (example: flow unit #10).

Lobes generally consist of three physically and structurally different components (Fig. 3.6). These are: 1) an outer chloritic selvage, 2) a flow-banded amygdaloidal rim and 3) a lithic central core. A fourth component, a grayish chloritized, sericitized "pumiceous" fine-grained hyaloclastite is sometimes present when the chloritic selvage is absent or minimal and forms a band of tens of cm to 1 m thick enveloping the lobe. It consists of small angular fragments of glassy material, which have been hydrated and subsequently replaced by chlorite. Angular granules of glass show internal patterns of conchoidal and perlitic cracks. It is interpreted to be a carapace of fine-grained devitrified rhyolite breccia around lobes, resulting from cooling and quenching of the external surface of the lobe during flowage. The outer zone of the lobe, the selvage, is a thin (few cm) chloritic hyaloclastite which is similar to chloritized sideromelane crusts mantling pillows. It shows variable development of "in situ" brecciation, perlitic cracks, orb texture and elongated and flattened amygdules. It resulted from the rapid chilling and quenching of the lava in direct contact with seawater or in contact with the porous water-soaked surrounding flow breccia. Rising gas bubbles from the central part of the lava lobes accumulated beneath the brittle

crust, restricting migration. As a result, an amygdaloidal (up to 1-2 cm long, < 30%), flow-banded rim developed parallel to the margin of lobe. This rim displays weak to strong flow-banding with elongate quartz amygdules parallel to the margin, and variable degrees of silicification and hyaloclastite development. The core of a lobe is massive, homogeneous, and often spherulitic. Lobes may be entirely silicified or may have only their margins silicified. They generally possess a granular or sugary texture that reflects the presence of spherulites. Well preserved fibro-radial spherulites (Fig. 4.2a) that may constitute up to 90% of the rock, occur in a groundmass of randomly fibrous laths to micropoikilitic, diffuse, anhedral coarse-grained quartz. Core of lobes may contain up to 5% amygdules (exceptionally 10%) filled by one or two of calcite, quartz, chlorite, or epidote. Lobes are also glomeroporphyritic and may contain quartz and/or plagioclase phenocrysts.

The **flow-brecciated rhyolites** are heterogeneous, ranging from flow-banded breccias, flow breccias to hyaloclastite breccias (or microbreccias), are of extremely varied appearance from flow to flow and within the same flow, and are devoid of any sedimentary structures. Depending of the types of structures and textures present within the breccias, they are called flow-banded breccia, flow breccia or hyaloclastite.

Flow-banded breccias are characterized by flow-banding which may be regular over a few centimetres, simply folded to highly contorted, and brecciated (Fig. 3.5a). Flow breccias are the most voluminous type of breccias exposed. They consists of rhyolitic fragments of lapilli size (2mm to 64mm), variably silicified or chloritized, aphyric or laminated (Figs 3.5c and 3.5d) enclosed in a finer-grained matrix of similar composition and of shards of chloritized rhyolitic obsidian and vitrophyric shards and granules. Fragments may be chaotically dispersed throughout the hyaloclastite matrix or oriented. Flow-banding brecciation is noticeable where laminated fragments have been silicified and rotated. Fragments within the flow breccias are sometimes very difficult to recognize because of silicification, chloritization, sericitization, and devitrification which render their boundaries diffuse and give a pseudoscoriaceous texture as described by de Rosen Spence (1976). The aphyric and laminated rhyolitic fragments derived from the disintegration of flow-banded margin and centre of lobes and the hyaloclastite shards are interpreted to be derived through disintegration and granulation of obsidian margins

Breccia with fragments smaller than 2 mm is called hyaloclastite breccia or microbreccia (de Rosen Spence 1976). Individual fragments are not distinguishable in hand samples but the texture is granular, rough and inhomogeneous. The surface of microbreccia weathers beige to rusty brown.

Microbreccia is composed of chloritized shards of rhyolitic obsidian, granules, and small ($< 2\text{mm}$) quartzo-feldspathic fragments in a chlorite-rich groundmass. The chloritic shards and granules are interpreted to be derived through disintegration and granulation of the selvages of lobes.

The flow breccias are monolithologic and the fragments and hyaloclastite matrix contain the same type, size, and amount of phenocrysts as the associated lava lobes.

Breccias with block-sized fragments are volumetrically low and areally restricted probably because of the overall low relief and gentle slopes of the Waite Rhyolite flows. They occur within flow unit #2, #8 and #10 as flank breccias and carapace breccias. The flank breccias of flow units #2 and #8 are poorly sorted, matrix-supported, and contain silicified angular to subangular fragments of up to 0.75 m (Figs. 3.5e and 3.5f). They have been interpreted as subaqueous debris flows derived through slumping of the flow margins and carapace breccias. The locally restricted and discontinuous carapace breccia deposits occur along the upper surface of the flows. The carapace breccia of flow unit #10 is composed of blocky, unsorted, non-bedded, matrix to framework supported, angular silicified fragments of lobes in a flow-banded matrix. All the fragments derived from the brecciation of lobes. In place, "in situ" brecciation of lobes into coarse angular fragments and their dispersion into the matrix is observed (Figs. 3.7e and 3.7f).

Description of flow units

Flow unit #1

Flow unit #1 consists of one silicified rhyolite lava flow forming the base of the Waite Rhyolite formation. The flow is exposed for 2.5 km in the New Vauze area, and has a maximum thickness of 750 m adjacent to the VCF. The flow is quartz-feldspar porphyritic (< 2%), weakly amygdaloidal and locally spherulitic. The size of phenocrysts and spherulites is characteristically less than 1 mm. The main facies of flow unit #1 consists of numerous silicified lava lobes in flow-banded breccia. The lobes are of variable size but average about 25 m in length. The southward increase in thickness of this flow indicates that the flow may have originated in the Vauze mine sector, or adjacent to the Vauze Creek Fault (Fig. 3.8).

Flow unit #2

Flow unit #2 consists of several rhyolitic flows that extend hundred of metres from their eruptive vent. The flow unit outcrops over a distance of 2.6 km between the HCF and VCF. It also outcrops north of the HCF over a minimum distance of 1.6 km. The flows are weakly feldspar porphyritic (< 1%), spherulitic, amygdaloidal (~2%), sericitized and locally silicified. Flow-banded, locally flow-brecciated, rhyolite is

abundant. Silicified lobes having an apparent length up to 150 m are abundant toward the top of the flow unit #2.

A massive rhyolite dome occurs in the central part of flow unit #2. This dome is the feeder to flow unit #2 (Fig. 3.4).

A blocky breccia flow forms a local deposit within the distal facies of flow unit #2. The breccia rests conformably on a rhyolitic flow of lobate flow-banded facies. It consists of a chaotic, matrix-supported, poorly sorted assemblage of angular to subangular equant few cm to block-sized fragments (< 0.75 m). The fragments are white aphyric or laminated rhyolite enclosed in a variably chloritized or silicified flow breccia. Microscopically, the fragments and the matrix are feldspar-phyric ($< 1\%$), amygdaloidal and slightly spherulitic. The low aspect ratio (length/thickness), abrupt termination and chaotic structure of the breccia suggest emplacement from a subaqueous debris flow with a flow direction from the SE to the NW.

Flow unit #3

Flow unit #3 is a thin QFP (5% phenocrysts) underlying the New Vauze Andesite member. This flow is only present in the central part of the New Vauze area and its lateral extension is not known because it is crosscut by a younger diorite dyke (Fig. 1.3, in pocket). It is a weakly amygdaloidal ($\approx 1\%$), silicified flow-banded breccia.

At one locality immediately underlying the New Vauze Andesite, a talus breccia composed of angular to sub-rounded lapilli- to block-sized rhyolitic fragments (< 0.5 m) occurs in the distal margins of flow unit #3. The fragments are either amygdaloidal, spherulitic, laminated, aphyric or porphyritic (QFP) and the matrix is QFP ($\approx 5\%$ phenocrysts).

Flow unit #4

Flow unit #4 is the New Vauze Andesite member which is described on p. 56.

Flow unit #5

Flow unit #5 consists of one quartz-feldspar porphyritic (QFP; 5-10% phenocrysts) rhyolitic flow which has only been observed in the NW sector of the New Vauze area. The flow has a minimum length of 1.0 km south of the HCF. The flow is slightly spherulitic and of lobate, flow-banded facies, locally brecciated.

Flow unit #6

Flow unit #6 consists of one extensive QFP (10-15% phenocrysts). The flow has a minimum length of 1.5 km south of the HCF and 3 km north of the HCF. The dominant facies is small silicified lobes in silicified, sericitized flow-banded breccia. Within the flow breccia, lapilli-sized fragments show evidence of rotation. A smaller contemporaneous epidotized QFP

flow has been identified in the central part of the New Vauze area (Fig. 1.4, in pocket). This flow is interlayered with an andesitic flow breccia of the New Vauze member (Fig. 3.7c). Occurrence of interlayered rhyolitic and andesitic flows suggests contemporaneous felsic and mafic volcanism during a short interval of the extensive period of felsic volcanism that constitutes the Waite Rhyolite formation.

The QFP rhyolitic flow units #5 and #6 probably have their vents in areas north of the HCF or adjacent to it.

Flow unit #7

Flow unit #7 consists of one FP (3-5%) rhyolite flow having an apparent length of 2 km. Silicified rhyolite lobes occur in flow breccias, that are locally flow-banded rhyolite. The flows have a mottled appearance due to silicification. No feeder has been identified.

Flow unit #8

Flow unit #8 is a thick (225-300 m) flow that extends 3.75 km north and 1 km south from one of its eruptive vent, a E-W rhyolitic dyke, situated in the southern part of the NV-N area (Fig. 3.8). The flow consists of white siliceous massive lobes in flow-breccias of similar composition. Some of the large lobes are discordant to bedding and may have acted as feeders to the overlying flows. All the rhyolitic

facies are feldspar-phyric (2-3%), spherulitic, variably silicified and sericitized.

A large massive rhyolitic flow occurs in the Waite Lake area and is considered to be the surface expression of the "Vauze dome" observed underground at the Vauze mine (Lickus 1965). The massive rhyolitic flow at the Waite Lake area is texturally, mineralogically and chemically similar to rhyolitic flows of flow unit #8 of the New Vauze area described above. Several large rhyolitic lobes that have no chloritic selvage occur within the massive rhyolite flows of the Waite Lake area. They were presumably emplaced within the massive interior of the dome during endogenous growth. Because these lobes were not in direct contact with seawater, they did not develop a hyaloclastite selvage.

At the East Waite mine, a massive rhyolitic flow formed a dome which may have been the vent site for flow unit #8. The massive rhyolitic flow of the East Waite mine is contemporaneous with the "Vauze dome" and rhyolitic flows (flow unit #8) north of the VCF.

Flow unit #9

A small FP (15%) dacitic flow with an associated NE-SW feeder dyke is present near the top of the Waite Rhyolite formation. The flow is glomeroporphyritic, containing up to 15% albite phenocrysts in a groundmass of felted albite microlites with interstitial quartz, chlorite and accessory

calcite, sericite and opaques (hematite, leucoxene, rutile). Massive siliceous amygdaloidal FP lobes of apparent length up to 175 m are surrounded by amygdaloidal felsic flow breccia. The lapilli-size fragments (< 8 cm; average 3cm) within the breccia are silicified, FP (15% phenocrysts) and enclosed in a compositionally similar matrix.

Flow unit #10

This flow is localized at the top of the Waite Rhyolite formation. It is a thin (75-90 m), short (0.5 km) extensively silicified, felspar-phyric (5-10%), spherulitic and amygdaloidal flow. Silicified lobes of variable size are enclosed in silicified flow-banded rhyolite which is locally brecciated. "In situ" brecciation of lobes into coarse angular white siliceous fragments (1-30 cm) and their dispersion into the flow-banded breccia may be observed at the top and in the marginal parts of the flow. Two felsic dykes striking NE-SW are feeders to flow unit #10.

Feeders to rhyolitic flows

Individual rhyolitic flows erupted from separate deep (> 400 m) subaqueous vents. Six feeders to felsic flows have been recognized in the New Vauze area, and two possible feeders at the Vauze mine and at the East Waite mine. Of six feeders in the NV-N area, five are felsic elongated dyke-like features and one is preserved as a low relief dome (Fig. 3.8). Each

feeder is composed of one variety of rhyolite and thus fed only one flow, although more than one feeder can feed a rhyolitic flow. In the field, continuation of one feeder into rhyolitic flows was observed.

A massive rhyolite dome of about 200 m of diameter, marks the site of a possible feeder to flow unit #2 (Fig. 3.4). It is a massive, columnar-jointed, locally flow-banded and amygdaloidal FP (< 1%) rhyolite. The rhyolitic lava dome is in conformable contact with the surrounding rhyolite.

A 0.5 km long felsic dyke striking N045-070° is a feeder to flow unit #10. A similar dyke striking N035° could also have fed flow unit #10 but did not reach the present erosion surface. Both are feldspar-phyric (5-10%) and have a rhyodacitic composition. In thin section, albite phenocrysts occur in a groundmass of felted albite microlites with interstitial quartz, chlorite, sericite, calcite and accessory opaques.

In the NW sector of the NV-N area (Fig. 1.5, in pocket) a massive, spherulitic, amygdaloidal, QP (2-3%) rhyolitic dyke crosscuts the rhyolitic flows of the Splinter member.

Feeders to flow unit #8 are a thin (30-50 m), elongate (0.85 km) E-W rhyolite dyke in the NV-N area, a large massive rhyolite dome in the Waite Lake area ("Vauze dome"), and another dome at the East Waite mine. All the feeders are FP (< 1%) rhyolite. The rhyolitic feeder dyke in the NV-N area is a massive, white siliceous rhyolite which intrudes the rhyolites of flow unit #1 but which has conformable contacts

with a rhyolitic flow of unit #8. Also a rhyolitic dome located at the Vauze mine marks the site of a feeder for a rhyolitic flow that extended to the south. The surface exposure of this dome called the "Vauze dome" and of the single rhyolitic flow that extended from it for 1.7 km to the south has been mapped in detail by Smith (1984) in the Waite Lake area. The dome consists of a massive FP rhyolitic flow that is texturally, mineralogically and chemically similar to flow unit #8 in the New Vauze area. It has a minimum thickness of 450 m, and had its upper part offset by faulting and dioritic intrusion (de Rosen Spence 1976). Part of its flank outcrops in the Norbec area.

A rhyolitic dome in the area of the East Waite mine ("East Waite dome") marks the site of a vent for rhyolitic flows contemporaneous to the one that issued from the Vauze mine area. Collectively these contemporaneous flows form a low relief rhyolitic shield.

Paleotopography of rhyolitic flows

Flows of the Waite Rhyolite formation erupted from different local vents and formed large tabular or sheet-like bodies 0.5 to 5 km long, characterized by low slope (5° to 20° ; de Rosen Spence et al. 1980). The flows overlapped and coalesced to form a low-relief plateau. More viscous, massive flows formed low-relief domes (10 m to 100m high), or elongate dyke-like features that ponded over their eruptive vents.

New Vauze Andesite member

The New Vauze Andesite member is an intra-Waite Rhyolite unit that has been identified north of the Vauze Creek Fault only. North of the Hunter Creek Fault, it is interpreted to correspond to the Upper North Duprat Andesite (UNDA; Fig. 2.2). The Amulet Andesite could be interpreted as the stratigraphic equivalent of the New Vauze Andesite. The thickest section (>40 m) of the New Vauze Andesite is in the central part of the NV-N area. The flows become thinner toward the NW and SE where they are only 5-6 m thick.

The unit is composed of 3 andesitic flows: 2 flow breccias and one extensive pillowed flow (minimum length of 2.5 km) that can be traced across the area outlined by the HCF and VCF. The flow breccias were originally called "agglomerate" because of the presence of siliceous amoeboid fragments enclosed in a chloritic andesite matrix (Fig. 3.7d). Flow breccias are present at the base and at the top of the New Vauze Andesite member. Flow breccia 1 at the base of the member has only been observed in the central part of the NV-N area and is of very limited extent. It is a typical flow breccia identical to that at the top of the member, except for the presence of rhyolitic fragments which are absent in flow breccia 3. The flow breccias are composed of amygdaloidal (5-20%), silicified, amoeboid to subround fragments of poorly formed pillows of variable size (few cm to metres) in a fine-

grained, massive to locally brecciated andesitic matrix. The base of the flow breccia (first 10 m) comprises 2% subangular to rounded rhyolitic fragments ranging from <1 cm to 25 cm. A chemical analysis of a rhyolitic fragment and the surrounding andesitic material is given in appendix III (samples 545-86 and 543-86, respectively). The rhyolite fragments are quartz-feldspar porphyritic (QFP; quartz = 3-5%, <1.5 mm, feldspar = 2%, <1 mm), massive and brecciated. The brecciated fragments are composed of variably silicified, amygdaloidal, lapilli-sized andesite in a QFP matrix. Amygdules are filled by quartz and chlorite. Fragment boundaries are irregular and often ragged. The rhyolitic fragments form a minor component (<2%) of the flow breccia, derived from the immediately underlying QFP rhyolite flow unit #3.

Flow 2 is composed entirely of pillows of variable size. Most of the pillows have a normal size (1-3 m), are bun-shaped, with amygdules concentrated at the rim (5%-20%). Megapillows with concentric laminations are present in the thickest section of the New Vauze member. The weathered pillows are a distinctive buff-brown to rust, often amygdaloidal, with locally up to 15%-20% amygdules filled with calcite and chlorite. The amygdules vary in size from 2 mm to 0.8 cm (average 3 mm). Pillow margins are usually well defined and vary from less than 1 cm to 8 cm, and are chloritized and

carbonatized. Inter-pillow material such as hyaloclastite is scarce or absent.

Flow 3 is a flow breccia lithologically very similar to flow breccia 1. It is composed of variably silicified amygdaloidal (5%-20%), amoeboid to subrounded fragments in a fine-grained massive to brecciated andesite. The andesitic flow breccia is "interlayered" with massive to brecciated quartz-feldspar porphyritic (QFP) rhyolite flows and with flow breccia of silicified andesitic fragments in a QFP matrix (Fig. 3.7e).

Feeders to andesitic flows of the New Vauze member has not been recognized within the NV-N area, but a vent area is interpreted to occur where the flows attain their maximum thickness, i.e., adjacent to the Duprat-D'Alembert lineament.

3.2.6 Amulet Andesite formation

Distribution and thickness

The Amulet Andesite formation outcrops extensively south of the VCF (Fig. 1.3, in pocket). It has an estimated maximum thickness of 900 m (de Rosen Spence 1976). It conformably overlies the Waite Rhyolite formation and is separated from it by the Norbec Tuff, another areally extensive, massive to thinly bedded unit composed of ash sediment, chert and sulphides. It is the lateral exhalative facies of the Norbec, D-zone, East Waite, and Vauze massive sulphide deposits.

Flow facies

The Amulet Andesite formation in the Norbec area consists of 19 composite flows, distinguished by their vesicularity, intensity of concentric contraction fractures in pillows, and presence of plagioclase phenocrysts (Cousineau 1980). Three main facies were distinguished: massive, pillowed, and flow breccia (foreset-bedded). The massive facies is a proximal facies to the effusive vent area that consists of more than 50% of massive lava commonly overlain by pillow-lava and pillow-breccia (Dimroth et al. 1978, Cousineau and Dimroth 1982). Determination of flow direction by Cousineau (1980) has shown the feeding vent to be located in the vicinity of the massive facies. The pillowed facies is a distal facies that consists of more than 50% pillow-lava that may have thin sheets of massive lava at the base (Cousineau and Dimroth 1982). The brecciated facies consists of alternating thin bands of massive lava, pillow lava, and flow breccia and occurs at the top of the sequence.

The massive andesitic rocks are homogeneous, aphanitic and quartz-chlorite-epidote amygdaloidal (1-30%). A single lava flow may be 1 m to ≥ 200 m thick (Cousineau 1980); no grain size variation was observed within the flow.

The pillowed rocks are composed of well-formed bun-shaped pillows (Fig. 3.9a) to large (up to 2 m) elongate tubes. Cooling cracks and amygdules may rim the pillows.

Cousineau (1980) described breccias formed by the collapse of lava tubes.

The flow breccias consist mostly of small ($<0.5\text{m}$) isolated ellipsoid and amoeboid-shaped "pillows" (Figs. 3.9b and 3.9c), and some pillow-fragments and fragmented andesite in a hyaloclastite matrix. "In-situ" fragmentation of pillows and at a microscopic scale, of hyaloclastite, is characteristic. Many of the amoeboid-shaped fragments are amygdaloidal, more siliceous than the surrounding hyaloclastite-rich flow breccia, and have distinctive chilled margins (Fig. 3.9d).

Several thin tuffaceous exhalites occur within the Amulet Andesite formation. Also, a quartz and feldspar porphyritic rhyolite flow, the **East-Norbec Rhyolite member** is enclosed in the Amulet Andesite formation.

The Newbec massive sulphide deposit is situated at the top of the Amulet Andesite formation (Fig. 2.2) and consists of several small lenses of massive pyrrhotite, chalcopyrite, and pyrite (Gibson et al. 1984).

Petrography

The characteristic mineral assemblage of the Amulet Andesite is plagioclase (albite/oligoclase), quartz, chlorite, sericite, and epidote. Rocks may contain 2% plagioclase feldspar phenocrysts in a groundmass of pilotaxitic albite

microlites with interstitial chlorite, quartz, sericite, and epidote.

Feeders

Andesitic flows of the Amulet Andesite formation in the NV-N area extruded from a major feeding fissure located in the area of massive andesite, i.e., along 5 km long, synvolcanic structure trending east-northeast from the Old Waite, East Waite and Norbec D-zone mines (Cousineau and Dimroth 1982). West of the East Waite Mine, the fissure is defined by the andesitic dykes of the Old Waite Dyke Swarm (Gibson 1989).

Two other vent areas have been located by Gibson (1989) in the Amulet-Milllenbach sector and 1.0 km south of the Corbet Mine.

Paleotopography

Andesitic flows of the Amulet Andesite formation are very extensive and may be followed laterally for up to 8 km from their vent area (Dimroth et al. 1985). Dimroth et al. (1985) estimated the minimum surface area and volume of each of the large andesitic flows to be 40 km² and 2 km³ respectively. This suggests that the topography on which the andesitic lavas flowed was relatively flat.

The Amulet Andesite flows accumulated in a basin-like synvolcanic depression created by the Vauze Creek scarp and

the thick accumulation of the Waite Rhyolite flows and domes to the north.

In the Cousineau and Dimroth (1982) model, flow morphology of the andesites shows systematic changes away from the vent area from massive "proximal flows" to more "distal" pillowed and brecciated flows. This transition was interpreted by Cousineau and Dimroth (1982) to reflect decreasing flow velocity, and temperature, and increasing viscosity away from the vent area. Close to the vent, lava flows have a higher temperature and possibly a greater head, which would lead to greater flow velocity and a higher proportion of massive to pillowed flows. The opposite is expected at a distance from the vent. Also, as gases escape, viscosity would increase. Increasing vesicularity of the flows and higher proportion of flow breccias were interpreted to indicate shallowing-upward of the sequence during construction of the volcano and decreasing water depth (Cousineau and Dimroth 1982).

With time, the Amulet Andesite flows built constructional mounds, with massive lava flows eruption at the beginning of volcanism, pillowed lava as the slope steepened and flow breccias then resulting from peeling and tumbling of lobes and pillows ahead of flows.

Subsidence occurred along the Vauze Creek scarp with the Amulet Andesite basin being downfaulted. The downfaulting began shortly after the extrusion of the Waite Rhyolite flow

unit #8 and continued until the emplacement of the uppermost flow of the Amulet Andesite.

East Norbec Rhyolite member

The East Norbec Rhyolite is enclosed in the Amulet Andesite formation. It varies in thickness from 30 m to 90 m with a maximum of about 150 m near the Lake Dufault Granodiorite and the Newbec Breccia (Cormier and Labrie 1984).

The unit consists of amygdaloidal quartz-feldspar (1-3 mm) porphyritic rhyolite flows (QFP). The facies are mainly massive with flow breccia toward the south. A bedded, cherty, pyritic tuff (East Norbec Tuff), intersected in drill holes at the base of the East Norbec Rhyolite, averages 3.3 m in thickness (Cormier and Labrie 1984).

The East Norbec Rhyolite has previously been interpreted as a rhyolitic dyke but because of the presence of a tuff at its base and amygdules and flow breccias, it is now recognized as an extrusion.

3.2.7 Newbec Rhyolite formation

The Newbec Rhyolite consists of two massive domes of similar lithology separated by 125 m of Newbec Andesite flows. The stratigraphically lower dome has a maximum exposed thickness of 600 m whereas the upper dome is much smaller with a maximum exposed thickness of 280 m (Cormier and Labrie 1984). The thickest parts of the two domes lie approximately

on the same axis. They are cut by the Dufault Diorite and other numerous dioritic dykes and sills. These dykes may dilate the unit, resulting in two QFP rhyolite domes. No drill hole information is available to test this hypothesis.

The Newbec Rhyolite domes consist of a quartz (10-15%) and feldspar (5-10%) porphyritic rhyolite flow. Quartz grains are less than 3 mm in diameter and feldspars less than 1.5 mm in diameter. The facies are massive and locally brecciated. The rocks are gray to dark greenish gray on a fresh surface and whitish on a weathered surface. Amygdules, spherules, flow-banding, and columnar joints are scarce. In thin section, the rhyolite is massive, quartz-feldspar porphyritic to glomeroporphyritic in a groundmass of fibro-radial to recrystallized spherulites and fine-grained diffuse anhedral quartz grains and feldspar microlites. The quartz phenocrysts are euhedral to anhedral and the feldspars are usually euhedral. The feldspars are extremely altered to calcite, sericite, and chlorite and only the lath shape is preserved.

3.2.8 Newbec Andesite formation

The Newbec Andesite is composed of pillowed flows interlayered with flow breccias and a few massive lava flows (Fig.1.3, in pocket). Flows cannot be followed laterally for more than 1 km because they are cut by numerous dioritic dykes. All the flows show lateral continuity in their facies. None of the massive, pillowed or brecciated flows is

gradational into another. They are discrete and separate flows and are not vertical or lateral facies transitions of a single flow.

The facies are aphyric and commonly amygdaloidal (10-15%). Altered surfaces are rusty brown and fresh surfaces dark green to pale gray with a bleached appearance. The pillows, as well as the breccias, are locally altered to quartz-epidote and chlorite. Individual pillows are 1 to < 3 metres across, well formed, bun-shaped, and more or less equidimensional in plan. Amygdules are concentrated at the rim of the pillows. Pillow margins are usually very thin (maximum of 1-2 cm thick). They are brownish due to the high content of carbonates. No hyaloclastite is present as inter-pillow material but interstices between pillows are frequently filled by black quartz, and sulphides. Gibson (1989) described similar deposits within pillow lavas and breccias of the Rusty Ridge, Millenbach Andesite, Amulet Andesite, and Flavrian formations. He interpreted them as products of submarine hotspring activity, analogous to low-temperature (<200°C) smokers described by Styrer et al. (1981) along active mid-ocean ridges. The flow breccias within the Newbec Andesite are often quite spectacular, being composed of relatively small (2 cm to tens of cm) amoeboid, subangular to subrounded, variably silicified fragments in a carbonatized hyaloclastite matrix (Fig. 3.9e). Fragments contrast sharply with the surrounding darker matrix. Some resemble small intact

amoeboid-shaped pillows with distinctly silicified selvages and others are silicified broken-up fragments of the amoeboid-shaped pillows. Interstitial material is made up of smaller silicified fragments, chloritized hyaloclastite, and pieces of broken silicified crusts of fragments. The proportion of fragments to matrix may be as high as 7:1 by volume or as low as 1:3.

The Newbec Andesite formation may be traced to the north across the HCF where it stratigraphically overlies the Waite Rhyolite formation, and to the south across the VCF where it overlies the Amulet Andesite formation (Fig. 2.2). Between these two major faults, the thickness of the Newbec Andesite formation varies from 580 m to 442 m (excluding possible dilation by diorite dykes). Across the faults, the thickness and extent of the formation are unknown.

3.2.9 Fish Roe formation

The Fish Roe formation is a felsic unit composed of two members (Fig. 3.10): (1) an extensive (minimum length of 2.5 km) **massive flow** of dacitic composition overlain by (2) less extensive (0.5 km) **ash and lapilli tuffs** of rhyolitic composition. In the NV-N area, the Fish Roe formation has a thickness of 10-15 m. North of the HCF, it has an apparent thickness of about 80 m (Camiré 1989).

Member 1 is a **massive flow**, amygdaloidal (< 5% quartz) and characterized by small spherulites (< 4 mm in diameter;

average 1-2 mm) which give the unit its distinctive appearance of fish roe (Fig. 3.11a). In thin section, small (< 0.5 mm in diameter) feldspar phenocrysts (15-20%) completely pseudomorphed by quartz or calcite are randomly distributed through a devitrified mesostasis. Sometimes, they form a glomeroporphyritic texture. The feldspars often have round corner but retain a lath shape which may be up to 3 mm long. In thin section, the spherulites are outlined by a chlorite-oxide border (Fig. 3.11b) and display a radial arrangement of opaque needles (10-15%) which possibly represent former crystallites. The distribution of chlorite-oxide defines a network of interconnected subspherical to spherical domains of inferred devitrified glass that was referred to as orbicular texture by Lofgren (1971b). The orbs or spherical domains are composed of single or compound recrystallized spherulites. The spherulites consist of either quartz crystals that show fibro-radial extinction accentuated by tiny opaque needles or of fine-granular to coarse-granular quartz. The massive facies contains up to 1% amygdules of coarse crystals of quartz and fine-grained calcite; they have a fairly regular spherical shape, showing no evidence of deformation. Some rare small (≤ 1 cm) silicified felsic fragments were observed with the spherulitic facies. It also contains as much as 50% carbonate and 5-10% disseminated pyrite.

Member 2 is composed of ash and lapilli tuffs which have a more felsic composition than the underlying spherulitic

dacitic flow. It is inversely graded with a basal well bedded to laminated pyritic ash tuff grading to a lapilli tuff (Fig. 3.10). The contact between the ash tuff and the underlying spherulitic rhyolite is abrupt but irregular due to the topography. The contact between the ash tuff and the overlying lapilli tuff is gradational.

The ash tuff has a rhyolitic composition. It has been observed only in the NV-N area and the sequence exposed measures 5 m in length by 3.2 m thick. The dip of the beds varies between 60° to 65° NE. It is a thin-bedded (about 10 cm) to laminated (few mm), plane-bedded sediment with dark gray, fine ash beds interlayered with more vesicular grayish green weathered ash beds (Fig. 3.11c). Thin pyrite-rich ash beds occur at the base of the ash tuff deposit, close to its contact with the underlying dacitic flow. The irregular form and restricted occurrence of the ash tuff deposit (Fig. 3.12) reflects its deposition in irregular topographic depressions on the underlying spherulitic dacite (Fig. 3.11d). The ash tuff deposit mantled the topography but has also been topographically controlled. Isolated lenses of gray chert- and pyrite-rich ash have slumped into cracks on the underlying spherulitic flow. The ash tuff consists of 5% small angular broken and intact quartz crystals (< 0.2 mm in diameter), 30% deformed chloritized sideromelane shards and rare subround lithic clasts (< 1 mm) of interlocking microcrystalline quartz grains in a mesostasis of fine-grained quartz, chlorite,

sericite, carbonate, oxides, and sulphides which replace the fine volcanic ash particles (Fig. 3.11e). The ash tuff shows some sedimentary structures including grading, parallel lamination, slumping, and low angle cross-beds (Fig. 3.11f). Some disrupted layers of laminated sediments are interpreted as a result of ubiquitous minor synvolcanic, syndepositional faulting. Cross-beds may indicate reworking and lateral transportation by turbidity currents during deposition of the tuff or may indicate deposition of subaqueous base surges generated during hydrovolcanic eruptions. Bedding is defined by alternating laminae and beds rich in quartz, chlorite, and sulphides. Carbonates are abundant (10%) and form elongate clots.

The lapilli tuff is more extensive than the underlying ash tuff and has been traced south of the VCF (Fig. 1.3, in pocket). It consists of felsic lithic fragments (< 5 cm in diameter), pumice, rare chloritic fragments, and angular broken and intact quartz crystals (< 0.3 cm in diameter) in a ash matrix (Fig. 3.13a and 3.13b). Carbonates are abundant and may form up to 60% of the rock. The lithic fragments show a complete range in size from 0.5 cm to 5 cm in diameter; 90% of the fragments are less than 1 cm in diameter. They are poorly sorted and framework supported. The lapilli tuff shows no grading, except for one crudely graded unit which has the highest concentration of larger lithic and pumice fragments (Fig. 3.10). The predominant lithic fragment type is white to

cream weathering, aphyric and subangular to subrounded, and has a rhyolitic composition. The green-black curved angular mafic fragments which probably represent chloritized sideromelane shards, are less than 1 cm in diameter, and compose less than 5% of the lapilli tuff. The pumice (Fig. 3.13c) has an irregular to round shape, varies from less than 1 cm to 10 cm in diameter, and abundance is less than 5%. Microscopically, the white felsic fragments are composed of a mosaic of fine-grained microcrystalline quartz (95%), small feldspar microlites and interstitial chlorite, sericite, and carbonates. They usually have a finer-grained border. Some rare fibro-radial spherulites have been preserved. Few felsic fragments have quartz phenocrysts (1%). The ash matrix within the lapilli tuff deposit is composed of intact and broken quartz crystals (15-20%) in a fine mesostasis of quartz, chlorite, sericite, and carbonates (50-60%) which replace the fine volcanic ash particles and original glass. The quartz crystals have a secondary fine-grained siliceous rim which show parallel the same extinction under crossed-nicols.

Some rare felsic fragments have a similar composition to the underlying dacitic flow and are probably derived from it, but most fragments are foreign and juvenile material. Neither welding nor ballistic dispersal of fragments were apparent. This is consistent with an emplacement in a subaqueous environment. Some very amygdaloidal felsic lapilli-sized

fragments which resemble pumice have been observed and may suggest a shallow depth of eruption and emplacement.

Discussion of the origin of the ash and lapilli tuffs

The origin of the tuff deposit is not easy to discern because of the alteration which masks certain primary textures, and the lack of knowledge concerning its lateral extension. The minimum lateral dimension is around 0.5 km and maximum lateral dimension is unknown but may be of the order of 2 km. Also, subaqueous felsic pyroclastic deposits are generally poorly understood compared to their subaerial equivalents.

The ash and lapilli tuff deposits exhibit many characteristics of relatively small hydrovolcanic eruption products in a shallow marine environment. Similar hydrovolcanic eruptions have been reported by Gibson et al. (1989) in the CNVC and by Groves et al. (1989) in the Sturgeon Lake area, Ontario.

Evidence for hydrovolcanic eruption products in the Fish Roe tuff deposit includes the presence of a thin-bedded ash tuff deposit at the base of the succession and a more massive lapilli tuff deposit with a crude bedding alignment of larger lithic fragments in the upper portion, the presence of cross beds; the presence of lithic fragments and pumice in the same bed; and the limited lateral and vertical extent of the tuff deposit.

Felsic deposits from hydrovolcanic eruptions are defined as "phreatoplinian deposits" (Self and Sparks 1978) and typically occur as tuff rings (Wohletz and Sheridan 1983). They are formed by explosive interaction of magma and external water in a shallow subaqueous and (or) subaerial environment (Sheridan and Wohletz 1981, 1983, Groves et al. 1989). Such interaction leads to fine granulation of the magma and the formation of tuff cones and/or rings composed dominantly of laminated ash deposits (Walker 1973, Crowe and Fisher 1973, Williams and McBirney 1979). The Fish Roe tuff deposit probably occurred in a subaqueous environment because no ballistic fall features characteristic of subaerial deposits is observed, and it is underlain and overlain by andesitic pillowed flows.

In comparing the stratigraphy of tuff rings with the Fish Roe tuff deposit, one notices the absence of coarse explosion-breccia deposits commonly developed at the base of tuff rings (Wohletz and Sheridan 1983). The primary mechanism of emplacement of the coarse explosion breccia is ballistic fall (Fisher and Schmincke 1984, Wohletz and Sheridan 1983). They have been observed and described only in subaerial environments. Possibly because of the water depth, mild phreatomagmatic eruption and the relatively high water/magma ratio, only ash and lapilli tuff deposits occurred in the NV-N area. It has been demonstrated by Wohletz and Sheridan (1983) that the external water to magma ratio has a major

less than 1 m in size with well-developed concentric cooling fractures. Interstices are filled with either chlorite, quartz, gray bedded chert or massive black chert (Fig. 3.13d). Brecciated flows are commonly less than a few metres thick. They consist of poorly sorted, subrounded to subangular, amygdaloidal fragments in a chloritized or carbonatized hyaloclastic matrix.

Carbonatization is widespread within the D'Alembert Andesite and traces of disseminated pyrite and pyrrhotite are common. Locally, massive and pillowed flows are cross-cut by abundant thin veinlets and patches of quartz that stand out on a weathered surface. Numerous dioritic dykes have disrupted the andesitic succession of the D'Alembert Andesite formation.

2

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influence of the types of deposits formed from hydrovolcanic explosions as well as on the resulting volcanic edifice. In the general cases, under conditions of low water/magma ratios, explosive interaction will be rapid and pulsating and lead to the formation of thin-bedded ash deposits, surges, and flows, whereas under higher ratios, the explosive interaction may be mild, less explosive, and more continuous, forming more massive and thicker units of ash and lapilli tuffs.

3.2.10 D'Alembert Andesite formation

The D'Alembert Andesite formation stratigraphically overlies the Fish Roe formation (Fig. 2.2). It has been divided into lower and upper members by de Rosen Spence (1976) with an intervening bed of andesitic lapilli tuff. She estimated the total thickness of the D'Alembert Andesite formation at 400-500 m, the lower member being only 100 m thick. Only part of the lower member has been mapped.

Thin breccias and pillowed flows make up the D'Alembert Andesite formation. Few thin massive flows are present. Bedded tuffs may be followed for hundreds of metres within pillowed flows or interlayered between flow-breccias and pillowed flows.

Andesite is weakly to moderately amygdaloidal and sometimes feldspar-phyric. It weathers grayish brown to rusty brown, and is pale green to gray on fresh surfaces. Pillowed flows are usually less than 10 m thick. Pillows are usually

influence of the types of deposits formed from hydrovolcanic explosions as well as on the resulting volcanic edifice. In the general cases, under conditions of low water/magma ratios, explosive interaction will be rapid and pulsating and lead to the formation of thin-bedded ash deposits, surges, and flows, whereas under higher ratios, the explosive interaction may be mild, less explosive, and more continuous, forming more massive and thicker units of ash and lapilli tuffs.

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less than 1 m in size with well-developed concentric cooling fractures. Interstices are filled with either chlorite, quartz, gray bedded chert or massive black chert (Fig. 3.13d). Brecciated flows are commonly less than a few metres thick. They consist of poorly sorted, subrounded to subangular, amygdaloidal fragments in a chloritized or carbonatized hyaloclastic matrix.

Carbonatization is widespread within the D'Alembert Andesite and traces of disseminated pyrite and pyrrhotite are common. Locally, massive and pillowed flows are cross-cut by abundant thin veinlets and patches of quartz that stand out on a weathered surface. Numerous dioritic dykes have disrupted the andesitic succession of the D'Alembert Andesite formation.

3.2.11 Intrusive rocks

The main intrusive rocks underlying and limiting the NV-N area are: (1) synvolcanic andesitic and rhyolitic dykes, (2) Dufresnoy Diorite, Dufault Diorite and other unnamed dioritic dykes of synvolcanic to postvolcanic origin, (3) Lac Dufault granodiorite, (4) the Newbec breccia, and (5) the late diabase dykes (lamprophyres).

The andesitic and rhyolitic dykes crosscut the volcanic flows. They are massive intrusive bodies ranging in age from synvolcanic to postvolcanic but older than the Lac Dufault Pluton. The andesitic dykes are fine-grained, brown weathering and have a similar appearance to that of the andesitic flows they crosscut. Large (> 50 m), andesitic dykes (unit 2A) have been mapped by Cousineau (1980) in the Norbec area. They are concordant to discordant with the host rocks, homogeneous and fine-grained with a similar appearance to the massive andesitic flows, and small lenses of andesitic breccias may be present within these rocks.

NNE and EW striking synvolcanic **FP rhyolite dykes** crosscut rhyolite flows of the Waite Rhyolite formation. These dykes, feeders to specific rhyolite flows, are massive, feldspar-porphyritic (1-10%), weakly amygdaloidal (< 1%), and spherulitic (< 1%). Average composition of rhyolitic dykes ("feeders") are given in Table III.5, appendix III.

Synvolcanic to postvolcanic dioritic dykes occur as large sheet-like dykes that form a dense network in the NV-N area

comprising at least 20% of the rocks. They form two sets of large dykes, the main one oriented N20°W and dipping 65°-85°NE and another one striking N45°W and dipping < 45°NNE. A third set of smaller dykes with an apparent width of 5-15 m is oriented N50°-85°E. The large individual dykes can be exposed for more than 10 km in length and 175-200 m wide. They form long, regular masses and weather to low, rounded outcrops with brown to dark gray surfaces. They cross-cut the volcanic formations but are in turn intruded by the Lac Dufault pluton. Intrusive contacts are sharp, but in places fine-grained dioritic dykes are difficult to distinguish from massive andesitic flows. They are massive and generally homogeneous, although inhomogeneities such as angular xenoliths of host rocks, and grain-size variations from the margin to the centre of the dykes are not uncommon. Abundant epidote-stained patches and lesser quartz and epidote-quartz veinlets and veins occur in proximity to and within the large dioritic dykes. Small mafic and felsic dykes (as wide as 30 cm) crosscut the large dioritic dykes. Some are subparallel to the border of the dioritic dykes and possibly follow the same plane of weakness as the diorite and if so indicate steep dips to the east. Others are "discordant" and have variable orientation and dips.

The largest dyke is the **Dufresnoy Diorite**, a massive single dyke striking N20°W and dipping N65°-85°E which

occupies a regional NNE-SSE high angle reverse fault with the east fault block raised relative to the west.

The Dufault Diorite occurs at the southeast extremity of the Norbec area. It is a large north-striking intrusion characterized by its coarseness; mafic crystals average 3 to 4 mm in size but may be 5 cm long, and form acicular mafic aggregates spread out in fan shapes. This intrusion is believed to have caused the recrystallization of the Newbec Rhyolite (QFP) flow.

According to Cooke et al. (1931) and Wilson (1941), the composition of the dioritic dykes varies from gabbro to quartz-diorite, and chemical analyses from Lickus (1965), and de Rosen Spence (1976) reveal that the dioritic dykes are calcic tholeiites. Dioritic dykes sampled in the NV-N area are similar in composition to the andesites and, they straddle the calc-alkalic and tholeiitic fields on a Jensen (1976) diagram. They are composed essentially of subequal to variable proportions of plagioclase or its alteration products (50-60%) and pyroxene (10-40%). The plagioclase and pyroxene have been partly converted to secondary minerals of which actinolite, chlorite, epidote are the most abundant (40-60%). Accessory minerals such as quartz, apatite, zircon, and leucoxene are present. Grain size ranges from several mm to 1 cm. Least altered samples have an intersertal to subophitic texture characterized by euhedral to subhedral plagioclase and clinopyroxene phenocrysts in a mesostasis of chlorite,

actinolite, epidote, quartz and leucoxene. Epidote, chlorite and actinolite are widespread alteration products of the plagioclase and the clinopyroxene. Characteristics of the main minerals are listed in Table 3.5. Average chemical composition and representative compositions of the dioritic dykes are listed in Table III.9 of appendix III.

All the different sets of dioritic dykes are believed to be contemporaneous, although the age relations between the different dykes are not always clear. The dioritic dykes are probably coeval with volcanism of the Blake River Group and have possibly fed flows higher in the stratigraphic succession, although they are not visibly feeders of flows. However, they are only present close to the core zone of the Noranda Volcanic Complex, they do not cut the uppermost part of the volcanic sequence (Dimroth et al. 1982), they are cut by the Lac Dufault pluton, and they have been folded and metamorphosed with the country rocks. Thus, they may be considered synvolcanic.

The lack of drill hole information hampered the resolution of the origin and emplacement of the large dioritic dykes. An hypothesis is suggested concerning the emplacement of the N20°W intrusions: they occupy reverse faults with volcanic rocks upthrust along their eastern margin. The intrusion of dioritic bodies must have occurred during periods of relaxation of stress. The N45°W intrusions acted as sill-like bodies.

The geology of the **Lac Dufault pluton** has been briefly described by de Rosen Spence (1976) and Kennedy (1984). It is a composite granodioritic intrusion composed of east and west bodies. Both bodies have a granodioritic composition with 55-60% plagioclase, 35-40% quartz and <15% secondary mafic mineral (chlorite, epidote, ilmenite, sphene and biotite). The east body is probably a synvolcanic intrusion contemporaneous with the main intrusive phase of the Flavrian pluton; it shows the effects of regional deformation and is surrounded by a narrow, weak contact metamorphic aureole. The west body is a massive, structureless intrusion contemporaneous with the last intrusive phase of the Flavrian pluton (Kennedy 1984) and is surrounded by a pronounced contact metamorphic aureole. The age of the Lac Dufault pluton is controversial; the contact aureole around the pluton is considered to be overprinted by Kenoran metamorphic mineral assemblages by Allen and Goldie (1978) and Dimroth et al. (1983b), whereas de Rosen Spence (1976) and Gelinas et al. (1984) concluded that the aureole is entirely post-tectonic. Krogh (in Nunes and Jensen 1980) reported an age of 2701 Ma, and Mortensen (1987) reported an age of 2694 ± 8 Ma for the intrusion of the Lac Dufault pluton.

The **Newbec breccia** consists of rounded to angular fragments of diorite, gabbro, quartz-feldspar phyric rhyolite and aphyric rhyolite of variable size (< 20 m) in a fine-grained quartz-feldspar phyric rhyolite matrix. Because of the

types of fragments present within the Newbec breccia, it has been emplaced after the large dioritic intrusions and contemporaneously with or before the intrusion of the Lac Dufault pluton. It has been suggested by Smith (1983) that the Newbec Breccia was emplaced as a volatile-rich fluidized intrusion.

One N-NNW Matachewan diabase dyke (lamprophyre) is known in the NV-N area. This Proterozoic dyke is the last known intrusive event in the area.

3.3 FLOW MORPHOLOGY AND EMPLACEMENT

In the following sections, flow morphology and emplacement of subaqueous andesitic and rhyolitic flows are discussed. The emplacement of flows is an interpretation of the results of detailed geological mapping and stratigraphy.

3.3.1 Andesitic flows

Andesitic flows within the NV-N area are dominantly pillowed and brecciated and belong to the Waite Andesite formation, New Vauze member, Amulet Andesite, Newbec Andesite and D'Alembert Andesite formations. They are extensive and sheet-like structures that may be up to 10 km long (de Rosen Spence 1976). Being fluid, they flooded large areas. They also tended to accumulate in topographic depressions and buried the irregular relief created by the underlying rhyolitic flows and domes; facies mapped include massive, pillowed, and breccia

forms. The breccia facies includes the "pillow breccia" of Cousineau and Dimroth (1982) and the typical "flow breccia". Pillow breccia facies is not common within the NV-N area and occurs almost exclusively within the Amulet Andesite formation, whereas flow breccia facies is the most common type of andesitic breccia within the NV-N area. They consist of amoeboid-shaped fragments, and subangular to subrounded fragments in a finer-grained breccia matrix of variably chloritized hyaloclastite shards.

Only flows of the Amulet Andesite formation show an upward and lateral facies transition from massive to pillow to flow breccia. This represents the "idealized facies sequence" of Dimroth et al. (1979) and Cousineau and Dimroth (1982). With the exception of units of the Amulet Andesite formation, andesitic flows of the NV-N area rarely show a facies transition from massive to pillowed within the same flow. Most andesitic flows consist of one facies; i.e., entirely massive, pillowed and brecciated, or consist of two facies, such as massive facies grading to flow breccia. None of the massive flows grade vertically or laterally into a pillowed facies, except the uppermost flows of the Amulet Andesite formation where thin massive flows developed pillows or lobe-like forms at their periphery. Massive, pillow, and sometimes breccia facies of andesitic flows of the NV-N area show good lateral continuity and sharp mutual contacts. This suggests that they are discrete flows rather than vertical or

lateral facies transitions of one flow. Massive andesitic flows of the Waite Andesite formation may show a vertical transition to flow breccia facies with large ribbon-like forms of massive lava projecting upward into the flow breccia. Pillowed flows of the Waite Andesite, Newbec Andesite and D'Alembert Andesite formations do not show an upward transition to pillow breccia but are overlain by flow breccia. The contact between the pillowed flows and the flow breccia is sharp and the flow breccia consists mostly of amoeboid-shaped fragments and broken fragments in a hyaloclastite matrix. The flow breccias form discrete and restricted flows intercalated within pillowed flows or at the top of the pillowed flows.

Pillowed flows within the NV-N area are interpreted to have formed in a manner similar to subaerial tube-fed pahoehoe flows described by Peterson and Swanson (1974) and Ballard and Moore (1977) on the Island of Hawaii and in mid-ocean ridge basalts; massive flows formed similarly to submarine pahoehoe sheet flows (Ballard et al. 1979). The flow breccias may have formed in a manner similar to pillow breccias overlying pillowed flows. The ribbon-like forms (or lobes) derived from the underlying massive flows correspond to "injections" of massive andesite into the overlying flow breccia during the flow advance. The amoeboid fragments are isolated and detached fragments from the ribbon-like forms. Fragmentation of the ribbons, lobes and amoeboid fragments during flowage produced

the angular, blocky fragments and the granulation and brecciation of the glassy crusts enveloping the fragments which produced the hyaloclastite.

Flow morphology of the Waite Andesite formation is characterized by relatively thin massive flows (<50m) that grade vertically and laterally into flow breccias. The flow breccia facies consists of large ribbon-like forms of massive andesite that grade to amoeboid-shaped and angular, blocky fragments in a fine-grained hyaloclastite matrix.

Flow morphology of andesites such as in the Amulet Andesite formation shows systematic change from proximal massive and pillowed andesites to more distal brecciated andesites (Hargreaves and Ayres 1979; Cousineau and Dimroth 1982; Dimroth et #6

Flow unit #6 consists of one extensive QFP (10-15% phenocrysts). The flow has a minimum length of 1.5 km south of the HCF and 3 km north of the HCF. The dominant facies is small silicified lobes in silicified, sericitized flow-banded breccia. Within the flow breccia, lapilli-sized fragments show evidence of rotation. A smaller contemporaneous epidotized QFP flow has been identified in the central part of the New Vauze area (Fig. 1.4, in pocket). This flow is interlayered with an andesitic flo foreset-bedded facies. Increasing vesicularity of the flows and higher proportion of flow breccias were interpreted to indicate shoaling-upward of the sequence during

construction of the volcano and an increasing shallow water environment (Cousineau and Dimroth 1982).

Andesitic flows of the Newbec Andesite and D'Alembert Andesite formations are also good examples of distal volcanic facies and upward-shoaling sequences. These andesites are dominated by flow breccias, and thin pillowed and massive flows, relatively high vesicularity and numerous thin, discrete and disrupted units of laminated, crystal-vitric tuff. According to Dimroth et al. (1985), the presence of thick units of flow breccias, much of which may be foreset-bedded, the association of pillowed flows with cogenetic pyroclastic rocks and an upward increase of the vesicularity of the flows indicate shoaling of the volcanic sequence. Foreset-bedding could not be recognized with certainty within the Newbec Andesite and D'Alembert Andesite formations because of the lack of sufficient outcrop and the small size of outcrop. However, their volcanic facies are very similar to those of the uppermost flows of the Amulet Andesite, with a high ratio (10:1) of flow breccias and pillowed flows to massive flows, and a ratio of 1:1 for flow breccias to pillowed flows. According to Dimroth et al. (1985) a ratio of 1:1 or greater for brecciated to massive or pillowed flows is characteristic of shallow marine environments. Moreover, the apparently disorganized association of pillowed flows and flow breccias with some variability of strike may suggest the presence of foreset-bedded facies. In addition, the high

vesicle content ($\approx 10-15\%$) throughout the Newbec Andesite and D'Alembert Andesite formations may be indicative of solidification at a shallow water depth. High vesicle content is not always indicative of shallow water depth and not all shallow marine flows are highly vesiculated, since their vesiculation also depends on the degree to which volatiles were exsolved and lost before solidification of the lava. Nonetheless, there are no reason to presume a different relation of vesicularity of andesite and water depth of eruption, since vesicularity of flows is at least in part a function of water depth (Moore 1965, Jones 1969, Cousineau and Dimroth 1982).

3.3.2 Rhyolitic flows

Recently, it has been suggested that subaqueous rhyolite may behave with surprising fluidity. Cas (1978) has reported very large subaqueous rhyolitic sheet-flows. Bevins and Roach (1978) and Bevins et al. (1982) described rhyodacitic pillow lava and pillow breccia in SW Wales. Furnes et al. (1980) described subglacial rhyolite flows in Iceland and de Rosen Spence et al. (1980) discussed the emplacement mechanism of subaqueous rhyolite. Rhyolites of the NV-N area are interpreted as good examples of relatively fluid subaqueous rhyolite flows. They were, presumably, relatively fluid because a combination of large magma volumes, relatively rapid effusion rates, high eruption temperatures and little loss of

volatile content could have imparted low enough bulk viscosities to the lavas that they flowed away from their eruptive vents.

Rhyolites, mostly of the Waite Rhyolite formation, comprise at least a third of the rocks of the NV-N area. Flow morphology of the Waite Rhyolite is similar in many aspects to that of subaqueous basaltic/andesitic flows described by Dimroth et al. (1978) and Baragar (1984) and to subaerial flows of Iceland described by Christiansen and Lipman (1966) and de Rosen Spence et al. (1980). The flows erupted from different local vents as underwater, quiet effusions that formed large tabular or sheet-like bodies 0.5 to 5 km long, characterized by low slopes (5° - 20° ; de Rosen Spence et al. 1980). The thickness of individual flows ranges from 25 m to over 400 m and shows only minor variation along strike. The flows overlap and coalesce to form low-relief lava-shields or plateaus. More viscous, massive flows tended to form low-relief domes 10 m to 100 m high, or elongate dyke-like features that tend to pond over their eruptive vents. Rhyolitic domes have much smaller volumes than corresponding flows. The lobe/flow breccia facies is the most voluminous type of rhyolitic flow within the NV-N area.

Facies distribution is spatially organized and gradational, with proximal massive and flow-banded rhyolites grading radially into more distal facies composed of massive lobes enclosed in flow-banded breccias and microbreccias. In

the proximal facies, a vertical facies sequences consist of, in ascending order, large massive lobes in flow-banded rhyolites (sometimes brecciated) and local deposits of carapace rhyolitic breccias. Within more distal facies, the vertical sequence consists of smaller lobes engulfed by flow breccias/microbreccias grading upward into finer-grained flow breccias and microbreccias without lobes.

Schematic cross-sections through idealized rhyolitic flows of the Waite Rhyolite formation are illustrated in Fig. 3.3. The different flow facies were emplaced as follows: massive rhyolitic lavas were extruded from venting areas (fissures) and initially may have formed domes and/or large tabular flows having low slopes. Large rhyolitic lobes may be present within the proximal facies of flows where they were emplaced within the interior of the flows by successive pulses of magma that occurred during continued and sustained volcanic activity. These large lobes may have acted as feeders to other flows and therefore promoted the advance of the lavas to the flow front. The formation of massive rhyolite domes or large rhyolite lobes within the proximal flow facies may be attributed to the rate and volume of lava effusion rather than difference in composition, viscosity, or temperature of extrusion. As the moderately viscous lavas flowed, internal shear resulted in the formation of flow-banded rhyolites and some flow breccias; brecciation occurred wherever the deformation rate became too great to be accumulated by plastic

flowage. As the distance from the source increased and the velocity of the lavas decreased, protruding "fingers" of massive lava in flow-banded breccias formed. The massive rhyolitic lobes are parts of the flows and are not later intrusions as suggested by Yamagishi and Dimroth (1985). They may have formed in a similar manner to tube-fed pahoehoe flows (Ballard et al. 1979), i.e., the flow front advanced like a prograding pillow delta fed by bifurcating and meandering tubes. At the flow front, the lobes branched and budded into smaller lobes. Breccias formed along the margins and upper surface of the flows by autobrecciation of lobes, and spalling and granulation of their hyaloclastite selvages. During the flow process, a zone of high temperature and viscosity gradient developed at the boundary between the selva and the core of lava-lobes. The lava within this zone has the properties of a Bingham fluid with high apparent viscosity. This viscosity distribution caused the magma within the lava-lobes to flow as a "plug"; shear was concentrated at the margin of the "plug" and caused the development of flow-banding. Flow breccias formed predominantly by viscous flowage with the fragments derived mainly from disintegration of massive lava lobes (during downslope flowage). The chaotic, poorly sorted nature of the flow breccia and microbreccia, and the absence of broken quartz or feldspar phenocrysts and pumice support the hypothesis of autobrecciation of lobes during flow advance as the mode of formation of breccias and

not by pyroclastic eruption as suggested by Gelinas (personal communication 1982). Transition from massive lobes to surrounding flow breccias was by: 1) disintegration of the selvage and the flow-banded rim of the lobes, 2) brecciation of the margins and the massive core of the lobes into coarse, angular fragments (0.5 m in size) and 3) gradual dispersal of the fragments into the preexisting flow breccias. Ultimately, the lobes were completely disintegrated into flow breccia material. Some breccias (carapace breccias) were also formed by surface quenching, surface fracturing and marginal disintegration of the upper surfaces of the flows in contact with cold seawater. These breccias formed small and discontinuous deposits. Isolated lobes formed by the pinching off of protruding fingers of massive lava. The flow-banding at the lobe margin formed during flowage and is interpreted to be the product of shear development between two materials of different viscosities: the lobe interior is less viscous (high temperature, relatively rich in volatiles) than the surrounding porous flow breccia (lower temperature, poor in volatiles, partly chilled). The high content of amygdules (up to 30%) concentrated within the flow-banded rim of lobes indicates that the lava-lobes were relatively volatile-rich and that the volatiles were retained in the lava-lobes and only exsolved from the core (< 5% amygdules) to the rim of lobes where they concentrated. Hyaloclastite selvages formed on lobes upon contact between the hot lava and the cooler

seawater or the water soaked surrounding flow breccias. Most of the lobes within the distal flow facies have a chloritic hyaloclastite selvage, whereas the larger lobes of the proximal flow facies not always have this insulating selvage. This suggests that the large rhyolitic lobes of proximal facies were not exposed to seawater and were emplaced within the hot interior of the flows. Lobes of more distal flow facies (which comprise the bulk of the Waite Rhyolite flows) were emplaced in water-soaked flow breccias or flowed downward in direct contact with seawater. Once developed, flow-banding and flow-brecciation rendered the lava more permeable and provided avenues for fluids to interact with the rocks. Spilitization, secondary silicification, alteration of glass to quartz and chlorite, and recrystallization of devitrification textures developed (ref. chapter 4).

3.4 STRATIGRAPHIC CORRELATIONS

3.4.1 Stratigraphic correlations across the Hunter Creek

Fault

Stratigraphic correlation of the NV-N volcanic succession with the volcanic succession north of the Hunter Creek Fault system is illustrated in Fig. 2.2. The lack of outcrop, and drill hole information hampered the definition of the Hunter Creek volcanic stratigraphy and therefore correlation with the NV-N area. Two traverses done north of the HCF (Fig. 1.7) and

detailed mapping done in close proximity to the fault system outlined the following correlation with the NV-N area.

The d'Alembert, Newbec Andesite, Fish Roe formations and Waite Rhyolite flow units #7, #5-6 are traceable from the NV-N area to the Hunter Creek area. The Fish Roe formation was recognized north of the HCF by Camiré (1989). The Upper North Duprat Andesite (UNDA; Fig. 2.2) is the stratigraphic equivalent to the New Vauze Andesite member and the Amulet Andesite formation. The lowermost flow units #1 and #2 of the Waite Rhyolite formation are tentatively correlated with a rhyolitic unit underlying the Upper North Duprat Andesite north of the HCF. This correlation is based on the stratigraphic position of these formations rather than on petrographic and textural similarities.

3.4.2 Stratigraphic correlations across the Vauze Creek

Fault

Lithostratigraphic correlation of the NV-N volcanic succession across the synvolcanic VCF is illustrated in Fig. 2.2. The D'Alembert Andesite formation occurs north and south of the VCF. The Fish Roe formation is traceable from the New Vauze area to the Norbec area but pinches out a few hundreds of metres south of the VCF. The Newbec Andesite formation occurs north and south of the VCF and is traceable from several km north of the HCF to several km south of the VCF. The Amulet Andesite formation extends from the VCF south to

the Beauchastel Fault, over a distance of 10.5 km (Gibson 1989). It is stratigraphically equivalent to the New Vauze Andesite member north of the VCF and the Upper North Duprat Andesite north of the HCF. The rhyolitic flows of the Waite Rhyolite formation that outcrop south of the VCF have petrographic and textural similarities to flow unit #8 of the Waite Rhyolite formation north of the VCF. South of the VCF, the Waite Andesite formation has been intersected in numerous drill holes. A stratigraphic equivalent to the Splinter member south of the VCF is possibly the Norbec Rhyolite member that was encountered only in drill holes.

3.4.3 Stratigraphic correlations across the Dufresnoy Diorite

The Dufresnoy Diorite dyke is a massive single dyke which occupies a regional NNE-SSE high angle reverse fault with the east fault block raised relative to the west. Consequently, the volcanic succession of the NV-N area is raised relative to the succession west to the Dufresnoy Diorite, but is traceable across the Dufresnoy Diorite. South of the VCF, the Waite Rhyolite formation is thrust up along the eastern side of the Dufresnoy Diorite and later movement along the VCF displaced the uppermost flows of the Amulet Andesite formation against the Waite Rhyolite formation.

3.5 STRUCTURE

The volcanic sequence of the CNVC was successively affected by synvolcanic deformation and by folding and faulting related to the Kenoran Orogeny. According to Mortensen (1987), the entire volcanic sequence of the Noranda area accumulated within 5 Ma around 2703-2698 Ma, and the bulk of the Kenoran deformation and metamorphism was between 2698 $\pm$ 1 and 2694 $\pm$ 4 Ma.

Volcanic rocks of the CNVC have been interpreted by de Rosen Spence (1976) as having been gently folded about E-W trending, east plunging antiform during the Kenoran Orogeny. Dimroth et al. (1983a) and Gibson (1989) consider the CNVC to be an eastward younging homoclinal succession. Rocks of the NV-N area formed a gently arched homoclinal sequence dipping 35° to 60°E, and striking NNW in the New Vauze area and N in the Norbec area. Two minor open folds in the area, gently east plunging, have been noted by de Rosen Spence (1976) but have not been observed by the author: the Duprat syncline is a E-trending fold in the Norbec area and the SE extremity of the Quebec-Copper anticline occurs in the south west portion of the New Vauze area (Fig. 3.14). Schistosity is weakly developed and generally parallel to the strike of the formations: strike is N280°-310° and dip is 60°-85°E. A local circular area of 450 m in diameter within the Waite Rhyolite formation exhibits a well developed foliation. The relative lack of deformation of volcanic rocks of the CNVC is

attributable to buttressing by the surrounding and underlying Flavrian-Powell-Dufault intrusive complex. The Flavrian-Powell-Dufault intrusive complex and the overlying volcanics behaved as a wedge, pushed to the west between the Hunter Creek and Horne Creek Faults during compression (Dimroth et al. 1982). Faulting during the Kenoran Orogeny in the study area was mainly restricted to reactivation of synvolcanic faults.

Synvolcanic deformation, mainly faulting, accompanied the main period of volcanism and was active at various stages during successive collapse of the Noranda cauldron. Local subsidence, limited by flexures and/or faults, was controlled by the accumulation of volcanic material. Synvolcanic faults are sites of abrupt changes in thickness and facies of correlated volcano-stratigraphic units (de Rosen Spence 1976, Lichtblau and Dimroth 1980, Cousineau and Dimroth 1982, Gibson 1989). Also tilting of fault blocks occurred during the volcano-tectonic activity of the CNVC.

The volcanic sequence of NV-N area is cut by two major systems of pre-Kenoran faults, NE- and NW-trending faults, that were active during the formation of the volcanic pile and were slightly reactivated later, probably during the main period of folding related to the Kenoran Orogeny. The NE-trending faults are represented by the VCF and the Waite-Norbec graben structure defined by Cousineau and Dimroth (1982). The VCF strikes N245°-260° and dips vertically (or

northerly at high angle). It was a synvolcanic fault scarp marking the northern edge of the linear basin forming the Waite-Norbec paleofissure. This synvolcanic basin has had a strong topographic control on the extrusion of the Amulet Andesite which could partly explain its absence north of the VCF. The VCF appears to have displaced the uppermost flows of the Amulet Andesite formation against the Waite Rhyolite formation, with only minor displacement of the overlying Newbec Andesite formation. The apparent latest movement along the VCF was left lateral, but the dip-slip component is unknown. The Waite-Norbec graben structure represents a feeder zone for the Amulet Andesite formation, with two main volcanic centres located by Cousineau (1980) at the East Waite and Norbec Mines. Dimroth et al. (1985) concluded that tectonic downfaulting on this graben began shortly after the emplacement of the Waite Rhyolite flow unit #8 and continued until the emplacement of the uppermost flows of the Amulet Andesite formation.

The NW-trending synvolcanic faults comprises two sets respectively oriented N20°W with dips of 65°-85°NE, and N45°W with dips of 45°-65°NNE. These faults are occupied by dioritic dykes and are sometimes characterized by upthrust of the volcanic units on the eastern side. The latest movement on these faults post-dates the main period of folding associated with the Kenoran Orogeny, and the emplacement of the Flavrian Pluton to the west, but pre-date that of the Dufault Pluton.

Younger structures in the NV-N area are faults and shears which trend ENE-WSW, the most prominent of which is the HCF. The HCF is not a single fault but a fault zone that consists of several faults more or less parallel to each other. The HCF system strikes $N240^{\circ}$ - 250° and dips vertically (or northerly at high angle). It has been defined as a post-volcanic fault system by Camiré (1989). Apparent late movement along the HCF, which consists of reverse faults, was dextral but the dip-slip component is unknown. The last movements along the NNE-SSW faults occurred after the emplacement of the major granitic and dioritic intrusions but before that of the Proterozoic N-S Matachewan diabase dyke (lamprophyre); probably during the late period of the Kenoran Orogeny. Other unnamed NNE-SSW trending postvolcanic faults and shear zones occur in the NV-N area.

A structural lineament striking $N45^{\circ}$ - 55° , known as the Duprat-D'Alembert Lineament, is clearly visible on air photos. Apparent late movement along this lineament is small and dextral.

The only known post-Kenoran igneous activity in the NV-N area is the N-NNW-trending Matachewan diabase dyke (lamprophyre).

3.6 SUMMARY AND DISCUSSION

The Noranda Volcanic Complex was interpreted by de Rosen Spence (1976), Dimroth et al. (1982, 1983a) as a large

subaqueous shield-like volcano, 40-50 km in diameter, with a central subsidence zone, 20 km wide. The central subsidence zone (Central Noranda Volcanic Complex (CNVC)) was interpreted by Gibson (1989) as a cauldron structure with structural boundaries defined by the HCF to the north, Beauchastel-Horne Faults to the south, the Flavrian pluton to the west, and the D'Alembert Shear/Dufault pluton to the east. An alternative volcanic environment for the CNVC might be a subaqueous extensional rift basin. The CNVC grew by voluminous eruption of alternating basaltic to andesitic and rhyolitic lava-flows, and concomitant synvolcanic faulting and volcano-tectonic subsidence. Subsidence was accommodated by synvolcanic faults and structures.

The CNVC is composed of numerous overlapping and coalescing small volcanoes which are dissected by synvolcanic faults and intrusions (de Rosen Spence 1976). Because some volcanic formations do not continue across synvolcanic faults and because facies changes are related to the individual volcanoes, the NV-N area may be treated as two individual blocks: New Vauze and Norbec. In fact, they form respectively a low relief lava-shield or plateau and a small subsidence structure of approximately 3.0-3.5 km in diameter within the main Central Noranda cauldron defined by de Rosen Spence (1976), Dimroth et al. (1982) and Gibson (1989) or alternatively a submarine extensional rift basin.

Rhyolitic and andesitic flows erupted mainly from fissures located along synvolcanic faults and structures. Rhyolites form large tabular flows 0.5 to 5 km long, characterized by low slopes that overlapped and coalesced to construct a broad low relief lava-shield. More viscous, massive flows formed low-relief domes 10 m to 100 m high, or elongate dyke-like features that ponded over their eruptive vents. Andesitic flows are extensive and sheet-like structures that may be up to 10 km long (de Rosen Spence 1976). Being fluid, they flooded large areas. They also accumulated in topographic depressions and buried the irregular relief created by the underlying rhyolitic flows and domes. Minor pyroclastic eruptions, chiefly hydrovolcanic eruptions (e.g. Fish Roe tuffs), occurred between two main periods of andesitic volcanism and the uppermost intraformational flow contacts of the Amulet Andesite, Newbec Andesite and D'Alembert Andesite formations are marked by thin units of bedded tuffs and plane bedded andesitic hyaloclastite units.

Fig. 3.15 illustrates a schematic N-S cross-sections that provide a resume of the volcano-tectonic history of the NV-N area. Diagram A is a section after extrusion of the Waite Andesite formation, diagram B is after extrusion of the Waite Rhyolite formation, and section C is after extrusion of the Newbec Andesite, Fish Roe, and D'Alembert Andesite formations. The volcano-tectonic history of the NV-N area is summarized as follow:

1. The first volcanic eruption within the NV-N area began with the extrusion of rhyolitic flows of the Amulet formation in a relatively deep water environment. Following the extrusion of the rhyolitic flows, the paleotopography was characterized by a domal structure with slopes in the range of 20°-30°. Synvolcanic faulting and subsidence may have accompanied the extrusion of rhyolitic flows.
2. Following the extrusion of the Amulet rhyolite flows, a brief hiatus in volcanic activity was marked by widespread hotspring activity and the deposition of the "C" Contact Tuff on the irregular paleotopography of the Amulet formation. During this period, known volcanologic massive sulphide deposits (F-shaft, D-62 lens, Moosehead, Amulet C, Amulet #11 shaft, and Lac Dufault #1) formed at this stratigraphic level in regions south of the NV-N area.
3. Extensive and voluminous andesitic flows of the Waite Andesite formation flooded a large area from the HCF to the Old Waite Mine sector in the south. They accumulated in topographic depressions and buried the irregular relief created by the subjacent rhyolitic flows and fault blocks. In the NV-N area, the andesitic pillowed flows

conformably capped the domal structure of the Amulet formation. The pinch out of the lower member of the Waite Andesite formation against the HCF and its thinning against the Amulet formation suggest considerable topographic relief in that sector of the NV-N area.

4. The andesitic volcanism of the Waite Andesite formation was locally interrupted at one time by a short period of rhyolitic volcanism (Splinter member).

By analogy with other andesitic flows within the CNVC (Gibson 1989) and to well studied basaltic/andesitic flows in Hawaii, the paleotopography after the extrusion of the Waite Andesite formation was probably relatively smooth and formed low slopes. The remarkable continuity of individual andesitic flows (up to 5 km; de Rosen Spence 1976) is consistent with this hypothesis.

5. Submarine hotspring activity and formation of massive sulphide deposits (first lens of the Old Waite mine) occurred during a brief period of quiescence.
6. Extensive and voluminous rhyolitic flows (Waite Rhyolite formation) erupted from different local fissures or vents as underwater quiet and sustained eruptions with relatively rapid effusion rates. The flows extend several km from their feeding fissures and form long tabular

bodies that consist of several rhyolitic flows (compound flows). The overlapping and coalescing of the compound flows constructed low relief lava shields or plateaus. The different rhyolitic flows erupted on paleosurfaces that are characterized by the attitude of the upper surface of the underlying flows. Some of the flows, as flow unit #9, may have erupted on a paleosurface that was tilted prior to its eruption because the flow is not disposed symmetrically with respect to its vent.

7. Andesitic volcanism occurred contemporaneously with rhyolitic volcanism of the Waite Rhyolite formation. Within the New Vauze sector, andesitic flows of the New Vauze member erupted contemporaneously to rhyolite flow units #4 and #5 of the Waite Rhyolite formation (Fig. 1.4; in pocket). Feeders to the New Vauze Andesite member have not been recognized within the NV-N area, but a vent area is interpreted to occur where the flows are thickest, i.e., in proximity to the Duprat-D'Alembert lineament.
8. Hotspring activity with formation of volcanogenic massive sulphide deposits (Vauze, Norbec-D-zone, and East Waite) occurred at the end of one major period of felsic volcanism (flow unit #8).

9. To the south, andesitic flows of the Amulet Andesite formation, with a major ENE-trending feeding fissure near the Old-Waite, East Waite and Norbec-D-zone mines (Fig. 3.16), accumulated in a basin-like synvolcanic depression (Norbec block) created by the rhyolitic flows of the Waite Rhyolite formation and the Vauze Creek scarp to the north.

The volcanic sequence is cut and offset by synvolcanic faults which may have been the site of feeders to volcanic formations and may have accommodated the subsidence. Abundant evidence shows that synvolcanic faulting and passive volcano-tectonic subsidence occurred during volcanism. One area of major subsidence is the VCF, which is considered to be a synvolcanic fault scarp marking the northern edge of the basin where the Amulet Andesite accumulated. The Amulet Andesite formation is not present north of the VCF, except its stratigraphic equivalent, the New Vauze Andesite member. The absence of the Amulet Andesite flows north of the VCF is probably due to the low relief rhyolitic shield formed by flows of the Waite Rhyolite formation and, to some extent, to tectonic downfaulting along the VCF. This downfaulting may have started during or shortly after andesitic volcanism of the New Vauze member and the first flows of the Amulet Andesite formation. If subsidence occurred at that time, the displacement along the VCF was probably

minor since flow unit #8 of the Waite Rhyolite formation has been identified north and south of the VCF. Major tectonic downfaulting of the basin along this fault probably began shortly after the emplacement of the Waite Rhyolite flow unit #8 and continued until the emplacement of the uppermost flows of the Amulet Andesite formation.

The Amulet Andesite flows generally show an upward increasing vesicularity (Cousineau and Dimroth 1982) and the uppermost flows, as well as flows within the Newbec Andesite and d'Alembert Andesite formations are foreset-bedded breccias. This suggests upward-shoaling of the sequence. This upward increase in amygdules and occurrence of numerous plane-bedded andesitic hyaloclastite beds within the Amulet Andesite, Newbec Andesite, and d'Alembert Andesite formations and also the presence of pumiceous fragments within the Fish Roe formation suggest decreasing water depth with continuing volcanism.

10. Hotspring activity accompanied the uppermost andesitic volcanism of the Amulet Andesite, the end of which is marked by a period of quiescence and formation of the Newbec deposit.
11. Facies of the Newbec Andesite and D'Alembert Andesite are very similar to the facies of the Amulet Andesite

with a high ratio of flow breccias and pillowed flows to massive flows (5:1). They consist of alternating thin (few m) elongate lenses of massive lava, pillow lava and flow breccia. They are vesiculated throughout ($\approx 10-15\%$). Massive flows are confined to thin flows within the flow breccia facies or flows forming the base of the sequence. Presence of thick units of flow breccia, much of which is foreset-bedded, the association of pillowed flows with cogenetic pyroclastic rocks and upward increasing vesicularity indicate shoaling of the sequence.

12. Following the eruption of the Newbec Andesite flows, a period of quiet, extensive dacitic eruption occurred (massive dacitic flow of the Fish Roe) which is immediately followed by some hot spring activity and hydrovolcanism (rhyolitic tuffs of the Fish Roe formation) in a shallow water depth environment. No subsidence accompanied this felsic volcanism.

Table 3.1. Volcanic formations, members and corresponding lithologies in the New Vauze-Norbec area.

FORMATION, MEMBER		LITHOLOGY	
<u>New name</u>	<u>Abbreviation</u>	<u>Old name</u>	
D'Alembert Andesite	DA	Idem ¹	Andesite
Fish Roe	FR	Fish Roe Rhyolite ¹	Dacite and Rhyolite
Newbec Andesite	NA	Idem ¹	Andesite
Newbec Rhyolite	NR	Idem ¹	Rhyolite
Amulet Andesite	AA	Idem ¹	Andesite
East Norbec Rhyolite member	AAenr	Idem ¹	Rhyolite
Waite Rhyolite	WR	Idem ¹	Rhyolite
New Vauze Andesite member	WRnv	Not known	Andesite
Waite Andesite, upper member	WAu	Waite Andesite ¹	Andesite
Splinter member	WAS	Not known	Rhyolite
Waite Andesite, lower member	WAL	Waite Andesite ¹	Andesite
Amulet, lower member	Al	Amulet ¹ Rhyolite ¹	Rhyolite
Rusty Ridge Andesite	RR	Idem ¹	Andesite

¹de Rosen Spence (1976)

Table 3.2. Physical characteristics of the "C" Contact Tuff.

Appearance	Laminated, light grey, quartz-rich laminae inter-layered with green andesitic ash and pyritic beds.
Lithology	Pyrite-rich tuffaceous exhalite bedded to laminated.
Thickness	Unit: few cm to 1.5 m. Beds: commonly < 4 cm.
Composition	Andesitic lapilli-ash: 70-75% Quartz-rich layer: 20% Pyrite-rich beds: 5-10%
Texture	Parallel laminations Graded bedding Load casts Flame structures Soft sediment folds
Alteration	Chloritization
Sulphides	Py; traces of Cp, Po, Sp
Oxides	Rt

Abbreviations: Cp = chalcopyrite, Py = pyrite, Po = pyrrhotite, Sp = sphalerite, Rt = rutile.

Table 3.3. Characteristics of the sulphide minerals of the "C" Contact Tuff.

SULPHIDE	PYRITE	CHALCOPYRITE	SPHALERITE	PYRRHOTITE
HABIT	Euh grains	Anh agg	Anh masses	Subrounded grains
TEXTURE	Recx Py has Po, Ccp inclusions		Blebs of Ccp	
GRAIN SIZE	Variable	< 0.5 mm	< 0.02 mm	< 0.025mm
OCCURRENCE	Forms bands parallel to the bedding planes, and diss in Qtz-rich layers.	Diss in Qtz-rich layers. Fractures filling in Py-rich bands. As inclu- sions in Py grains.	Diss in Qtz-rich layers.	Inclusions in Py grains. Few grains diss in Qtz-rich layers.
ASSOCIATIONS	Ccp and Po	Py, Sp, Po	Ccp, Po, Py	Py, Po

Abbreviations: Euh = euhedral, Anh = anhedral, Recx = recrystallized, Diss = disseminated, cx = crystal, Qtz = quartz, Py = pyrite, Ccp = chalcopyrite, Sp = sphalerite, Po = pyrrhotite.				

Table 3.4. Characteristics of the Waite Rhyolite flow units in the New Vause-Norbec area.

Flow unit	Comp.	Phenocrysts	Max. thick (m)	App. length (km)
1	Rhy	Qtz < 2%; < 1 mm Fp < 2%; < 1 mm	750	2.5
2	Rhy	Fp < 1-2 %; < 1 mm	400	2.6
3	Rhy	Qtz ~ 5% Fp ~ 5%	25 (min)	0.7 (min)
4	And	rare Fp	40	2.5
5	Rhy	Qtz ~ 5-10%; < 1.5 mm Fp ~ 5-10%; < 1 mm	40	1.5
6	Rhy	Qtz ~ 10-15%; < 2 mm Fp ~ 10-15%; < 1.25 mm	125	1.5
7	Rhy	Fp ~ 3-5%; < 0.75 mm	120	1.4
8	Rhy	Fp ~ 2-3%; < 0.75 mm	440	3.8
9	Rhy	Fp ~ 15%	130	0.5
10	Rhy	Fp ~ 5-10%; < 1 mm	165	0.5

 Abbreviations: Qtz = quartz, Fp = feldspar, Rhy = rhyolite,
 And = andesite, min = minimum, comp = composition.

Table 3.5. Characteristics of major minerals of New Vauze-Norbec dioritic dykes.

Mx	Vol. %	Size	Form	Occurrence (mode)	Alteration
Pl	40-60%	<0.25mm -1cm	Euh to subh; slender to stubby laths.	Form a felty open network texture.	Fine, granular Epidote
Cpx	10-40%	<1cm	Euh to subh, or large anh to subh plates.	Oikocrysts partially to wholly enclosing plagioclase.	Chl, Ep, Act
Act	10-25%	<0.1mm	Fibrous aggregates.	Fine rims or feathery overgrowths on clinopyroxene.	
Ep	5-10%	<0.25mm	Anhedral grains.	Alt product of plagioclase and clinopyroxene.	
Chl	5-10%	<0.25mm	Fibrous aggregates.	Alt product of plagioclase and clinopyroxene.	
Qtz	0-5%	<5 mm	Anhedral grains.	Oikocrysts which partially enclose plagioclase; fg interstitial; rare granophyric intergrowth with plagioclase.	
Lx	tr	<0.25mm	Anhedral grains.	Forms trellised intergrowths with Ilmenite.	

 Abbreviations: anh = anhedral, subh = subhedral, euh = euhedral, alt = alteration, fg = fine-grained, Pl = plagioclase, Cpx = clinopyroxene, Act = actinolite, Ep = epidote, Qtz = quartz, Chl = chlorite.

Fig. 3.1.

- A. "C" Contact Tuff.**
- B. Silicified ribbon-like forms of massive amygdaloidal andesite, upper member of the Waite Andesite formation.**
- C. Amoeboid-shaped andesitic fragments in a finer-grained andesitic matrix, upper member of the Waite Andesite formation.**
- D. Subangular to subround silicified amygdaloidal fragments in fine-grained hyaloclastite matrix, upper member of the Waite Andesite formation.**
- E. Silicified amygdaloidal ribbon-like forms in fine-grained chloritized-epidotized hyaloclastite matrix, upper member of the Waite Andesite formation. Scale bar is 2 cm long.**
- F. "In situ" fragmentation of a silicified amoeboid andesitic fragment, upper member of the Waite Andesite formation.**

Fig. 3.2.

- A. Highly contorted flow-banding within the Splinter member of the Waite Andesite formation.**
- B. Irregular, white diffuse silicified patches within the flow-banded facies of the Splinter member.**
- C. Massive siliceous rhyolitic lobes enclosed in fine-grained rhyolitic breccia, Splinter member, Waite Andesite formation. The lobes have a sharp contact with the surrounding breccia.**
- D. Rhyolitic flow breccia of the Splinter member, Waite Andesite formation. Note the laminated and siliceous amygdaloidal fragments in a finer-grained chloritized brecciated matrix.**
- E. Columnar joints within the massive facies of the Waite Rhyolite formation.**
- F. Contorted flow-banding, Waite Rhyolite formation.**

Fig. 3.3. Schematic cross-sections through subaqueous rhyolitic flows of the Waite Rhyolite formation. (A) Flow unit #2, (B) flow unit #8, and (C) flow unit #10.

LEGEND

Diorite dyke

Massive rhyolite

Flow-banded rhyolite

Flow breccia

Rhyolite lobe

Intrusive contact

Fracture, joint

Section

Fig. 3.4. Rhyolite dome, flow unit #2, Waite Rhyolite formation.

Fig. 3.5.

- A. Broken flow-banding within the flow-banded facies of the Waite Rhyolite formation.
- B. Massive siliceous rhyolite lobe enclosed in a fine-grained rhyolite breccia and hyaloclastite, Waite Rhyolite formation.
- C. Rhyolite flow breccia, Waite Rhyolite formation.
- D. Rhyolite flow breccia, Waite Rhyolite formation. Note the flow-banded chloritized fragments in a silicified matrix.
- E. Flank blocky breccia of a rhyolitic flow, Waite Rhyolite formation, flow unit #2.
- F. Flank blocky breccia, Waite Rhyolite formation, flow unit #8.

Fig. 3.6. Schematic massive rhyolite lobe, Waite Rhyolite formation.

Fig. 3.7.

- A. "In situ" brecciation of a massive rhyolitic lobe, Waite Rhyolite formation.
- B. Idem.
- C. Irregular contact between andesitic flow breccia of the New Vauze member and quartz-feldspar porphyritic (QFP) rhyolite flow of the Waite Rhyolite formation.
- D. Andesitic flow breccia of the New Vauze member, Waite Rhyolite formation.
- E. Silicified, amygdaloidal andesitic fragments enclosed in a quartz-feldspar porphyritic rhyolite matrix.

Fig. 3.8. Surface distribution of flow unit #1, 2, 4, 5, 6, 7, 8, and 10 of the Waite Rhyolite formation, feeder dykes and dome; arrows indicate inferred flow directions.

Fig. 3.9.

- A. Bun-shaped pillows, Amulet Andesite formation.
- B. Amoeboid-shaped "pillows", Amulet Andesite formation.
- C. Two isolated amoeboid-shape "pillows", and one irregular-shaped "pillow" (above hammer), Amulet Andesite formation.
- D. Small siliceous amoeboid-shaped "pillows" with distinctive chilled margins.
- E. Subround, subangular, and amoeboid-shaped siliceous andesitic fragments, flow breccia of the Newbec Andesite formation. Note the two silicified crusts within some fragments.

Fig. 3.10. Stratigraphic column of the Fish Roe formation.

Fig. 3.11.

- A. Massive spherulitic dacitic flow of the Fish Roe formation.**
- B. Spherulites outlined by a chlorite-oxide groundmass. Scale bar is 0.1 mm long.**
- C. Well bedded ash tuff, Fish Roe formation.**
- D. Irregular paleotopographic contact between the massive spherulitic flow and the rhyolitic ash tuff.**
- E. Finely laminated ash tuff, Fish Roe formation. The dark bands are chlorite-rich and the lighter bands are quartz-rich. Scale bar is 0.1 mm long.**
- F. Cross-beds within the ash tuff unit of the Fish Roe formation**

Fig. 3.12. Geological map of the Fish Roe formation, New Vauze-Norbec area.

Fig. 3.13.

- A. Felsic lithic fragments, and pumiceous fragment (centre of photo) in a ash matrix, rhyolitic lapilli tuff, Fish Roe formation.**
- B. Broken quartz crystals and pumiceous fragments in an ash matrix, Fish Roe formation. Scale bar is 0.025 mm long.**
- C. Pumiceous fragment within the lapilli tuff unit of the Fish Roe formation. Scale bar is 0.025 mm long.**
- D. Dark gray chert between carbonatized pillows of the D'Alembert: Andesite formation.**

Fig. 3.14. Approximate location of the fold axes defined by de Rosen Spence (1976). QCA = Quebec Copper Anticline, DS = Duprat Syncline.

Fig. 3.15. Schematic NS cross-sections and interpreted volcano-tectonic history of the New Vauze-Norbec area.

Fig. 3.16. Flow directions in the Amulet Andesite formation and location of the feeding fissure. Modified from Cousineau and Dimroth (1982).

CHAPTER 4. DISTRIBUTION OF ALTERATION FACIES

4.1 GENERAL STATEMENTS

Volcanic rocks of the New Vauze-Norbec area (NV-N), although readily identified from their structures and textures, are variably altered. Field and petrographic observations of six recognizable alteration facies are presented in this chapter: 1) devitrification, 2) spilitization, 3) silicification, 4) epidote-quartz alteration, 5) chloritization, 6) sericite-carbonate alteration. Devitrification is not strictly an alteration process but since most rocks in the NV-N area exhibit devitrification textures, it will be discussed below. No mineralogical evidence (other than devitrification textures) for early alteration, such as seafloor weathering and diagenesis, has been observed. Gibson (1989) observed textural evidences for an initial stage of low temperature ($<200^{\circ}\text{C}$) alteration or diagenesis within andesitic and rhyolitic hyaloclastites and flows.

The definition of alteration facies is based on the presence of distinctive mineral assemblages and is generally named for the dominant alteration mineral present. The mineralogy, texture and distribution of the alteration types are summarized below in the relative order of their formation.

The distribution of alteration facies in the NV-N area is shown in Figure 4.1.

Semi-conformable and discordant alteration types are recognized in the NV-N area. Devitrification, spilitization, silicification, and epidote-quartz alteration, and chloritization are semi-conformable alteration whereas sericite-carbonate alteration is discordant. The sericite-carbonate alteration is generally of limited extent and are superimposed on semi-conformable alteration zones. Semi-conformable alteration zones are laterally extensive and are so pervasive within specific units of the NV-N area that the original chemical composition of rocks is drastically changed (chapter 5). However, the composition and intensity of alteration had little influence on textures, so primary textures of the rocks are preserved.

Devitrification of glass to silicified and chloritized volcanic rocks, spilitization, epidote-quartz alteration, silicification, and chloritization result in mineralogically similar assemblages to those formed during regional greenschist metamorphism (Winkler 1979). However, in this study, they are considered to be an effect of alteration contemporaneous with volcanism and not the products of low grade regional metamorphism. The lack of these alteration mineral assemblages and facies in metamorphosed dioritic dykes supported this statement.

4.2 DEVITRIFICATION

Devitrification refers to crystallization of glassy volcanic rocks to produce fine-grained fibrous textures (Lofgren 1971a, b) such as spherulites, axiolites, orb textures, and variolites.

4.2.1 Rhyolites and dacites

Devitrification textures are common and abundant within rhyolitic flows of the NV-N area. They are present in all rhyolite flow units of the Waite Rhyolite formation, Amulet formation, the Splinter member, and in the massive dacitic flow of the Fish Roe formation. The most common devitrification features are spherulites. In the field, devitrification textures are best observed as small spherulites ($\leq 1\text{mm}$ in diameter) within the massive lava lobes of rhyolite flows, and as larger spherulites (up to 10 mm in diameter) within flow unit #10 of the Waite Rhyolite formation and the dacitic flow of the Fish Roe formation.

The general succession observed in the development of devitrification texture in rhyolitic flows of the NV-N area is: fibro-radial spherulite (Fig. 4.2a), recrystallization of spherulites into either sectors or coarser fibres (Fig. 4.2b), overgrowths of spherulites by quartz as micropoikiloblastic quartz texture (Fig. 4.2c), and eventual transition to fine granular quartz texture (Fig. 4.2d). With time and optimum conditions, rhyolites will probably be

recrystallized to a coarse, granular mosaic of quartz (Lofgren 1971a). The degree of recrystallization and consequently of alteration in the rhyolites of the NV-N area increases from massive to lobe to flow-banded and flow breccia facies. Several of the devitrification textures listed above may be present within a rhyolitic flow facies, although one texture is usually predominant within a facies. The original fibrous spherulitic texture is well preserved in the lobe facies; cores of lobes display only weak recrystallization. This may be due to the fact that the cores of lobes cooled slowly enough to crystallize and were protected by relatively impermeable silicified margins which were the product of rapid cooling, incomplete devitrification and replacement of the residual glass by silica. Relict fibrous spherulites were not as well preserved in the massive facies or were not originally abundant. The texture of the massive facies consists of small dispersed fibrous spherulites in a groundmass of micropoikiloblastic quartz anhedral and ill-formed plagioclase microlites. The flow-banded and flow-brecciated facies are more highly recrystallized consisting of coarse fibrous spherulites in fine- to intermediate-granular texture. This is probably due to the greater permeability of the flow-banded and flow breccia facies; the flow bands and interstices within the flow breccias provided avenues for fluids, which reacted with the rocks and became hydrated and thus were easily altered (eventual alteration of residual glass to

chlorite and quartz). Smith (1984) observed in rhyolite flows of the Waite Rhyolite formation that the degree of spherulite development and recrystallization varies in different rhyolitic facies and that all of the devitrification textures may be present in the same rhyolitic facies but in variable quantities. De Rosen Spence (1976) had suggested that distinct differences in devitrification textures were present in different facies of the rhyolitic flows. Smith (1984) concluded that because of the presence of several devitrification textures in the same rhyolitic facies, temperature controls spherulite morphology only in their initial phase of formation, and their present forms are the products of recrystallization that occurred after spherulite formation.

Widespread recrystallization of the original devitrification minerals to mosaics of interlocking anhedral blebby quartz and feldspar can make interpretation of devitrification textures and recognition from silicification difficult. However, in the least altered rhyolites, devitrification microstructures are only partially recrystallized and comprise well-formed fibro-radial and dispersed microspherulites in a felsitic groundmass, close-packed aggregates of fibrous spherulites, and less commonly, feldspar microlitic textures. In the most altered and recrystallized rhyolites, spherulitic textures are obliterated

and replaced by aggregates of granular blebby quartz and the matrix consists of a mosaic of interlocking blebby quartz.

Another devitrification texture common to vitrophyres and flow top breccias are the perlitic cracks which result from expansion of glass during hydration and the associated release of residual stresses incurred during cooling (Ross and Smith 1955, Friedman and Smith 1958). Subsequent to hydration and perlitic fracturing, extensive volumes of the glassy rock may have been readily altered by fluids moving along the fracture network. Alteration of the perlitic rhyolites involved minerals nucleating along the perlitic fractures and growing into the glass on either side so that the glass between the perlitic cracks is progressively replaced. The perlitic fractures themselves are preserved by a thin infilling rich in chlorite and/or opaques and/or sericite.

The abundance of relict perlitic fracture networks and devitrification textures within most rhyolites of the NV-N area indicates that most of them were initially glassy. However, the felsitic texture of the feeder dykes and some rhyolitic flows, as flow unit #9, of the Waite Rhyolite formation suggests that they may have totally or partially crystallized from the magma.

Lofgren (1970, 1971a, b) was able to simulate experimentally many devitrification textures, including spherulites, bow-tie aggregates, axiolites and orb texture.

He found that the morphology of devitrification textures varied according to temperature, rate of cooling, amount of water in the glass and the presence of alkalis in solution; slow cooling and sufficient water favour the formation of fibro-radial spherulites, whereas rapid cooling or deficiency of water favour formation of "ill-formed" spherulites (incomplete devitrification), perlitic textures and replacement of residual glass by silica minerals and chlorite. Quartzofeldspathic spherulites with nearly circular outlines crystallized around 400°C. Between 400°C and 600°C, bow-tie shaped aggregates and spherulites recrystallized as micropoikilitic quartz and fine-granular intergrowths. At 700°C, lath-like fibres or open framework circular clusters of spaced fibres and microlitic textures occurred.

Several of the devitrification textures listed above are found in rhyolites of the NV-N area. Because, several devitrification textures can be found in one rhyolitic flow facies, it is suggested, contrary to Lofgren (1971a, b) and de Rosen Spence (1976), that temperature did not control the actual spherulite morphology, but that the latter resulted from subsolidus recrystallization.

4.2.2 Andesites

In andesites, the only devitrification textures observed are variolites and perlitic cracks. The variolites are spherulite-like radiating aggregates of mainly plagioclase.

Variolites may in part result from devitrification, but where they occur in the margins of pillows, they may be the product of quench-induced crystallisation. Perlitic textures occur mainly in andesitic hyaloclastites. Perlitic cracks filled by quartz and opaque minerals (Fe-Ti oxides) and chlorite aligned parallel to the cracks attest of the original glassy nature of the andesite and according to Gibson (1989) may represent former relict texture of fibropalagonite.

4.3 SPILITIZATION

Spilitization is the most pervasive and widespread alteration type that affected all the volcanic rocks of the Noranda area. Its pertinent mineral assemblages are interpreted from petrography of the least altered volcanic rocks in the NV-N area. Andesitic rocks are characterized by the mineral assemblage albite-chlorite-actinolite-quartz-epidote-calcite-sphene/leucoxene and rhyolitic rocks are characterized by the assemblage quartz-albite-chlorite-sericite-calcite.

Least altered andesites have a felted or pilotaxitic texture with albite microlites and interstitial quartz, chlorite, actinolite, and accessory epidote, calcite and leucoxene. Albite occurs as pseudomorphs after plagioclase microlites. Some andesitic flows may contain up to 5% albite phenocrysts.

Least altered rhyolites usually exhibit fibrous spherulitic textures in a groundmass of variably recrystallized microcrystalline quartz and albite with some interstitial chlorite, sericite, calcite, epidote and leucoxene. Quartz phenocrysts are usually homogeneous and fresh though they may be recrystallized around grain boundaries and they may be embayed. Plagioclase phenocrysts are relatively fresh and exhibit albite twins.

Discussion

Similar mineral assemblages may also have resulted from greenschist facies regional metamorphism and from high-temperature hydrothermal metamorphism as observed within the pillow lava sequence of the Troodos complex (Gillis and Robinson 1985, Spooner 1977, Lydon and Jamieson 1984) and the upper km of mid-oceanic crust (Muehlenbachs 1979, Donnelly et al. 1980, Stakes and O'Neil 1982, Alt et al. 1986). Rocks of the NV-N area have their primary textures preserved and no recognizable metamorphic fabric is observed. According to Gibson (personal communication), the spilitic assemblage pseudomorphed earlier alteration mineral assemblage, i.e., palagonite, clay minerals, and zeolites. For these reasons and also because they have typical spilitic chemical composition (chapter 5), the mineral assemblage observed in the least altered rocks of the NV-N area is possibly the product of an early subsolidus hydrothermal alteration. This

is in agreement with other studies done in the Noranda (Gibson 1989) and Matagami Lake (MacGeehan 1978) areas of the Eastern Abitibi greenstone belt.

4.4 SILICIFICATION

Silicification occurs mainly as a semi-conformable, widespread alteration within some rhyolitic flows of the Waite Rhyolite formation. It is pervasive in the dacitic flow of the Fish Roe formation, and flows of the upper members of the Waite Andesite formation.

Silicification of rhyolites and andesites corresponds to replacement of glass or the original minerals by various amounts of fine-grained quartz (and albite) to produce a white-weathering rock.

Silicification of andesitic flows of the upper member of the Amulet formation in the CNVC has been studied by Gibson (1979) and Gibson et al. (1983). Gibson (1989) also studied the spatial distribution, temporal relationships and possible relationship of silicification to attendant volcanogenic massive sulphide (VMS) deposits. MacGeehan and MacLean (1980) described a major zone of silicic alteration within basalts and rhyolites beneath the VMS deposits at Matagami Lake, Quebec. Silicified basalts have been noted several hundred metres stratigraphically beneath the massive sulphide deposits at Snow Lake, Manitoba (Skirrow 1987). Silicified volcanoclastic rocks, pillow lavas, and sediments have been

described by Paris et al. (1985) and Duchac and Hanor (1987) in the Barberton greenstone belt, South Africa.

4.4.1 Waite Rhyolite formation

Silicification is the most abundant hydrothermal alteration facies (other than spilitization and devitrification) of the Waite Rhyolite formation. It is semi-conformable, laterally extensive, widespread and of variable intensity. Silicification is weak to intense in zones localized at flow-top breccias, along the VCF and other synvolcanic faults, in proximity to synvolcanic dykes (or feeders) and within the uppermost flows (flow units #8, #9, and #10).

Silicification within the rhyolites is not always easy to discern because of the siliceous nature of the rhyolites and their white inherent colour on weathered surface. In the field, silicification of rhyolite flows is most apparent in white-weathering siliceous lobes (Fig. 3.5b) and large white-weathering siliceous fragments (Fig. 4.2e). These are mainly composed of quartz and albite, surrounded by darker-weathering flow breccia containing more chlorite, sericite and epidote. Silicification is also present as groundmass replacement within flow breccias (Figs. 3.5d and 4.2f), as irregular white diffuse patches up to 1 m in diameter (Figs. 4.3a and 4.3b), as halos mantling amygdules (Fig. 4.3c) and fractures, as amygdule fillings, and as small veinlets (Fig. 4.3d).

Silicified rhyolites are characterized by the mineral assemblage quartz and albite. Quartz usually occurs as fine-grained granular or blebby crystals that overgrow spherulites, replace the groundmass, fill the amygdules and fractures and variably replace the plagioclase microlites and phenocrysts. In the most silicified rhyolites, feldspar phenocrysts can be completely replaced by quartz.

Silicification of massive lobes

In the field, silicified white-weathering lobes are sometimes difficult to distinguish from the devitrified and recrystallized white-weathering lobes. But the high SiO_2 content of some altered lobes, and petrographic evidence attest to their silicification. In the field, small lobes are usually entirely silicified and appear as white aphyric massive rock. Larger lobes may be silicified only along the flow-banded amygdaloidal margins with a width of few cm to 1 metre. The core of those lobes remain unsilicified and is characterized by a granular texture which reflects the presence of spherulites (< 5 mm). The thin chloritic selvage of lobes and the vitrophyre enveloping the lobes devitrified respectively to a dark brown weathering and yellowish green sericitic material.

Silicification of fragments

Within most flow breccias, discernible fragments of massive siliceous lobes and of margins of lobes are white-weathering and are surrounded by a darker finer-grained brecciated material. The fragments are "quartz-amygdaloidal" and the amygdules are filled and mantled by quartz. Microscopically, the silicified fragments consists of fine-grained diffuse and recrystallized spherulites in a groundmass of micropoikilitic quartz. Flow-banded fragments are marked by thin, white, silicified bands alternating with chlorite-epidote-rich bands. The silicified bands are defined by variably recrystallized spherulites and fine anhedral quartz grains.

Coarse angular to subangular fragments (< 1 m) within flow breccias are silicified and have sharp boundaries with the fine-grained brecciated material. Smaller fragment (less than a few cm) are more difficult to distinguish because of their size and their diffuse outlines, obliterated by devitrification and subsequent silicification or chloritization. Silicified fragments within the blocky flow breccia of flow unit #2 have broken and incompletely silicified rims (Fig. 4.3e), which suggest that the fragments were previously silicified before their emplacement.

Silicification of the groundmass

Scattered zones of intensely silicified groundmass of flow breccias are present within all flow units of the Waite Rhyolite formation and are extensive within flow unit #8. Zones may be extensive (km size) or small, irregular and diffuse patches (tens of metres long). They appear as massive, white-weathering material composed of fine-grained blebby quartz and silicified and recrystallized microspherulites enclosing more chloritic fragments having sharp or diffuse boundaries. When silicification is intense, the fine-grained granular and blebby quartz totally replaced the groundmass and the spherulites, leaving only remnants of the former fragments now represented by a mixture of chlorite, sericite, carbonates and quartz.

Silicification adjacent to Vauze Creek Fault

Rhyolites of flow unit #1 adjacent to the VCF are characterized by intense silicification of the massive lobes, silicification of the groundmass of flow breccias, and presence of quartz veins. Unfortunately, the lack of outcrops near the VCF precludes verification of the hypothesis that the VCF might be a channelway for hydrothermal fluids.

Irregular silicified patches

White diffuse and irregular silicified patches of metre-size occur sporadically within all facies of the rhyolitic

flows. They usually centre on the most amygdaloidal part of flows or on fractures. Silicification of this style is controlled mostly by vesicules. White siliceous halos mantling quartz amygdules may merge and overlap forming large mottled silicification patches which may give an erroneous heterogeneous and brecciated aspect to the rock.

In summary, silicification within the Waite Rhyolite formation took place preferentially along permeable zones, flow-top breccias, flow contacts, amygdaloidal zones in flows, adjacent to faults and synvolcanic intrusions. It is controlled by primary permeability of the flows and is most intense and pervasive within flows near the top of the formation.

4.4.2 Waite Andesite formation

Silicification is more easily discerned in the andesitic rocks than in the rhyolitic rocks due to the contrast between the greenish least altered andesite and the whitish silicified andesite.

Silicification of andesitic flows in the Waite Andesite formation is intense and pervasive but not widespread because it is mainly restricted to the upper member and to one flow within the lower member. The upper member of the Waite Andesite formation consists mainly of an andesitic flow breccia which has been previously interpreted (de Rosen Spence 1976) as a rhyolite because of its siliceous appearance. An

estimated 75% of the rocks of the upper member have been silicified and epidote-quartz altered³. Silicification and epidote-quartz alteration (described in the next section) of andesitic flows of the Waite Andesite formation are spatially associated and controlled by the original permeability of the flows. The silicified flows consist of amoeboid-shaped fragments of massive white siliceous amygdaloidal andesite (Figs. 4.3f and 4.4a), and ribbon-like fingers (Fig. 4.4b) in a matrix of chloritized, epidotized and locally silicified hyaloclastite and massive flow-banded chloritic andesite. Most of the fragments are totally silicified but some are silicified only at their margins (Fig. 4.4c), or variably silicified along amygdules which gives them a mottled and frayed appearance with diffuse or sharp margins (Fig. 3.1f). The outline of broken amoeboid silicified fragments is usually sharp. The silicified fragments are generally only a few cm thick, but a few metres long. Silicified ribbon-like and amoeboid fragments are zoned (Fig. 3.1e): a) a dark grayish green, chloritic selvage (1-5 mm thick); b) a light-green silicified "margin" (1-2 mm thick) containing quartz, chlorite and epidote; and c) a white-weathering zone of intensely silicified andesite. The silicified zone is characterized by numerous elongate quartz amygdules and flow-bands parallel to the longest dimension of the fragments. The hyaloclastite surrounding the siliceous fragments consists of small chloritized fragments in chloritized-epidotized matrix. The

epidote forms cm-size aggregates or is disseminated through the matrix. Also, silicification usually follows the outline of the fragments, and never truncates the fragment boundaries. Some silicified fragments show "in situ" brecciation and were obviously broken during flowage. Parts of some fragments are intensely silicified, particularly where elongated amygdules and flow-banding are abundant.

Silicification also manifests itself as irregular white patches up to few metres in diameter and as halos mantling quartz-epidote amygdules (Fig. 4.4d) and fractures. The alteration is not pervasive since it affected only the fragments and zones around amygdules and fractures, and not the matrix. The result is a heterogeneous-looking rock with brownish green areas adjacent to white siliceous patches and fragments; contacts may be gradational or sharp.

Within the lower member of the Waite Andesite formation, silicification is mainly restricted to flow unit #2 as cm-sized siliceous bands, quartz amygdules and as amygdaloidal silicified fragments within flow-top breccia.

Another silicification texture, "silica dumping" (Gibson et al. 1983), can be observed as irregular, small quartz veinlets crosscutting the andesites. It is widespread within the pillowed flow at the top of the lower member of the Waite Andesite formation. The pillows have quartz-filled concentric thermal contraction cracks, several mm thick, and the amygdules are filled by quartz.

In summary, silicification of andesitic flows is most pronounced within flow breccias of the upper member of the Waite Andesite formation, where it occurs mainly as regular to contorted siliceous ribbon-like forms, pervasively silicified amoeboid fragments, and irregular white-weathering patches. Overall, silicification preferentially developed along amygdaloidal bands or zones, flow breccias and fractures.

4.4.3 Fish Roe formation

The massive spherulitic flow of the Fish Roe formation is intensely silicified. Its primary composition was probably dacitic, but is now rhyolitic.

Silicification manifests itself by total replacement of feldspar phenocrysts by mosaic of quartz grains (Fig. 4.5a) and spherulites and groundmass by quartz. Amygdules are also filled by quartz.

Under plane-polarized light, spherulites define interconnected networks of spherical domains rimmed by chlorite and opaque minerals and are defined by radial arrangement of opaque needles. Under crossed nicols, the spherulites are not as well defined and are revealed as fine-grained granular quartz or in the least altered samples by single or polycrystalline patches of anhedral quartz grains with shadowy to undulose extinction. Often, spherulites are

recrystallized to sectors, but retain some relic of fibrous textures.

4.5 EPIDOTE-QUARTZ ALTERATION

Epidote-quartz altered rocks are characterized by various amounts of epidote and quartz which produce a greenish-white-weathering andesitic rock and a yellowish-green weathering rhyolitic rock. It is essentially a variation of the silicification process with addition of epidote, but it is not as widespread. Within andesites and rhyolites, it forms irregular epidote-quartz-rich patches (Fig. 4.4e) and round spots, and fills amygdules (Fig. 4.4d). It is widespread with andesitic flow breccias of the upper member of the Waite Andesite formation and rare with rhyolitic flows of the Waite Rhyolite formation.

4.5.1 Waite Andesite formation

Epidote-quartz alteration has the same distribution as silicification and is restricted to andesitic flow breccias of the upper member of the Waite Andesite formation, where it appears mainly as mottled epidote-quartz patches and spots, and amygdule infilling. It has not been observed in pillowed flows as described by Smith (1984) in the upper member of the Amulet formation and by Skirrow (1987) in the Snow Lake area, Manitoba.

The irregular metre-wide greenish-white patches which have been called "mottled alteration" by Gibson et al. (1983) consist of a fine-grained mixture of epidote-quartz. The quartz is usually fine-grained and granular whereas the epidote forms aggregates of prismatic crystals. These patches are irregularly distributed, but seem to concentrate in permeable zones such as amygdules and fractures. Epidote-quartz aggregates first developed around quartz amygdules, and eventually extended from them to form diffuse and irregular patches; locally these patches may have coalesced to form larger (few metres wide) mottled zones. These patches are similar in size, texture and colour to those in silicified andesites and rhyolites except for the additional presence of epidote.

The mineral epidote also occurs as aggregates or disseminated grains scattered through the matrix of the hyaloclastite and as amygdule infilling. The hyaloclastite surrounding the siliceous fragments consists of small chloritized fragments in chloritized-epidotized groundmass. Amygdules are filled by fibrous prismatic epidote with or without calcite and/or quartz.

4.5.2 Waite Rhyolite formation

Epidote-quartz alteration is rare in the Waite Rhyolite formation and is restricted to flow unit #6 where the latter is interlayered with an andesitic flow breccia of the New

Vauze Andesite member and where it is proximal to a synvolcanic rhyolitic dyke (feeder). Epidote-quartz alteration within this flow occurs as small diffuse patches and spots. The mineral epidote is abundant along flow laminae in the flow-banded breccia and occurs as disseminated grains in the flow breccia. Primary textures in this flow are destroyed and completely recrystallized to a granular mosaic of epidote and quartz (< 50%), sericite (40%) and carbonate (5-10%). Quartz phenocrysts are limpid and plagioclase is altered to numerous grains of epidote, sericite and chlorite. Plagioclase is now albite and the epidote group mineral is epidote (Table II.7, appendix II). Some lath-shaped minerals, probably feldspars, have been totally replaced by epidote. Elsewhere, as in other flow units of the Waite Rhyolite formation, small quantities (< 5%) of epidote are present as disseminated grains or filled amygdules.

4.6 CHLORITIZATION

Most of the chlorite in the andesites and rhyolites of the NV-N area occurs within the groundmass of flows where it replaced the original sideromelane and obsidian mesostasis.

4.6.1 Rhyolites

Chloritization is not a widespread alteration type in rhyolites of the NV-N area. Chlorite is restricted to flow breccia as material replacing shard fragments, as interstitial

material replacing the original glass and as amygdule fillings.

In the Waite Rhyolite formation, chloritization is weak and restricted to flow breccias, to vitrophyre and altered flow-tops. Chlorite rarely exceeds 25% of the Waite Rhyolite flows but it may compose up to 35% of the flow breccias of the Splinter member as interstitial material, chloritized fragments, amygdule fillings, and outlines of perlitic cracks. Chlorite occurs as disseminated flakes, fine-grained aggregates and narrow veinlets.

The most chloritized rhyolitic flow in the NV-N area belongs to the lower member of the Amulet formation. It consists of a flow breccia composed of strongly chloritized angular fragments in a groundmass of fine-grained granular quartz (Fig. 4.5b). Spherulites which display all stages of recrystallization and replacement by quartz are sometimes clearly visible within the chloritized fragments. Feldspar phenocrysts in the least altered sample of the Amulet formation are absent or completely obliterated; they are replaced by chlorite in the chloritized brecciated facies.

4.6.2 Andesites

Chloritization of andesitic rocks is best developed in the matrix of flow breccias of the upper member of the Waite Andesite formation. Chlorite filled amygdules, and replaced the hyaloclastite shards and the fine-grained matrix.

Chloritization is most intense in isolated zones of the NW sector of the New Vauze area. It also affected the andesitic and rhyolitic tuffs. Fine-grained glass particles are commonly chloritized, regardless of their original composition. Chloritization of rhyolitic shards (de Rosen Spence et al. 1980) is as common as the chloritization of andesitic hyaloclastite (Dimroth and Lichtblau 1979) during seafloor alteration.

The chloritization described above is chemically similar to (chapter 5), but mineralogically and texturally different from, that in alteration pipes associated with massive sulphide deposits described by Riverin and Hodgson (1980), in which all primary textures and minerals are destroyed.

4.7 SERICITE-CARBONATE ALTERATION

Sericite-carbonate alteration is characterized by the mineralogical association sericite-carbonate-quartz. Sericite and carbonate occur in a ratio of 1:1 to 2:1. Sericitization and carbonatization are considered together in this study because they are closely associated in the field and petrographically they form a fine-grained mixture. They comprise a discordant alteration facies that was superimposed on earlier silicification and that variably affected all stratigraphic units in the NV-N area. Sericite-carbonate alteration is more common in rhyolitic than in andesitic

flows. Calcite is the dominant carbonate species, but ankerite occurs locally.

In rhyolite, sericite and carbonates are most abundant along flow bands and laminae, in the matrix of flow breccia, along flow tops, along joints, and along foliation planes (Fig. 4.5c). They form discordant alteration zones. The more massive parts of domes and flows are relatively free of sericite and carbonate, whereas flow breccias and hyaloclastites are rich in sericite.

Sericite and carbonate may constitute more than 50% of the modal composition of the rock. When sericite is dominant over carbonate, rhyolites are recognized in the field by the distinct yellowish-green colour. In addition, it clearly reveals the regional deformation as recrystallization takes up strain and the rock becomes foliated; this is lacking in other rocks that contain much less phyllosilicate. When carbonate is dominant, rocks are recognized in the field by their brownish to rusty brown colour.

Sericite occurs as discontinuous lenses, and small veinlets, and as well foliated, fine-grained, plate-like aggregates which are often associated with carbonates. Calcite typically occurs as disseminated fine anhedral grains, as replacement of plagioclase, as aggregates (0.2mm to 0.5 cm) and as amygdule fillings. Plagioclase phenocrysts are good indicators of the progressive sericitization and carbonatization of the felsic volcanic rocks. Close to the

least altered assemblages and within the massive parts of flows and domes, sericite and calcite occur as disseminated grains and fine-grained crystal aggregates respectively within and/or as narrow rims around plagioclase phenocrysts (Fig. 4.4d). In the most altered rhyolites, plagioclase phenocrysts are completely replaced by sericite and calcite.

An intense sericitic alteration zone occurs as a well defined circular area, 450 m in diameter, in flow unit #8 of the Waite Rhyolite formation. This zone reveals the strong tectonic overprint and a well-developed foliation N280-310°/60-80°E (Fig. 4.5e). More than 50% sericite occurs mainly as crosscutting veinlets with hematite and pyrite, some as disseminated flakes in the groundmass and as disseminated grains in plagioclase. The rhyolite is completely recrystallized with a groundmass composed of fine-grained granular quartz with undulose extinction, and dispersed, well formed round recrystallized spherulites. Sericite is molded around spherulites and rarely crosscuts them. Plagioclase phenocrysts are sometimes deformed and oriented parallel to the foliation.

4.8 TIMING AND ORIGIN OF ALTERATION

Spilitization, silicification, epidote-quartz alteration, and chloritization are semi-conformable synvolcanic alteration events that are the product of a fluid/rock interaction controlled essentially by the primary permeability of the

andesitic and rhyolitic flows. Sericitization and carbonatization comprise discordant alteration and are postvolcanic processes since they affected both volcanic rocks and late intrusions.

The semi-conformable alteration assemblages are interpreted to be the result of fluid/rock interaction contemporaneous with volcanism and not the result of post-volcanism, isochemical, greenschist-facies regional metamorphism. In the field, altered rocks may readily be distinguished from greenschist facies regionally metamorphosed rocks by their heterogeneous and brecciated appearance and their occurrence in specific flows or stratigraphic units. The distribution and abundance of alteration minerals with silicification, epidote-quartz alteration, and chloritization is irregular and not as homogeneously distributed as when formed by regional greenschist metamorphism. These alteration types are usually restricted to permeable zones of flows and are not present within synvolcanic andesitic and dioritic dykes. Similar alteration facies associated with volcanic rocks have been documented in Matagami, Quebec (MacGeehan 1978; MacGeehan and MacLean 1980; MacLean and Kranidiotis 1987), Noranda, Quebec (Parry and Hutchinson 1981; Gibson et al. 1983), Wawa, Ontario (Morton and Nebel 1984), Snow Lake, Manitoba (Skirrow 1987) and Onaman area, NW Ontario (Osterberg et al. 1987). Some of the alteration facies described in rocks of the NV-N area are also similar to the ones observed in

extrusive rocks of the Troodos complex (Spooner 1977, Lydon and Jamieson 1984, Gillis and Robinson 1985) and in rocks of the upper levels of the modern oceanic crust ((Muehlenbachs 1979, Donnely et al. 1980, Stakes and O'Neil 1982, Alt et al. 1986)).

In agreement with other studies done in the Noranda area and in the Abitibi belt, it is concluded that regional metamorphism postdated the alteration types described and that the alteration minerals have been recrystallized by regional metamorphism. In the NV-N area, this conclusion is based on the crosscutting nature of some synvolcanic dykes which exhibit greenschist facies mineral assemblages and no alteration facies as described above.

The spatial distribution of the semi-conformable alteration types to specific stratigraphic units of the NV-N area suggests that the preferred paths of fluid migration within the extrusive sequence was parallel to the strata and largely a function of their permeability.

Devitrification constitutes the first process that affected the volcanic rocks of the NV-N area, although little petrographic evidence (except spherulites, variolites, and relict perlite structure) remains of this initial low temperature process. This occurred during and shortly after the emplacement of flows and was mainly the result of the percolation of seawater into the crackled and brecciated

volcanic rocks. Its development may be explained by Lofgren's (1970, 1971a, b) experiments on the role of water in the devitrification, hydration and alteration of volcanic glass to quartz and chlorite and those of Kennedy (1950) on the solubility of silica in water (chapter 5).

Spilitization is a pervasive and widespread alteration type that affected all the volcanic rocks of the NV-N area. The mineralogy and chemistry of rocks changed slightly during spilitization (chapter 5) but their original primary textures are preserved. The mineral assemblages of spilitized andesites and rhyolites characterized the assemblages of least altered andesites and rhyolites of the NV-N area. Spilitization preceded silicification, epidote-quartz alteration, chloritization, and sericite-carbonate alteration and contrary to the latter, it does not seem to have been controlled by volcanic stratigraphy and major tectonic structures.

Silicification of volcanic flows in the NV-N area occurs near the top of the flow units and formations, adjacent to synvolcanic faults and intrusions and within amygdaloidal flow breccias. It appears that silicification is mainly restricted to flow breccias of the upper member of the Waite Andesite formation and to the uppermost flows of the Waite Rhyolite formation. This suggests that silicification was mainly controlled by the permeability of certain flows and occurred

contemporaneously with volcanism below the seawater/rock interface. According to de Rosen Spence (1976), silicification is related to cooling of rocks whereas for Gibson (1989), Gibson et al. (1983), MacGeehan (1978), and Skirrow (1987), attributed it to the interaction of a hot fluid with volcanic rocks in a shallow sub-seafloor hydrothermal system.

Silicification within the Waite Andesite formation is almost exclusively restricted to the upper member. Underlying pillowed flows of the lower member are not pervasively silicified indicating that the hydrothermal system was stratabound, i.e., confined to the upper member of the formation and that fluid flow was probably lateral.

Silicification within the Waite Rhyolite formation is widespread and pervasive within the uppermost flows and intense in proximity to the VCF and the feeder dykes. This suggests, first, that fluid flow was lateral and confined to the more permeable flow-top of the formation, but that, secondly, fluid flow was also vertical and confined to conduits that channelled hydrothermal fluids.

The lateral and vertical variations in the intensity and distribution of the epidote-quartz alteration are similar to that of silicification in the upper member of the Waite Andesite formation. Epidote-quartz alteration is rare in rhyolitic flows, probably because of the primary low Ca content of rhyolites. It is a synvolcanic process that was

mainly controlled by the permeability of flows, and occurred contemporaneously with silicification and within the sub-seafloor hydrothermal system.

Harrigan and MacLean (1976) presented an account of epidote-rich alteration patches developed in gabbro dykes and volcanic rocks from Matagami Lake and they interpreted them to be the product of hydrothermal alteration during interaction of a fluid with cooling intrusions. Epidotization of diorite plutons at Al Hadah, Saudi Arabia was interpreted by Marzouki et al. (1979) to result from the interaction of deep formation water with the dioritic rocks during cooling. And epidote-quartz alteration with the Troodos pillow lava succession resulted from the interaction of evolved seawater and an underlying igneous complex at a depth of 2-3 km within a sub-seafloor hydrothermal system (Spooner 1977, Heaton and Sheppard 1977, Schiffman and Smith 1988).

Chloritization is not a widespread alteration type within rocks of the NV-N area. It is restricted to flow breccias where it replaced the original glass shards, and interstitial glass, and filled amygdules. Chloritization is a synvolcanic process that probably results from devitrification and subsequent alteration of rocks. According to de Rosen Spence (1976), chloritization is related to the cooling of the flows, and is closely associated with silicification.

Sericitization and associated carbonatization occur in cross-cutting zones of the volcanic rocks. They are clearly transgressive processes that post-dated silicification, epidote-quartz alteration and chloritization and they may be the products of late-stage processes.

Fig. 4.1. Distribution of alteration facies within the New Vauze-Norbec area.

Fig. 4.2.

- A. Fibro-radial spherulites within the Waite Rhyolite formation, sample 634-86. Scale bar is 0.05 mm long.
- B. Recrystallization of spherulites into coarse fibres, sample 650-86. Scale bar is 0.05 mm long.
- C. Overgrowths of spherulites by quartz as micropoikiloblastic quartz texture, sample 582-86. Bar scale is 0.05 mm long.
- D. Spherulites completely recrystallized to blebby quartz, sample 651-86. Bar scale is 0.1 mm long.
- E. Silicified amygdaloidal rhyolitic fragments within flank breccias of the Waite Rhyolite formation.
- F. Silicified matrix of flow breccia, Waite Rhyolite formation.

Fig. 4.3.

- A. Irregular diffuse white-weathering siliceous patches, Waite Rhyolite formation. Note the flow-banding.
- B. Irregular amygdaloidal white-weathering siliceous patches, Waite Rhyolite formation.
- C. Silicified halos mantling quartz amygdules, Splinter member, Waite Andesite formation.
- D. Small quartz veinlets within rhyolitic flows of the Waite Rhyolite formation.
- E. Rhyolitic fragments with incompletely silicified rim.
- F. White silicified, amygdaloidal andesitic fragments, Waite Andesite formation.

CHAPTER 5. GEOCHEMISTRY

5.1 INTRODUCTION

The purpose of the geochemical study was to assess the chemical mobility during synvolcanic alteration of volcanic rocks, principally the rhyolites, and to characterize the andesitic and rhyolitic formations of the NV-N area. Such studies are important because they provide information on the physical and chemical properties of alteration fluids that are reflected in the chemical signatures of the different volcanic formations. Such information can be applied to mineral exploration strategy.

An understanding of the geochemistry of altered volcanic rocks of the New Vauze-Norbec (NV-N) area requires some knowledge of the "primary" geochemistry of the protolith rocks. So the geochemistry of the "least altered" volcanic rocks of the area will first be discussed and geochemistry of more altered rocks will followed. For the purposes of this study, "least altered" rocks are characterized by the mineral assemblage of the spilitized rocks, i.e. albite-chlorite-actinolite-quartz-epidote-calcite-sphene/leucoxene for the andesites and quartz-albite-chlorite-sericite-calcite for the rhyolites.

Major, trace and rare earth element analyses are listed in appendix III. Average composition of flow facies of the volcanic formations and members are listed in Tables III.1 to

3

MICROCOPY RESOLUTION TEST CHART
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Fig. 4.4.

- A. Silicified amoeboid fragments within the upper member of the Waite Andesite formation
- B. Silicified ribbon-like forms within the upper member of the Waite Andesite formation.
- C. Andesitic amoeboid fragments with a silicified rim and a more chloritic centre, Waite Andesite formation.
- D. Silicified halos mantling quartz-epidote amygdules in pillowed andesite of the Waite Andesite formation.
- E. Epidote-quartz patches within the Waite Andesite formation.

Fig. 4.5.

- A. Quartz crystals replacing plagioclase phenocryst, sample 160-85, Fish Roe formation. Scale bar is 0.025 mm long.
- B. Chloritized rhyolitic fragments within the Amulet formation. Sample 86-85. Scale bar is 0.1 mm long.
- C. Sericite and calcite in the groundmass of flow-banded rhyolite, sample 374-86. Scale bar is 0.05 mm long.
- D. Plagioclase phenocrysts altered to aggregates of calcite and sericite crystals. Sample 640-86. Scale bar is 0.025 mm.
- E. Intense sericite alteration zone marked by a well-developed foliation within the Waite Rhyolite formation.

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Major, trace and rare earth element analyses are listed in appendix III. Average composition of flow facies of the volcanic formations and members are listed in Tables III.1 to

III.9 in appendix III. Andesite in this study refers to rocks of basaltic and andesitic composition.

The geochemistry of volcanic rocks of the NV-N area is complex because of the different alteration events, namely diagenesis, spilitization, hydrothermal alteration and metamorphism that have affected the rocks. The geochemical variability is due to a number of factors including the primary geochemical characteristics of the rocks on eruption, hydrothermal alteration contemporaneous with volcanism and alteration associated with the regional metamorphism. Chemical changes that occurred during initial seafloor weathering are virtually impossible to assess because of the subsequent replacement of early alteration minerals by later alteration mineral assemblages (chapter 4).

5.2 GEOCHEMICAL CHARACTERISTICS OF VOLCANIC ROCKS

1. As previously shown by de Rosen Spence (1976), Gelinas et al. (1977) and Ujike and Goodwin (1987) for volcanic rocks of the CNVC, the least altered and altered volcanic rocks of the NV-N area are classified as subalkalic (Fig. 5.1a).
2. On the basis of their SiO_2 content, volcanic rocks of the NV-N area were classified as andesite, dacite, and rhyolite. The diagram $\text{Al}_2\text{O}_3 - \Sigma\text{FeO} + \text{TiO}_2 - \text{MgO}$ (Fig.

5.2) of Jensen (1976) generally supports the SiO_2 classification. Least altered rhyolites and andesites plot in their appropriate fields (Fig. 5.3) but silicified andesites plot in the rhyolitic and dacitic fields and chloritized-sericitized flow brecciated rhyolites plot in the dacitic field (Fig. 5.4).

3. Most volcanic rocks of the NV-N area have low Ca and high Al contents relative to typical compositions of unaltered equivalents (LeMaitre 1976). Data of the NV-N area plotted on an alkali ratio diagram (Fig. 5.5) show that most of the volcanic rocks lie within the spilite field, whereas data of most of the dioritic dykes plot within the igneous spectrum field. This suggests that early spilitization affected the volcanic rocks and not the later dioritic dykes of the NV-N area.
4. Scatter diagrams with SiO_2 (Fig. 5.6) and Al_2O_3 (Fig. 5.7) on the abscissa and the other major elements on the ordinate show a large range of SiO_2 contents for andesite (47.4% to 82.3%), 64.3% to 82.2% SiO_2 for rhyolites and the Al_2O_3 content range from 8.6% to 17.9% for rhyolites and 9.9% to 20.1% for andesites.

Andesites and rhyolites show a decrease in Al_2O_3 , FeO, MgO, MnO, TiO_2 , CaO, and P_2O_5 contents with an increase in SiO_2 . Na_2O and K_2O show no distinct trend

with SiO_2 , although K_2O is slightly more enriched in some rhyolitic samples.

The variations of Na_2O and CaO levels in rocks of the NV-N area are attributed to their addition and subtraction during spilitization of rocks.

5. On the basis of major element geochemistry using the diagrams (1) SiO_2 vs $\text{FeO}t/\text{MgO}$ (Fig. 5.1b) of Miyashiro (1974), (2) AFM (Fig. 5.8) of Irvine and Baragar (1971), and (3) $\text{Al}_2\text{O}_3 - \Sigma\text{FeO} + \text{TiO}_2 - \text{MgO}$ (Fig. 5.2) of Jensen (1976), volcanic rocks of the NV-N area plot in both tholeiitic and calc-alkaline fields.

On the popular AFM diagram (Fig. 5.8), least altered rhyolites plot in the tholeiitic field and altered rhyolites straddle the tholeiitic - calc-alkaline field boundary. Least altered andesites plot within the calc-alkaline field on a AFM diagram and altered andesites straddle the tholeiitic - calc-alkaline field boundary on such adiagram. On the Jensen diagram (Fig. 5.3), least altered and altered rhyolites are assigned to the tholeiitic field, whereas least altered and altered andesites straddle the tholeiitic and calc-alkalic fields. This inconsistency suggests that volcanic rocks of the NV-N area are not readily subdivided into tholeiitic and calc-alkaline affinities because of the mobility of alkali, Fe, Mg, Mn and P during hydrothermal

alteration. This evidently results from the dissolution of essential minerals which contain these elements and precipitation of alteration products which do not.

Gelinas et al. (1984) suggested the use of "immobile" trace element ratios, Zr/Y and Ti/Zr to discriminate between tholeiitic and calc-alkaline units (values of <4 and >70 respectively for tholeiitic andesites). According to this, volcanic rocks of the NV-N area have a tholeiitic affinity.

6. Rhyolites and andesites of the NV-N area have different concentrations of large-ion lithophile elements (LIL: Ba, Rb, K, Sr), high field-strength elements (HFS: Th, Nb, P, Zr, Hf, Ti, Y), and rare earth elements (REE: La, Ce, Nd, Sm, Eu, Gd, Dy, Yb). The difference in concentration of LIL, HFS, and REE elements between least altered and altered andesites and rhyolites is well illustrated on the spidergrams of Figures 5.9 to 5.11. The profiles defined by the LIL element content of the least altered, epidote-quartz altered and chloritized rhyolites are similar, but those defined by the silicified rhyolites are totally different. LIL element content of the least altered and altered andesites is variable and the profiles are not "regular". The least altered and altered rhyolites have similar but slightly different HFS element content. The HFS element concentration of least altered

and altered andesites is similar (except for Ti, which is higher in least altered andesites). Least altered andesites are much more enriched in LIL elements and slightly more enriched in HFS elements than typical MORB.

5.3 GEOCHEMISTRY OF LEAST ALTERED VOLCANIC ROCKS

The chemical composition of the least altered volcanic rocks of the NV-N area can be deduced from the geochemistry of the spilitized volcanic rocks. Least altered volcanic rocks have low Ca and high Na contents relative to typical compositions of unaltered equivalents (LeMaitre 1976). This is due to replacement of calcic plagioclase by albite, therefore fixation of Na and balanced release of Ca to solution according to the following reaction (Seyfried et al. 1988):

The release of Ca into solution may at one point favour the precipitation of calcic-rich minerals, as epidote, calcite, and actinolite. Spilitic alteration is largely a mineralogical change as the main chemical change to the rocks is hydration, and a loss of Ca for an equal gain of Na (Vallence 1974). According to de la Roche et al. (1974), Si and Na are introduced together, while Ca is released and Al remain in place during the spilitization. The spilitization of basalts necessitates a metasomatic introduction of Na and perhaps of Si, with a simultaneous release of Ca. According to others,

the spilites are also strongly enriched in H_2O , CO_2 and Fe^{3+} and to a lesser extent in CaO .

Within the volcanic succession of the Troodos ophiolite complex, albitization started above $200^\circ C$ in the "zeolite facies" and persisted into the "greenschist facies" ($250-450^\circ C$) where albite, chlorite, minor epidote and quartz constitute the spilitic assemblage (Lydon and Jamieson 1984). According to Arnorsson et al. (1983a, b), the conversion of calcic plagioclase to albite occurred at temperatures less than $200^\circ C$ in volcanics of the geothermal system of Iceland.

Least altered andesites and rhyolites of the NV-N area have a tholeiitic affinity. They have relatively low Al_2O_3 , and relatively flat REE patterns (Figs. 5.12a and 5.13a). Least altered rhyolites have a slightly fractionated ((La/Yb) $_n$ = 2.6-3.1) chondrite-normalized REE profile and display negative europium anomalies characteristic of tholeiites. Their REE abundances vary between 74 and 100 times chondrite and the europium anomalies (Eu/Eu*; Tab. 5.1) vary between 0.63 to 0.75. Altered rhyolites have different concentrations in REE (Figs. 5.13b and 5.14a). The least altered andesites have slightly fractionated REE profiles ((La/Yb) $_n$ = 2.7-4.5) and are characterized by negative and positive europium anomalies (Fig. 5.12a). Their REE abundances vary between 28 to 42 and their REE profile is also characteristic of tholeiitic rocks. In summary, from the andesites to the

rhyolites, the REE show an enrichment in both LREE and HREE and an increasingly negative europium anomaly.

The absolute concentration in trace element and rare earth element content of least altered andesites and rhyolites and altered andesites and rhyolites is variable, but their trace element ratios, as Y/Zr , Y/Nb , Yb/Zr , La/Zr , La/Sm and La/Yb are similar (Tables 5.1 and 5.2). This relation is well illustrated by the linear variations of Y relative to Zr, La vs Zr (Fig. 5.15) and Yb vs Zr (Fig. 5.16). The constant ratios of those elements in the andesitic and rhyolitic formations of the NV-N area suggests that they are comagmatic. On the diagram Zr vs Ti (Fig. 5.17), fresh and most altered rhyolites and andesites are compositionally distinct and define overall one tight linear array for the rhyolites and one broad field for the andesites that project toward the origin. The tight linear array of the rhyolites reflects the relative immobility of these components during alteration, whereas the broad field of the andesites reflects the mobility of the Ti and Zr during alteration. Several samples of the Splinter member plot between the main trends, which also suggests that one of the two components was probably mobile during alteration. Dacitic rocks of the Fish Roe formation plot outside the main trends in this diagram, and they have a more enriched REE profile (Fig. 5.14a), which may suggest a different magmatic origin or the mobility of all the REE during alteration.

5.4 GEOCHEMISTRY OF ALTERED VOLCANIC ROCKS

5.4.1 Introduction

In order to determine relative gains and losses of constituents during alteration, representative altered and least altered samples of equivalent lithologic units were compared by using the computational and graphical method of Grant (1986), which is called the "isocon method". Least altered andesites and rhyolites are the freshest rocks in the NV-N area and are considered to be the precursor to altered andesites and rhyolites. The "isocon method" provides a simple and direct means for considering changes in mass, volume and concentration within equivalent units during hydrothermal alteration. This method involves the establishment of a reference line corresponding to zero concentration change (the isocon) as determined by a best fit to the chemical data. The isocon is simply a graphical simultaneous solution to Gresen's equation (1967) for zero concentration change. The advantage of the isocon method is that the isocon may be established on the immobility of one component, a group of components, or on mass or volume. Once the isocon, and thus any change in mass or volume is chosen, then the determination of chemical gains and losses relative to concentration in the precursor rock can be determined graphically or mathematically by the amount of displacement away from the reference isocon.

The diagrams were prepared by plotting the weight percent of major and minor oxides and trace elements (ppm) of altered

and unaltered samples which are to be compared. Then, taking into consideration the lithology and type of alteration being compared, isocons for constant volume, or mass, and components typically considered to be immobile (e.g., Al, Ti, Zr, REE) were generated and compared to each other and to the isocon which statistically was a best fit for the plotted data points. Choice of the reference isocon for the data points fixes the compositional, mass, or volume changes to be interpreted from the data. Those elements which plot below the reference isocon are interpreted to have been lost, and those which plot above, gained during alteration.

An isocon diagram comparing least altered and altered rhyolite is presented in Figure V.1 in appendix V; Table V.1 in appendix V lists the volume change and the fractional gain and loss of each component relative to the amount in the least altered rocks. Those elements which exhibit only minor gains and losses ($\approx 0-10\%$) generally approximate the best-fit isocon as do negligible volume and mass changes ($0-10\%$).

The geochemical characteristics of the major alteration facies in the NV-N area are described below. The superposition of some alteration types (e.g. sericite-carbonate alteration on silicification) and the presence of contemporaneous and complementary alteration types (e.g. spilitization and silicification) hampers resolution of the precise alteration signatures for some facies. Also, silicified, epidote-quartz altered, and chloritized rocks have undergone previous

diagenetic and spilitic alteration. Therefore, the calculated mass gains and losses attendant to an alteration type are only an approximation and reflect all the chemical changes inherited from the complex hydrothermal-metamorphic history of the sample. The most altered samples characteristic of the different types of alteration discussed in chapter 4 were selected for this study.

5.4.2 Alteration of rhyolites

Figure 5.18 shows the calculated mass gains and losses of chemical components across a rhyolitic lobe from the centre to the surrounding flow breccia relative to the least altered rhyolitic lobe. The centre of lobe is siliceous and characterized by spherulitic texture (spherulites slightly recrystallized to blebby granular quartz; Fig.4.1d). The white colour, the occurrence of halos mantling elongate amygdules and the high SiO_2 content of rim of lobe attest to its silicification. The chloritic selvage has a brownish colour and a fine-grained hyaloclastite texture. The surrounding flow breccia consists of silicified fragments in a more mafic, fine-grained breccia matrix. Also shown in Figure 5.18 is the range of gains and losses in about 12 altered lobes studied. Since Al_2O_3 , Zr, TiO_2 , plot close to a line through the origin in the isocon plots of less altered versus altered samples, these components are inferred to have been relatively immobile (except Ti loss and Zr addition from epidotized rhyolites)

whereas elements such as Na, Ca, Mg, Si, Fe, K, Mn, Rb, Sr, and Ba are generally mobile. The gains and losses of Figure 5.18 were measured directly from the isocon plots, so that immobile behaviour is indicated by very small deviations from the zero-change line (i.e. the isocon).

The centre of lobes is enriched in Ca, K, Rb, Sr and depleted in Fe, Mg, and Mn compared to least altered rhyolites. Y and REE are slightly depleted but this variation is within the sampling and analytical errors. The margin of lobes shows a slight enrichment in Si, an enrichment in Na, and losses in Fe, Mg, Mn, Ca, and K compared to the centre of lobes. The chloritic selvage of lobes is depleted in Ca, Na, Mn, and Y, and enriched in Mg and K. The surrounding flow breccias are enriched in Si, Fe, Mg, Mn, Ca, and K and depleted in Na. Most chemical components in the silicified margin of lobes have opposite trends to those of the chloritic selvage and element enriched in the margin of lobes are more or less balanced by depletions of the same element in the selvage. Al, Zr, Ti, REE do not show much variation.

In summary, most major elements (except Al and Ti) were mobile during alteration of the lobes. REE, Ti, Al_2O_3 , and Zr do not show much variation, and the variation is within sampling and analytical errors. This suggests that the REE and Ti, Zr, and Al have not been very mobile during moderate silicification and chloritization of rhyolitic lobes. The centres of the large lobes were generally not silicified but

recrystallized to a spherulitic texture with blebby granular quartz selectively replacing the spherulites.

Figure 5.19 illustrates the mass gains and losses in pervasively silicified, and moderately chloritized, epidote-quartz altered, and sericite-carbonate altered rhyolites relative to the least altered rhyolites.

Pervasively silicified rhyolites show an enrichment in Si, and depletion in Fe, Mg, and Mn. Most of the REE elements, except Sm and Eu which are slightly depleted, are relatively immobile. Th, Hf, Zr, Y, Al, and Ti do not show any variation during silicification. The REE and HFS interelement ratios between silicified and least altered rhyolites are similar (Table 5.1). The behavior of Ca, Na, K, and P is variable and reflects the epidote-quartz alteration of the samples and more specifically the state of alteration of feldspar. Loss of Fe, Mn and Mg reflects the replacement by a mosaic of fine-grained quartz of the groundmass composed of chlorite, sericite and feldspar. Loss of Fe, Mn, and Mg during silicification of rhyolites is also illustrated qualitatively in the Jensen diagram of Figure 5.4b. On a AFM diagram (Fig. 5.8), the alteration trend is towards alkali enrichment, due to the addition of Na and loss of Fe, and Mg, and thus resembles a calc-alkaline differentiation trend or the alkali-enrichment part of a tholeiitic differentiation trend.

Epidote-quartz altered rhyolites display large gains of Ca, K, Rb, and Sr, have slightly higher Si, Mg, Zr, Th, and HREE values and lower Na, Fe, Mn, P, and Y values than the least altered rhyolites. Al, Ti, and Hf are the least mobile components. Ca and Sr, as K and Rb, have similar ionic radii, so they behave coherently. P has a high ionic potential and may be soluble as complex anions in hydrothermal fluids (Mason 1966, Leshner et al. 1986); it probably reflects here the breakdown of apatite. These chemical changes reflect well the mineralogical changes that occur during epidote-quartz alteration. The gain in Ca, the small change in Si, and the constant Al correspond to the appearance of epidote and quartz. The depletion of Na corresponds with the destruction of the plagioclase and the decrease of Fe and Mn correspond with the replacement of chlorite by epidote and quartz.

Chloritized rhyolites are enriched in Mg and K, and are depleted in Ca, Na, and P. Mg (and Fe) is retained in the chlorite and the enrichment in K reflects the abundance of sericite in the groundmass and as minute crystals on the feldspars. Ti, Al, Zr, and REE do not show much variation, except for Sm and Eu which have been depleted.

Sericite-carbonate altered rhyolites display enrichment in Si, Ti, Ca, and K, and depletion in Mg and Na. Al and Zr are immobile. The enrichment in Si reflects the prior silicification of these rocks. The larger alkali elements (K and Ca) were concentrated in sericite and calcite during the

breakdown of feldspar, whereas the smaller Na and Mg ions were excluded.

REE element mobility

The REE data for altered rhyolites are plotted in Figures 5.13 and 5.14 and show the following features: 1) the LREE profile for the altered rhyolites is parallel to that of the least altered rhyolites, 2) moderately silicified rhyolites have similar REE contents to those of the least altered rhyolites, 3) pervasively silicified and chloritized rhyolites have similar REE profiles (except for lower Eu content in chloritized rhyolites) and both have slightly lower REE content than the least altered rhyolites, and 4) epidote-quartz altered rhyolite is slightly enriched in HREE compared to the least altered rhyolites, which probably reflects crystallization of trace-element-enriched phases, such as zircon. Gains and losses calculated by Grant's method indicate that pervasively silicified rhyolites are slightly depleted in Sm and Eu, and the other REE elements remained relatively immobile. The only analyzed epidote-quartz altered rhyolite is enriched in HREE compared to the least altered rhyolites. LREE and HREE in chloritized rhyolites have been relatively immobile, except for Sm and Eu which have been slightly depleted. REE profile of chloritized sample #542-86 is similar (except for slightly lower Eu value) than the profile of sample #443-86 (silicified rim of lobe). Pervasively

silicified sample #386-86 has also a similar REE profile to unsilicified devitrified rhyolite and according to Grant's method do not show much variation in REE.

In summary, most REE elements (except Sm, Eu for silicified and chloritized rhyolites and Yb for epidote-quartz altered rhyolite) are relatively immobile during alteration. The LREE (specially Eu^{+2}) have larger ionic radii than the HREE and are potentially more mobile; they also have low ionic potentials and are concentrated mainly in feldspars which altered easily. The small differences in most REE and HFS (Zr, Hf, Th, and Y) element contents between least altered rhyolites and strongly silicified rhyolites are less than that required by simple dilution of REE during silicification. A process such as congruent dissolution, implying the transport of these elements in proportion to their primary abundance in every type of alteration studied seems unlikely because the concentration of different trace elements varies among different accessory phases (Clark 1984), and preservation of trace element ratios during alteration and trace element mobilization would be fortuitous. Thus, elements which preserve interelement ratios have probably remained relatively immobile. The computations suggest that a volume differential between altered and least altered rhyolites could account for the differences in absolute concentrations of Al, Ti, HFS, and REE. Mass balance calculations suggest that intense silicification was accompanied by large volume increases,

relative conservation of volume for epidote-quartz alteration, and a small volume decrease for chloritization of rhyolites.

5.4.3 Alteration of andesites

Figure 5.20 shows the calculated mass gains and losses of chemical components in silicified, chloritized, and epidote-quartz altered andesites.

Three samples (#401, #115, #349) of silicified ribbon-like fragments, one silicified pillow (#251) and one silicified flow breccia (#348) of the upper member of the Waite Andesite formation are plotted in Figure 5.3. Based on constancy of ratios of Al_2O_3 in altered and least altered andesites, Si, Na, Ca, K, P, Sr, Zr, Y and REE (middle and HREE) are enriched, and Fe, Mg, and Mn are depleted in ribbon-like fragments. Silicified pillow and flow breccia show the same element behavior.

The behavior of the chemical components during epidotization is about the same as that during silicification. Epidote-quartz altered andesitic flow breccias are enriched in Si, Ca, Na, P, Zr, Y, and REE and depleted in Mg and Mn. Similar enrichment in Ca, Sr, and REE has been reported by Ludden et al. (1982) in an epidotized margin of a pillow from the Rouyn Noranda region. Marzouki et al. (1979) noted an increase in Ca, Fe, and Sr content, a depletion in Mg, Na, K, and Ba content and relatively constant Al, Ti, Y and Zr in epidotized diorite. Epidotized cores of pillows in the Snow

Lake area, Manitoba, display large gains of Ca and are depleted in Na (Skirrow 1987).

The flow breccia samples chosen to quantify the chloritization are slightly and variably chloritized and possibly sericitized as sericite is abundant in the rocks. The most chloritized sample is enriched in Fe, Mg, K, and Zr and depleted in Si and Na.

Compared to least altered andesites, silicified, epidote-quartz altered and chloritized andesites have higher REE element abundances (Fig. 5.20).

The REE and HFS interelement ratios in altered andesites are similar, but differ from the least altered andesites (Table 5.1).

5.5 SUMMARY AND CONCLUSION

Many geochemical studies have demonstrated the mobility of major elements during hydrothermal alteration. Trace elements such as Al, Ti, Zr, Nb, Y and the REE remain relatively immobile in rocks subject to low-grade metamorphism and/or hydrothermal alteration (e.g., Pearce and Cann 1973, Winchester and Floyd 1977, Humphris et al. 1978, Floyd and Winchester 1978, Ludden et al. 1982, Whitford et al. 1989). Low mobility of Al is commonly assumed in low grade metamorphic rocks and in several types of hydrothermal alteration (e.g., MacGeehan 1978, Strong et al. 1979, Costa et al. 1983, Morton and Nebel 1984, MacLean and Kranidiotis

1987, Duchac and Hanor 1987). It has also been claimed that under large XCO_2 gradients and in some cases of extreme alteration, some of the elements mentioned above are, in fact, mobile (e.g., Hynes 1980, Finlow-Bates and Stumpfl 1981, Larson 1984, Wynne and Strong 1984, Murphy and Hynes 1986). REE are regarded as immobile under conditions of low grade metamorphism (Humphris et al. 1978, Ludden et al. 1982), but mobility of certain REE has also been reported in alteration associated with some volcanogenic mineralization; for example, the alteration zone below massive sulphide ore bodies may have been leached of their LREE and middle REE (Campbell et al. 1984) or of all their REE (MacGeehan and MacLean 1980), or may have also been enriched in LREE (MacLean 1988). Also low temperature seafloor alteration can lead to LREE enrichment in pillow basalts (Ludden and Thompson 1979), or depletion of all the REE (Staudigel and Harth 1983).

Using the elements of low mobility as monitors, mass gains and losses of other constituents and volume changes during alteration of rhyolites and andesites were calculated.

The most silicified rhyolites of the NV-N area are enriched in Si, Na and depleted in Fe, Mg, and Mn. Ti, Al, HFS, REE (except for lower Sm and Eu values) are relatively immobile. The epidote-quartz altered rhyolites are strongly enriched in Ca, K, slightly enriched in HREE and Zr and depleted in Na, Fe, P, Y. The chloritized rhyolites are enriched in Mg, and depleted in Ca, Na, and P. The REE

remained relatively immobile, except for lower Sm and Eu values.

The most silicified andesites are enriched in Si, Na, Ca, K, P, Zr, Y and REE (middle and HREE) and depleted in Fe, Mg and Mn. LREE are relatively immobile and the difference in their absolute concentrations can be explained by a volume change between altered and least altered andesites. The most chloritized andesites are enriched in Fe and Mg and depleted in Si, Na.

MacGeehan and MacLean (1980) showed that all the REE and Ti were mobile during silicification of basalts from Matagami in Quebec. Gibson et al. (1983) in their study of silicification of the Amulet Rhyolite in the Noranda district, assumed that rock volume was conserved. This assumption was based on the preservation of the original volcanic texture even in the most altered sample and the excessive volume changes (10-70%) required if Ti and Al were assumed to have been immobile. During silicification of andesitic rocks, Si and Ca were added, and Al, Fe, Mg, and Ti were removed. Reinterpretation of these data by Grant (1986) using the "isocon" method and assuming constant Al, indicates that Fe, Mg, Ti, and P were removed and Si, Na, Ca, and K were added during silicification. Lesher et al. (1986) determined that REE, Y, Zr, Th, and Hf were relatively immobile during silicification, epidotization, chloritization and sericitization. According to them, Al and Ti were mobile but

on consideration of sampling and analytical errors, they suggested that the variations in the gains and losses of Al and Ti may not be significant. Skirrow (1987) determined that Ti, Zr, Al and HREE were immobile during silicification, and epidotization of pillows in the Edward Lake area, Manitoba. LREE appear to have been mobile and may have been enriched in the silicified and epidotized parts of the pillow; the REE (except Yb) were slightly depleted during silicification of felsic volcanoclastic rocks. Osterberg et al. (1987) showed that Al remained constant and Zr, Ti were slightly mobile during hydrothermal alteration of felsic volcanic rocks in the vicinity of the Headway-Coulee massive sulphide occurrence in NW Ontario.

The results of Osterberg et al. (1987) and those of Lesher et al. (1986) and Skirrow (1987), agree with our results concerning the low mobility of Al, Ti, and Zr during silicification, but differ from the mobility of the REE observed during alteration of rocks of the NV-N area.

In summary, relative to the least altered rhyolites, silicified rhyolites are enriched in Si, Na, and depleted in Fe, Mg, and Mn. The most silicified andesites are also enriched in Si, Na, and depleted in Fe, Mg, Mn, but contrary to the silicified rhyolites, they are enriched in REE. Mass balance calculations suggest that intense silicification was accompanied by large volume increases (< 40%). Lesher et al. (1986) indicated volume changes as large as 30% during

silicification. Epidotized rhyolites and andesites are slightly enriched in REE compared to silicified andesites. The epidote-quartz altered rhyolites are enriched in Ca, K, REE and Zr and depleted in Na, Fe, P, Y. Volume was slightly increased during epidotization. The chloritized rhyolites and andesites are enriched in Fe, Mg, and depleted in Ca, Na. P and REE (except Yb) are enriched within the chloritized andesites, whereas they are depleted within the chloritized rhyolites. Volume is slightly decreased within the chloritized rhyolites and the andesites. The sericitized rhyolites are enriched in Si, Ca, K, and depleted in Na. The calculated volume changes during alteration of rocks of the NV-N area are consistent with the well preserved volcanic texture of the rocks, although Lesher et al. (1986) indicated that a 30% volume change during silicification corresponds to a 9.1% linear change that would be difficult to resolve in the fine-grained mesostasis of the rocks.

Table 5.1. Average trace element contents of least altered and altered rhyolites and andesites.

Rhyolites

	L.a. n=3	Sil. n=5	Ep-Qtz n=1	Chl n=2
(La)n	85 ± 11	63 ± 7	90	70 ± 5
La/Sm	1.9 ± 0.1	2.1 ± 0.1	1.9	2.0 ± 0.1
La/Yb	2.8 ± 0.2	2.6 ± 0.3	2.6	2.2 ± 0.1
Eu/Eu*	0.7 ± 0.05	0.7 ± 0.03	0.8	0.6 ± 0.1
Ti/Zr	5.0 ± 0.9	5.1 ± 0.25	3.3	4.5 ± 0.7
Al/Zr	213 ± 18	218 ± 16	180	202 ± 32
Y/Zr	0.2 ± 0.02	0.22 ± 0.06	0.21	0.2 ± 0.06

Andesites

	L.a. n=5	Sil. n=1	Ep-Qtz n=1	Chl n=1
(La)n	35 ± 5	42	48	52
La/Sm	2.0 ± 0.5	1.8	1.6	1.7
La/Yb	3.5 ± 0.6	2.4	2.3	2.7
Eu/Eu*	0.9 ± 0.2	0.9	0.9	0.9
Ti/Zr	72 ± 15	41	35	42
Al/Zr	794 ± 200	474	446	493
Y/Zr	0.31 ± 0.1	0.16	0.30	0.28

 Abbreviations: L.a. = least altered, Sil.= silicified, Ep-Qtz = epidote-quartz altered, Chl = chloritized, n = number of samples.
 Eu*: calculated by linear interpolation between chondrite-normalized Sm and Gd.

Table 5.2. Al_2O_3 and TiO_2 (wt.%) and ratios of trace element content of volcanic formations of the New Vauze-Morbec area.

	Waite Andesite (n=36)	Amulet Andesite (n=18)	D'Alembert Andesite (n=3)	Morbec Andesite (n=33)	New Vauze Andesite (n=10)
Al_2O_3	9.9-17 (14.3 $\pm$ 2.0)	13.2-20.1 (16.0 $\pm$ 1.4)	13.6-17.1 (15.1 $\pm$ 1.5)	12-18.7 (15.6 $\pm$ 1.7)	13.0-15.3 (14.1 $\pm$ 0.7)
TiO_2	0.6-1.8 (1.1 $\pm$ 0.2)	0.5-1.6 (1.1 $\pm$ 0.2)	0.5-0.6 (0.6 $\pm$ 0.04)	0.6-1.7 (1.2 $\pm$ 0.2)	1.24-1.56 (1.36 $\pm$ 1.0)
	(n=25)	(n=21)	(n=3)	(n=12)	(n=9)
Ti/Zr	22-80 (37 $\pm$ 12)	28-323 (75 $\pm$ 60)	38-48 (45 $\pm$ 5)	53-151 (103 $\pm$ 26)	74-115 (97 $\pm$ 13)
Al/Zr	308-740 (350 $\pm$ 190)	363-1884 (972 $\pm$ 504)	778-1293 (1033 $\pm$ 210)	1157-1874 (1381 $\pm$ 249)	736-1111 (878 $\pm$ 135)
Y/Zr	0.1-0.3 (0.2 $\pm$ 0.06)	0.1-1.0 (0.2 $\pm$ 0.2)	0.1-0.3 (0.2 $\pm$ 0.08)	0.1-0.5 (0.3 $\pm$ 0.1)	0.2-0.4 (0.3 $\pm$ 0.06)
Y/Nb	0.5-4.0 (1.7 $\pm$ 0.9)	0.3-3.0 (1.2 $\pm$ 0.8)	0.3-1.0 (0.7 $\pm$ 0.3)	0.5-3.0 (1.4 $\pm$ 0.9)	1.0-4.0 (1.7 $\pm$ 1.1)
	(n=4)	(n=1)	(n=1)	(n=1)	(n=1)
La/Zr	0.09-0.13 (0.1 $\pm$ 0.02)	0.07	0.13	0.12	0.08
(La/Sm)n	1.6-2.8 (2 $\pm$ 0.5)	1.7	2.6	1.6	1.6
(La/Yb)n	2.3-4.0 (2.9 $\pm$ 0.6)	2.7	4.5	3.1	3.1
Eu/Eu*	0.8-1.0 (0.9 $\pm$ 0.07)	1.0	0.7	1.1	1.2
	(n=129)	(n=25)	(n=3)	(n=3)	
	Waite Rhyolite	Splinter member	Fish Roe (rhyolite)	Fish Roe (dacite)	
Al_2O_3	8.6-16.1 (11.5 $\pm$ 0.4)	9.9-17.9 (12.5 $\pm$ 1)	10.1-11.3 (10.8 $\pm$ 0.5)	9.7-10.7 (10.3 $\pm$ 0.4)	
TiO_2	0.2-0.7 (0.3 $\pm$ 0.04)	0.2-1.2 (0.6 $\pm$ 0.2)	0.2-0.4 (0.3 $\pm$ 0.1)	0.9-1.0 (0.9 $\pm$ 0.04)	
	(n=119)	(n=15)	(n=2)	(n=2)	
Ti/Zr	3.5-15 (5.3 $\pm$ 2.3)	4.7-20.3 (13 $\pm$ 8)	6.3-6.8 (6.5)	(12.4-12.8) (12.6)	
Al/Zr	158-272 (201 $\pm$ 19)	199-399 (280 $\pm$ 58)	255-260 (258)	132	
Y/Zr	0.1-0.3 (0.2 $\pm$ 0.05)	0.1-0.4 (0.2 $\pm$ 0.06)	0.22	0.4	
Y/Nb	1.0-7.0 (2.8 $\pm$ 0.9)	1.3-5.8 (2.5 $\pm$ 1.3)	1.7	3.2-4.5 (3.9)	
	(n=19)	(n=2)	(n=1)	(n=1)	
La/Zr	0.07-0.1 (0.08 $\pm$ 0.01)	0.06		0.09	
(La/Sm)n	1.6-2.3 (2.0 $\pm$ 0.2)	1.8-1.9		1.2	
(La/Yb)n	2.1-3.4 (2.7 $\pm$ 0.4)	1.7-2.2		1.6	
Eu/Eu*	0.5-0.8 (0.6 $\pm$ 0.07)	0.4-0.7		0.5	

(2.0 $\pm$ 0.1): Arithmetic mean and standard deviation, (n=2) = number of samples.

Fig. 5.1. (A) SiO₂ - Na₂O + K₂O diagram for all the rocks of the New Vauze-Norbec area; symbols same as figure (B). (B) SiO₂-FeO/MgO diagram of Miyashiro (1974) for rocks of the New Vauze-Norbec area.

Fig. 5.2. (A) Jensen diagram of average composition of the volcanic formations of the New Vauze-Norbec area. Chemical components calculated as molecular proportions (Jensen 1976). (B) Jensen diagram of representative chemical analyses of volcanic rocks of the NV-N area.

Fig. 5.3. Jensen diagram of compositional field of altered and least altered andesites and rhyolites of the New Vauze-Norbec area. Chemical components calculated as molecular proportions (Jensen 1976).

Fig. 5.4. Jensen diagram of the least altered and altered andesites of the Waite Andesite formation (A) and of the least altered and altered rhyolites of the Waite Rhyolite formation (B).

Fig. 5.5. Alkali ratio diagram of Hughes (1973) to illustrate the spilite composition of most rocks of the New Vauze-Norbec area.

Fig. 5.6. Harker diagrams of major element oxide versus SiO_2 for volcanic rocks of the New Vauze-Norbec area. FR=Fish Roe, WA=Waite Andesite, AA=Amulet Andesite, NA=Newbec Andesite, DA=D'Alembert Andesite, WRnv=New Vauze member, WR=Waite Rhyolite, Al=Amulet, Was=Splitter member.

Fig. 5.6. Continued.

Fig. 5.7. Variation diagrams of major element oxide versus Al_2O_3 for volcanic rocks of the New Vauze-Norbec area.

Fig. 5.8. (A) AFM plot of least altered volcanic rocks of the New Vauze-Norbec area. A = Na₂O + K₂O, F = FeO = 0.8998 Fe₂O₃, M = MgO, in weight percent. Field boundary from Irvine and Baragar (1971). (B) AFM plot of all the volcanic rocks of the New Vauze-Norbec area .

Fig. 5.9. (A) "Spidergrams" of least altered rhyolites of the Waite Rhyolite formation. (B) "Spidergrams" of the silicified rhyolites of the Waite Rhyolite formation. WR₁ = Waite Rhyolite, flow unit #1. Methods of construction of the Spidergrams are explained in appendix VI.

Fig. 5.10. (A) "Spidergrams" of epidote-quartz altered rhyolite of the Waite Rhyolite formation. (B) "Spidergrams" of the chloritized rhyolites of the Waite Rhyolite formation. WR₁ = Waite Rhyolite, flow unit #1. Methods of construction of the Spidergrams are explained in appendix VI.

Fig. 5.11. (A) "Spidergrams" of least altered andesites. AA = Amulet Andesite, DA = D'Alembert Andesite, NA = Newbec Andesite, WA = Waite Andesite. (B) "Spidergrams" of altered andesites of the Waite Andesite formation. Methods of construction of the Spidergrams are explained in appendix V.

Fig. 5.12. Chondrite-normalized rare earth element profiles of the least altered andesites (A) and altered andesites (B).

Fig. 5.13. Chondrite-normalized rare earth element profiles of the least altered rhyolites (A) and altered rhyolites of the Waite Rhyolite formation (B). WR₁ = Waite Rhyolite formation, flow unit #1.

Fig. 5.14. Chondrite-normalized rare earth element profiles of altered rhyolites (A) and feeder dykes of the Waite Rhyolite formation (B). WAs = Splinter member of the Waite Andesite formation, FR = Fish Roe formation, WR₁ = Waite Rhyolite formation, flow unit #1.

Fig. 5.15. (A) Plot of Y vs. Zr for all analysed rhyolites and andesites of the New Vauze-Norbec area. (B) Plot of La vs. Zr for andesites and rhyolites of the New Vauze-Norbec area.

Fig. 5.16. Plot of Yb vs. Zr for all rhyolites and andesites of the New Vauze-Norbec area.

Fig. 5.17. Plot of Zr vs. Ti for all analysed rocks of the New Vauze-Norbec area. The linear arrays projecting toward the origin reflect the overall low mobility of these components during the alteration.

Fig. 5.18. Mass gains and losses across rhyolitic lobes and adjacent flow breccia of the Waite Rhyolite formation and the range of gains and losses of all rhyolitic lobes studied. Mass changes were calculated by Grant's (1986) method as a percentage of the mass proportion of each chemical component in the least altered samples.

Fig. 5.19. Mass gains and losses in silicified, epidote-quartz altered, chloritized, and sericite-carbonate altered rhyolites of the New Vauze-Norbec area. Mass changes were calculated by Grant's (1986) method as a percentage of the mass proportion of each chemical component in the least altered samples from the same flow of the Waite Rhyolite formation.

Fig. 5.19. Continued.

Fig. 5.20. Mass gains and losses in silicified, epidote-quartz altered, and chloritized andesites of the Waite Andesite formation of the NV-N area. Mass changes were calculated by Grant's (1986) method as a percentage of the mass proportion of each chemical component in the least altered samples from the Waite Andesite formation.

Fig. 5.20. Continued.

CHAPTER 6. OXYGEN ISOTOPE GEOCHEMISTRY

6.1 INTRODUCTION

An oxygen isotope study of volcanic rocks of the New Vauze-Norbec (NV-N) area was undertaken to constrain 1) the oxygen isotope composition of unaltered and altered andesites and rhyolites; 2) the temperature and $\delta^{18}\text{O}$ of the fluids associated with alteration of the andesites and rhyolites; and 3) the source of the fluids responsible for alteration of the andesites and rhyolites.

Characterization of fluids and the extent of their involvement in alteration of andesite and rhyolite flows of the NV-N area are important with regard to their possible relation to the genesis of yet undiscovered massive sulphide deposits.

Earlier oxygen isotope studies of hydrothermally altered rocks associated with massive sulphide deposits have yielded valuable information regarding the composition, temperature and origin of ore-forming hydrothermal solutions. For example, in the Abitibi belt, isotopic studies of hydrothermal alteration zones include those of the Amulet "A" Cu-Zn massive sulphide deposit (Beaty and Taylor 1982), the Cu-Zn D-68 Zone (Ikingura et al. 1989), the Zn-Pb-Cu Kidd Creek mine (Beaty et al. 1988) and the Cu-(Zn)-Au Horne mine (MacLean and Hoy 1989). Also, Beaty and Taylor (1982) reported some oxygen

isotope data on country rocks surrounding the deposits. Oxygen isotope studies of altered volcanic rocks are rare in other areas of the Abitibi belt, although the volcanic stratigraphy and the volcanology are well known.

Representative samples of least altered (as judged on the basis of preservation of their "original mineralogy" and textures) and altered volcanic rocks, as well as veins and amygdules associated with the Waite Andesite, Waite Rhyolite and Amulet formations were selected along three NE-SW transects across the NV-N area (Fig. 6.1). Rocks chosen for analysis are variably silicified, sericitized, epidotized, chloritized and carbonatized, and vary in form through massive, lobate, flow brecciated rhyolites, feeder dykes, and pillowed and flow brecciated andesites. Results and brief descriptions of the samples are given in Tables 6.1, 6.2 and 6.3. Oxygen isotope compositions of whole-rock samples of andesites and rhyolites, and quartz and feldspar phenocrysts from the rhyolites were analyzed. Oxygen isotopic composition of mineral separates of quartz, feldspar, epidote, chlorite and calcite from veins and amygdules in the Waite Andesite and Waite Rhyolite formations provide a data base for geothermometry and for fluid-composition calculations.

Whole-rock and mineral samples were prepared for isotopic analysis using standard methods. Oxygen isotope analyses were conducted using standard procedures described in appendix I. The isotopic data are presented in the standard δ -notation

(defined below), with the reproducibility of whole-rock and mineral samples typically 0.2‰ or better (appendix I).

6.2 DEFINITIONS

Oxygen isotope ratios in samples (reported in delta (δ) notation, i.e., per mil) are related to the standard (SMOW = Standard Mean Ocean Water) as follow:

$$\delta^{18}\text{O} = [(R_A - R_{\text{std}}) / R_{\text{std}}] \times 10^3$$

where R_A is the $^{18}\text{O}/^{16}\text{O}$ ratio in the sample and R_{std} is the $^{18}\text{O}/^{16}\text{O}$ ratio in the standard.

Also of interest are the oxygen-isotope fractionations between coexisting minerals, such as quartz and epidote, or between individual minerals and the hydrothermal fluid (H_2O -dominated). These fractionations are often approximated by the difference between δ -values for two substances; e.g., $\Delta_{\text{Qz-Ep}} = \delta_{\text{Qz}} - \delta_{\text{Ep}}$. The δ -value is precisely related to the fractionation factor, α , in the following way:

$$\Delta_{\text{Qz-Ep}} = (1000 + \delta_{\text{Qz}}) / (1000 + \delta_{\text{Ep}})$$

and $1000 \ln \alpha_{\text{Qz-Ep}} \approx \delta_{\text{Qz}} - \delta_{\text{Ep}} = \Delta_{\text{Qz-Ep}}$

6.3 RESULTS

6.3.1 Waite Andesite formation

Whole-rock $\delta^{18}\text{O}$ values of the Waite Andesite formation (Table 6.4) range between 5.2 and 9.7 with an average value of 7.5 ± 1.0 (1σ ; $n=14$). The lower member of the Waite Andesite formation has values ranging between 5.2 and 7.7, and the upper member has values ranging between 6.8 and 9.7 (Fig. 6.2). These and other data discussed below, reveal that weak regional metamorphism has not resulted in homogenization of oxygen isotopic values for the whole succession.

The least altered andesites of the lower member have $\delta^{18}\text{O}$ values of 5.2 and 5.8; close to the average $\delta^{18}\text{O}$ value of 5.5 reported for unaltered MORB (Muehlenbachs and Clayton 1972a, Kyser 1980). In contrast, silicified andesites of the lower member have higher $\delta^{18}\text{O}$ values of 6.6 to 7.7.

The least altered andesites of the upper member have whole-rock $\delta^{18}\text{O}$ values of 7.3 to 7.6, which are in the range of values of the silicified andesites of the lower member. This indicates that although these rocks have not undergone noticeable mineralogical alteration other than spilitization, they have undergone some isotopic exchange with circulating fluids. Very fine-grained groundmass, feldspar phenocrysts and microphenocrysts and glass are the most susceptible to such exchange. The silicified andesites have $\delta^{18}\text{O}$ values between 7.8 and 9.7 and the chloritized andesites have $\delta^{18}\text{O}$ values between 6.8 and 7.2. The whole-rock $\delta^{18}\text{O}$ values show a general

increase from 5.2 in the less altered rocks of the lower member of the Waite Andesite formation to 9.7 in the highly altered rocks of the upper member (Fig. 6.2).

Splinter member

Rhyolites of the Splinter member are variably silicified, chloritized, and sericite-carbonate altered. They have whole-rock $\delta^{18}\text{O}$ values (6.7 to 9.3) similar to those of the upper member of the Waite Andesite formation (Fig. 6.2).

The $\delta^{18}\text{O}$ values are typically higher in massive, less altered rhyolite ($\delta^{18}\text{O} = 9.3$) than in the chloritized and sericitized-carbonatized crackle-breccias developed in rhyolites ($\delta^{18}\text{O} = 6.7$ and 8.3). Crackle-breccias have been extensively depleted in alkalis. The oxygen isotope value of the least altered rhyolite ($\delta^{18}\text{O} = 9.3$) is much higher than assumed primary $\delta^{18}\text{O}$ value of 7 for unaltered rhyolite (Taylor 1974, Taylor and South 1985), and therefore suggesting that the "least altered" rhyolite has undergone some isotopic exchange. The variations in $\delta^{18}\text{O}$ values in rocks of initially similar chemical composition indicates a lack of oxygen isotope homogenization during progressive alteration and probably different water:rock ratios in the massive lavas and the brecciated lavas due to a different permeability.

Rhyolites of the Splinter member have lower $\delta^{18}\text{O}$ (e.g., 6.7 to 9.3) than rhyolites of the Waite Rhyolite formation

(e.g., 8.6 to 13.7). This is due, in part to the fact that these rocks are chloritized. Chlorite is known to concentrate ^{16}O relative to most other minerals during "greenschist facies" alteration (Taylor 1974). Low $\delta^{18}\text{O}$ values are also commonly observed in chlorite-rich alteration assemblages associated with Phanerozoic massive sulphide deposits (e.g., Kuroko: Hattori and Muehlenbachs 1980; West Shasta: Casey and Taylor 1982, South and Taylor 1985, Taylor and South 1985; Troodos: Heaton and Sheppard 1977). Also, rhyolites of the Splinter member may have been less permeable and therefore did not react with the fluids to the extent that did rhyolites of the Waite Rhyolite formation.

6.3.2 Waite Rhyolite formation

Rhyolites of the Waite Rhyolite formation have whole-rock $\delta^{18}\text{O}$ ranging between 8.6 and 13.7 with an average of 11.1 ± 1.3 ($n=36$). Quartz phenocrysts from these rocks have $\delta^{18}\text{O} = 8.7-11.7$ with an average of 10.0 ± 0.9 ($n=18$) and feldspar phenocrysts $\delta^{18}\text{O} = 8.4-12.6$ with an average of 11.0 ± 1.2 ($n=13$) (Fig. 6.3, Table 6.5).

Least altered rhyolites have $\delta^{18}\text{O}$ whole-rock values of 8.6-10.9, quartz phenocrysts = 8.7-9.9 and feldspar phenocrysts = 8.4-10.4, whereas visibly altered rhyolites have higher $\delta^{18}\text{O}$ whole-rock values which vary from 10.7 to 13.7, quartz phenocrysts with $\delta^{18}\text{O} = 9.1-11.7$, and feldspar

phenocrysts with $\delta^{18}\text{O} = 8.7\text{--}12.6$ (Table 6.5). Clearly, the oxygen isotope data indicate that even the least altered rocks, which do not exhibit mineralogical evidence of hydrothermal alteration other than devitrification and spilitization, are in isotopic disequilibrium (e.g., $\delta^{18}\text{O}_{\text{wr}} > \delta^{18}\text{O}_{\text{Qtz}}$) resulting from exchange of oxygen isotopes with hydrothermal fluids. Figure 6.4 shows that nearly all samples studied have $\delta^{18}\text{O}_{\text{wr}} > \delta^{18}\text{O}_{\text{Qtz}}$.

Silicified rhyolites have $\delta^{18}\text{O}$ whole-rock values of 11.1 to 13.7, i.e., are isotopically heavy by comparison to the least altered rhyolites (Table 6.5, Fig. 6.5). The highest quartz phenocryst $\delta^{18}\text{O}$ values (range = 9.1 to 11.7) and the lowest feldspar phenocryst $\delta^{18}\text{O}$ values (range = 10.8 to 12.6) are also slightly larger than those of phenocrysts from the least altered rhyolites. This is consistent with the interpretation that silicification involved extensive (higher integrated water/rock ratios) reaction with fluids.

Epidote-quartz altered rhyolites also have $\delta^{18}\text{O}$ whole-rock values (11.2 to 11.6) and quartz-phenocryst $\delta^{18}\text{O}$ values (9.8 to 10) higher than those of the least altered rhyolites, representing more extensive isotopic exchange.

Sericitized rhyolites have the most enriched whole-rock $\delta^{18}\text{O}$ values (12.5 to 13.7). A carbonatized rhyolite has a whole-rock $\delta^{18}\text{O}$ value of 10.5, and a $\delta^{18}\text{O}$ of quartz of 10.2.

6.3.3 Isotopic zonation

The whole-rock $\delta^{18}\text{O}$ values of the rhyolite flows show a broad increase with stratigraphic height along the different transects (Fig. 6.6). Along transect I, the δ -values show a broad increase from the base of flow unit #2 (10.0) to the top of the Waite Rhyolite formation (10.8). For transect II, the δ -values increase systematically from flow unit #1 (range = 8.6-9.3) to flow unit #10 (12.7). Finally in transect III, the δ -values increase from flow unit #1 (range = 9.0-12.9; average 10.5 ± 1.4) to flow unit #9 (12.8). Transect II illustrates best this increase in whole-rock $\delta^{18}\text{O}$ with the stratigraphic height in the Waite Rhyolite formation. This increase mimics the regional isotopic enrichment with stratigraphic height (see, 6.5 discussion) and to some extent, reflects the increase in silicification of the uppermost flows of the Waite Rhyolite formation: i.e., flow unit # 8, #9, and #10. Altered samples plot away from a line joining the least altered samples (dashed lines of Fig. 6.6).

Whole-rock $\delta^{18}\text{O}$ increases toward the top of individual flow units of the Waite Rhyolite formation. For example, transect I: from the base (10.0) to the top (11.7) of flow unit #2; transect II: from the base (8.6) to the top (9.3) of flow unit #1, from the base (9.2) to the top (12.5) of flow unit #2, and from the base (12.4) to the top (13.7) of flow unit #8; transect III: from the base (9.2) to the top (12.9) of flow unit #1. This is interpreted to have resulted from an

increase in permeability and fluid flow toward the top of individual flows, and interaction with seawater at relatively low temperatures.

The whole-rock, quartz and feldspar phenocrysts $\delta^{18}\text{O}$ values of massive flow facies are typically lower than those of the lobe and flow breccia facies (Table 6.6). This is because massive lava flows are not as permeable to seawater as the flow breccias, where percolating seawater can easily penetrate and alter the rocks. Also, massive flows initially consisted of more crystalline and less glassy material than the breccias, and therefore reacted less severely.

The range of whole-rock $\delta^{18}\text{O}$ of feldspar porphyritic (FP) and quartz-feldspar porphyritic (QFP) rhyolite flows is similar, although the range of values for the QFP is not as wide as the range of values for the FP: values range from 9.2 to 13.7 for the FP rhyolites and from 8.6 to 11.9 for the QFP rhyolites.

6.3.4 Veins and amygdules.

$\delta^{18}\text{O}$ of quartz in quartz and epidote-quartz veins and in amygdules of the lower and upper members of the Waite Andesite formation varies between 11.0 and 14.2 (Table 6.7). $\delta^{18}\text{O}$ of epidote varies between 4.9 and 5.7. The ranges of $\delta^{18}\text{O}$ of calcite and epidote in epidote-calcite amygdules are 9.5-10.4 and 3.6-5.0, respectively.

$\delta^{18}\text{O}$ of quartz in veins is 12.4-12.8, and quartz from amygdules has $\delta^{18}\text{O} = 13.8$. These δ -values are higher than those of quartz phenocrysts from any of the rhyolites. The $\delta^{18}\text{O}$ signature of the quartz veins cutting rhyolitic rocks (average $\delta^{18}\text{O} = 12.6 \pm 0.2$) is heavier than the vein in andesitic rocks ($\delta^{18}\text{O} = 11.1$). The $\delta^{18}\text{O}$ values of quartz from veins are generally lower than those of the amygdules. Veins have possibly acted as hydrothermal conduits and they filled later than did vesicles. Consequently, they may have recorded different temperatures of equilibrium, i.e., veins have recorded hydrothermal fluids at higher temperature of equilibrium than did amygdules which have recorded lower temperature fluids. Other plausible explanations for the difference in $\delta^{18}\text{O}$ values of veins and amygdules are the different effective water:rock ratios for the vein and amygdule-filling fluids and the possible different $\delta^{18}\text{O}$ values of the fluids.

$\delta^{18}\text{O}$ values of quartz from a quartz-chlorite vein and a quartz-feldspar vein in the Waite Rhyolite formation are 14.3 and 14.6, respectively (Table 6.7), which are much higher than simple quartz veins in rhyolites. Except for the fact that these veins cut a feeder dyke, the relative chronology of the veins in the geologic history of the area is uncertain. They could be late-stage fracture fillings formed during the waning stages of hydrothermal alteration or they could be much later.

If so, the temperature would have been lower than during the peak of hydrothermal activity related to the volcanism and their respective $\delta^{18}\text{O}$ values higher (for similar $\delta^{18}\text{O}$ of fluid).

The $\delta^{18}\text{O}$ of feldspar in quartz-feldspar veins are the same as the feldspar phenocrysts of the rhyolites indicating complete isotopic exchange of the feldspar phenocrysts with fluid.

6.4 GEOTHERMOMETRY

The mineral-quartz and epidote-calcite fractionations and calculated temperatures, and fluid compositions of the veins and amygdules associated with the rhyolites and andesites are given in Table 6.8. The calculated temperatures of formation of epidote-quartz veins and infilling of amygdules in andesitic rocks based on the epidote-quartz fractionation equation of Bottinga and Javoy (1975) are between 225°C and 260°C. The equations used for other calculations are given in Tables 6.9 and 6.10. The epidote-quartz fractionations (Δ) in amygdules and veins are generally similar (Table 6.7). The small range of the epidote-quartz fractionation (5.5 to 6.2) may imply that quartz-epidote alteration occurred over a limited range of temperature (225°C to 260°C), and suggests little subsequent modification. Assuming that epidote-quartz vein and amygdular formations are coeval with the epidote-quartz alteration and

the silicification episodes, than the epidote-quartz alteration and the silicification of rocks of the NV-N area occurred at $\approx 225^{\circ}\text{--}260^{\circ}\text{C}$. But the possibility exists that they are not contemporaneous.

Kennedy (1984) indicated that epidote-quartz alteration patches within the Flavrian pluton occurred at temperatures on the order of 350°C and epidote stain alteration along fractures occurred at 220°C . In modern, active geothermal systems, epidote-group minerals occur at temperatures $\geq 260^{\circ}\text{C}$ (Keith et al. 1968, Tomasson and Kristmannsdottir 1972). In rocks of two geothermal boreholes of the Asal Rift, Republic of Djibouti, epidote appears at temperatures around 250°C (Fouillac et al. 1989). Epidote-quartz alteration in the Troodos pillow lavas, which is similar to epidote-quartz alteration of the upper member of the Waite Andesite formation, formed at temperatures $> 300^{\circ}\text{C}$ and within the deepest part of the hydrothermal system. Epidote-quartz veins from a pillowed section of DSDP Hole 504B have epidote $\delta^{18}\text{O}$ values of 2.4 to 3.1 and quartz values of 7.7 to 11.7, for estimated temperatures of precipitation around $300^{\circ}\text{C--}350^{\circ}\text{C}$ with a $\delta^{18}\text{O}$ of fluid of +2 suggesting that the fluid was seawater that had gained $\delta^{18}\text{O}$ through high-temperature exchange with basalts (Alt et al. 1986).

Calculated temperatures of epidote-calcite amygdules in pillows of the upper Waite Andesite formation from epidote-

calcite fractionation equation of Matthews et al. (1983) are between 120°C and 200°C. These temperatures may indicate disequilibrium between calcite and epidote or may correspond to temperatures of recrystallization of calcite (assuming little or no change in $\delta^{18}\text{O}$ of epidote and the fluid).

Calculated temperatures for a quartz-chlorite vein and a quartz-feldspar vein in rhyolite rocks are 287°C and 197°C respectively.

6.5 DISCUSSION

6.5.1 General statements

Volcanic rocks of the NV-N area are pervasively spilitized and characterized by the mineral assemblage albite-chlorite-actinolite-quartz-epidote-calcite-sphene/leucoxene for andesites and quartz-albite-chlorite-sericite-calcite for rhyolites. These mineralogical assemblages characterize the least altered volcanic rocks of the NV-N area. By analogy with other studies done on recent subaqueous volcanic rocks (Staudigel and Hart 1983, Dimroth and Lichtblau 1979, Furnes 1978, Baragar et al. 1977), volcanic rocks of the NV-N area must have undergone an initial seafloor weathering process and diagenetic alteration at low temperatures (< 200°C). However, very little petrographic evidence of low temperature diagenetic alteration (except devitrification) is observed within rocks of the NV-N area. Gibson (1989) observed relict textures of palagonitization in andesite and rhyolite

vitrophyres and hyaloclastites of the Noranda area. Silicification, epidote-quartz alteration, and chloritization are not as widespread and pervasive as earlier diagenetic alteration and spilitization. They are restricted to certain zones and flows where they are superimposed on these earlier alteration facies (diagenesis and spilitization). Consequently, several alteration types (devitrification, spilitization, silicification, epidote-quartz alteration, and chloritization) may all be present in the same flow unit within the NV-N area but with variable intensity. Gibson (1989) interpreted this as "progressive superposition of alteration types during burial and continued volcanism".

The $\delta^{18}\text{O}$ data from the NV-N area indicate that most of the rocks have undergone some $\delta^{18}\text{O}$ enrichment relative to assumed primary $\delta^{18}\text{O}$ values of 6 to 8 (average 7) for rhyolite (Taylor 1974, Taylor and South 1985) and 5.5 for basalt-andesite (Kyser 1980). Submarine basalts recovered from the North Mid-Atlantic Ridge range in $\delta^{18}\text{O}$ from 2.8 to 6.8 with an average of 5.8 ± 0.2 (e.g., Muehlenbachs and Clayton 1972b). Fresh rhyolites from Phanerozoic calc-alkaline (andesitic) volcanic terranes typically have $\delta^{18}\text{O} = 6$ to 10 (Taylor 1968, 1974, Hattori and Muehlenbachs 1980, Taylor and South 1985, Beatty et al. 1988). In addition, most of the rhyolites of the NV-N area have undergone some ^{18}O enrichment relative to the assumed primary $\delta^{18}\text{O}$ of the rhyolitic magma ($\delta^{18}\text{O} \approx 8$). The oxygen isotope composition of the rhyolitic magma was

estimated using $\Delta^{18}\text{O}_{\text{qtz-magma}}$ to be ≈ 1.5 (Taylor and South 1985) and average quartz phenocrysts $\delta^{18}\text{O} = 9.4 \pm 0.4$ (1 σ ; n=10)).

Whole-rock oxygen isotope compositions of altered rocks from ophiolite complexes and mid-oceanic crust show a depletion in $\delta^{18}\text{O}$ with depth. The altered basalts from the "upper zone" (zeolite facies) of DSDP Hole 504B (Deep Sea Drilling Project Hole) drilled into the oceanic basement have $\delta^{18}\text{O}$ values up to +12‰, whereas rocks from the deeper greenschist facies zone have $\delta^{18}\text{O}$ values between 4.7 and 7.0‰ (Alt et al. 1986). Oxygen isotope data from the pillow basalt section of the Samail Ophiolite give whole-rock $\delta^{18}\text{O}$ values = 10.7 to 12.7, and whole-rock $\delta^{18}\text{O}$ values of 4.9 to 11.3 for the underlying sheeted dykes (Gregory and Taylor 1981). Rocks of the Troodos Ophiolite have a similar $\delta^{18}\text{O}$ distribution (Heaton and Sheppard 1977)

Most altered pillow lavas from ophiolite complexes in the world consistently have a range of whole-rock $\delta^{18}\text{O}$ of about 10 to 14 (Spooner et al. 1974, Magaretz and Taylor 1976, Heaton and Sheppard 1977). These high $\delta^{18}\text{O}$ values have been interpreted to be due to the interaction of the basalts with seawater at low temperatures (<150°C; Heaton and Sheppard 1977, Stakes and O'Neil 1982, Bohlke et al. 1984). Early studies of oxygen isotope compositions of seafloor rocks showed that weathering of basalts by cold seawater causes

increases in $\delta^{18}\text{O}$ of the rocks (Taylor 1977, Garlick and Dymond 1970, Muehlenbachs and Clayton 1972a), whereas "greenschist grade hydrothermal metamorphism" of rocks results in whole-rock $\delta^{18}\text{O}$ depletions (Muehlenbachs and Clayton 1972b). Subsequent studies of rocks from the seafloor and from exposed fragments of ocean crust in ophiolites have substantiated these results (Heaton and Sheppard 1977, Gregory and Taylor 1981, Cocker et al. 1982, Stakes and O'Neil 1982, Bohlke et al. 1984). More recently, the oxygen and carbon isotopic compositions of seafloor hydrothermal fluids have been measured directly (Craig et al. 1980), and theoretical modeling of the exchange of oxygen isotopes and major elements between basalt and seawater has been carried out (Bowers and Taylor 1985). The oxygen isotope values of altered volcanic rocks of the NV-N area have the same range of values as do altered basalts of the Troodos and Samail ophiolites, and therefore may be attributed to similar alteration processes. In view of the widespread diagenetic and spilitic alteration and the local silicification and epidote-quartz alteration of volcanic rocks, the high $\delta^{18}\text{O}$ signature and the final $\delta^{18}\text{O}$ profile is most likely due to a combination of these alteration processes. Also, the altered rocks of the NV-N area are enriched in ^{18}O compared to the least altered rocks which again indicates that the high $\delta^{18}\text{O}$ signatures are not primary magmatic features.

6.5.2 Modelling of silicification

The most dominant alteration facies (other than spilitization and early diagenesis) is silicification of flows of the upper member of the Waite Andesite and Waite Rhyolite formations (chapter 4); some altered rocks of the NV-N area show an increase in $\delta^{18}\text{O}_{\text{wr}}$ with increase in SiO_2 (Fig. 6.5). Altered rocks of the Waite Andesite formation show an increase in whole-rock $\delta^{18}\text{O}$ from the least altered to silicified andesites. Silicified rhyolites are also enriched in $\delta^{18}\text{O}$ compared to least altered rhyolites, although the enrichment is not as pronounced. Isotopic exchange accompanying silicification may explain the general distribution of the data of the andesites and of some of the rhyolites of Figure 6.5. To verify this, a simple mixing model involving progressive silicification of a MORB and of a fresh rhyolite (Fig. 6.7) was attempted using a typical composition for MORB at 50% SiO_2 and $\delta^{18}\text{O} = 5.5$ (Kyser 1980). The large dot is a typical composition for fresh rhyolite at 72% SiO_2 and $\delta^{18}\text{O} = 7$ (Taylor 1974, Taylor and South 1985). The solid lines depict the isotopic variation from fresh MORB to silicified MORB, i.e. they show the progressive change in whole-rock $\delta^{18}\text{O}$ values of the MORB with silicification. The dashed lines show the change in whole-rock $\delta^{18}\text{O}$ values of fresh rhyolite with addition of silica. Fractional crystallization does not play a role in this model, although it does determine a small difference between basalt, andesite and rhyolite. The

calculations were done for temperatures of 100°C, 150°C, 200°C, 250°C and assuming an oxygen isotopic composition of water = +2. The distribution of the andesites data could be controlled by addition of silica at temperatures varying between 100°C and 175°C. The distribution of the rhyolite data cannot be simply explained by addition of silica alone, but rather is strongly controlled by the isotopic enrichment of feldspar at low temperatures. This isotopic enrichment of the feldspar is thus partly responsible for the high whole-rock $\delta^{18}\text{O}$ values of the rhyolites and the distribution of the data. In fact, in contrast to quartz phenocrysts which have apparently retained some of their primary magmatic oxygen with only subordinate crystallisation or re-equilibration, the feldspar phenocrysts continued to exchange oxygen isotopes faster and to lower temperatures than quartz. Alternatively, they interacted with fluids of higher $\delta^{18}\text{O}$ values. Figure 6.8 illustrates the isotopic disequilibrium between most quartz and feldspar phenocrysts and the positive and negative values of the quartz-feldspar fractionations ($\Delta\text{Qtz-Fp}$) in rhyolites.

6.5.3 $\delta^{18}\text{O}$ comparison with other altered volcanic rocks

The measured $\delta^{18}\text{O}$ values of most altered andesites and rhyolites of the NV-N area are higher than those of hydrothermally altered analogous rock types elsewhere in the world. For example, in the Kuroko deposits of Japan, the sericite-chlorite alteration zone of felsic volcanic rocks

from the footwall of the deposits (< 1,000 m from ore) typically have $\delta^{18}\text{O}$ values of 4.6 to 8.0 (Green et al. 1983). The $\delta^{18}\text{O}$ values of hydrothermal quartz from the Kuroko orebodies range from 7.2 to 10.8 and are inferred to have been deposited at high temperatures (250°C to 350°C) from fluids with $\delta^{18}\text{O} = -1$ to 4. Oxygen isotopic values of altered rocks of the NV-N area are similar to altered rocks of the mid-ocean crust and ophiolite complexes (Muehlenbachs and Clayton 1972b, Heaton and Sheppard 1977, Gregory and Taylor 1981, Cocker et al. 1982, Stakes and O'Neil 1982, Bohlke et al. 1984, Alt et al. 1986, Fouillac et al. 1989) and to altered rocks of the West Shasta district, California (Taylor and South 1985).

Andesites of the NV-N area have similar whole-rock $\delta^{18}\text{O}$ values to those reported by Beaty et al. (1988) for volcanic rocks of the BRG (i.e., 6.0 to 9.7). Whole-rock $\delta^{18}\text{O}$ values of andesites of Beaty and Taylor (1982) range from 5.2 to 6.7, but decrease to about 4.5 in proximity to the Amulet upper "A" ore deposit and are as low as 3.6 in the alteration pipe. Least altered andesites and rhyolites of the Amulet Andesite and Millenbach Rhyolite formations of the Noranda area have $\delta^{18}\text{O}$ values = 6.3 and 5.8-6.1, respectively (Ikingura et al. 1989). Kennedy (1984) reported whole-rock $\delta^{18}\text{O}$ values of 1.3 and 3.6 for altered andesites in proximity to the Flavrian pluton. The only other $\delta^{18}\text{O}$ values in the Abitibi belt close

to those of the NV-N area are the silicified and sericitized rhyolites of the Horne mine, Noranda, with whole-rock $\delta^{18}\text{O}$ values of 10.5 and quartz phenocrysts $\delta^{18}\text{O} = 9$ to 12 (MacLean and Hoy 1989). The Balaklala Rhyolite and the Copley Greenstone of the West Shasta District in California have $\delta^{18}\text{O}$ values of 7.6 to 13.3 and 3.5 to 11.6, respectively.

In other words, compared to hydrothermally altered rocks elsewhere, including hydrothermally altered andesites and rhyolites from the same greenstone belt, the whole-rock $\delta^{18}\text{O}$ values of altered andesites and rhyolites of the NV-N area are generally higher. But they are in the same range of values as the low-temperature altered basalts of ophiolite complexes and mid-oceanic crust and the low-temperature regionally altered volcanic rocks of the BRG and the West Shasta District. Taking $\delta^{18}\text{O}$ values of +5.5 and +7.0 (Kyser 1980, Taylor 1974, Taylor and South 1985) as averages for unaltered andesite and rhyolite respectively, the altered rocks of the NV-N area have been enriched in ^{18}O by 1 to 5 per mil for andesite and by 4 to 7 per mil for rhyolite subsequent to extrusion. Taking $\delta^{18}\text{O}$ value ≈ 8 for the primary composition of the rhyolitic magma, the rhyolites have been enriched in ^{18}O by 1 to 6 during subsolidus processes. Some of the $\delta^{18}\text{O}$ values of the least altered andesites and rhyolites of the NV-N area, however, are similar to those of fresh igneous rocks. The similarity of the whole-rock $\delta^{18}\text{O}$ values of altered country rocks surrounding

the Amulet "A" Cu-Zn deposit in Noranda to those of fresh igneous rocks, was attributed by Beatty and Taylor (1982) to the isotopic composition and the temperature of the altering fluid, such that the rocks did not undergo significant isotopic exchange.

6.5.4 Oxygen isotope composition and origin of altering fluids.

The oxygen isotope fractionations between natural alteration minerals and water are often used to estimate the isotopic composition of alteration fluids in order to determine their provenance and to estimate the water/rock ratios during alteration. Due to many uncertainties discussed by Clayton et al. (1989), care must be taken in the selection of mineral-water fractionation factors. The oxygen isotope fractionation factors used here are given in Table 6.8.

Oxygen isotope fractionation factors between quartz and water are based on the quartz-water data of Clayton et al. (1972), quartz partition function ratios of Clayton et al. (1989), and the calculated water partition function ratios of Bottinga and Javoy (1973). Clayton et al. (1989) mentioned that the isotopic fractionations for all studied systems calculated in this way are systematically 1.5 to 2.0 less positive than the experimental values, which may indicate that the calculated partition function ratios for water are too large by a factor of $\approx 15\%$.

Calculated fluid compositions associated with the formation of various amygdules and veins from silicified andesites and rhyolites are given in Table 6.8. The calculated $\delta^{18}\text{O}$ of the fluids for the epidote-quartz amygdules and veins vary between 1.1-2.8 and 3.2-4.7, respectively (Table 6.8). These values are consistent with slightly evolved seawater that underwent enrichment in ^{18}O by oxygen isotope exchange with the aquifer volcanic rocks. Assuming an average equilibrium temperature of 225°C and average $\delta^{18}\text{O}$ of quartz = 11.5 ± 0.2 , the calculated $\delta^{18}\text{O}$ of the hydrothermal fluid associated with epidote-quartz veins and amygdules is about 2.5 ± 0.4 . The calculated $\delta^{18}\text{O}$ values of the fluid at various temperatures with an assumed average $\delta^{18}\text{O}$ of quartz = 11.5 ± 0.2 are given in Table 6.11. Beaty and Taylor (1982) demonstrated that the hydrothermal fluid associated with alteration and ore deposition at the Amulet "A" Cu-Zn deposit in Noranda was seawater with $\delta^{18}\text{O} = 0.5 \pm 1$.

6.5.5 Possible sources for the altering fluids

The most plausible source for the altering fluids having the $\delta^{18}\text{O}$ values given above is evolved seawater formed by interaction with volcanic rocks at relatively low temperatures ($\leq 250^{\circ}\text{C}$). The extensive Na-metasomatism (spilitization) and the requirement of a relatively high water:rock ratio during this initial pervasive and widespread alteration suggests that

evolved seawater was the possible predominant constituent of the altering fluid.

Boiling of an aqueous fluid in a hydrothermal environment could also have contributed to the ^{18}O enrichment of the hydrothermal fluids. Because boiling of an aqueous fluid produces bubbles of ^{18}O -depleted vapor, by material balance the coexisting liquid is enriched in ^{18}O . Such processes could have been accentuated in the uppermost flows of the Waite Rhyolite formation, in an environment of upward shoaling sequences (chapter 3).

The $\delta^{18}\text{O}$ of fluids for the quartz-chlorite and quartz-feldspar veins may also be estimated from the quartz-water fractionation. The $\delta^{18}\text{O}$ of the fluids is 6.9 and 2.7 or 8.7 and 5.1 depending of which quartz-water fractionation equation used (see Table 6.7). These high values are consistent with evolved seawater that underwent enrichment in $\delta^{18}\text{O}$ by oxygen isotope exchange with aquifer rocks at high rock:water ratio or hydrothermal fluids having a magmatic component, i.e., magmatic water exsolved from the magma chamber, or an enrichment resulting from boiling of an aqueous fluid.

6.5.6 Regional isotopic zonation

The whole-rock $\delta^{18}\text{O}$ values in the NV-N area increase with stratigraphic height (Fig. 6.10). Three SW-NE transects (Fig. 6.6) also illustrate that the whole-rock $\delta^{18}\text{O}$ values increase

with stratigraphic height. A relatively systematic $^{18}\text{O}/^{16}\text{O}$ increase with stratigraphic height is also present at the scale of the CNVC. The lowermost volcanic formation, the Flavrian Andesite, has whole-rock $\delta^{18}\text{O}$ values of 1.4 to 3.6 (Kennedy 1984). Silicified andesites of the upper member of the Amulet formation have whole-rock $\delta^{18}\text{O}$ values of 3.7 to 4.7 (Watkinson, personal communication). The Amulet Andesite around the Amulet "A" deposit has whole-rock $\delta^{18}\text{O}$ values ranging from 5.2 to 6.7 (Beaty and Taylor 1982). Least altered andesites and rhyolites of the Amulet Andesite and Millenbach Rhyolite formation have $\delta^{18}\text{O}_{\text{wr}} = 6.3$ and 5.8-6.1, respectively (Ikingura et al. 1989). Volcanic rocks of the NV-N area have whole-rock $\delta^{18}\text{O}$ values ranging from 5.2 to 13.7.

Volcanic rocks of the Central Noranda Volcanic Complex (CNVC) thus exhibit both ^{18}O enrichments and ^{18}O depletions relative to primary magmatic $\delta^{18}\text{O}$ values and systematic increase in whole-rock $\delta^{18}\text{O}$ from the lowest to the highest levels in the entire volcanic sequence is observed. The final $\delta^{18}\text{O}$ profile is the cumulative result of a long history of subsolidus alteration at variable temperatures and water:rock ratios.

The distribution of alteration types within the volcanic sequence and the isotope variation with stratigraphic height enabled construction of a model for the temporal and evolutionary relationship of the alteration facies within the

NV-N volcanic sequence. The first stage of alteration history of rocks of the NV-N area is similar to that occurring in mid-oceanic crust and in ophiolite complexes, where a decrease in whole-rock $\delta^{18}\text{O}$ occurred systematically with increasing depth, i.e., from the zeolite facies pillowed basalts to the greenschist facies sheeted dykes and gabbros (Muehlenbachs and Clayton 1972b, Heaton and Sheppard 1977, Gregory and Taylor 1981, Cocker et al. 1982, Stakes and O'Neil 1982, Bohlke et al. 1984, Alt et al. 1986, Fouillac et al. 1989). The high water:rock ratios (10-100) and low temperature ($\leq 200\text{-}250^\circ\text{C}$) alteration of the upper extrusive section (zeolites facies) of the ophiolites produced rocks with high $\delta^{18}\text{O}$, whereas higher temperature ($\geq 250\text{-}300^\circ\text{C}$) hydrothermal metamorphism at lower water:rock ratio (<1) of rocks of the greenschist facies produces a decrease in $\delta^{18}\text{O}$ of rocks. This gradient exists within rocks of the NV-N area and corresponds to the widespread and pervasive low temperature burial hydrothermal metamorphism characterized by the diagenetic and spilitic alteration mineral assemblages. Other alteration facies of high $\delta^{18}\text{O}$ signature, namely, silicification and epidote-quartz alteration within the volcanic sequence of the NV-N, cannot be explained only by the above process. Consequently, another episode of alteration subsequent to diagenesis and spilitization must have occurred.

The following "model" of progressive alteration during the volcanism of the NV-N area may explain the $\delta^{18}\text{O}$ gradient

and anomalies. Figure 6.11 illustrates the different stages of alteration with their corresponding $\delta^{18}\text{O}$ values within the volcanic sequence of the NV-N area.

1. Initial diagenetic alteration of volcanic rocks of the NV-N area was probably characterized by low-temperature alteration and high water:rock ratio in the upper parts of the volcanic succession and its modification to higher temperatures (maximum 200°C) and slightly lower water:rock ratio with burial.

This alteration promoted the decrease in permeability through precipitation of palagonite, opal, calcite, zeolite, and clay minerals in amygdules and pore-spaces of breccias in response to increasing temperature during progressive burial.

Overall, relatively high water:rock ratio, high permeability and low temperatures prevailed during early diagenetic alteration and resulted in whole-rock $\delta^{18}\text{O}$ enrichment of the rocks.

2. The second pervasive and widespread alteration event was spilitization which corresponds to the early greenschist facies burial hydrothermal metamorphism observed in many ophiolite complexes (Spooner 1977, Heaton and Sheppard 1977, Gregory and Taylor 1981, Schiffman and Smith 1988).

With continued volcanism, the thickness of the volcanic pile increased and subsidence occurred at approximately the same rate as new flows erupted. Consequently, as the pile sank down under the weight of added volcanic rocks, spilitic assemblage began to develop in response to increasing burial temperature, and interaction with isotopically more evolved seawater than occurred within the overlying rocks. Under these conditions, water:rock ratio was probably lowered due to a decrease in permeability with depth, and altered volcanic rocks acquired a lower $\delta^{18}\text{O}$ than rocks stratigraphically above, thus masking the earlier higher $\delta^{18}\text{O}$ exchange history. Overall, a $\delta^{18}\text{O}$ gradient vs stratigraphic height was obtained which reflects a gradient in temperature and water:rock ratio in the geothermal system.

From diagenesis to spilitization, composition of evolving fluid changed from original seawater to a more evolved solution. This evolution of the fluid influenced the composition of the alteration facies assemblage and the $\delta^{18}\text{O}$ values of rocks and at some point the epidote-quartz alteration may have been favoured over spilitization. Epidote-quartz altered rocks of the NV-N area have higher $\delta^{18}\text{O}$ values than do their least altered counterparts, and this is possibly due to

progressive reaction of fluids resulting from the spilitization and its subsequent enrichment in ^{18}O .

3. The third alteration event within rocks of the NV-N area was silicification, which was focussed on andesites of the upper member of the Waite Andesite formation and on restricted zones and flows of the Waite Rhyolite formation (Fig. 6.12).

Silicified rocks of the NV-N area have unusually high whole-rock $\delta^{18}\text{O}$ values compared to least altered rocks and other altered rocks in the Noranda area and elsewhere, including silicified rocks of the Amulet formation which have $\delta^{18}\text{O}$ values of 3.7-4.7 (Watkinson, personal communication) and silicified and chloritized andesites of the Recent Galapagos Rift deposit which have $\delta^{18}\text{O}$ of 4.5 and 3.6, respectively (Jonasson, personal communication). These high $\delta^{18}\text{O}$ values for rocks of the NV-N area are problematic since hydrothermally silicified rocks are interpreted elsewhere to have resulted from the interaction of evolved hot fluid (150-300°C) with rocks under relatively high water:rock ratio. Under these conditions, the $\delta^{18}\text{O}$ signature of silicified rocks is expected to be low. It is evidently not the case for the silicified rocks of the NV-N area. Two hypotheses are suggested:

1) Zones of silicification within the NV-N volcanic sequence were highly permeable zones of high fluid-flow where low temperature fluids interacted with previously devitrified and spilitized rocks in a subseafloor environment.

2) Progressive reaction of the fluids with rocks during diagenesis and spilitization led to the enrichment of the fluids in ^{18}O relative to seawater. Boiling of an aqueous fluids could have also contributed to the ^{18}O enrichment of the fluids as reaction of seawater with high-level intrusions (if depth of water was appropriate for boiling).

6.6 SUMMARY AND CONCLUSIONS

Volcanic rocks have undergone ^{18}O enrichment to varying degrees relative to assumed primary values of 5.5 for basalt-andesite and 7 for rhyolite: altered andesite has $\delta^{18}\text{O}$ values higher by 1 to 5 per mil and altered rhyolites have $\delta^{18}\text{O}$ values higher by 4 to 7.

One of the most significant conclusions of this study is that the volcanic rocks of the NV-N area are unusually rich in ^{18}O compared to hydrothermally altered volcanic rocks elsewhere. However, they are similar to rocks that underwent low temperature burial hydrothermal metamorphism signature elsewhere in the Abitibi belt.

The model presented above suggests at least two main episodes of alteration: 1) a widespread and pervasive low temperatures seawater weathering event and a burial hydrothermal metamorphism varying with depth from high to low $\delta^{18}\text{O}$ values, and 2) a more restricted low temperature alteration event and/or high $\delta^{18}\text{O}$ of the fluid characterized by high $\delta^{18}\text{O}$ rock values.

The whole-rock $\delta^{18}\text{O}$ increase with stratigraphic height reflects a gradient in temperature and water:rock ratio in a geothermal system possibly driven by the underlying Flavrian magmatic body.

Table 6.1. Oxygen isotope composition ($\delta^{18}\text{O}\%$) and SiO_2 of rocks along transect I.

Sample	Fm	Flow	Description	SiO2 (%)
					W.rx	Qtz	Fp	Ep	
TRANSECT I									
259-86	Al		Mass "a", mod silic	77.30	9.2				
394-86	WAl		Pill, sl alt (chlor)	53.90	5.2				
251-86	WAl		Pill "a" sil	62.90	7.7				
3-88	WAl		Qtz-Ep amygdule				12.5		
							12.0		
13-88	WAl		Qtz-Ep amygdule				11.8		6.9
4-87	WAs		Rhyolitic dyke	76.90	7.0	11.0			
242-86	WAs		Rhy. mass. spher	74.70	9.3				
12-87	WAs		Rhy. Fbx	76.00	6.7			7.9	
398-86	WAs		Rhy. Fbx	72.90	8.3				
401-86	WAu		Frgs "a" sil, Fbx	69.90	8.2				
402-86	WAu		Fbx, mat chl	54.00	6.8				
202-86	WAu		Mass "a", sl alt	57.70	7.3				
204-86	WAu		Fbx, "a", sil	53.30	7.2				
222-86	WAu		Pill "a", Qtz, Ep	58.10	7.8				
41-85	WAu		Fbx "a", silic, chlor	59.60	7.8				
373-86	WR	2	Mas, sl ser, carb, sil	74.00	10.0				
388-86	WR	2	Fbx	76.50	11.6				
387-87	WR	2	Fbx, chlor matrix	71.50	11.7			12.6	
382-86	WR	5	QFP mass, sl alt (chlor, seric, silic)	74.80	10.9	9.9	10.4		
384-86	WR	5	QFP lobe, sl alt (seric, carbo, silic)	77.30	11.5	9.1	10.9		
385-86	WR	5	QFP Fbx mod carbo, seric	70.40		9.7			
634-86	WR	7	FP lobe, Fb, sulph	74.90	11.5				
23-85	WR	8	Fb, high seric	75.40	10.8				

Abbreviations: W.rx = Whole-rock, Qtz = quartz, Fp = feldspar, Ep = epidote, Cal = calcite, sil = silica, Chl = chlorite, "a" = amygdule, alt = altered, chlor = chloritized, silic = silicified, epido = epidotized, mass = massive, spher = spherulitic, rhy = rhyolite, fbx = flow breccia, pill = pillow.

Table 6.2. Oxygen isotope composition ($\delta^{18}\text{O}\%$) and SiO_2 of rocks along transect II.

Sample	Fm	Flow	Description	SiO2 (%)	$\delta^{18}\text{O}$				
					Wrx	Qtz	Fp	Ep	Chl
TRANSECT II									
536-86	WR	1	Fbx sl alt (chlor, silic)	72.60	8.6	8.7			
534-86	WR	1	Mass, sl alt	75.60	8.8	8.8	8.4		
531-86	WR	1	Fbx, sl alt	74.40		9.7			
523-86	WR	1	Fbx, sl alt	76.80	9.3				
556-86	WR	2	Fb, var silic	74.30	9.2				
604-86	WR	2	Feeder, sl chlor, mod seric, carbo	74.70	9.5				
542-86	WR	2	Fbx, mod chlor	72.40	10.7				
661-86	WR	2	Fbx	73.60	12.5				
579-86	WR	2	Lobe, sl alt	71.90	10.9				
645-86	WR	3	FP, Fbx, Fb	76.10	10.2	9.8			
593-86	WR	6	QFP, Fbx, high epido	73.50	11.6	9.8			
584-86	WR	6	QFP, Fbx, high epido	70.20	11.2		9.3		
620-86	WR	6	QFP, Fbx, high seric mod epido	75.50		10.0	10.6		
618-86	WR	6	QFP, Fbx, silic	70.00		11.2			
626-86	WR	6	QFP, Fbx, mod seric, silic	70.10	9.9		10.0		
18-87	WR	6	QFP, Fbx, sl chlor, carbo mod seric	74.00	11.6	9.1	11.4		
19-87	WR	6	QFP lobe, high silic	79.90		11.2			
637-86	WR	7	Lobe, mod silic	75.50	11.8				
660-86	WR	8	Fbx, spher, sl seric, carbo						
658-86	WR	8	Fbx, schist, seric, sulph	74.20	13.0				
36-85	WR	8	Lobe Fb. seric, sulph	76.90	13.7				

Table 6.2. Continued.

Sample	Fm	Flow	Description	SiO2 (%)	$\delta^{18}\text{O}$				
					W.r.x	Qtz	Fp	Ep	Chl
TRANSECT II									
566-86	WR	10	Feeder, FP, mod seric, carbo	68.60	12.5				
663-87	WR	10	Feeder, FP mod carbo, chlor	67.90	12.0	10.7			
9-88	WR	10	Qtz-Fp vein in Rhy feeder			14.6	10.3		
18-88	WR	10	Qtz-Chl vein in Rhy feeder			14.3			5.9
15-87	WR	10	Fp lobe spher Mod carbo, silic	75.20	12.7		12.6		

Table 6.3. Oxygen isotope composition ($\delta^{18}\text{O}\text{‰}$) and SiO_2 of rocks along transect III.

Sample	Fm	Flow	Description	SiO2 (%)	Wrx	$\delta^{18}\text{O}$				
						Qtz	Fp	Ep	Cal	
TRANSECT III										
27-87	WAl		Fbx "a", silic		6.6					
29-87	WAl		Pill		5.8					
309-86	WAU		Fbx, Fb, "a"	64.60	9.7					
			mod epido, chlor, silic							
319-86	WAU		Pill "a"	56.50	7.6					
348-86	WAU		Fbx, hyalo	67.70	8.5					
349-86	WAU		Fbx, frags "a" sil	71.50	8.5					
1-88	WAU		Qtz amygdule in pill			12.1				
2-88	WAU		Qtz amygdule in pill			11.0				
6-88	WAU		Qtz-Ep amygdule in pill			11.3		5.8		
								7.4		
7-88	WAU		Qtz amygdules			12.9				
8-88	WAU		Qtz amygdule in Fbx			15.9				
10-88	WAU		Cal-Ep amygdule in pill					3.6	10.4	
11-88	WAU		Cal-Ep amygdule in pill					3.6	9.8	
12-88	WAU		Cal-Ep amygdule in pill					4.5	9.5	
15-88	WAU		Qtz amy			13.5				
16-88	WAU		Qtz amygdule in pill			14.2				
17-88	WAU		Cal-Ep amygdule					5.0		
19-88	WAU		Qtz-Ep vein			11.1		4.9		
4-88	WR	1	Qtz vein			12.4				
						12.9				
5-88	WR	1	Qtz vein			12.8				

Table 6.3. Continued.

Sample	Fm	Flow	Description	SiO2 (%)	$\delta^{18}\text{O}$				
					W.r.x	Qtz	Fp	Ep	Cal
TRANSECT III									
14-88	WR	1	Qtz "a" in Fbx			13.8			
317-86	WR	1	Fbx, Fb "a" mod silic, chlor	71.40	9.2	9.6			
324-86	WR	1	Fbx	74.10	9.0				
356-87	WR	1	Mass, alt	74.00	9.3				
368-86	WR	1	Mass, spher	70.50	9.5				
442-86	WR	1	Lobe, mod carbo	75.90	11.4	11.0			
443-86	WR	1	Rim of sil lobe	80.90	11.1	11.4			
448-86	WR	1	Lobe spher	73.70		10.8			
439-86	WR	1	Lobe, sil	80.50	12.9				
440-86	WR	1	Fbx, mod seric, sulph	74.30	11.9	11.7	10.8		
455-86	WR	8	Feeder, FP, mass	74.90	11.3				
647-86	WR	8	QFP, Fbx, high carbo	65.00	10.5	10.2			
653-86	WR	8	Qtz vein in Fbx	73.80		12.7			
643-86	WR	9	Lobe	73.80	12.8		11.9		
642-86	WR	9	Fbx	68.20			12.6		

Table 6.4. Whole-rock $\delta^{18}\text{O}$ values of andesites of the lower and upper members of the Waite Andesite formation.

	Lower member	Upper member
Least altered (n = 2)	5.2 - 5.8 (X = 5.5)	7.3 - 7.6 (X = 7.5)
Silicified (n = 4)	6.6 - 7.7 (X = 7.2 $\pm$ 0.5)	8.2 - 9.7 (X = 8.7 $\pm$ 0.6)
Chloritized (n = 2)		6.8 - 7.2 (X = 7.0)
Epidote-quartz alteration (n = 2)		7.8 (X = 7.8)

 X: arithmetic mean, $\pm$ 0.x: standard deviation.

Table 6.5. Oxygen isotopic compositions ($\delta^{18}\text{O}$) of the Waite Rhyolite formation. All values are in per mil relative to SMOW.

All rhyolites

W.rx	8.6 to 13.7	(X = 11.1 ± 1.3 ; n = 36)
Qtz	8.7 to 11.7	(X = 10.0 ± 0.9 ; n = 18)
Fp	8.4 to 12.6	(X = 11.0 ± 1.2 ; n = 13)

Least altered rhyolites

W.rx	8.6 to 10.9	(X = 9.6 ± 0.9 ; n = 7)
Qtz	8.7 to 9.9	(X = 9.2 ± 0.5 ; n = 4)
Fp	8.4 & 10.4	(X = 9.4)

Silicified rhyolites

W.rx	11.1 to 13.7	(X = 12.1 ± 0.8 ; n = 11)
Qtz	9.1 to 11.7	(X = 10.6 ± 1.0 ; n = 6)
Fp	10.8 to 12.6	(X = 11.8 ± 0.8 ; n = 3)

Epidote-quartz altered rhyolites

W.rx	11.2 & 11.6	(X = 11.4)
Qtz	9.8 & 10.0	(X = 9.9)
Fp	8.7 to 10.6	(X = 9.5 ± 0.8 ; n = 3)

Sericitized rhyolites

W.rx	12.5 to 13.7	(X = 13.1 ± 0.5 ; n = 3)
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Chloritized rhyolite

W.rx	10.7
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Carbonatized rhyolite

W.rx	10.5
Qtz	10.2

Abbreviations: W.rx = whole-rock, Qtz = quartz,
Fp = feldspar.

X: arithmetic mean, ± 0.1 : standard deviation, n: number of analyses.

Table 6.6. Oxygen isotopic ranges of different flow facies of the Waite Rhyolite formation.

Flow facies	$\delta^{18}\text{O}$		
	Whole-rock	Quartz	Feldspar
Massive	9.3 - 10.9	8.8 - 9.9	8.4 - 10.4
Flow-banded	9.2 - 10.8	-	-
Lobe	10.9 - 13.7	9.1 - 11.4	10.9 - 11.9
Flow breccia	8.6 - 13.0	9.1 - 11.7	10.0 - 12.6
Feeder	9.5 - 12.5	-	10.7

Table 6.7. Mineral $\delta^{18}\text{O}$ compositions of veins and amygdules within the Waite Rhyolite and Waite Andesite formations.

		Waite Andesite	Waite Rhyolite
Qtz "a"	Qtz	11.0 - 14.2 ($X = 12.7 \pm 1.1$; $n = 5$)	13.8
Ep-Qtz "a"	Qtz	11.3 - 12.0 ($X = 11.7 \pm 0.3$; $n = 3$)	
	Ep	5.7 and 5.8	
Ep-Cal "a"	Cal	9.5 - 10.4 ($X = 9.9 \pm 0.4$; $n = 3$)	
	Ep	3.6 - 5.0 ($X = 3.9 \pm 0.4$; $n = 4$)	
Qtz vein	Qtz		12.4 - 12.8 ($X = 12.6 \pm 0.2$)
Ep-Qtz vein	Qtz	11.1	
	Ep	4.9	
Qtz-Fp vein	Qtz		14.6
	Fp		10.3
Qtz-Chl vein	Qtz		14.3
	Chl		5.9

Abbreviations: Qtz = quartz, Ep = epidote, Cal = calcite, Fp = feldspar, Chl = chlorite, "a" = amygdale.
 X: arithmetic mean, ± 0.2 : standard deviation, n: number of analyses.

Table 6.8. Oxygen isotope fractionations (Δ) for mineral pairs and calculated temperatures and fluid compositions. Temperatures were calculated according to equations listed in Table 6.9.

EPIDOTE-QUARTZ AMYGDULES

Sample	Qtz	Ep	Δ Ep-Qtz	T°C	$\delta^{18}\text{O}_{\text{H}_2\text{O}}^1$	$\delta^{18}\text{O}_{\text{H}_2\text{O}}^2$
3-88	12.0	-	-	-	-	-
13-88	11.8	5.7*	6.1	233	2.0‰	4.1‰
6-88	11.3	5.8	5.5	260	2.8‰	4.7‰

EPIDOTE-QUARTZ VEIN

19-88	11.1	4.9	6.2	229	1.1‰	3.2‰
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EPIDOTE-CALCITE AMYGDULES

Sample	Cal	Ep	Δ Ep-Cal	T°C	$\delta^{18}\text{O}_{\text{H}_2\text{O}}^1$
10-88	10.4	3.6	6.8	122	-4.5‰
11-88	9.8	3.6	6.2	141	-3.5‰
12-88	9.5	4.5	5.0	187	-0.7‰

QUARTZ-CHLORITE VEIN

Sample	Qtz	Chl	Δ Qtz-Chl	T°C	$\delta^{18}\text{O}_{\text{H}_2\text{O}}^1$	$\delta^{18}\text{O}_{\text{H}_2\text{O}}^2$
18-88	14.3	5.9	8.4	287	6.9‰	8.7‰

QUARTZ-FELDSPAR VEIN

Sample	Qtz	Fp	Δ Qtz-Fp	T°C	$\delta^{18}\text{O}_{\text{H}_2\text{O}}^1$	$\delta^{18}\text{O}_{\text{H}_2\text{O}}^2$
9 - 88	14.6	10.3	4.3	197	2.7‰	5.1‰

1 Based on Clayton et al. (1972)

2 Based on Clayton et al. (1989) and Bottinga and Javoy (1973, 1975) as described in the text. * Corrected value.

Table 6.9. Oxygen isotope fractionation equation parameters for mineral-water systems, where $1000 \ln \alpha = A (10^6 T^{-2}) + B$.

System	A	B	Source
Calcite	2.78	-2.89	Friedmann and O'Neil (1977)
Quartz	3.38	-3.4	Clayton et al. (1972)
Quartz	2.94	-3.77	Clayton et al. (1989)

Table 6.10. Oxygen isotope fractionation equation parameters for mineral pairs, where $1000 \ln \alpha = A (10^6 T^{-2}) + B$

System	A	B	Source
Quartz-albite	0.95	-	Clayton et al. (1989)
Quartz-chlorite	2.01	1.99	Wenner and Taylor (1971)
Quartz-epidote	1.56	-	Bottinga and Javoy (1975)
Calcite-epidote	1.06	-	Matthews et al. (1983)

Table 6.11. Calculated isotopic compositions of fluids at various temperatures. $1000 \ln \alpha = 3.38 (10^6 T^{-2}) - 3.34$ (Clayton et al. 1972)

Temp. (C°)	$\delta^{18}\text{O}_{\text{H}_2\text{O}}$
100	+9.4
150	+3.9
200	+0.2
250	-2.5
300	-4.6

Fig. 6.1. Location of $\delta^{18}\text{O}$ samples along transects I, II and III.

Fig. 6.2. Histograms of whole-rock $\delta^{18}\text{O}$ values of the Amulet, Waite Andesite and Waite Rhyolite formations.

WAITE RHYOLITE

Fig. 6.3. Histograms of whole-rock, quartz and feldspar phenocrysts $\delta^{18}O$ values of the Waite Rhyolite formation.

Fig. 6.4. Quartz phenocryst and whole-rock oxygen isotope composition of selected samples. Note that whole-rock $\delta^{18}\text{O}$ values of most samples are higher than the associated quartz phenocryst $\delta^{18}\text{O}$ values.

Fig. 6.5. Variation of whole-rock $\delta^{18}\text{O}$ versus SiO_2 of hydrothermally altered rocks of the lower (WAL), upper (WAL) and Splinter (WAS) members of the Waite Andesite formation and the Waite Rhyolite formation (WR).

4

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Fig. 6.6. Whole-rock $\delta^{18}O$ values along transects I, II, and III. Transects located on Figure 6.1. Dashed lines show trend of least altered samples.

Fig. 6.7. Diagram showing the isotopic enrichment curves varying from fresh MORB ★ to silicified MORB (solid lines) and from fresh rhyolite ● to silicified rhyolite (dashed lines).

Fig. 6.8. Quartz $\delta^{18}\text{O}$ values versus feldspar $\delta^{18}\text{O}$ values of coexisting minerals in rhyolites.

Fig. 6.9. Comparison of range of oxygen isotope values of volcanic rocks from different regions. D-68 (Ikingura et al. 1989), Amulet "A" (Beaty and Taylor 1982, Beaty et al. 1988), Corbet (Urabe et al. 1983), Flavrian Andesite (Kennedy 1984), West Shasta district (Taylor and South 1985).

Fig. 6.10. Whole-rock, quartz phenocryst, and feldspar phenocryst oxygen isotope composition of volcanic rocks of the NV-N area plotted as function of stratigraphic height.

N

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Fig. 6.11. Diagrams illustrating the evolution of the alteration events during the volcanism of the New Vauze-Norbec area. (A) After extrusion of the Waite Andesite formation. (B) After extrusion of the Waite Rhyolite formation. Variation of approximate temperatures and $\delta^{18}O$ with depth is plotted.

Spilitization

Epidote-Quartz alteration

Massive sulphide

Fig. 6.12. Schematic NS cross-section illustrating the distribution of silicification and epidote-quartz alteration within the New Vauze-Norbec area.

CHAPTER 7. DISCUSSION

In this chapter, the origin of the different alteration types in rocks of the New Vauze-Norbec (NV-N) area is discussed in light of their spatial distribution, their temporal relationships, their mineralogy, and their geochemistry. Interpretation of the data is facilitated by comparison with modern hydrothermal systems and experimental fluid/rock interaction data.

7.1 GENERAL STATEMENTS

The most widespread alteration types in rocks of the NV-N area are devitrification, spilitization, and silicification. The epidote-quartz alteration is common in andesites but is rare in rhyolites, reflecting their low Ca content.

Field evidence suggests that the different alteration assemblages and facies are the results of synvolcanic alteration processes and not the products of isochemical, regional low grade metamorphism: 1) their absence in metamorphosed dioritic dykes, 2) their common restriction with specific flows and stratigraphic units of high primary permeability, 3) the irregular and inhomogeneous distribution of alteration minerals, and 4) the gradational contacts between altered and least altered rocks. Similar alteration assemblages and facies that have been interpreted as synvolcanic alteration processes, have also been described in

other volcanic terrains, such as the Troodos Ophiolite complex (Spooner 1977, Lydon and Jamieson 1984, Gillis and Robinson 1985), the upper km of mid-oceanic crust (Muehlenbachs 1979, Donnelly et al. 1980, Stakes and O'Neil 1982, Alt et al. 1986), the Matagami Lake area (MacGeehan 1978, MacGeehan and MacLean 1980), and the Snow Lake area, Manitoba (Skirrow 1987).

Field evidences, geochemical data, fluid-rock experiments, and comparison with modern and other ancient hydrothermal systems, suggest that the different alteration assemblages and facies in the NV-N area resulted from progressive and continued superposition of the different alteration types during volcanism and burial hydrothermal metamorphism.

7.2 DEVITRIFICATION

Devitrification is common in rhyolites of the NV-N area. It affected all the rhyolitic lava flows to variable degrees during and shortly after their emplacement.

Several of the devitrification textures listed in chapter 4, which according to Lofgren (1971a, b) and de Rosen Spence (1976) represent variable thermal stages of crystallization, are present in the same rhyolitic flow facies of the NV-N area. For this reason, it is suggested that the observed devitrification textures are the products of variable degrees

of recrystallization and that temperature plays a role only in their initial stage of formation.

The chemical changes associated with devitrification of rhyolites are difficult to assess because of overprinted alteration. However, experimental studies of Lofgren (1970, 1971a, b) provide an insight into the chemistry accompanying hydration and devitrification, i.e., variations of up to 2% of SiO_2 , H_2O , $\text{Fe}_2\text{O}_3/\text{FeO}$, Na_2O and K_2O contents.

7.3 SPILITIZATION

Spilitization is a widespread and pervasive alteration type that affected uniformly all the volcanic rocks of the NV-N area, but that did not affect the syn- to postvolcanic dioritic intrusions. It is mainly a mineralogical change corresponding to the conversion of Ca-plagioclase to albite. According to Gibson (personal communication), the spilitic assemblage pseudomorphed earlier alteration assemblage, i.e., palagonitization and devitrification.

The mineral assemblage of the spilitized rocks of the NV-N area is similar to the mineral assemblage resulting from the greenschist regional metamorphism in the Abitibi belt (Jolly 1980, Gelinas et al. 1982). Although, the volcanic rocks do not have any recognizable metamorphic fabric, and therefore cannot result from regional metamorphism. The spilitic assemblage of rocks of the NV-N area is also similar to the mineral assemblage observed in the extrusive sequence

1977, Lydon and Jamieson 1984) and of the Samail Ophiolite (Reinhardt 1974, Smewing et al. 1984) where spilitization was attributed to an early hydrothermal metamorphism. Numerous schemes for the generation of spilitic rocks have been proposed (Amstutz 1974), but since the discovery of submarine hydrothermal metamorphism that preserved the primary textures (Coombs 1954), the genesis of spilitic rocks has often been attributed to this process. Spilitized rocks of the NV-N area may also be the product of early subaqueous hydrothermal metamorphism occurring almost immediately after burial.

In the Troodos Ophiolite, the appearance of the spilitic assemblage starts in the zeolite facies at temperature of 200°C and persists into the greenschist facies at temperatures > 300°C, where albite, chlorite, epidote, actinolite, and quartz occur (Spooner 1977, Heaton and Sheppard 1977). Extensively albitized basalts from the ophiolite-hosted Turner-Albright sulphide deposit (Oregon) indicate formation temperatures in the range of 140°-200°C, based on oxygen isotope geothermometry (Zierenberg et al. 1988). In metabasalts and sheeted dykes of the oceanic crust (DSDP Hole 504B), albite appears at temperatures of 200°-250°C (Alt et al. 1986). In volcanic rocks of the Asal geothermal field of the Republic of Djibouti, albite appears at 210°C. Therefore, as illustrated in Figure 6.11, it is reasonable to assume temperatures $\geq 200^{\circ}\text{C}$ for the spilitization of rocks of the NV-

N area. These temperatures are lower than those of the experiments discussed below.

Experimental seawater-basalt reactions done at temperatures and conditions inferred for the spilitization of rocks may provide an insight into the chemical changes that occurred during spilitization in natural systems. Elemental gains and losses in the rocks during the different fluid/rock reaction experiments are summarized in Fig. 7.1. Seawater-basalt experiments have demonstrated that the main factors controlling the alteration mineral assemblage products are the temperature, pressure, water:rock ratio, pH, and fluid and rock composition (Bischoff and Dickson 1975, Seyfried and Bischoff 1977, Mottl 1983, Rosenbauer and Bischoff 1984, Seyfried and Janecky 1985, Seyfried et al. 1978, 1988).

In seawater-basalt reaction experiments designed to simulate conditions within the upper parts of the hydrothermal system (zeolite and greenschist facies, i.e., at $\approx 150^{\circ}$ – 300° C and under relatively high water:rock ratio), the most common alteration products are the smectite, smectite-chlorite, chlorite, tremolite-actinolite, and talc (Bischoff and Dickson 1975, Mottl 1983, Seyfried et al. 1988). Addition of Na to the rocks is favoured under water:rock ratio < 35 and at high temperatures (Mottl 1983). Under these conditions, chlorite-albite-epidote-actinolite-quartz assemblages occurred. Na-fixation is also strongly dependent on the initial concentrations of Na in the fluid. Fluids more saline than

1988). The modal abundance of albitic plagioclase, and consequently the degree of Na enrichment in the rock, is directly limited if the fluids contain high contents of dissolved Mg. In effect, Na-fixation occurs only for fluids characterized by sufficiently high Na/Mg ratios (Seewald 1987). Mottl (1983) recognized an inverse correlation between Mg enrichment and the degree of Na enrichment in metabasalts from the Mid-Atlantic Ridge. Thus, a continuous supply of a Mg-depleted, Si-rich fluid with a high modal Na/Ca ratio would tend to albitize the basalt (Seyfried et al. 1988). This is precisely the situation within the upflow zones of active hydrothermal systems (Von Damm et al. 1985) where Si-rich, Mg-free, and Ca-depleted fluids reacted with fresh or previously altered basalts and resulted in extensive albitization of these basalts. On the scale of individual pillows, Seyfried et al. (1978) and Seewald (1987) showed that removal of Mg from seawater at the pillow margin (owing to chlorite formation) may provide high Na/Mg ratio fluids for the pillow-core alteration and albitization.

Experiments designed to simulate conditions deep within the subseafloor geothermal system have reacted "evolved" seawater (Mg-depleted, Na-Ca-K-Cl solution) with basalt and 4 m NaCl brine with devitrified andesite at temperatures of 300°-500°C and variable water:rock ratios (Rosenbauer and Bischoff 1984, Ellis 1968; Fig. 7.1). Under these conditions,

various amount of Na enrichment in the rocks occurred. In the "evolved" seawater-basalt reaction, Ca-rather than Mg-hydrolysis is prominent and clinozoisite and tremolite-actinolite are the alteration products (section 7.5). In the NaCl brine-andesite reaction, strong leaching of Fe, Mg, Ca, and Mn and intense Na-metasomatism occurred (Ellis 1968). Therefore, the experiment that most closely reproduce the conditions approaching spilitization, involve NaCl brine and devitrified andesite. In this case, devitrification of andesite may have led to partial hydration of the rock, providing a source of H^+ .

In summary, after consideration of the experimental and theoretical data and comparison with other natural systems, spilitization of rocks seems to be favoured under conditions of burial hydrothermal metamorphism in a shallow subseafloor environment proximal to a magmatic heat source. The seawater-basalt experiments suggest that low temperatures ($< 150^{\circ}$ - $300^{\circ}C$) and relatively high water:rock ratios (< 35) occurred in the upper parts of the volcanic sequence, whereas lower water:rock ratios ($< 5-10$) and higher temperatures occurred in the deeper parts of the volcanic sequence. The composition of the altering solutions evolved from seawater in the upper parts of the volcanic sequence to Mg-depleted, silica-rich, high Na/Ca solutions in deeper parts of the volcanic sequence, where spilitization of rocks is favoured. This evolution of the solutions with depth is accompanied by a reduction in the

permeability of rocks (reduction in the water:rock ratio) and changes in the composition of the alteration assemblage and in the $\delta^{18}\text{O}$ values of the rocks.

7.4 SILICIFICATION

7.4.1 Distribution and evidence for its origin

From Figures 4.1 and 6.12, it appears that two degrees in the intensity of silicification occur: 1) a widespread and weak alteration and 2) a more focussed and intense alteration. These two types of silicification have the same lithological and petrographic characteristics (chapter 4), but are of different intensity and distribution.

The weak silicification is pervasive and widespread within the Waite Rhyolite formation. The distribution of this alteration is controlled by the original permeability of the rhyolitic flows as indicated by its distribution, and increase toward the uppermost few metres of the flows and at the external solidified crust of the flows. It is also more pervasive in the distal parts of the rhyolitic flows where flows are thinner and perhaps more permeable, i.e., the flow breccias, the hyaloclastites, and the flow-banded rhyolites. However, it is also present where flows are thick. As suggested by field evidences, silicification began shortly after the extrusion of the volcanic rocks. Silicification is due to the combination of processes such as, percolation of silica-saturated solution through fractures and breccias,

mixing of cold seawater with evolved silica-saturated solution, interaction of silica-saturated solution with cooling flows at or near the seafloor, and essentially lateral fluid flow.

Glasses are metastable, are readily altered and hydrated by low-temperature solutions, thereby releasing silica to solution. Palagonitization of basaltic glass is characterized by gain in H_2O , Fe, $\pm$ K and $\pm$ Ti and loss in Si, Al, Mg, Ca, and Na. The components lost may go into solution or may be accommodated within authigenic clay minerals, zeolites, calcite, and opal precipitates (Hay and Iijima 1968, Furnes 1973). Devitrification of rhyolitic glass is also accompanied by significant chemical changes since it occurs through the depolymerisation effects of water in breaking the Si-O-Si bridges and hydrolysing tetrahedral oxygen to OH^- . Lofgren (1970, 1971a, b) found that there were variations in SiO_2 , H_2O , Fe_2O_3/FeO ratio, Na_2O , and K_2O contents. De Rosen Spence (1976) suggested that when silica-saturated solution encountered the hot surface of lava lobes and massive lava, the dissolved silica abruptly precipitated and replaced the undevitrified glass. The accompanying loss in Fe, Mg, and Mn from the lobes and the massive rhyolite was fixed in subjacent breccias.

Recognition of the early and weak episode of silicification in the field is hampered by the difficulty in distinguishing it from devitrified and recrystallized

rhyolites. However, microscopically, the two can be distinguished: spherulites are overgrown by quartz and irregular quartz blebs partially replaced the groundmass within the silicified rhyolites. Also, evidence of silica precipitation occurs in the form of small quartz veinlets and quartz amygdules.

The intense silicification occurs within relatively thick flows, such as the uppermost flows of the Waite Andesite and the Waite Rhyolite formations, in proximity to vent areas, faults, and feeder dykes and within some feeder dykes. As for the weak and widespread silicification, the distribution of the more intense silicification is also controlled by permeability of the flows as indicated by its increase towards the uppermost flows of formations and in proximity to synvolcanic faults and feeder dykes.

The intense silicification is explained by progressive sealing of the system by precipitation of silica accompanied by rise of the temperature gradients with the onset of hydrothermal activity. The decrease in permeability with depth and progressive silicification accounted for the more restricted occurrence of the intense silicic alteration, i.e., its focus along major faults and feeder dykes. Therefore, vertical upward fluid flow of silica-saturated solution occurred along synvolcanic faults and vent areas, and their eventual discharge at or near the seafloor may produced a precipitate of silica-rich laminae, the "cherty" component of

the tuffaceous exhalites (sections 3.2.3 and 3.2.9). Two of these siliceous units occur at the top of the Waite Andesite and Waite Rhyolite formations. Relatively close to the seawater/rock interface, the mixing of inflowing cold seawater and outflowing of relatively hot silica-saturated solutions favoured the precipitation of silica. This "silica dumping" is common near the top of the formations, where it occurs as fracture fillings, breccia matrix infillings, and in inter-pillow voids

Because of the following constraints, silicification probably resulted from relatively low-temperature, evolved seawater-rock reactions in a shallow subseafloor environment: 1) the silicified rocks have high $\delta^{18}\text{O}$ values, which imply low temperature fractionation and/or ^{18}O -enriched fluids, 2) the synvolcanic feeder dykes are silicified, and 3) the distribution of this alteration is controlled by the permeability of the flows and feeders. Consequently, the altering solutions must have preferentially followed permeable pathways, such as fractures, synvolcanic faults, brecciated units and flow tops.

In summary, the weak and intense silicification types are contemporaneous and are parts of an evolving, continued, and dynamic hydrothermal system of fluid/rock interactions in a shallow subseafloor environment. The system evolved from an early, widespread and unfocussed silicification event to a more focussed and intense silicification event. This decrease

in the pervasiveness of silicification from widespread to restricted, is interpreted to result from the decrease in permeability of the volcanic rocks due to progressive self-sealing.

7.4.2 Gains and losses of chemical components

Elemental gains and losses in rhyolites and andesites are summarized in Fig. 7.2. Silicification mainly involved addition of Si and loss of Fe, Mg, and Mn, and is manifested by the precipitation of quartz.

Because of the lack of experimental fluid/rock interaction studies duplicating the silicification process, it is difficult to obtain a complete understanding of the process. Several experiments were carried on seawater/basalt reactions at various temperatures, pressures, water:rock ratios, pH, and fluid and rock compositions to model the hydrothermal alteration of the basalts and to reproduce the composition of seafloor vent fluids. Some of these fluid/rock experiments are summarized in Fig. 7.1. The experiments that most closely reproduce the gains and losses in silicified rocks of the NV-N area involve 1) reaction of basalt with evolved seawater (Mg-depleted, Na-Ca-K-Cl solution) at temperatures of 300°-500°C, water:rock ratio of 0.5-3, low pH, and pressures between 162 bars and 1000 bars, and 2) reaction of NaCl brine with a devitrified andesite at 350°-500°C, and high water:rock ratio. In the first reaction, Si leaching and

Ca addition occur through a large range of temperatures, whereas Na fixation is favored at temperatures $> 400^{\circ}\text{C}$. In the second reaction, strong leaching of Fe, Mg, Ca, and Mn occurred along with intense Na-metasomatism. Acidity in both reactions was generated by Na-fixation reactions. Although Si is leached rather than added to the rocks in the experiments, the other element fluxes can be compared to those deduced for silicification. The behaviour of Mg in the evolved seawater experiments is not clearly explained by Rosenbauer and Bischoff (1984). At high temperatures, it seems that Mg is neither leached nor added to the rocks and at low temperatures, Mg is added to the rocks. In rocks of the NV-N area, Mg was leached during silicification, therefore Mg-hydrolysis cannot be invoked as H^{+} -producing reactions.

Most of the seawater/basalt experiments were done at relatively high temperatures and pressures, and under these conditions, silica is leached from the rocks rather than added, as required by the silicification process. Therefore, hydrothermal circulation of a hot fluid having the composition of seawater is not a viable mechanism to silicify the rocks of the NV-N area. In contrast with most high temperature basalt/seawater interactions, low temperature ($< 150^{\circ}\text{C}$) fluid circulation at shallow depth can generate silica-saturated solutions and possibly silicify the rocks. Reaction at constant temperature of a silica-saturated solution with rocks

to form albite promoted the buffering of silica concentration to near-saturation levels.

Low temperature silica-rich solutions and silicified rocks have been described from modern ocean floor. Bertin and Keene (1975) described tholeiitic hyaloclastites cemented by opal of inorganic origin in the vicinity of the Lau Basin spreading centre. $\delta^{18}\text{O}$ values of the opal indicate temperatures of less than 100°C . Moderately low-temperature, silica-enriched fluids have also been intersected during drilling in a 6.2 m.y. pillow lava sequence on the southern limb of the Costa Rica rift (Anderson et al. 1982). And Infilling of pores by silica at temperatures of up to 105°C was reported by Elders and Bird (1974) in a near-surface geothermal field in California.

7.4.3 Sources of silica

Several sources of silica have been proposed for silicification of rocks in different volcanic terrains (Paris et al. 1985), although the exact derivation of the silica and the silicification process are still disputed. Some proposed that silica was introduced primarily from seawater, others that silica originated from magmatic sources, that silica was generated by a devitrification process, and finally that silica came from rocks located in areas lateral to and below the silicified units. Seawater is very low silica and consequently cannot acted solely as a silicifying agent. A

magmatic component for some of the silica is possible due to the fact that a high-level felsic body (the Flavrian pluton) is present at the base of the volcanic succession. Although the underlying devitrified and spilitized rocks are much more favorable source units for most of the silica required to silicify the overlying rocks. As discussed in the previous sections (7.2 and 7.3), SiO_2 is released to solution during diagenesis and spilitization episodes. With time and increasing alteration, the solution evolved from original seawater to silica-saturated solution and may have become more enriched in ^{18}O . Experiments on seawater/basalt reactions have shown that Si is released to solution at temperature $\geq 150^\circ\text{C}$ (Seyfried and Bischoff 1977, Seyfried and Mottl 1982). Solutions in contact with silica as in volcanic glass, will acquire elevated amounts of silica with increasing temperature (Kennedy 1950). A solution may contain a larger amount of silica if in equilibrium with amorphous silica, cristobalite, or chalcedony rather than quartz (Fig. 7.3). Gibson et al. (1983) suggested that fresh volcanic glass in contact with solution may have contributed SiO_2 to the solution to similar extent as amorphous silica in rocks of the Amulet formation.

In summary, the fluid responsible for silicification was evolved seawater that interacted with volcanic rocks during previous alteration events, i.e., devitrification and spilitization. These solutions migrated laterally and vertically in upwelling portions of a convective flow system

along feeder dykes, faults, and fractures. According to the oxygen isotope data, temperatures of silicification for rocks of the NV-N area are likely to be relatively low, i.e., $\approx 150^{\circ}$ - 250°C . Higher temperatures (150° - 300°C) have been estimated by Gibson (1989) and temperatures of 350° - 450°C have been estimated by MacGeehan (1978) and Skirrow (1987).

7.4.4 Precipitation of silica

The conditions under which silica precipitated can only be estimated because of the lack of experimental fluid-rock reaction data duplicating the chemical characteristics of silicification encountered in the field. Moreover, the absence of modern oceanic analogue to silicification of the type occurring in the NV-N area precludes measurement of the wide range of temperature, pressure, pH, and water:rock ratio conditions under which silica can be precipitated. Therefore, interpretation regarding the origin and processes of precipitation of silica is severely limited.

In order to precipitate silica, saturation must first be attained (Fournier 1983). This may be done by:

- 1) rapid heating of a solution in equilibrium with quartz above its maximum solubility temperatures (Fig. 7.4),
- 2) moving a solution into zones of fresh volcanic glass,
- 3) neutralization of high and low pH solutions,

- 4) cooling of a solution (by mixing with cooler waters, boiling, conduction, or adiabatic expansion) in equilibrium with silica, and
- 5) decreasing the pressure.

Condition #1 can be achieved by imposing a higher temperature thermal regime on a fluid-rock system, and by percolation of a relatively cool fluid into a hotter area. Rapid heating of a silica-saturated solution above its solubility maximum, i.e., $\approx 340^{\circ}\text{C}$, has often been proposed as a mean to precipitate silica. Experimental studies have found that silica solubility in water generally increases with temperature (Kennedy 1950), but it is also dependant on pressure and salinity (Fournier and Potter 1982, Fournier et al. 1982, Fournier 1985; Fig. 7.4). For seawater (i.e., 3.2% NaCl; Bischoff and Rosenbauer 1984), the solubility of quartz is slightly increased but it is quite close to that of pure water. MacGeehan (1978) and MacGeehan and MacLean (1980) suggested that silicification at Matagami Lake resulted from rapidly heating a silica-saturated solution above its solubility maximum by bringing it in contact with an intrusion. Fournier (1983) and Bischoff and Rosenbauer (1984) similarly proposed that superheating of silica-rich fluids led to the silicification of rocks near intrusions. Furthermore, Gibson (1989) suggested that silica saturated solutions in equilibrium with quartz at $150^{\circ}\text{--}300^{\circ}\text{C}$ precipitated upon reaction with hot, ponded lava flows. Such rapid increases in

temperature of silica-saturated solutions may have caused silicification at the margin of lava lobes and massive lava flows and, for the silicification in proximity to feeder dykes in the NV-N area. But another process must be responsible for the intense semiconformable silicification of the uppermost flows of the Waite Andesite and Waite Rhyolite formations, because of their $\delta^{18}\text{O}$ values and correspondingly relatively low calculated temperatures of alteration (chapter 6). Silica could have precipitated due to mixing and cooling of a silica-saturated solution with cold seawater near the top of the formations.

Condition #2: Laboratory experiments under hydrothermal conditions show that volcanic glass can release silica to solution to about the same extent as amorphous silica (Dickson and Potter 1982, Fournier 1985). Long exposure of low pH, low temperature solutions to fresh volcanic glass may maintain supersaturation of silica (Seyfried and Janecky 1985, Fournier 1985). Gibson (1979) mentioned that silica could be precipitated where a solution that had been in contact with fresh volcanic glass moved into a higher temperature zone in which quartz was stable (silica would have been precipitated to achieve equilibrium, since the solubility of quartz is less than that of amorphous silica). Even at constant temperature, silica would precipitate from such fluids.

Condition #3: Neutralization of low and high pH solutions can induce precipitation of silica (Fournier 1985). As shown

in Figure 7.5, silica solubility increases with pH in alkaline solutions, and low pH solutions can also be supersaturated in silica. It follows from Fournier (1985), that it is unlikely that variations of pH can provide sufficiently high concentrations of dissolved silica in most natural hydrothermal waters, to be the mechanism of precipitation of large amounts of silica in rocks of the NV-N area.

In summary, the mechanism of silicification remains unresolved, but probably it involved interaction of silica-saturated solutions derived from previously devitrified and spilitized rocks with volcanic rocks at low temperatures and low pH conditions. Silica oversaturation would have been facilitated by sustained low temperatures, low pH, and long exposure of solutions to volcanic glass.

Rapid heating of silica-saturated solutions near feeder dykes could have led to local silica precipitation. However, the mechanism of rapid silicification within the broader semiconformable weak and intensely silicified zones is not as well defined. It probably occurred as the result of quenching of silica-saturated solutions by mixing with cooler waters, by adiabatic cooling, or by simple conductive cooling.

7.5 EPIDOTE-QUARTZ ALTERATION

Andesites and rhyolites of the NV-N area gained Ca and lost Fe, Mn, and Mg during epidote-quartz alteration (Fig. 7.2). These gains and losses are similar to those documented

in experimental reactions involving "evolved" seawater (Mg-depleted, Na, Ca, K, Cl solution) and basalt at 300°-500°C and under low water:rock ratios (Fig. 7.1; Rosenbauer and Bischoff 1984, Seyfried and Janecky 1985, Seyfried et al. 1988). Under these experimental conditions, Ca-rather than Mg-hydrolysis predominates: significant Ca and some Na are gained, and Si, K, Fe, Mn, Cu, and Zn are leached from the rocks, resulting in the precipitation of clinozoisite, tremolite, and actinolite (Seyfried and Janecky 1985).

The mineral assemblage of the epidotized volcanic rocks of the NV-N area (i.e. quartz-albite-clinozoisite-epidote-actinolite) is identical to the mineral assemblage of the greenschist facies regional metamorphism (Winkler 1979). Small rounded spots (less than 0.5 m in diameter), common to regionally metamorphosed rocks of the Abitibi belt (Gelinas et al. 1977), are present in metamorphosed dioritic dykes of the NV-N area. The epidote-quartz spots of the metamorphosed diorites differ in size and abundance from the epidote-quartz patches of volcanic rocks. Also, based on the elemental gains and losses calculated (chapter 5), the $\delta^{18}\text{O}$ values obtained, and the temperature calculated (chapter 6), the epidote-quartz mineral assemblages of volcanic rocks of the NV-N area are considered to be the product of evolved seawater-rock interactions prior to regional metamorphism. This is consistent with the conditions under which epidote-quartz mineral assemblages precipitate in experiments, in modern,

active geothermal systems (temperatures $\geq 260^{\circ}\text{C}$; Keith et al. 1968, Tomasson and Kristmannsdottir 1972); and in ancient volcanic terrains (Troodos Ophiolite, Heaton and Sheppard 1977, Lydon and Jamieson 1984; Matagami Lake, MacGeehan 1978, MacGeehan and MacLean 1980; Noranda, Gibson et al. 1983, Gibson 1989).

At the Krafla geothermal field in Iceland, the epidote-quartz assemblage occurs above 300°C (Kristmannsdottir 1975). At the Asal geothermal field in the Republic of Djibouti, epidote appears at temperatures of $\approx 250^{\circ}\text{C}$ (Fouillac et al. 1989). In rocks of the Salton Sea geothermal system, epidote-group mineral assemblage formed at temperatures exceeding 300°C (Keith et al. 1968). And Alt et al. (1986) identified an epidote-quartz-sulphide-albite alteration assemblage in dyke rocks at hole 504B which, based on fluid inclusion and oxygen isotopic data was thought to have formed at temperatures between 200°C and 380°C .

Epidote-quartz alteration facies of rocks of the Waite Andesite formation is similar to the epidote-quartz alteration facies of the pillowed basalt in the Troodos Ophiolite, which formed at temperatures $\approx 300^{\circ}\text{C}$ and within the deepest part of the hydrothermal system. Lydon and Jamieson (1984) proposed that the epidote-quartz alteration in rocks of the Troodos Ophiolite formed under low water:rock ratios, in a closed chemical system bounded by intersecting dykes, and as the result of progressive equilibration of calcite and chloritic

host rock. The formation of epidote is promoted by a supply of calcium and hydrogen ion from the chloritization of basalt or low temperature mineral precursors derived from deeply circulating seawater, such as calcite and anhydrite. MacGeehan (1978) considered the epidote-quartz alteration facies in Matagami Lake area, to represent the hydrothermal channelways for the formation of massive sulphide deposits, and MacGeehan and MacLean (1980) noted that basaltic units containing the epidote-quartz zones were depleted in Fe, Mg, Zn, and Cu, the elements enriched in the hydrothermal alteration pipes immediately below the massive sulphide deposits. Gibson (1989) considered that the epidote-quartz alteration of volcanic rocks in the Noranda area is chemically complementary to the spilitized volcanic rocks.

During spilitization and chloritization, gain in Na, Mg, and loss of Ca are the preponderant chemical exchange in seawater/basalt reactions at temperatures $> 150^{\circ}\text{C}$ and result in magnesium-rich chloritic rocks (section 7.3). The formation of epidote-quartz alteration assemblage, on the other hand, requires the reverse of this chemical exchange, and involves gains in Ca and loss of Mg. To produce epidote-quartz alteration by this mechanism, low water:rock ratio and Ca-rich solutions (e.g., seawater that had previously reacted with the devitrified and spilitized rocks) are required. Low water:rock ratio is contrary to the result obtained in experiments in which Mg-hydrolysis predominates. Therefore,

Fig. 7.1. Elemental gains and losses in the rocks during fluid/rock experiments. ↑ = gain, ↓ = loss.

COMPARISON OF ELEMENTAL GAINS AND LOSSES

Spilitization

Experimental

New Vauze-Norbec area

Epidote-quartz alteration

Experimental

Rosenbauer & Blechhoff (1984)

New Vauze-Norbec area

Epidote-rich seafloor basalt

Humphris & Thompson (1978)

Silicification

Experimental

None

New Vauze-Norbec area

Fig. 7.2. Comparison of elemental gains and losses in the rocks during fluid/rock experiments, in natural systems and in the New Vauze-Norbec area. ↑ = gain, ↓ = loss.

Fig. 7.3. Calculated solubility of quartz, chalcedony, cristobalite, and amorphous silica at the vapour pressure of the solution. From Fournier and Rowe (1966).

Fig. 7.4. Calculated solubilities of quartz in water up to temperatures of 900°C at indicated pressures. The shaded area represents the region of retrograde solubility. From Fournier (1985).

Fig. 7.5. Solubility of quartz from 25° to 300°C at pH values ranging from 7 to 10 (solid lines). The dashed line shows the solubility of amorphous silica at neutral pH. From Fournier (1985).

CHAPTER 8. CONCLUSIONS

1. The 3000 m thick volcanic sequence of the New Vauze-Norbed (NV-N) area was emplaced at the end of a period of cauldron subsidence or extensional rifting subaqueously within the upper part of the Noranda Shield Volcanic Complex. This volcano grew by voluminous eruption of subaqueous andesitic and rhyolitic lava-flows, and concomitant synvolcanic faulting and volcano-tectonic subsidence accomodated along synvolcanic faults.
2. The NV-N area consists of two structural blocks, the New Vauze and the Norbec blocks, dissected by the Vauze Creek synvolcanic fault. The New Vauze block represents a low relief lava-shield or plateau constructed by the rhyolitic flows of the Waite Rhyolite formation, and the Norbec block represents a small subsidence structure within the main Central Noranda structure.
3. The Archean volcanic succession of the NV-N area consists of 17 alternating subaqueous andesitic and rhyolitic flows with less than 2% dacitic flows and pyroclastic rocks.
4. Volcanic rocks are relatively undeformed, metamorphosed to lower greenschist facies and intruded by numerous large

dioritic dykes and the granodioritic pluton of the Lake Dufault.

5. Rhyolitic flows erupted from different local vents and formed large tabular flows 0.5 to 5 km long, characterized by low slope ($< 20^\circ$). The flows are spherulitic, amygdaloidal, quartz-feldspar porphyritic and feldspar porphyritic. They consist of four distinct facies: massive, flow-banded, lobe-flow breccia, and flow breccia. The flows show distinct facies change from the feeding vent to the flow front. The proximal facies consists of massive to flow-banded rhyolite that grades radially into a facies composed of large lava lobes enclosed in flow-banded, locally flow-brecciated rhyolites. The distal facies consists of fewer and smaller isolated rhyolitic lobes enclosed in abundant flow breccias. Rhyolitic breccias and microbreccias form a carapace on the upper surfaces of the flows. Flank breccias, interpreted as debris flows, occur at the terminus of some flows. Local massive and low relief domes and elongated dyke-like features cutting the strata, mark the sites of felsic volcanic vents.

6. Two-thirds of the volcanic rocks of the NV-N area are andesitic flows which are, for the most part, pillowed and brecciated. They erupted from fissures and formed extensive and sheet-like structures up to 10 km long that flooded large areas, accumulated in topographic depressions and buried the

irregular relief created by the underlying rhyolitic flows and domes.

7. Pyroclastic rocks consist of ash and lapilli tuffs of hydrovolcanic origin. The ash and lapilli tuffs are composed of two components, a clastic or tuffaceous component and a chert/sulphide or exhalative component. The tuffaceous component consists of a waterlain ash that originated from mild explosive volcanic activity and the chert/sulphide component is a chemical constituent introduced through discharge of submarine hot springs.

8. The volcanic sequence of the NV-N area is interpreted as a primary tholeiitic, basaltic/andesitic-rhyolitic bimodal succession.

9. The volcanic rocks have been chemically altered by synvolcanic, semiconformable alteration processes of devitrification, spilitization, chloritization, epidote-quartz alteration, and silicification. Sericite-carbonate alteration is a discordant alteration type and is a postvolcanic process that affected the volcanic rocks and the late intrusions.

10. Initial diagenesis followed by widespread and pervasive spilitization uniformly altered all the volcanic rocks.

Spilitized rocks correspond to the least altered rocks and have low Ca and high Na contents. Spilitization is interpreted to result from subaqueous hydrothermal metamorphism that occurred shortly after burial. Diagenesis and spilitic alteration "fixed" the high $\delta^{18}\text{O}$ values of the rocks.

11. Epidote-quartz alteration and silicification were alteration processes subsequent to and superimposed on spilitization. Epidote-quartz alteration is mainly confined to the upper member of the Waite Andesite formation and is rare in rhyolitic flows. Silicification affected the upper member of the Waite Andesite formation and the flows of the Waite Rhyolite formation. Mass balance calculations show that Ca, K, HREE and Zr were added and Na, Fe, P, Y were depleted in the rocks during epidote-quartz alteration. The most silicified rhyolites and andesites are enriched in Si, Na and depleted in Fe, Mg, Mn. Al, Ti, HFS, and REE remained relatively immobile during alteration.

12. Epidote-quartz alteration resulted from the interaction of evolved seawater with previously devitrified and spilitized rocks at low water:rock ratios and temperatures $\geq 250^\circ\text{C}$ in a subseafloor environment.

13. Silicification resulted from the interaction of silica-saturated solutions with rocks at relatively low-temperature

and low-pH conditions in shallow subseafloor environment. Silicification occurred early after the extrusion of the volcanic rocks. The mechanism of silicification may have been the quenching of silica-saturated solution by mixing with cooler waters. The silica precipitation would have been facilitated by sustained low temperatures, low pH, and long exposure of solutions to fresh volcanic glass. Another possible mechanism of silicification is the decrease to near saturation level of silica concentrations in supersaturated solutions by reaction with the rocks at nearly constant temperature, promoted by Na-fixation reactions.

14. The whole-rock $\delta^{18}\text{O}$ values of volcanic rocks of the NV-N area increase with stratigraphic height from 5.2 to 12.7. This isotopic variation is the result of progressive, continued, and superposition of different semiconformable alteration types during continuing volcanism and burial metamorphism.

REFERENCES

- Abbey, S. 1979. Reference materials - Rock samples SY-2, SY-3, MRG-1. CANMET Report 79-35.
- Abbey, S. 1980. Studies in "standard samples" for use in the general analysis of silicate rocks and minerals -Part 6: 1979 edition of "usable" values. Geological Survey of Canada, paper 80-14.
- Abbey, S. 1983. Studies in "standard samples" of silicate rocks and minerals 1969-1982. Geological Survey of Canada, Paper 83-15: 114 p.
- Abolins, U. 1977. Geological compilation, New Vauze project, two maps. Asarco Exploration Co. of Canada.
- Alt, J.C. Muehlenbachs, K. and Honnorez, J. 1986. An oxygen isotopic profile through the upper kilometer of the oceanic crust, DSDP Hole 504B. Earth and Planetary Science Letter, 80: 217-229.
- Amstutz, G.C., ed. 1974. Spilites and Spilitic Rocks. Springer-Verlag New York Heidelberg Berlin: 482 p.
- Anderson, R.N., Honnorez, J., Becker, K., Adamson, A.C. Alt, A.C., Emmermann, J.C., Kempton, P.D., Kinoshita, H., Laverne, C., Mottl, M.J. and Newmark, R.L. 1982. DSDP hole 504B, the first reference section over 1 km through layer 2 of the oceanic crust. Nature, 300: 589-594.
- Arnorsson, S., Gunnlaugsson, E., and Svavarsson, H. 1983a. The chemistry of geothermal waters in Iceland. II. Mineral equilibria and independent variables controlling water compositions. Geochimica et Cosmochimica Acta, 47: 547-566.
- Arnorsson, S., Gunnlaugsson, E., and Svavarsson, H. 1983b. The chemistry of geothermal waters in Iceland. III. Chemical geothermometry in geothermal investigations. Geochimica et Cosmochimica Acta, 47: 567-577.
- Ballard, R.D. and Moore, J.G. 1977. Photographic atlas of the Mid-Atlantic ridge rift valley. Springer Verlag, Berlin, 114 p.

- Ballard, R.D., Holcomb, R.T. and Van Andel, T. 1979. The Galapagos Rift at 86° W: 3. Sheet flows, collapse pits, and lava lakes of the Rift Valley. *Journal of Geophysical Research*, 84: 5407-5422.
- Baragar, W.R.A. 1968. Major element geochemistry of the Noranda volcanic belt, Quebec-Ontario. *Canadian Journal of Earth Sciences*, 5: 773-790.
- Baragar, W.R.A. 1984. Pillow formation and layered flows in the Circum-Superior Belt of eastern Hudson Bay. *Canadian Journal of Earth Sciences*, 21: 781-792.
- Baragar, W.R.A., Plant, A.G., Pringle, G.J. and Schau, M. 1977. Petrology and alteration of selected units of mid-Atlantic ridge basalts sampled from sites 332 and 335, DSDP. *Canadian Journal of Earth Sciences*, 14: 837-874.
- Barrette, J.G. 1980. New Vauze Property, Dufresnoy township, Quebec. Geological Report and 1 map. Corporation Falconbridge Copper, Quebec.
- Barton, P.B., Jr. 1978. Some ore textures involving sphalerite from the Furotobe Mine, Atika prefecture, Japan. *Mining Geology*, 28: 293-300.
- Beaty, D.W., Taylor, H.P. Jr. and Coad, P.R. 1982. Some petrologic and oxygen isotopic relationships in the Amulet Mine, Noranda, Quebec, and their bearing on the origin of Archean massive sulphide deposits. *Economic Geology*, 77: 95-108.
- Beaty, D. W., Taylor, H.P. Jr. 1988. An oxygen isotope study of the Kidd Creek, Ontario, volcanogenic massive sulfide deposit: evidence for a high $\delta^{18}\text{O}$ ore fluid. *Economic Geology*, 83: 1-17.
- Bertine, K.K. and Keene, J.B. 1975. Submarine barite-opal rocks of hydrothermal origin. *Science*, 188: 150-152.
- Bevins, R.E. and Roach, R.A. 1978. Pillow lava and isolated-pillow breccia of rhyodacitic composition from the Fishguard Volcanic Group, Lower Ordovician, S.W. Wales, United Kingdom. *Journal of Geology*, 87: 193-201.
- Bevins, R.E., Howells, M.F., Kokelaar, B.P. and Roach, R.A. 1982. Volcanic processes in marginal basins. Geological Society of London, Volcanic Studies Group, Wales Field Meeting, September 1-8, Guidebook.

- Bischoff, J.L. and Dickson, F.W. 1975. Seawater-basalt interaction at 200°C and 500 bars: Implications for the origin of sea-floor heavy-metal deposits and regulation of seawater chemistry. *Earth and Planetary Science Letters*, 25: 385-397.
- Bischoff, J.L. and Rosenbauer, R.J. 1984. The critical point and two phase boundary of seawater, 200-500°C. *Earth and Planetary Science Letters*, 68: 172-180.
- Bohlke, J.K., Alt, J.C. and Muehlenbachs, K. 1984. Oxygen isotope-water relationships in altered deep sea basalts: low temperature mineralogical controls. *Canadian Journal of Earth Sciences*, 21: 67-77.
- Bonnichsen, B. and Kauffman, D.F. 1987. Physical features of rhyolite lava flows in the Snake River Plain volcanic province, southwestern Idaho. In *The Emplacement of Silicic Domes and Lava Flows*. Edited by J.H. Fink. Geological Society of America, Special Paper 212: 119-145.
- Bottinga, Y. and Javoy, M. 1973. Comments on oxygen isotope geothermometry. *Earth and Planetary Science Letters*, 20: 250-265.
- Bottinga, Y. and Javoy, M. 1975. Oxygen isotope partitioning among the minerals in igneous and metamorphic rocks. *Review in Geophysical Space Physic*, 13: 401-418.
- Bowers, T.S. and Taylor, H.P. 1985. An integrated chemical and stable isotope model of the origin of midocean ridge hot spring systems. *Journal of Geophysical Research*, 90: 12583-12606.
- Camiré, G. 1989. Volcanic stratigraphy in the Hunter Creek Fault area, east of the Flavrian pluton, Rouyn-Noranda, Québec. M.Sc. thesis, Carleton University: 213 p.
- Campbell, I.H., Leshner, C.M., Coad, P., Franklin, J.M., Gorton, M.P. and Thurston, P.C. 1984. Rare-earth element mobility in alteration pipes below massive Cu-Zn sulphide deposits. *Chemical Geology*, 45: 181-202.
- Cas, R.R. 1978. Silicic lavas in Paleozoic flyschlike deposits in New South Wales, Australia: Behavior of deep subaqueous silicic flows. *Geological Society of American Bulletin*, 89: 1708-1714.
- Cas, R.A.F. and Wright, J.V. 1987. Volcanic successions: modern and ancient. Allen and Unwin, London, 529 p.

- Casey, W.H. and Taylor, B.E. 1982. Oxygen, hydrogen, and sulfur isotope geochemistry of a portion of the West Shasta Cu-Zn district, California. *Economic Geology*, 77: 38-49.
- Christiansen, R.L. and Lipmann, P.W. 1966. Emplacement and thermal history of a rhyolite lava flow near Fortymile Canyon, southern Nevada. *Geological Society of America Bulletin*, 77: 671-684.
- Clark, A.M. 1984. Mineralogy of the rare earth elements. In *Rare Earth Element Geochemistry*. Edited by P. Henderson: 33-61.
- Clayton, R.N. and Epstein, S. 1958. The relationship between O^{18}/O^{16} ratios in coexisting quartz, carbonate, and iron oxides from various geological deposits. *Journal of Geology*, 66: 352-373.
- Clayton, R.N. and Mayeda, T.K. 1963. The use of bromine pentafluoride in the extraction of oxygen from oxides and silicates for isotopic analysis. *Geochimica et Cosmochimica Acta*, 27: 43-52.
- Clayton, R.N., O'Neil, J. and Mayeda, T.K. 1972. Oxygen isotope exchange between quartz and water. *Journal of Geophysical Research*, 77: 3057-3067.
- Clayton, R.N., Goldsmith, J.R. and Mayeda, T.K. 1989. Oxygen isotope fractionation in quartz, albite, anorthite and calcite. *Geochimica et Cosmochimica Acta*, 53: 725-733.
- Cocker, J.D., Griffin, B.J. and Muehlenbachs, K. 1982. Oxygen and carbon isotope evidence for seawater-hydrothermal alteration of the Macquarie Island ophiolite. *Earth and Planetary Science Letters*, 61: 112-122.
- Cole, J.W. 1970. Structure and eruptive history of the Tarawera Volcanic Complex. *N.Z.J. Geol. Geophys.*, 13: 879-902.
- Comba, C.D.A. 1977. Summary report on the Waite Dufault Mines Ltd. option, Duprat township, Noranda, Quebec. Falconbridge Copper Ltd., internal report: 44 p.
- Cooke, H.C., James, W.F. and Mawdsley, J.B. 1931. Geology and ore deposits of Rouyn-Harricana region, Quebec. *Geological Survey of Canada*, 166: 314 p.

- Coombs, D.S. 1954. The nature and alteration of some triassic sediments from Southland, New Zealand. Transactions of the Royal Society of New Zealand, 82: 65-109.
- Cormier, J.M. and Labrie, M. 1984. Report on results and recommendations for exploration in the East Norbec/D'Alembert area. Corporation Falconbridge Copper, internal report: 40 p.
- Costa, U.R. Barnett, R.L. and Kerrich, R. 1983. The Matagami Lake Mine Archean Zn-Cu sulphide deposit, Quebec: hydrothermal coprecipitation of talc and sulphides in a sea-floor brine pool - evidence from geochemistry, $^{18}\text{O}/^{16}\text{O}$, and mineral chemistry. Economic Geology, 78: 1144-1203.
- Cousineau, P.A. 1980. Stratigraphie et faciès des Andésites Amulet, près de la Mine Norbec, Rouyn Noranda, Québec. M.Sc. thesis, Université du Québec à Chicoutimi, Chicoutimi, Québec.
- Cousineau, P.A. and Dimroth, E. 1982. Interpretation of the relations between massive, pillowed and brecciated facies in an Archean submarine volcano - Amulet Andesite, Rouyn Noranda, Canada. Journal of Volcanology and Geothermal Research, 13: 83-102.
- Craig, H., Welhan, J.A., Kim, K., Poreda, R. Lupton, J.E. 1980. Geochemical studies of the ^{21}N EPR hydrothermal fluids, EOS 61: 592.
- Crowe, B.M. and Fisher, R.V. 1973. Sedimentary structures in base-surge deposits with special reference to cross-bedding, Ubehebe Craters, Death Valley, California. Geological Society of America Bulletin, 84: 663-682.
- Dickson, F.W. and Potter, J.M. 1982. Rock-brine chemical interactions: Final report, Electric Power Research Institute Project 653-2, AP-2258: 89 p.
- Dimroth, E. and Lichtblau, A.P. 1979. Metamorphic evolution of Archean hyaloclastites, Noranda area, Canada. Part I: Comparison of Archean and Cenozoic seafloor metamorphism. Canadian Journal of Earth Sciences, 16: 1315-1340.
- Dimroth, E. and Rocheleau, M. 1979. Volcanology and sedimentology of Rouyn Noranda area. Guidebook, Excursion A1. Quebec 1979. Geological Association of Canada: 200 p.

- Dimroth, E., Cousineau, P., Leduc, M. and Sanschagrin, Y. 1978. Structure and organization of Archean subaqueous basalt flows, Rouyn Noranda area, Quebec, Canada. *Canadian Journal of Earth Sciences*, 15: 902-918.
- Dimroth, E., Imreh, L., Rocheleau, M. and Goulet, N. 1982. Evolution of the south-central part of the Archean Abitibi Belt, Quebec. Part I: Stratigraphy and paleogeography model. *Canadian Journal of Earth Sciences*, 19: 1729-1758.
- Dimroth, E., Imreh, L., Goulet, N. and Rocheleau, M. 1983a. Evolution of the south-central segment of the Archean Abitibi Belt, Quebec. Part II: Tectonic evolution and geomechanical model. *Canadian Journal of Earth Sciences*, 20: 1355-1373.
- Dimroth, E., Imreh, L., Goulet, N. and Rocheleau, M. 1983b. Evolution of the south-central segment of the Archean Abitibi Belt, Quebec. Part III: Plutonic and metamorphic evolution and geotectonic model. *Canadian Journal of Earth Sciences*, 20: 1374-1388.
- Dimroth, E., Gelinas, L., Rocheleau, M., Provost, G. and Tasse, G. 1975. Guidebook field trip and field conference on the volcanology and sedimentology of the Rouyn-Noranda area. Office of the Resident Geologist, Quebec Department of Natural Resources, CP 277, Rouyn, Quebec.
- Dimroth, E., Hocq, M., Cousineau, P., Leduc, M. and Sanschagrin, Y. 1979. A facies model of subaqueous basalt flows. *Geological Association of Canada, Abstract with Programm*, 4: 46.
- Dimroth, E., Imreh, L., Cousineau, P., Leduc, M. and Sanschagrin, Y. 1985. Paleogeographic analysis of mafic submarine flows and its use in the exploration for massive sulphide deposits. In *Evolution of Archean Supracrustal Sequences*. Edited by L.D. Ayres, P.C. Thurston, K.D. Card and W. Weber. *Geological Association of Canada, Special Paper* 28: 203-220.
- Donnelly, T.W., Thompson, G. and Salisbury, M.H. 1980. The chemistry of altered basalts at site 417, Deep Sea Drilling Project Leg 51. In *Initial Reports of the Deep Sea Drilling Project Legs 51, 52 and 53, Part 2*. Edited by T.W. Donnelly, J. Francheteau, W. Bryan, P. Robinson, M. Flower, M. Salisbury et al.: 1319-1330.

- Duchac, K.C. and Hanor, J. 1979. Origin and timing of the metasomatic silicification of an early Archean komatiite sequence, Barberton Mountain Land, South Africa. *Precambrian Research*, 37: 125-146.
- Dugas, J. 1966. Relationship of mineralization to Precambrian stratigraphy in the Rouyn-Noranda area, Quebec. In *Precambrian Symposium*, Geological Association of Canada, Special Paper, 3: 43-55.
- Elders, W.A. and Bird, D.K. 1974. Active formation of silicified cap rocks in arenaceous sands in a low-temperature, near-surface geothermal environment, in the Salton Trough of California, USA. *International Symposium on water-rock interaction*, abstract. Geological Survey of Czechoslovakia, Prague: 150-157.
- Eldridge, C.S., Barton, P.B., Jr. and Ohmoto, H. 1983. Mineral textures and their bearing on formation of the Kuroko orebodies. *Economic Geology*, Monograph 5: 241-281.
- Ellis, A.J. 1968. Natural hydrothermal systems and experimental hot-water/rock interaction: reactions with NaCl solutions and trace metal extraction. *Geochimica et Cosmochimica Acta*, 32: 1356-1363.
- Finlow-Bates, T. and Stumpfl, E.F. 1981. The behaviour of so-called immobile elements in hydrothermally altered rocks associated with volcanogenic submarine exhalative ore deposits. *Mineralium Deposita*, 16: 319-328.
- Fink, J.H. 1983. Structure and emplacement of a rhyolitic obsidian flow: Little Glass Mountain, Medicine Lake Highland, northern California: *Geological Society of America Bulletin*, 94: 362-380.
- Fink, J.H. and Manley, C.R. 1987. Origin of pumiceous and glassy textures in rhyolite flows and domes. In *The Emplacement of Silicic Domes and Lava Flows*. Edited by J.H. Fink. Geological Society of America, Special Paper 212: 77-88.
- Fisher, R.V. and Schmincke, H.-U. 1984. *Pyroclastic rocks*. Springer-Verlag, New York, NY: 471 p.
- Floyd, P.A. and Winchester, J.A. 1978. Identification and discrimination of altered and metamorphosed volcanic rocks using immobile elements. *Chemical Geology*, 21: 291-306.

- Fouillac, A.M., Fouillac, F., Cesbron, F., Pillard, F. and Legendre, O. 1989. Water-rock interaction between basalt and high-salinity fluids in the Asal Rift, Republic of Djibouti. *Chemical Geology*, 76: 217-289.
- Fournier, R.O. 1983. A method of calculating quartz solubilities in aqueous sodium chloride solutions. *Geochimica et Cosmochimica Acta*, 47: 579-586.
- Fournier, R.O. 1985. The behavior of silica in hydrothermal solutions; In Berger, B.R. and Bethke, P.M. (eds.), *Geology and Geochemistry of Epithermal Systems, Reviews in Economic Geology*, 2: 45-61.
- Fournier, R.O. and Potter, R.W. II. 1982. An equation correlating the solubility of quartz in water from 25° to 900°C at pressures up to 10,000 bars. *Geochimica et Cosmochimica Acta*, 47: 587-596.
- Fournier, R.O. and Rowe, J.J. 1966. Estimation of underground temperatures from the silica content of water from hot springs and wet-steam wells. *American Journal of Science*, 264: 685-697.
- Fournier, R.O., Rosenbauer, R.J. and Bischoff, J.L. 1982. The solubility of quartz in aqueous sodium chloride solution at 350°C and 180 to 500 bars. *Geochimica et Cosmochimica Acta*, 46: 1975-1978.
- Friedmann, I. and O'Neil, J.R. 1977. Compilation of stable isotope fractionation factors of geochemical interest. In *Data of Geochemistry*, sixth edition, chapter KK. Edited by M. Fleischer. U.S. Geological Survey, Paper 440-kk: 12 p.
- Friedmann, I. and Smith, R.L. 1958. The deuterium content of water in some volcanic glasses. *Geochimica et Cosmochimica Acta*, 15: 218-228.
- Furnes, H. 1978. Element mobility during palagonitization of a subglacial hyaloclastite in Iceland. *Chemical Geology*, 22: 249-264.
- Furnes, H., Fridleifsson, I.B. and Atkins, F.B. 1980. Subglacial volcanics - on the formation of acid hyaloclastites. *Journal of Volcanology and Geothermal Research*, 8: 95-110.
- Fyfe, W.S., Price, N.J. and Thompson, A.B. 1978. *Fluids in the earth's crust*. Amsterdam, Elsevier: 383 p.

- Garlick, G.D. and Dymond, J.R. 1970. Oxygen isotope exchange between volcanic materials and ocean water. *Geological Society of America Bulletin*, 81: 2137-2142.
- Gelinas, L. and Ludden, J.N. 1984. Rhyolitic volcanism and the geochemical evolution of the Archean Central Ring Complex: the Blake River Group volcanics of the southern Abitibi belt, Superior Province. *Physics of the Earth and Planetary Interiors*, 35: 77-88.
- Gelinas, L., Mellinger, M. and Trudel, P. 1982. Archean mafic metavolcanics from the Rouyn-Noranda district, Abitibi Greenstone Belt, Quebec. 1. Mobility of the major elements. *Canadian Journal of Earth Sciences*, 19: 2258-2275.
- Gelinas, L., Trudel, P. and Hubert, P. 1984. Chemostratigraphic division of the Blake River Group, Rouyn Noranda area, Abitibi, Quebec. *Canadian Journal of Earth Sciences*, 21: 220-231.
- Gelinas, L., Brooks, C., Perrault, G., Carigan, J., Trudel, P. and Grasso, F. 1977. Chemo-stratigraphic subdivisions within the Abitibi volcanic belt, Rouyn-Noranda District. In Baragar, W.R.A., Coleman, L.C. and Hall, J.M., *Volcanic Regimes in Canada*, Geological Association of Canada, special paper, 16: 265-296.
- Gibson, H.L. 1979. Geology of the Amulet Rhyolite formation, Turcotte Lake Section, Noranda area, Quebec. M.Sc. thesis, Carleton University, Ottawa, Ontario: 154 p.
- 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.
- Gibson, H.L. and Lichtblau, A.P. 1986. Subaqueous rhyolite flows of the Central Mine Sequence, Noranda, Quebec. *Geological Association of Canada, Abstracts*, 11: 72.
- Gibson, H.L., Walker, S.D. and Coad, P.R. 1984. Surface geology and volcanogenic base metal massive sulfide deposits and gold deposits of Noranda and Timmins. *Geological Association of Canada - Mineralogical Association of Canada, Field Trip 14*: 155 p.
- Gibson, H.L., Watkinson, D.H. and Comba, C.D.A. 1983. Silicification: Hydrothermal Alteration in an Archean Geothermal System within the Amulet Rhyolite Formation, Noranda, Quebec. *Economic Geology*, 78: 954-971.

- Gibson, H.L., Watkinson, D.H. and Comba, C.D.A. 1989. Subaqueous phreatomagmatic explosion breccias at Euttercup Hill, Noranda, Quebec. *Canadian Journal of Earth Sciences*, 26: 1428-1439.
- Gillis, K.M. and Robinson, P.T. 1985. Low-temperature alteration of the extrusive sequence, Troodos Ophiolite, Cyprus. *Canadian Mineralogist*, 23: 431-441.
- Gilmour, P. 1965. The origin of the massive sulphide mineralization in the Noranda district, northwestern Quebec. *Geological Association of Canada*, 16: 63-81.
- Goldfarb, M.S., Converse, D.R., Holland, H.D. and Edmond, J.M. 1983. The genesis of Hot Spring Deposits on the East Pacific Rise, 21°N. *Economic Geology*, Monograph 5: 184-197.
- Goldie, R.J. 1976. The Flavrian and Powell Plutons, Noranda Area, Quebec, Ph.D. Thesis, Queen's University, Kingston, Ontario.
- Goldie, R.J. 1978, Metamorphism of the Flavrian and Powell Plutons, Noranda Area, Quebec. *Journal of Petrology*, 20: 227-238.
- Goodwin, A.M. 1972. The Superior Province. In *Variations in tectonic styles in Canada*. Geological Association of Canada, Special Paper, 11: 527-623.
- Goodwin, A.M. 1977. Archean volcanism in Superior Province, Canadian Shield. In Baragar, W.R.A., Coleman, L.C. and Hall, J.M., *Volcanic Regimes in Canada*, Geological Association of Canada, Special Paper, 16: 205-441.
- Goodwin, A.M. 1982. Archean volcanoes in south-western Abitibi belt, Ontario and Quebec: formation, composition and development. *Canadian Journal of Earth Sciences*, 19: 1140-1155.
- Grant, J.A. 1986. The isocon diagram - A simple solution to Gresens' equation for metasomatic alteration. *Economic Geology*, 81: 1976-1982.
- Green, G.R., Ohmoto, H., Date, J. and Takahashi, T. 1983. Whole-rock oxygen isotope distribution in the Fukazawa-Kosaka area, Hokuriku district, Japan, and its potential application to mineral exploration. *Economic Geology*, Monograph 5: 395-411.

- Gregory, R.T. and Taylor, H.P. 1981. An oxygen isotope profile in a section of cretaceous oceanic crust, Samail Ophiolite, Oman: Evidence for $\delta^{18}\text{O}$ buffering of the oceans by deep (> 5km) seawater-hydrothermal circulation at mid-ocean ridges. *Journal of Geophysical Research*, **86**: 2737-2755.
- Gresens, R.L. 1967. Composition - volume relationships of metasomatism. *Chemical Geology*, **2**: 47-55.
- Groves, D.A., Morton, R.L. and Franklin, J.L. 1989. Physical volcanology of the footwall rocks near the Mattabi massive sulphide deposit, Sturgeon Lake, Ontario., *Canadian Journal of Earth Sciences*, **25**: 280-291.
- Hargreaves, R. and Ayres, L.D. 1979. Morphology of Archean metabasalt flows, Utik Lake, Manitoba. *Canadian Journal of Earth Sciences*, **16**: 1452-1466.
- Harrigan, D.B. and MacLean, W.H. 1976. Petrography and geochemistry of epidote alteration patches in gabbro dykes at Matagami, Quebec. *Canadian Journal of Earth Sciences*, **13**: 500-511.
- Hattori, K. and Muehlenbachs, K. 1980. Marine hydrothermal alteration at a Kuroko ore deposit, Kosaka, Japan. *Contribution to Mineralogy and Petrology*, **74**: 285-292.
- Hay, R.L. and Iijima, A. 1968. Petrology of palagonite tuffs of Koko Craters, Oahu, Hawaii. *Contribution to Mineralogy and Petrology*, **17**: 141-154.
- Heaton, T.H.F. and Sheppard, S.M.F. 1977. Hydrogen and oxygen isotope evidence for seawater-hydrothermal alteration and ore deposition, Troodos Complex, Cyprus. In *Volcanic Processes and Ore Genesis*, Geological Society of London, Special Publication, **7**: 42-57.
- Hughes, C.J. 1973. Spilites, keratophyres and the igneous spectrum. *Geological Magazine*, **6**: 513-527.
- Humphris, S.E. and Thompson, G. 1978. Hydrothermal alteration of oceanic basalts by seawater. *Geochimica et Cosmochimica Acta*, **42**: 107-125.
- Humphris, S.E., Morrison, M.A. and Thompson, R.N. 1978. Influence of rock crystallization history upon subsequent lanthanide mobility during hydrothermal alteration of basalts. *Chemical Geology*, **23**: 125-137.

- Hutchison, M.N. and Scott, S.D. 1981. Sphalerite geobarometry in the Cu-Fe-Zn-S system. *Economic Geology*, 76: 143-153.
- Hynes, A. 1980. Carbonatization and mobility of Ti, Y and Zr in Ascot Formation metabasalts, S.E. Quebec. *Contributions to Mineralogy and Petrology*, 75: 79-87.
- Ikingura, J.R., Bell, K. and Watkinson, D.H. 1989. Hydrothermal alteration and oxygen and hydrogen isotope geochemistry of the D68 Zone Cu-Zn massive sulphide deposit, Noranda District, Quebec, Canada. *Mineralogy and Petrology*, 40: 155-172.
- Irvine, T.N. and Baragar, W.R.A. 1971. A guide to the chemical classification of the common volcanic rocks. *Canadian Journal of Earth Sciences*, 8: 523-549.
- James, W.F. 1924. The Rouyn map-area, Timiskaming county, Quebec. Geological Survey of Canada, Summary report, CI: 126-144.
- Jensen, L.S. 1976. A new cation plot for classifying subalkalic volcanic rocks. Ontario Division of Mines. Miscellaneous paper 66: 22 p.
- Jolly, W.T. 1980. Development and degradation of Archean Lavas, Abitibi area, Canada, in light of major element geochemistry. *Journal of Petrology*, 21: 323-363.
- Jones, J.G. 1969. Pillow lavas at depth indicators. *American Journal of Science*, 267: 181-195.
- Kalogeropoulos, S.I. and Scott, S.D. 1989. Mineralogy and geochemistry of an Archean tuffaceous exhalite: The Main Contact Tuff, Millenbach Mine area, Noranda, Quebec. *Canadian Journal of Earth Sciences*, 26: 88-105.
- Keith, T.E.C., Muffler, L.J.P. and Cremer, M. 1968. Hydrothermal epidote formed in the Salton Sea geothermal system, California. *American Mineralogist*, 53: 1653-1644.
- Kennedy, G.C. 1950. A portion of the system silica-water. *Economic Geology*, 45: 629-653.
- Kennedy, L.P. 1984. The geology and geochemistry of the Archean Flavrian Pluton, Noranda, Quebec. Ph.D. thesis, Western Ontario University, London, Ontario: 277 p.

- Knuckey, M.J., Comba, C.D.A. and Riverin, G. 1982. Structure, metal zoning and alteration at the Millenbach deposit, Noranda, Quebec. In *Precambrian Sulphide Deposits*. Edited by R.W. Hutchinson, C.D. Spence and J.M. Franklin. Geological Association of Canada, Special Paper 25: 255-296.
- Kojima, S. and Sugaki, A. 1985. Phase relations in the Cu-Fe-Zn-S system between 500° and 300°C under hydrothermal conditions. *Economic Geology*, 80: 158-171.
- Koski, R.A., Clague, D.A. and Oudin, E. 1984. Mineralogy and chemistry of massive sulfide deposits from the Juan de Fuca Ridge. *Geological Society of America Bulletin*, 95: 930-945.
- Kristmannsdottir, H. 1975. Hydrothermal alteration of basaltic rocks in Iceland geothermal areas. Second U.N. Symposium on the Development and Utilization of Geothermal Resources, Proceedings: 441-445.
- Krogh, T.E. and Davis, G.L. 1971. Zircon U-Pb ages of Archean metavolcanic rocks in the Canadian Shield. Carnegie Institute of Washington, Washington, DC, Geophysical Laboratory Report 1970-1971: 241-242.
- Kyser, T.K. 1980. Stable and rare gas isotopes and the genesis of basic lavas and mantle xenoliths. Ph.D. thesis, University of California, Berkeley.
- La Roche, H., de, Rocci, G. and Juteau, Th. (1974). Essai de caractérisation chimique des associations spilîtiques. In *Spilites and Spilitic Rocks*, edited by G.C. Amstutz. International Union of Geological Sciences, Series A, number 4, Springer-Verlag, New York: 39-58.
- Larson, P.B. 1984. Geochemistry of the alteration pipe at the Bruce Cu-Zn volcanogenic massive sulfide deposit, Arizona. *Economic Geology*, 79: 1880-1896.
- Lefebure, D. 1983. Exploration potential of principal contacts on west Norbec. Corporation Falconbridge Copper, internal report: 8 p.
- Le Maitre, R.W. 1976. The chemical variability of some common igneous rocks. *Journal of Petrology*, 17: 589-637.
- Leshner, C.M., Gibson, H.L. and Campbell, I.H. 1986. Composition volume changes during hydrothermal alteration of andesite at Buttercup Hill, Noranda District, Quebec. *Geochimica et Cosmochimica Acta*, 50: 2693-2705.

- Lichtblau, A.P. and Dimroth, E. 1980. Stratigraphy and facies at the south margin of the Archean Noranda caldera, Noranda, Quebec. Current Research, Part 1A, Geological Survey of Canada, Paper 80-1A: 756.
- Lickus, R.J. 1965. Geology and geochemistry of the ore deposits at the Vauze Mine, Noranda district, Quebec. Ph.D thesis, McGill University, Montreal, Quebec: 135 p.
- Lofgren, G. 1970. Experimental devitrification rate of rhyolite glass. Geological Society of America Bulletin, 81: 553-560.
- Lofgren, G. 1971a. Experimentally produced devitrification textures in natural rhyolitic glass. Geological Society of America Bulletin, 82: 111-124.
- Lofgren, G. 1971b. Spherulitic textures in glassy and crystalline rocks. Journal of Geophysical Research, 76: 5635-5649.
- Ludden, J. and Hubert, C. 1986. Geologic evolution of the Late Archean Abitibi greenstone belt of Canada. Geology, 14: 707-711.
- Ludden, J.N. and Thompson, G. 1979. An evaluation of the behavior of the rare earth elements during the weathering of sea-floor basalt. Earth and Planetary Science Letters, 43: 85-92.
- Ludden, J., Gelinas, L. and Trudel, P. 1982. Archean metavolcanics from the Rouyn-Noranda district, Abitibi Greenstone Belt, Quebec - 2. Mobility of trace elements and petrogenetic constraints. Canadian Journal of Earth Sciences, 19: 2276-2287.
- Ludden, J., Hubert, C. and Gariepy, C. 1986. The tectonic evolution of the Abitibi greenstone belt of Canada. Geological Magasin, 123: 153-166.
- Lydon, J.W. and Jamieson, H.E. 1984. The generation of ore-forming hydrothermal solutions in the Troodos ophiolite complex. Some hydrodynamic and mineralogical considerations. In Current Research, Part A, Geological Survey of Canada, Paper 84-1A: 617-625.
- MacGeehan, P.J. 1978. The geochemistry of altered volcanic rocks at Matagami, Quebec: A geothermal model for massive sulphide genesis. Canadian Journal of Earth Sciences, 15: 551-570.

- MacGeehan, P.J. and MacLean, W.H. 1980. An Archean sub-seafloor geothermal system "calc-alkali" trends, and massive sulphide genesis. *Nature*, 286: 767-771.
- MacLean, W.H. 1988. Rare earth element mobility at constant inter-REE ratios in the alteration zone at the Phelps Dodge massive sulphide deposit, Matagami, Quebec. *Mineralium Deposita*, 23: 231-238.
- MacLean, W.H. and Hoy, L.D. 1989. Alteration at the Horne Mine, Noranda, Quebec. Canadian Institut of Mining and Metallurgy, abstract, paper no. 94, 82: 86.
- MacLean, W.H. and Kranidiotis, P. 1987. Immobile elements as monitors of mass transfer in hydrothermal alteration: Phelps Dodge Massive Sulfide deposit, Matagami, Quebec. *Economic Geology*, 82: 951-962.
- Magaritz, M. and Taylor, H.P. Jr. 1976. Oxygen and hydrogen isotope studies of serpentinization in the Troodos ophiolite complex, Cyprus. *Earth and Planetary Science Letters*, 23: 8-14.
- Manley, C.R. and Fink, J.H. 1987. Internal textures of rhyolite flows as revealed by research drilling. *Geology*, 15: 549-552.
- Marzouki, F., Kerrich, R. and Fyfe, W.S. 1979. Epidotisation of diorites at Al Hadah, Saudi Arabia: Fluid influx into cooling plutons. *Contributions to Mineralogy and Petrology*, 68: 281-284.
- Mason, B. 1966. *Principles of Geochemistry*. Wiley, New York. 329 p.
- Matsuhisa, Y., Goldsmith, J.R. and Clayton, R.N. 1979. Oxygen isotopic fractionation in the system quartz-albite-anorthite-water. *Geochimica et Cosmochimica Acta*, 43: 1131-1140.
- Matthews, A., Goldsmith, J.R. and Clayton, R. 1983. Oxygen isotope fractionation between zoisite and water. *Geochimica et Cosmochimica Acta*, 47: 645-654.
- Miyashiro, A. 1974. Volcanic rock series in island arcs and active continental margins. *American Journal of Science*, 274: 321-355.
- Moore, J.G. 1965. Petrology of deep-sea basalt near Hawaii. *American Journal of Science*, 263: 40-52.

- Mortensen, J.K. 1987. Preliminary U-Pb zircon ages for volcanic and plutonic rocks of the Noranda-Lac Abitibi area, Abitibi Subprovince, Quebec. Current Research, Part A, Geological Survey of Canada, Paper 87-1A: 581-590.
- Morton, R.L. and Nebel, M.L. 1984. Hydrothermal alteration of felsic volcanic rocks at the Helen siderite deposit, Wawa, Ontario. Economic Geology, 79: 1318-1333.
- Mottl, M.J. 1983. Metabasalt, axial hot springs, and the structure of hydrothermal systems at mid-ocean ridges. Geological Society of America Bulletin, 94: 161-180.
- Muehlenbachs, K. 1979. The alteration and aging of the basaltic layer of sea floor: oxygen isotope evidence from DSDP/IPOD legs 51, 52 and 53. In T. Donnely, J. Francheteau, W. Bryan, P. Robinson, M. Flower, M. Salisbury et al., Initial Reports of the Deep Sea Drilling Project 51-53, Part 2. U.S. Government Printing Office, Washington, D.C.: 1159-1167.
- Muehlenbachs, K. 1980. Alteration of the oceanic crust and the $\delta^{18}\text{O}$ history of seawater. In Stable isotopes in high temperature geological processes. Edited by Valley, J.W., Taylor, H.P. Jr. and O'Neil, J.R. Reviews in mineralogy, 16, Mineralogical Society of America: 425-444.
- Muehlenbachs, K. and Clayton, R.N. 1972a. Oxygen isotope studies of fresh and weathered submarine basalts. Canadian Journal of Earth Sciences, 9: 172-184.
- Muehlenbachs, K. and Clayton, R.N. 1972b. Oxygen isotope geochemistry of submarine greenstones. Canadian Journal of Earth Sciences, 9: 471-478.
- Murphy, J.B. and Hynes, A.J. 1986. Contrasting secondary mobility of Ti, P, Zr, Nb and Y in two metabasaltic suites in the Appalachians. Canadian Journal of Earth Sciences, 23: 1138-1144.
- Normark, W.R., Morton, J.L., Koski, R.A., Clague, D.A. and Delaney, J.R. 1983. Active hydrothermal vents and sulfide deposits on the southern Juan de Fuca Ridge. Geology, 11: 158-163.
- Normark, W.R., Lupton, J.E., Murray, J.W., Delaney, J.R., Johnson, H.P., Koski, R.A., Clague, D.A. and Morton, J.L. 1982. Polymetallic sulfide deposits and water-column of active hydrothermal vents on the southern Juan de Fuca Ridge. Marine technology Society Journal, 16: 46-53.

- Nunes, P.D. and Jensen, L.S. 1980. Geochronology of the Abitibi Metavolcanic belt, Kirkland lake area - A progress report. In The Kuroko and related volcanogenic massive sulphide deposits. Edited by E.G. Pye. Economic Geology Monograph 5: 9-114.
- Osterberg, S.A., Morton, R.L. and Franklin, J.M. 1987. Hydrothermal alteration and physical volcanology of Archean rocks in the vicinity of the Headway-Coulee massive sulfide occurrence, Onaman area, northwestern Ontario. Economic Geology, 82: 1505-1520.
- Paradis, S., Ludden, J. and Gelinas, L. 1988. Evidence for contrasting compositional spectra in comagmatic intrusive and extrusive rocks of the late Archean Blake River Group, Abitibi, Quebec. Canadian Journal of Earth Sciences, 25: 134-144.
- Paradis, S., Watkinson, D.H. and Jonasson, I.R. 1989. Volcanology and stratigraphy of the Noranda Volcanic Complex, New Vauze-Norbec area, Québec. Submitted to the Journal of Volcanology and Geothermal Research.
- Paris, I., Stanistreet, I.G. and Hughes, M.J. 1985. Cherts of the Barberton Greenstone belt interpreted as products of submarine exhalative activity. Journal of Geology, 93: 111-129.
- Parry, S. and Hutchinson, R.W. 1981. Origin of a Complex Alteration Assemblage, Four Corners Cu-Zn Prospect, Quebec, Canada. Economic Geology, 76: 1186-1201.
- Pearce, J.A. and Cann, J.R. 1973. Tectonic setting of basic volcanic rocks determined using trace element analyses. Earth Planetary Science Letters, 19: 290-300.
- Peter, J.M. and Scott, S.D. 1988. Mineralogy, composition, and fluid-inclusion microthermometry of seafloor hydrothermal deposits in the southern trough of Guaymas Basin, Gulf of California. Canadian Mineralogist, 26: 567-587.
- Peterson, D.W. and Swanson, D.A. 1974. Observed formation of lava tubes during 1970-71 at Kilauea volcano, Hawaii. Studies in Speleology, 2: 209-223.
- Ramdohr, P. 1980. The ore minerals and their intergrowths. Pergamon Press, second edition: 1174p.

- Reinhardt, B. 1974. The relationships between spilites and other members of the Oman Mountains Ophiolite suite. In *Spilites and Spilitic Rocks*, edited by G.C. Amstutz. International Union of Geological Sciences, Series A, number 4, Springer-Verlag, New York: 207-228.
- Riverin, G. 1977. Wall-rock alteration at the Millenbach Cu-Zn mine, Noranda, Quebec. Ph.D. thesis, Queen's University, Kingston, Ontario: 255 p.
- Riverin, G. and Hodgson, C.J. 1980. Wall-rock alteration at the Millenbach Cu-Zn mine, Noranda, Quebec. *Economic Geology*, 75: 424-444.
- Roberts, W.M.B. 1965. The synthesis of copper-iron sulfides at low temperature and implication of their crystallization behaviour. Commonwealth Mining and Metallurgy Congress, 8th, Melbourne, Australia, 6: 1260-1274.
- Rosen Spence, A.F. de. 1969. Genèse des roches à cordiérite-anthophyllite des gisements cupro-zincifères de la région de Rouyn-Noranda, Québec, Canada. *Canadian Journal of Earth Science*, 6: 1339-1346.
- Rosen Spence, A.F. de. 1976. Stratigraphy, development and petrogenesis of the central Noranda volcanic pile, Noranda, Quebec. Ph.D. thesis, University of Toronto, Toronto, Ontario.
- Rosen Spence, A.F. de, Provost, G., Dimroth, E., Gochnauer, K. and Owen V. 1980. Archean subaqueous felsic flows, Rouyn-Noranda, Quebec, Canada, and their quaternary equivalents. *Precambrian Research*, 12: 43-77.
- Rosenbauer, R.J. and Bischoff, J.L. 1984. Uptake and transport of heavy metals by heated seawater: A summary of the experimental results. In *Hydrothermal processes at seafloor spreading centers*. Edited by Rona, P.A., Bostrom, K., Laurier, L. and Smith, K.L.Jr. Plenum, New York.
- Ross, C.S. and Smith, R.L. 1955. Water and other volatiles in volcanic glass. *American Mineralogist*, 40: 1071-1089.
- Schiffmann, P. and Smith, B.M. 1988. Petrology and O-isotope geochemistry of a fossil seawater hydrothermal system within the Solea graben, northern Troodos Ophiolite, Cyprus. *Journal of Geophysical Research*, 93: 4612-4625.

- Seewald, J.S. 1987. Na and Ca metasomatism during hydrothermal basalt alteration: an experimental and theoretical study. M.Sc. thesis, University of Minnesota, Minneapolis, Minnesota.
- Self, S. and Sparks, R.S.J. 1978. Characteristics of widespread pyroclastic deposits formed by the interaction of silicic magma and water. *Bulletin of Volcanology and Geothermal Research*, 41-3: 1-17.
- Seyfried, W.E. Jr. and Bischoff, J.L. 1977. Hydrothermal transport of heavy metals by seawater: the role of seawater/basalt ratio. *Earth and Planetary Science Letters*, 34: 71-77.
- Seyfried, W.E. Jr. and Janecky, D.R. 1985. Heavy metal and sulfur transport during supercritical hydrothermal alteration of basalt: Influence of fluid pressure and basalt composition and crystallinity. *Geochimica et Cosmochimica Acta*, 49: 2545-2560.
- Seyfried, W.E. Jr. and Mottl, M.J. 1982. Hydrothermal alteration of basalt by seawater under seawater-dominated conditions. *Geochimica et Cosmochimica Acta*, 45: 135-147.
- Seyfried, W.E. Jr., Mottl, M.J. and Bischoff, J.L. 1978. Seawater/basalt ratio effects on the chemistry and mineralogy of spilites from the ocean floor. *Nature*, 275: 211-213.
- Seyfried, W.E., Jr., Berndt, M.E. and Seewald, J.S. 1988. Hydrothermal alteration processes at mid-ocean ridges: constraints from diabase alteration experiments, hot-spring fluids and composition of the oceanic crust. *Canadian Mineralogist*, 26: 787-804.
- Sheridan, M.F. and Wohletz, K.H. 1981. Hydrovolcanic explosions I. The systematics of water-pyroclast equilibration. *Science*, 212: 1387-1389.
- Sheridan, M.F. and Wohletz, K.H. 1983. Hydrovolcanism: basic consideration and review. *In* Explosive volcanism. Edited by M.F. Sheridan and F. Barberi. *Journal of Volcanology and Geothermal Research*, 17: 1-29.
- Shimazaki, H. 1980. Cooling history of orebody recorded in sphaleite: an example from the Tsumo skarn deposits. Japan. *Jour. Fac. Sci. University of Tokyo*, ser. 2, 20: 61-76.

- Skirrow, R.G. 1987. Silicification in a semiconformable alteration zone below the Chisel Lake massive sulphide deposit, Manitoba. M.Sc. thesis, Carleton University, Ottawa, Ontario: 171 p.
- Skoog, D.A. and West, D.M. 1962. Fundamentals of analytical chemistry. Edited by Holt, Rinehart and Winston.
- Smewing, J.D., Christensen, N.I., Bartholomew, I.D. and Browning, P. 1984. The structure of the oceanic upper mantle and lower crust as deduced from the northern section of the Oman ophiolite. In *Ophiolites and Oceanic Lithosphere*, edited by I.G. Gass, S.J. Lippard, and A.W. Shelton. Geological Society, special publication no 13, Blackwell Scientific Publications, London: 41-54.
- Smith, T.L. 1984. Textures, field relationships and flow morphology of the Waite Rhyolite formation, Noranda, Quebec. B.Sc. thesis, Carleton University, Ottawa, Ontario.
- South, B.C. and Taylor, B.E. 1985. Stable isotope geochemistry and metal zonation at the Iron Mountain Mine, West Shasta District, California. *Economic Geology*, 80: 2177-2195.
- Spence, C.D. 1964. Geological map of the New Vauze property. Consolidated Zinc Corporation of Canada Limited, 1 map, unpublish.
- Spence, C.D. 1975. Volcanogenic features of the Vauze sulphide deposit, Noranda, Quebec. *Economic Geology*, 70: 102-114.
- Spence, C.D. and de Rosen Spence, A.F. 1975. The place of massive sulphide mineralization in the volcanic sequence at Noranda, Quebec. *Economic Geology*, 70: 90-101.
- Spooner, E.T.C. 1974, Sub-sea-floor metamorphism, heat, and mass transfer; an additional comment. *Contributions to Mineralogy and Petrology*, 45: 169-173.
- Spooner, E.T.C. 1977. Hydrodynamic model for the origin of the ophiolitic cupriferous pyrite ore deposits of Cyprus. In *Volcanic processes in ore genesis*, Geological Society of London, special publication, 7: 58-71.
- Stakes, D.S. and O'Neil, J.R. 1982. Mineralogy and stable isotope geochemistry of hydrothermally altered oceanic rocks. *Earth and Planetary Science Letters*, 57: 285-304.

- Staudigel, H. and Hart, S.R. 1983. Alteration of basaltic glass: Mechanisms and significance for the oceanic crust-seawater budget. *Geochimica et Cosmochimica Acta*, 47: 337-350.
- Styrt, M.M. Brackmann, A.J. Holland, H.D., Clark, B.C. Pistha-Arnond, V., Eldridge, C.S. and Ohmoto, H. 1981. The mineralogy and the isotopic composition of sulphur in hydrothermal sulphide/supphate deposits on the East Pacific Rise, 21°N lattitude. *Earth Planetary Science Letters*, 382-390.
- Sun, S.S. 1980. Oceanic Leads. *Phil. Transaction of the Royal Society of London*, A297: 409-445.
- Tane, J.-L. 1989. Une nouvelle approche du problème des spilites: les démixtions en phase liquide au sein du magma. *Compte Rendu de l'Académie des Sciences de Paris, Série II*: 2039-2046.
- Taylor, H.P. Jr. 1968. The oxygen isotope geochemistry of igneous rocks. *Contributions to Mineralogy and Petrology*, 19: 1-71.
- Taylor, H.P. Jr. 1974. The application of oxygen and hydrogen isotope studies to problems of hydrothermal alteration and ore deposition. *Economic Geology*, 69: 843-883.
- Taylor, H.P. Jr. 1977 Water/rock interactions and the origin of H₂O in granitic batholiths. *Journal of the Geological Society of London*, 133: 509-558.
- Taylor, H.P. Jr. and Epstein, S. 1962. Relationship between O¹⁸/O¹⁶ ratios in coexisting minerals of igneous and metamorphic rocks. Part I: Principles and experimental results. *Geological Society of America Bulletin*, 73: 461-480.
- Taylor, B.E. and South, B.C. 1985. Regional stable isotope systematics of hydrothermal alteration and massive sulfide deposition in the West Shasta District, California. *Economic Geology*, 80: 2149-2163.
- Thompson, R.N., Morrison, M.A., Dickin, A.P. and Hendry, G.L. 1983. In Continental basalts and mantle xenoliths, Ecited by C.J. Hawkesworth and M.J. Norry. Nantwich, Shiva: 158-185.
- Till, R. 1974. Statistical methods for the earth scientist. Edited by Macmillan.

- Tomasson, J. and Kristmannsdottir, H. 1972. High temperature alteration minerals and thermal brines, Reykjanes, Iceland. *Contributions to Mineralogy and Petrology*, 36: 123-134.
- Turner, F.J. 1948. Mineral and structural evolution of metamorphic rocks. *Geological Society of America Memoir*, 30.
- Ujike, O. and Goodwin, A.M. 1987. Geochemistry and origin of Archean felsic metavolcanic rocks, central Noranda area, Quebec, Canada. *Canadian Journal of Earth Sciences*, 24: 2551-2567.
- Vallance, T.G. 1974. Pyroxene and the basalt. Spilitic Relation. In *Spilites and Spilitic Rocks*, edited by G.C. Amstutz. International Union of Geological Sciences, Series A, number 4, Springer-Verlag, New York: 59-70.
- Walker, G.P.L. 1973. Lengths of lava flows. *Phil. Transactions of the Rooyal Society of London*, A274: 107-118.
- Wenner, D. and Taylor, H.P. Jr. 1971. Temperatures of serpentinization of ultramafic rocks based on $^{18}\text{O}/^{16}\text{O}$ fractionation between coexisting serpentine and magnetite. *Contribution to Mineralogy and Petrology*, 32: 165-185.
- Whitford, D.J. McPherson, W.P.A. and Wallace, D.B. 1989. Geochemistry of the host rocks of the volcanogenic massive sulfide deposit at Que River, Tasmania. *Economic Geology*, 84: 1-21.
- Wiggins, L.B. and Craig, J.R. 1980. Phase relations in the CuFeS_2 -FeS join. *Tohoku University, Scientific Report*, series 3, 16: 283-293.
- Williams, H. and McBirney, A. 1979. *Volcanology*. Freeman, Cooper and Co., San Francisco: 1-391.
- Wilson, M.E. 1913. Kewagama Lake map-area, Quebec. *Geological Survey of Canada*, memoir 39: 139 p.
- Wilson, M.E. 1935. Rock alteration at the Amulet Mine, Noranda District, Quebec. *Economic Geology*, 30: 478-492.
- Wilson, M.E. 1941. Noranda District, Quebec. *Geological Survey of Canada*, Memoir 229, 169 p.
- Wilson, M.E. 1962. Rouyn-Beauchastel map areas, Quebec. *Geological Syrvey of Canada*, memoir 315.

- Winchester, J.A. and Floyd, P.A. 1977. Geochemical discrimination of different magma series and their differentiation products using immobile elements. *Geochemical Geology*, 20: 325-344.
- Winkler, H.G.F. 1979. *Petrogenesis of metamorphic rocks*. 5th ed. Springer-Verlag, Berlin, Heidelberg, New York, NY: 1-348.
- Wohletz, K.H. and Sheridan, M.F. 1983. Hydrovolcanic explosions II. Evolution of basaltic tuff rings and tuff cones. *American Journal of Sciences*, 283: 385-413.
- Wynne, P.J. and Strong, D.F. 1984. The Strickland prospect of southwestern Newfoundland: A lithogeochemical study of metamorphosed and deformed volcanogenic massive sulfides. *Economic Geology*, 79: 1620-1642.
- Yamagishi, H. and Dimroth, E. 1985. A comparison of Miocene and Archean rhyolite hyaloclastites: evidence for a hot and fluid rhyolite lava. *Journal of Volcanology and Geothermal Research*, 23: 337-355.
- Zierenberg, R.A., Shanks, W.C. III, Seyfried, W.E., Jr., Koski, R.A. and Strickler, M.D. 1988. Mineralization, alteration and hydrothermal metamorphism of the ophiolite-hosted Turner-Albright sulfide deposit, southwestern Oregon. *Journal of Geophysical Research*, 93: 4657-4675.

APPENDIX I. SAMPLE PREPARATION AND ANALYTICAL METHODS

APPENDIX I. SAMPLE PREPARATION AND ANALYTICAL METHODS

I.1 ANALYSIS

Samples 200A-86 to 670-86, NED-1-86 to NED-17-86, and 4-87 to 19-87 were analysed for major and trace elements by x-ray fluorescence spectrometry at X-Ray Assay Laboratories (XRAL), Don Mills, Ontario, using a Philips PW1600 simultaneous x-ray fluorescence spectrometer.

Samples 2-84 to 28-84 and 1-85 to 125-85 were analysed for major and trace elements using x-ray fluorescence spectrometry at MetricLab Inc., Ste-Marthe-sur-le-Lac, Quebec, and at the geochemical laboratory of Minnova Inc., Noranda, Quebec.

Major, trace and rare earth elements of 30 samples (some of -86 and -87 samples) were analysed by the Analytical Chemistry Section of the Geological Survey of Canada (GSC) by XRF wavelength dispersive analysis and ICP analysis (Inductive Coupled Plasma).

Standards G-2 and MRG-1 were sent to XRAL. Standards G-2, MRG-1 and an internal standard ENDV-86-BS were sent to the GSC laboratories. More than 40 reference materials, most of them being tabulated in Abbey's "preferred" values compilation (1980, 1983) were used for calibration of the XRF spectrometer at XRAL and GSC laboratories.

Oxygen isotope analyses were made on 82 samples at the Stable Isotope Geochemical laboratory of B.E. Taylor, GSC by

an analytical procedure involving oxidation by chlorine trifluoride.

I.2 SAMPLE PREPARATION

Whole rock samples

All samples were cleaned of any weathered surface, split in two and one half crushed to -1/4 inch in a jaw crusher and the other half kept for petrographic studies. A fraction of the crushed material was ground to powder in a chrome steel mill.

Data for major element oxides (SiO_2 , TiO_2 , Al_2O_3 , FeO_t , MnO , MgO , CaO , Na_2O , K_2O , P_2O_5) and trace elements (Ba, Nb, Rb, Sr, Y, Zr) were obtained by X-ray fluorescence analysis using fused pellets. A 1.3 gram sample, after roasting at 950° for 1 hour, was fused with 5 grams of lithium tetraborate in a platinum crucible. The melt was cast into a 40 mm button. The button was analysed on a x-ray fluorescence spectrometer. The system was calibrated using more than 40 reference materials, most of them being tabulated in Abbey's "preferred" values compilation (Abbey, 1980, 1983). LOI is obtained from the roasting mentioned above. All elements determined are summed and any samples less than 98% or higher than 101% were automatically repeated. This gives control over the button preparation.

Thirty powder samples were submitted for Y and rare earth elements (La, Ce, Nd, Sm, Eu, Gd, Dy, Yb) analysis (ICP

analysis) to the Analytical Chemistry Section of the GSC. These elements were determined from trace solution after 10 times pre-concentration and separation of major elements using ion exchange resin.

Mineral separate samples

Sixty-two mineral separate samples were selected for oxygen isotope analysis. Quartz, epidote, feldspar and chlorite (-40+80 mesh) were first isolated by sieving coarsely crushed material (>2 cm). Then, they were hand-picked individually under a binocular microscope and washed repeatedly in methanol and dried. The samples were finally powdered to < 200 mesh.

I.3 WHOLE-ROCK ANALYSIS

The international standards G-2 and MRG-1, an internal standard ENDV-86-BS and duplicates of unknowns were used to monitor the analytical reliability of the whole-rock chemical analyses listed in appendix II, so both precision (or reproducibility) and accuracy of the analyses can be calculated. Results of the tests are presented in Tables I.1 to I.6. The laboratories also ran standards for internal verification. These results were not distributed.

Accuracy of chemical analysis

The accuracy of the x-ray fluorescence technique used by XRAL and GSC for major and minor elements was tested by comparing the analyses of G-2 and MRG-1 with the "usable" values of Abbey (1983). For MRG-1, the results shown in Table I.1 indicate departures of less than 10% of the concentrations of major elements (except K_2O and P_2O_5) at XRAL and very low departures (except Na_2O and K_2O) at the GSC laboratories. The results of G-2 show a departure of less than 7% of the major element concentrations (Table I.2; analysis done at XRAL). The accuracy of the ICP technique for major elements, with departures of less than 12%, is not as good as the XRF technique (Table I.2). The accuracy of the x-ray fluorescence technique (XRAL or GSC laboratories) for trace elements is poor (Tables I.1 and I.2). Much better accuracy and precision are obtained for trace elements done by ICP technique (Table I.3).

Data presented by XRAL comparing their values of G-2 and MRG-1 with the "usable" values of Abbey (1979) show a departure of less than 20% of the trace element concentrations.

Detection limits

Detection limits given by XRAL for whole rock analysis done by x-ray fluorescence are 0.01% and 10 ppm for major and

minor elements respectively. Detection limits for major elements determined by x-ray fluorescence at GSC laboratories are as follow:

0.40% : SiO_2 and Al_2O_3

0.02% : TiO_2 and P_2O_5

0.10% : FeO , MgO , CaO

0.50% : Na_2O

0.05% : K_2O

0.01% : MnO

Detection limits for trace elements determined at the GSC laboratories are listed in Table I.4.

Precision (reproducibility) of samples and fused pellet

The precision of the analysis was estimated by analyzing one set of duplicate sample (#604-86) prepared as splits after crushing and submitted blind to XRAL (Table I.5). Also the internal standard ENDV-86-BS was used to monitor the precision of the x-ray fluorescence and ICP techniques done at the GSC.

The internal standard ENDV-86-BS used in lava analyses at the GSC has been repeated many times and has been used to measure the precision of the analyses. Good precision should be $< 5\%$; $< 10\%$ is acceptable and $> 10\%$ is poor. Estimates of precision for analyses of ENDV-86-BS are listed in Table 6. The range in precision for major elements by x-ray fluorescence at the GSC laboratories is 0.01% to $\pm 4.2\%$. Precision is poor for trace elements done by x-ray

fluorescence and excellent for trace elements done by ICP-ES technique (Table I.6).

Two fused pellets were made from #604-86 powder sample to test the homogeneity of the powdered sample and the reproducibility of the fusion method. The duplicate analysis is compared to the original analysis and the reproducibility of the sample preparation procedure is within $\approx 2\%$ of the concentration of major elements, within $\approx 10\%$ of the concentration of the minor elements, and within the precision of the XRF technique itself (Table I.5).

I.4 OXYGEN ISOTOPE GEOCHEMISTRY - ANALYTICAL METHOD

I.4.1 General statement

The oxygen isotope analyses were carried out on powdered whole-rock samples and mineral separates at the stable isotope-geochemical laboratory of B.E. Taylor, Geological Survey of Canada (GSC).

Oxygen isotope analyses of silicate minerals and whole rock samples have been determined using an analytical procedure involving oxidation by chlorine trifluoride (Clayton and Epstein 1958, Taylor and Epstein 1962, Clayton and Mayeda 1963). The oxygen in silicates and whole rock samples is extracted by ClF_3 attack as O_2 and converted to CO_2 using the analytical technique described in the following section.

The oxidizing reagent used in the present work is chlorine trifluoride (ClF_3). Ten mg to 15 mg of samples

reacted with an appropriate amount of ClF_3 . The ClF_3 can be handled in the laboratory in a metal vacuum system using nickel reaction vessels, because it reacts with glass at room temperature and above, but shows no reaction at liquid nitrogen temperature. At 600°C , nickel is the only material known to be suitable for reaction vessels for containing ClF_3 .

Measured oxygen yields for minerals and whole rock have consistently been in the range of 98%-103%.

$^{18}\text{O}/^{16}\text{O}$ ratios of the CO_2 were determined on a mass spectrometer (VG-SIRA 12) in the OCCGS/GSC stable isotope laboratory. δ -values reported are normalized to SMOW (Standard Mean Ocean Water) and SLAP (Standard Light Antarctic Precipitation). The data are expressed in δ -values (per mil: ‰) relative to SMOW, where $\delta = (R_A - R_{\text{SMOW}})/R_{\text{SMOW}} \times 10^3$ (R_A and R_{SMOW} are the $^{18}\text{O}/^{16}\text{O}$ of the sample and the standard respectively). The reproducibility of the analysis is within $\pm 0.2\%$.

1.4.2 Analytical procedure

Whole rock samples were taken as splits of powdered samples prepared for major oxide and trace element geochemical analysis. Mineral samples were hand-picked under binocular microscope to the best purity ($> 95\%$) possible.

Approximately 10 mg of powdered quartz samples and 15 mg of epidote, feldspar, chlorite and whole rock samples were used. Powdered samples were pre-heated at $125\text{--}135^\circ\text{C}$ overnight

to drive off adsorbed and interlayered water. Twelve samples (11 unknown and 1 standard) were run at a time.

Twelve sample powders were sequentially loaded under positive pressure of argon for 1 hour. The ClF_3 line was specially designed to permit rapid heating with a zero blank (B.E. Taylor, personal communication). After loading, the reaction vessel manifold was evacuated of excess argon for 1 hour. The reaction vessels were then charged with reagent (by freezing). The reagent was slowly transferred into the metal line and this was condensed into the reaction vessels at -197°C ($\pm 2^\circ\text{C}$). The charged tubes, while still in liquid nitrogen, were evacuated for 10-15 seconds to remove any non-condensable gases. The reaction vessels were finally isolated, resistance furnaces put in place, and then heated for 12-16 hours at selected temperatures to affect the reaction. Quartz, feldspar, and whole rock samples were reacted at 575°C for 12-16 hours; epidote-group minerals were reacted at 600°C for 12-16 hours. After reaction, the reaction vessels were cooled to -197°C and the oxygen from each vessel sequentially converted to CO_2 by the reaction $\text{C} + \text{O}_2 \rightarrow \text{CO}_2$ for mass spectrometric analysis. The oxygen sample was passed through two liquid nitrogen cooled traps which serve to freeze CO_2 produced by reaction of oxygen and a heated carbon rod at about 750°C . The conversion of an oxygen sample to carbon dioxide (CO_2) takes 3 minutes. The residual pressure after CO_2 conversion was measured by a vacuum gauge that indicates

the amount of non-condensable gases present in the conversion unit. These gases were subsequently pumped out of the system, purifying the CO_2 sample. The CO_2 was transferred to a manometer and its volume measured at room temperature. The oxygen yields of the silicate minerals were calculated to determine the completeness of the reaction. CO_2 was transferred cryogenically to a sample tube which is sealed with a torch, and stored for subsequent mass spectrometric analysis.

The entire extraction of a set of 12 samples takes about 2-3 hours. By running the ClF_3 reactions overnight, and extracting the oxygen in the morning, one can complete a set of 12 samples each day.

Before a new extraction is made, the gaseous products of the previous reactions held in the 12 reaction vessels have to be removed via a KBr trap (at 200°C) and a liquid nitrogen storage trap. The reaction vessels are then heated at 575°C for one hour. The furnaces are removed and the vessels are isolated.

1.5 ELECTRON MICROPROBE ANALYSES OF MINERALS

Mineral analyses were done at Carleton University using a Cambridge Microscan 5 electron microprobe.

The electron beam voltage was maintained at 20 kV for the epidote-group minerals with a sample current of 40 nA. The operating voltage was at 15 kV for the feldspar and chlorite

minerals and the sample current at nA. Counting times were 20 seconds.

The analyses were calibrated against a small variety of standard material.

Feldspar analyses had Ca calibrated on a synthetic anorthite, Na calibrated on natural albite, and K calibrated on natural Kakanui hornblende.

Chlorite analyses had Fe, Mg, and K calibrated on Kakanui hornblende, Al, Ca, and Si calibrated on a synthetic anorthite, and Mn calibrated on a natural ilmenite.

Epidote analyses had Fe, Mg, Mn, and Ti calibrated on Kakanui hornblende, and Ca calibrated on a synthetic anorthite.

The criterion for an acceptable analysis was an oxide total of $100\% \pm 2\%$ (on a volatile- or H_2O -free basis) and a satisfactory formula.

TABLE I.1. Accuracy of standard MRG-1 (x-ray fluorescence technique).

Std Lab Mtd	"Usable" Abbey (1983) XRF	MRG-1 XRAL XRF	MRG-1 GSC XRF	A (%) XRAL XRF	A (%) GSC XRF
(wt%)					
SiO ₂	39.32	39.30	39.70	-0.05	0.97
TiO ₂	3.69	3.69	3.74	0.00	1.35
Al ₂ O ₃	8.50	8.06	8.50	-5.18	0.00
FeO _t	17.82	17.70	18.20	-0.67	2.13
MnO	0.17	0.16	0.17	-5.88	0.00
MgO	13.49	12.60	13.39	-6.60	-0.74
CaO	14.77	14.60	14.81	-1.15	0.27
Na ₂ O	0.71	0.76	0.60	7.04	-15.49
K ₂ O	0.18	0.20	0.16	11.11	-11.11
P ₂ O ₅	0.06	0.07	0.06	16.16	0.00
(ppm)					
Rb	20	26	8	150	225
Sr	214	277	260	-18	6
Y	<10	24	16	-38	50
Zr	77	146	105	-27	39
Nb	36	15	20	80	-25
Ba	27	95	50	-4	90

MRG-1: Gabbro from Mount Royal, Montreal, Quebec; CCRMP.
 G-2: Westerley Granite from Sullivan quarry at Bradford, Rhode Island; USGS.
 A (%): Mean % relative error = accuracy (Skoog and West 1962).

$$\sum_{i=1}^n \frac{OB_i - A \times 100}{A} / n$$

OB_i = ith value for standard
 A = actual certified value
 n = number of runs

TABLE I.2. Accuracy of standard G-2 (x-ray fluorescence technique).

Std Lab Mtd	"Usable" Abbey (1983)	G-2 XRAL XRF	G-2 GSC ICP	A (%) XRAL XRF	A (%) GSC ICP
(wt%)					
SiO ₂	69.22	69.20	63.00	-0.03	-8.99
TiO ₂	0.48	0.49	0.44	2.08	-8.33
Al ₂ O ₃	15.40	15.30	13.50	-0.65	-12.34
FeO _t	2.69	2.51	2.44	-6.69	-9.29
MnO	0.03	0.03	0.03	0.00	0.00
MgO	0.75	0.70	0.75	-6.67	0.00
CaO	1.96	1.88	1.96	0.00	-4.08
Na ₂ O	4.06	4.34	3.89	6.90	-4.19
K ₂ O	4.46	4.49	4.14	0.01	-7.17
P ₂ O ₅	0.13	0.13	0.12	0.00	-7.69
(ppm)					
Rb	170	183	n.a.	8	n.a.
Sr	480	571	n.a.	19	n.a.
Y	11	<10	n.a.	-9	n.a.
Zr	300	293	n.a.	-2	n.a.
Nb	13	13	n.a.	0	n.a.
Ba	1900	1940	1800	2	-5

MRG-1: Gabbro from Mount Royal, Montreal, Quebec; CCRMP.
 G-2: Westerley Granite from Sullivan quarry at Bradford, Rhode Island; USGS.
 A (%): Mean % relative error = accuracy (Skoog and West 1962).

$$\sum_{i=1}^n \left(\frac{\text{OBi} - A \times 100}{A} \right) / n$$

OBi = ith value for standard
 A = actual certified value
 n = number of runs
 n.a. = not analyzed

TABLE I.3. Accuracy of trace and rare earth element analysis of standards G-2 and MGR-1 done by ICP technique.

Std	MRG-1	MRG-1					
Lab	"Usable"	GSC					
Mtd	Abbey (1983)	ICP					
		Dup1	Dup2	X	SD	±C (%)	A (%)
(ppm)							
Ce	25	27	27	27	0	0	8
Dy	3	3.3	3.2	3.25	0.05	1.5	8
Eu	1.4	1.5	1.5	1.5	0	0	7
Gd	n.a.	4.8	4.4	4.6	0.2	4.4	-
La	10	10	9	9.5	0.5	5.3	-5
Nd	19	27	25	26	1	3.9	37
Sm	5	4.3	4.1	4.2	0.1	2.4	-16
Y	16	13	13	13	0	0	-18
Yb	1	0.9	0.8	0.85	0.05	5.9	-15

Std	G-2	G-2	
Lab	"Usable"	GSC	
Mtd	Abbey (1983)	ICP	
			A (%)
(ppm)			
Ce	160	160	0
Dy	2.3	2.3	0
Eu	1.4	1.4	0
Gd	5	3.9	-22
La	92	85	-7.6
Nd	58	58	0
Sm	7.2	7	-2.9
Y	11	11	0
Yb	0.86	0.70	-18.6

Dup1, 2: Duplicates
 X: Arithmetic mean
 SD: Standard deviation
 ±C%: Precision (see Table I.6)
 A (%): Accuracy (see Tables I.1 and I.2).
 n.a.: Not analyzed

TABLE I.4. Methods (Mtd) and lower detection limits (DL) for trace elements.

	Lab.	Mtd	DL (ppm)		Lab.	Mtd	DL (ppm)
Ba	GSC	XRF	2	XRAL	XRF	10	
Nb	GSC	XRF	3	XRAL	XRF	10	
Rb	GSC	XRF	2	XRAL	XRF	10	
Sr	GSC	XRF	2	XRAL	XRF	10	
Y	GSC	XRF	2	XRAL	XRF	10	
Zr	GSC	XRF	2	XRAL	XRF	10	
La	GSC	ICP	0.5				
Ce	GSC	ICP	0.5				
Nd	GSC	ICP	0.5				
Sm	GSC	ICP	0.3				
Eu	GSC	ICP	0.1				
Gd	GSC	ICP	0.2				
Dy	GSC	ICP	0.2				
Yb	GSC	ICP	0.1				
Y	GSC	ICP	1.0				

TABLE I.5. Mean percent average deviation (M%AD; Skoog and West 1962): Reproducibility of duplicate sample pair #604-86.

Sample: #604-86
 Lab: XRAL
 Mtd: x-ray fluorescence

(Wt%)	Dup.1	Dup.2	X	SD	M%AD
SiO ₂	74.70	74.40	74.55	0.15	0.20
TiO ₂	0.23	0.24	0.24	0.01	2.13
Al ₂ O ₃	11.70	11.60	11.65	0.05	0.42
FeOt	3.61	3.63	3.62	0.01	0.28
MnO	0.09	0.09	0.09	0.00	0.00
MgO	0.67	0.64	0.65	0.02	2.29
CaO	1.33	1.26	1.29	0.04	2.70
Na ₂ O	5.51	5.27	5.39	0.12	2.23
K ₂ O	0.96	0.92	0.94	0.02	2.13
P ₂ O ₅	0.03	0.03	0.03	0.00	0.00
(ppm)					
Rb	20	18	19	1	5
Sr	70	56	63	7	11
Y	80	64	72	8	11
Zr	320	277	298	21	7
Nb	20	23	21	2	7
Ba	390	359	374	15	4

M%AD: Mean % average deviation (after Skoog and West 1962)

$$\sum \left(\frac{(\text{Dup}_{i1} - \text{Dup}_{i2})/2 \times 100}{X_i} \right) / n$$

Dup_{i1} and Dup_{i2} = value of the ith pair duplicates.

X_i: arithmetic mean of the ith pair of duplicates.

n: number of pairs.

TABLE I.6. Precision and analytical methods of the internal standard ENDV-86-BS at the GSC laboratories.

Std: ENDV-86-BS (MORB from Endeavour Segment, Juan de Fuca Ridge)
 Lab: GSC
 Mtd: x-ray fluorescence

	X (n=27)	SD	±C %
(wt%)			
SiO ₂	50.11	0.17	0.34
TiO ₂	1.55	0.02	1.29
Al ₂ O ₃	15.40	0.11	0.71
Fe _{0t}	9.42	0.12	0.01
MnO	0.19	0.00	0.00
MgO	7.54	0.06	0.80
CaO	11.71	0.06	0.51
Na ₂ O	2.90	0.06	2.07
K ₂ O	0.24	0.01	4.17
P ₂ O ₅	0.16	0.005	2.89
(ppm)			
Ba	112	15	13
Nb	n.a.	n.a.	n.a.
Rb	n.a.	n.a.	n.a.
Sr	145	7	5
Y	16	12	75
Zr	94	11	12

Std: ENDV-86-BS (MORB from Endeavour Segment, Juan de Fuca Ridge)
 Lab: GSC
 Mtd: ICP

(ppm)			
La	6.00	0.34	5.66
Ce	15.60	1.20	7.69
Nd	16.80	3.25	19.35
Sm	3.28	0.12	3.65
Eu	1.40	0.00	0.00
Gd	5.10	0.13	2.55
Dy	5.60	0.05	0.89
Yb	3.10	0.05	1.63
Y	29.60	0.49	1.66

Precision (Till 1974): $\pm C \% = (SD/X) \times 100$

C: coefficient of variation, SD: standard deviation, X: arithmetic mean, n.a.: not analyzed.

APPENDIX II. MINERAL CHEMISTRY

Table II. 1. Analyses of plagioclase, sample 672-86, Waite Rhyolite Formation.

(wt%)	#1	#2	#3	#4	#5	#6
SiO ₂	68.26	68.13	68.98	69.02	68.99	68.89
Al ₂ O ₃	19.60	19.41	19.71	19.78	19.94	19.71
Na ₂ O	11.62	11.63	11.76	11.71	11.69	11.74
CaO	0.25	0.11	0.17	0.22	0.35	0.19
K ₂ O	0.02	0.05	0.04	0.10	0.05	0.05
Total	99.76	99.33	100.66	100.83	101.03	100.58

Formula (basis 8 oxygens)

Si	2.989	2.995	2.992	2.990	2.984	2.991
Al	1.012	1.005	1.008	1.010	1.016	1.009
Na	0.987	0.991	0.989	0.984	0.980	0.988
Ca	0.012	0.005	0.008	0.010	0.016	0.009
K	0.001	0.003	0.002	0.006	0.003	0.003
Total	8.000	8.000	8.000	8.000	8.000	8.000

(wt%)	#7	#8	#9	#10
SiO ₂	69.08	69.48	69.72	68.31
Al ₂ O ₃	19.77	19.89	19.99	19.73
Na ₂ O	11.77	11.83	11.87	11.59
CaO	0.20	0.20	0.22	0.34
K ₂ O	0.04	0.05	0.04	0.03
Total	100.86	101.44	101.84	100.00

Formula (basis 8 oxygens)

Si	2.991	2.991	2.990	2.984
Al	1.009	1.009	1.010	1.016
Na	0.988	0.988	0.987	0.982
Ca	0.009	0.009	0.010	0.016
K	0.002	0.003	0.002	0.002
Total	8.000	8.000	8.000	8.000

Table II.3. Analyses of plagioclase, sample 350-86, Waite Andesite formation**Sample 350-86**

(wt%)	#1	#2	#3	#4
SiO₂	67.73	67.16	67.4	67.35
Al₂O₃	20.28	20.3	19.75	19.75
Na₂O	10.58	10.82	10.69	10.77
CaO	0.93	1.08	0.57	0.58
K₂O	1.11	0.53	1.08	0.93
Total	100.64	99.89	99.49	99.38

Formula (basis 8 oxygens)

Si	2.956	2.949	2.973	2.972
Al	1.043	1.051	1.027	1.027
Na	0.896	0.921	0.914	0.921
Ca	0.044	0.051	0.027	0.028
K	0.062	0.030	0.061	0.052
Total	8.000	8.000	8.000	8.000

Table II.4 . Analyses of plagioclases, sample 359-86, Waite Rhyolite formation**Sample 359-86**

(wt%)	#1	#2	#3	#4	#5	#6
SiO ₂	68.06	68.37	68.46	68.83	68.83	69.00
Al ₂ O ₃	19.58	19.50	19.66	19.62	19.53	19.69
Na ₂ O	11.59	11.68	11.66	11.72	11.79	11.80
CaO	0.27	0.14	0.25	0.13	0.06	0.15
K ₂ O	0.01	0.02	0.02	0.09	0.01	0.00
Total	99.50	99.72	100.05	100.39	100.23	100.64

Formula (basis 8 oxygens)

Si	2.987	2.994	2.989	2.994	2.997	2.993
Al	1.013	1.007	1.012	1.006	1.003	1.007
Na	0.986	0.992	0.987	0.988	0.996	0.993
Ca	0.013	0.006	0.011	0.006	0.003	0.007
K	0.001	0.001	0.001	0.005	0.001	0.000
Total	8.000	8.000	8.000	8.000	8.000	8.000

Table II.5. Analyses of epidote-group mineral, sample 594-86, Waite Rhyolite formation**Sample 594-86**

(wt%)	#1	#2	#3	#4	#5	#6	#7	#8	#9
SiO ₂	38.30	38.22	38.11	37.40	38.39	38.00	39.87	38.90	38.40
Al ₂ O ₃	26.89	26.97	23.98	22.67	26.66	26.67	26.95	27.97	26.09
FeO	7.89	8.05	11.29	12.73	8.44	8.33	7.42	7.12	8.91
MnO	0.29	0.24	0.25	0.19	0.16	0.20	0.50	0.33	0.27
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	23.41	23.27	22.68	22.69	23.36	22.99	22.56	23.34	23.04
TiO ₂	0.11	0.27	0.11	0.23	0.24	0.19	0.23	0.13	0.19
Total	96.87	97.02	96.42	95.91	97.25	96.38	97.53	97.79	96.90

Formula (basis 13 oxygens)

Si	3.187	3.177	3.244	3.234	3.189	3.183	3.269	3.187	3.208
Al	2.636	2.642	2.406	2.311	2.610	2.633	2.605	2.701	2.570
Fe	0.549	0.560	0.803	0.921	0.586	0.584	0.509	0.488	0.623
Mn	0.020	0.017	0.018	0.014	0.011	0.014	0.034	0.023	0.019
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	2.088	2.072	2.068	2.102	2.079	2.063	1.982	2.049	2.063
Ti	0.007	0.017	0.007	0.015	0.015	0.012	0.014	0.008	0.012
Total	8.487	8.485	8.546	8.597	8.490	8.489	8.413	8.456	8.495

Table II.6. Analyses of epidote-group mineral, sample 259-86, Amulet formation**Sample 259-86**

(wt%)	#1	#2	#3	#4	#5	#6	#7	#8
SiO ₂	37.22	37.79	37.67	37.97	38.29	37.65	39.09	37.96
Al ₂ O ₃	22.63	23.94	23.89	24.20	25.40	22.82	24.76	23.95
FeO	13.01	11.60	12.24	11.34	10.40	12.72	10.42	11.68
MnO	0.30	0.30	0.42	0.31	0.32	0.27	0.51	0.35
MgO	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
CaO	22.96	23.19	22.80	23.19	23.19	22.91	22.39	22.95
TiO ₂	0.35	0.19	0.18	0.29	0.12	0.57	0.25	0.28
Total	96.47	97.01	97.20	97.30	97.72	96.94	97.42	97.17

Formula (basis 13 oxygens)

Si	3.211	3.211	3.203	3.211	3.201	3.222	3.269	3.218
Al	2.300	2.398	2.395	2.412	2.503	2.302	2.440	2.393
Fe	0.939	0.825	0.870	0.880	0.727	0.910	0.729	0.828
Mn	0.022	0.022	0.031	0.022	0.023	0.020	0.036	0.025
Mg	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Ca	2.122	2.111	2.077	2.101	2.078	2.101	2.006	2.085
Ti	0.023	0.012	0.012	0.018	0.008	0.037	0.016	0.018
Total	8.617	8.579	8.588	8.566	8.540	8.592	8.496	8.567

Table II.7. Analyses of epidote-group mineral.

Sample (wt%)	6-88	10-88	11-88	12-88
SiO₂	34.64	36.89	37.36	37.36
Al₂O₃	20.61	23.53	23.24	22.69
FeO	13.31	11.39	12.03	12.66
MnO	0.22	0.08	0.20	0.20
MgO	0.11	0.07	0.14	0.00
CaO	22.20	22.73	22.90	22.14
TiO₂	0.16	0.20	0.16	0.08
Total	91.25	94.89	96.03	95.13

Formula (basis 13 oxygens)

Si	3.188	3.203	3.216	3.250
Al	2.236	2.408	2.358	2.327
Fe	1.024	0.827	0.866	0.921
Mn	0.017	0.006	0.014	0.015
Mg	0.016	0.009	0.018	0.000
Ca	2.189	2.114	2.112	2.064
Ti	0.011	0.013	0.011	0.005
Total	8.681	8.595	8.595	8.582

Note: Epidote mineral in amygdules of the Waite Andesite Formation.

APPENDIX III. WHOLE ROCK MAJOR AND TRACE ELEMENT COMPOSITION

Notes:

Samples -84 and -85 were analysed for most of the major and trace elements at the geochemical laboratory of Minnova Inc. Si, Al and Ti were analysed at Metric Lab, Quebec.

Samples -86, -87 and NED were analysed at X-Ray Assay Laboratories. Selected -86 and -87 samples were analysed at the Analytical Chemistry Section of the Geological Survey of Canada (GSC).

Abbreviations:

n.a. = not analysed

LOI = loss on ignition

den = density

Lab = laboratory

Table III.1. Average composition of the lower member of the Amulet Formation

	X n=6	SD
(wt%)		
SiO ₂	75.10	2.30
TiO ₂	0.35	0.04
Al ₂ O ₃	11.04	0.38
FeO	3.15	1.73
MnO	0.09	0.04
MgO	0.58	0.52
CaO	2.15	1.05
Na ₂ O	3.76	1.85
K ₂ O	1.59	1.37
P ₂ O ₅	0.06	0.00
LOI	1.46	1.30
Total	99.33	
(ppm)		
Rb	48	19
Sr	72	28
Y	76	13
Zr	300	27
Nb	24	5
Ba	322	267

X : arithmetic mean

SD : standard deviation

n : number of samples

Table III.2 . Average composition of flow facies of the Waite Andesite Formation

	Flow breccia Siliceous frags		Flow breccia Matrix	
	X n=6	SD	X n=6	SD
(wt%)				
SiO ₂	74.17	5.36	57.75	5.85
TiO ₂	0.85	0.11	1.18	0.17
Al ₂ O ₃	10.79	1.85	15.55	1.23
FeO	3.41	1.28	8.67	3.00
MnO	0.07	0.04	0.18	0.07
MgO	0.86	0.53	2.92	1.46
CaO	3.12	1.04	3.35	1.20
Na ₂ O	4.36	0.67	4.78	1.02
K ₂ O	0.46	0.15	0.65	0.57
P ₂ O ₅	0.32	0.04	0.40	0.03
LOI	1.95	0.64	2.88	0.92
Total	100.36		98.31	
(ppm)				
Rb	20	10	28	14
Sr	133	51	108	71
Y	33	19	38	7
Zr	148	25	218	34
Nb	18	4	26	10
Ba	213	64	322	197
Au	0.03	0.00	0.03	n.a.
Ag	0.50	0.00	1.00	n.a.
Cu	133	23	54	n.a.
Zn	16	4	100	n.a.
Co	22	3	48	n.a.
Ni	46	2	55	n.a.

X : Arithmetic mean

SD : Standard deviation

n : Number of samples

n.a. : Not analyzed

Table III.2 (cont'd).

	Massive flow		Pillowed flow		Flow breccia (Frag & matrix)	
	X n=4	SD	X n=5	SD	X n=13	SD
(wt%)						
SiO ₂	59.90	2.05	57.14	3.26	59.21	5.64
TiO ₂	1.04	0.16	1.26	0.15	1.16	0.21
Al ₂ O ₃	15.01	0.82	14.78	0.79	15.18	1.33
FeO	7.67	0.82	8.80	0.35	8.17	2.46
MnO	0.15	0.06	0.25	0.16	0.16	0.06
MgO	1.92	1.33	4.63	1.76	2.59	1.28
CaO	5.54	5.80	3.18	0.50	3.13	1.03
Na ₂ O	3.55	2.17	4.69	0.48	4.81	0.91
K ₂ O	0.43	0.28	0.50	0.48	0.76	0.60
P ₂ O ₅	0.37	0.04	0.23	0.06	0.40	0.07
LOI	2.41	0.69	3.23	0.95	2.89	0.92
Total	97.99		98.69		98.46	
(ppm)						
Rb	33	12	18	12	33	17
Sr	257	349	72	34	86	59
Y	30	14	32	12	41	11
Zr	173	31	136	24	224	34
Nb	30	14	22	10	29	9
Ba	163	90	224	125	309	163
Au	n.a.	n.a.	n.a.	n.a.	0.04	0.01
Ag	n.a.	n.a.	n.a.	n.a.	0.90	0.14
Cu	n.a.	n.a.	n.a.	n.a.	48	9
Zn	n.a.	n.a.	n.a.	n.a.	147	72
Co	n.a.	n.a.	n.a.	n.a.	48	10
Ni	n.a.	n.a.	n.a.	n.a.	45	7

Table III.3. Average composition of the lower and upper members of the Waite Andesite

	Lower member Pillowed flow		Upper member Flow breccia	
	X n=4	SD	X n=32	SD
(wt%)				
SiO ₂	55.35	4.45	62.28	7.40
TiO ₂	1.19	0.10	1.14	0.24
Al ₂ O ₃	14.12	0.82	14.27	2.04
FeO	8.67	1.62	6.74	2.57
MnO	0.34	0.18	0.13	0.06
MgO	4.94	1.93	2.35	1.45
CaO	2.00	1.12	3.49	2.31
Na ₂ O	3.03	1.79	4.54	1.21
K ₂ O	0.73	0.44	0.63	0.49
P ₂ O ₅	0.26	0.11	0.36	0.08
LOI	n.a.	n.a.	2.69	0.86
Total	90.63		98.62	
(ppm)				
Rb	15	5	29	17
Sr	40	30	118	152
Y	25	15	39	13
Zr	150	30	189	50
Nb	30	10	25	11
Ba	175	15	266	147
Au	0.03	0.00	0.04	0.01
Ag	1.25	0.25	0.76	0.42
Cu	26	4	129	197
Zn	139	56	322	384
Co	63	12	43	15
Ni	98	2	47	9

X : Arithmetic mean

SD : Standard deviation

n : Number of samples

Table III.4 . Average composition of flow facies of the Splinter member

	Flow breccia		Massive flow	
	X	SD	X	SD
	n=11		n=14	
(wt%)				
SiO ₂	70.85	5.61	70.56	3.00
TiO ₂	0.55	0.20	0.54	0.14
Al ₂ O ₃	12.21	1.24	12.22	1.09
FeO	5.23	1.98	4.77	0.95
MnO	0.11	0.08	0.09	0.02
MgO	1.61	0.76	1.37	0.67
CaO	1.58	1.07	1.28	0.80
Na ₂ O	3.71	1.09	3.15	1.48
K ₂ O	1.56	0.77	1.51	1.28
P ₂ O ₅	0.19	0.10	0.12	0.08
LOI	2.49	1.02	2.15	0.61
Total	100.09		97.76	
(ppm)				
Rb	51	28	45	15
Sr	51	34	45	15
Y	46	12	60	0
Zr	230	43	260	40
Nb	29	8	20	0
Ba	421	164	405	95

X : Arithmetic mean

SD : Standard deviation

n : Number of samples

Table III.5. Average composition of flow facies of the Waite Rhyolite Formation.

	Massive & flow-banded facies		Massive lobe		Margin of lobes		Flow breccia		Feeders	
	X	SD	X	SD	X	SD	X	SD	X	SD
(wt%)	n=31		n=33		n=5		n=54		n=6	
SiO ₂	74.41	1.62	76.29	3.83	70.84	4.22	73.61	2.80	69.87	2.58
TiO ₂	0.28	0.09	0.27	0.08	0.29	0.07	0.27	0.09	0.51	0.19
Al ₂ O ₃	11.24	0.78	10.84	1.71	13.44	1.83	11.24	1.28	12.63	0.96
FeO	3.47	0.79	2.79	1.53	4.56	1.69	3.84	1.10	4.48	0.99
MnO	0.08	0.03	0.08	0.04	0.09	0.05	0.10	0.05	0.11	0.04
MgO	0.51	0.22	0.33	0.25	0.86	0.15	0.74	0.47	1.01	0.55
CaO	1.59	1.02	1.48	0.82	0.59	0.19	1.90	1.31	2.05	0.60
Na ₂ O	3.84	1.38	4.18	1.50	2.06	1.45	3.14	1.63	4.99	1.14
K ₂ O	2.20	1.70	1.73	1.27	3.66	1.56	1.96	0.95	1.41	0.53
P ₂ O ₅	0.03	0.00	0.04	0.02	0.03	0.00	0.04	0.03	0.11	0.05
LOI	1.68	0.77	1.71	0.72	2.18	0.50	2.58	1.20	2.70	0.63
Total	99.33		99.74		98.60		99.42		99.87	
(ppm)										
Rb	53	37	56	36	130	27	71	40	42	20
Sr	47	25	46	25	27	11	64	55	63	26
Y	63	13	59	12	63	4	68	14	53	9
Zr	307	22	299	55	350	57	305	50	290	18
Nb	25	6	24	6	33	11	25	8	22	3
Ba	434	286	386	218	620	217	375	146	363	56

X : Arithmetic mean
SD : Standard deviation
n : Number of samples

Table III.6 . Average composition of flow facies of the New Vauze Andesite

	X	SD	X	SD
	n=4		n=4	
(wt%)				
SiO ₂	50.93	1.39	57.13	6.30
TiO ₂	1.41	0.10	1.21	0.31
Al ₂ O ₃	13.93	0.44	13.80	1.25
FeO	11.21	0.99	8.57	2.00
MnO	0.31	0.05	0.22	0.05
MgO	5.72	0.82	4.27	1.15
CaO	5.20	0.49	4.35	1.41
Na ₂ O	3.76	0.54	4.90	0.21
K ₂ O	0.41	0.20	0.38	0.35
P ₂ O ₅	0.53	0.05	0.45	0.14
LOI	5.24	2.16	3.60	1.45
Total	98.65		98.88	
(ppm)				
Rb	20	7	22	9
Sr	120	19	58	11
Y	33	8	38	8
Zr	88	15	130	71
Nb	20	7	23	8
Ba	172	35	188	98
Au	0.03	0.00	n.a.	
Ag	1.20	0.20	n.a.	
Cu	68	2	n.a.	
Zn	254	112	n.a.	
Co	60	5	n.a.	
Ni	133	3	n.a.	

X : Arithmetic mean

SD : Standard deviation

n : Number of samples

n.a. : not analyzed

Table III.7 . Average composition of flow facies of the Amulet Andesite Formation

	Massive flow		Pillowed flow		Flow breccia	
	X	SD	X	SD	X	SD
	n=8		n=6		n=4	
(wt%)						
SiO ₂	55.49	3.68	55.55	2.33	51.33	2.77
TiO ₂	1.17	0.20	1.15	0.25	0.91	0.14
Al ₂ O ₃	15.90	1.42	17.45	1.67	16.93	0.61
FeO	7.61	0.88	8.34	1.76	11.21	2.41
MnO	3.90	1.68	0.19	0.07	0.15	0.01
MgO	0.39	0.34	4.65	0.81	5.39	1.19
CaO	6.95	1.68	7.28	2.45	2.82	0.99
Na ₂ O	4.08	0.78	3.64	1.43	3.10	1.29
K ₂ O	0.56	0.30	1.29	2.03	3.34	1.87
P ₂ O ₅	0.24	0.09	0.17	0.05	0.20	0.16
LOI	2.49	0.44	3.13	0.75	3.35	0.34
Total	98.78		102.84		98.73	
(ppm)						
Rb	30	10	52	55	110	76
Sr	185	95	165	68	88	4
Y	24	15	20	8	22	17
Zr	131	53	87	27	115	74
Nb	20	7	18	4	20	0
Ba	276	152	188	64	558	183

X : Arithmetic mean

SD : Standard deviation

n : Number of samples

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MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS
STANDARD REFERENCE MATERIAL 1010a
(ANSI and ISO TEST CHART No. 2)

Table III.8. Average composition of flow facies of the Fish Roe Formation

	Rhyolitic tuff		Spherulitic flow	
	X	SD	X	SD
	n=2		n=2	
(wt%)				
SiO ₂	72.45	0.05	69.93	1.18
TiO ₂	0.33	0.09	0.92	0.04
Al ₂ O ₃	10.62	0.48	10.31	0.41
FeO	3.02	1.06	4.80	0.33
MnO	0.12	0.04	0.13	0.01
MgO	0.63	0.07	0.82	0.01
CaO	4.59	1.35	4.61	0.31
Na ₂ O	0.14	0.01	1.38	0.82
K ₂ O	3.28	0.01	2.25	0.31
P ₂ O ₅	0.04	0.00	0.17	0.00
LOI	3.23	0.00	4.52	0.27
Total	98.45		99.84	
(ppm)				
Rb	90		40	10
Sr	10		60	10
Y	50		170	10
Zr	230		425	5
Nb	30		45	5
Ba	330		335	25

X : Arithmetic mean

SD : Standard deviation

n : Number of samples

Table III.9. Average composition of the dioritic dykes

	X n=10	SD
(wt%)		
SiO ₂	51.40	4.08
TiO ₂	1.15	0.19
Al ₂ O ₃	14.94	1.39
FeO	6.66	2.68
MnO	0.10	0.05
MgO	4.89	1.10
CaO	7.31	1.91
Na ₂ O	2.98	0.99
K ₂ O	0.56	0.59
P ₂ O ₅	0.16	0.06
LOI	5.96	3.20
Total	96.11	
(ppm)		
Rb	50	37
Sr	127	42
Y	23	12
Zr	93	45
Nb	20	8
Ba	210	8
Au	0.04	0.01
Ag	0.90	0.23
Cu	91	49
Zn	165	60
Co	52	19
Ni	90	32

X : Arithmetic mean

SD : Standard deviation

n : Number of samples

Table III.10. Whole-rock major and trace element composition**AMULET FORMATION, lower member**

Sample#	74-85	107-85	255-86	256-86	257-86	259-87	395-86
(wt%)							
SiO ₂	63.40	76.50	78.80	70.20	75.90	77.30	71.90
TiO ₂	0.44	0.43	0.33	0.35	0.35	0.32	0.32
Al ₂ O ₃	10.91	11.11	11.00	11.20	10.50	10.70	11.70
FeO	8.60	3.08	1.37	6.70	3.22	1.76	2.75
MnO	0.12	0.17	0.04	0.10	0.10	0.05	0.07
MgO	2.72	0.66	0.16	0.64	0.09	0.27	1.63
CaO	0.34	0.39	1.58	2.16	3.74	3.01	2.04
Na ₂ O	1.40	0.73	6.37	2.49	4.05	5.42	3.50
K ₂ O	0.53	2.90	0.19	3.71	0.62	0.16	1.94
P ₂ O ₅	n.a.	n.a.	0.06	0.06	0.06	0.06	0.05
LOI	n.a.	n.a.	0.39	1.31	0.77	0.85	4.00
Total	88.46	95.97	100.29	98.92	99.40	99.90	99.90
(ppm)							
Rb	n.a.	n.a.	20	80	50	40	50
Sr	n.a.	n.a.	40	50	110	60	100
Y	n.a.	n.a.	70	80	70	60	100
Zr	n.a.	n.a.	310	310	250	300	330
Nb	n.a.	n.a.	20	30	20	20	30
Ba	n.a.	n.a.	80	800	200	110	420
Au	0.03	0.03	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	2.79	0.50	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	740	78	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	700	43	n.a.	n.a.	n.a.	n.a.	n.a.
Co	40	15	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	50	40	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.48	2.35	2.32	2.42	2.37	2.34	2.37

FeO: Total iron calculated as FeO

WAITE ANDESITE FORMATION, lower member

	103-85	106-85	251-86	394-86
(wt%)				
SiO ₂	53.20	51.40	62.90	53.90
TiO ₂	1.31	1.24	1.03	1.18
Al ₂ O ₃	14.99	13.30	13.30	14.90
Feo	6.73	11.00	8.48	9.27
MnO	0.47	0.16	0.17	0.56
MgO	5.70	4.97	1.90	7.19
CaO	1.68	0.45	3.55	2.35
Na ₂ O	3.18	0.11	4.86	3.99
K ₂ O	1.30	1.00	0.39	0.23
P ₂ O ₅	n.a.	n.a.	0.34	0.15
LOI	n.a.	n.a.	1.77	4.77
Total	88.56	83.63	98.69	98.49
(ppm)				
Au	0.03	0.03	n.a.	n.a.
Ag	1.00	1.50	n.a.	n.a.
Cu	30	22	n.a.	n.a.
Zn	195	83	n.a.	n.a.
Co	50	75	n.a.	n.a.
Ni	95	100	n.a.	n.a.
Rb	n.a.	n.a.	10	20
Sr	n.a.	n.a.	70	<10
Y	n.a.	n.a.	40	<10
Zr	n.a.	n.a.	180	120
Nb	n.a.	n.a.	40	20
Ba	n.a.	n.a.	160	190
den	2.53	2.60	2.50	2.59

FeO: Total iron calculated as FeO

SPLINTER MEMBER, Waite Andesite Formation

	69-85	70-85	71-85	72-85	73-85	87-85	88-85
(wt%)							
SiO ₂	68.40	65.50	73.20	69.50	72.80	69.80	66.60
TiO ₂	0.50	0.51	0.38	0.48	0.61	0.49	0.89
Al ₂ O ₃	12.63	11.94	9.52	13.39	11.37	10.98	13.19
Feo	6.05	7.45	5.30	4.35	3.35	5.30	5.78
MnO	0.15	0.12	0.10	0.09	0.11	0.08	0.12
MgO	1.79	2.12	1.39	1.19	1.03	2.00	2.12
CaO	0.62	0.34	0.39	0.95	0.34	0.39	1.34
Na ₂ O	2.21	0.08	0.70	1.99	0.94	0.81	4.26
K ₂ O	1.30	1.93	1.69	3.08	5.30	1.78	0.48
P ₂ O ₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	93.65	89.99	92.67	95.02	95.85	91.63	94.78
(ppm)							
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Au	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Ag	1.00	1.00	0.70	0.70	0.70	0.50	1.00
Cu	50	32	24	28	138	115	58
Zn	175	146	111	130	397	83	123
Co	35	35	30	25	20	35	30
Ni	40	50	35	35	30	45	50
den	2.42	2.45	2.39	2.39	2.36	2.41	2.42

FeO: Total iron calculated as FeO

SPLINTER MEMBER, Waite Andesite Formation

	89-85	91-85	94-85	95-85	97-85	99-85	100-85
(wt%)							
SiO ₂	70.50	63.50	63.70	61.20	77.30	59.20	73.00
TiO ₂	0.57	0.83	0.92	1.12	0.43	0.70	0.50
Al ₂ O ₃	12.30	13.22	13.59	13.07	11.00	12.98	12.17
Feo	5.27	6.20	6.43	7.10	3.38	8.85	3.78
MnO	0.10	0.12	0.28	0.42	0.11	0.21	0.07
MgO	1.26	2.20	2.32	2.60	1.13	3.32	0.86
CaO	1.96	1.06	0.73	0.84	0.62	0.78	1.00
Na ₂ O	3.72	3.77	3.45	1.24	3.18	2.43	3.50
K ₂ O	0.17	1.11	0.77	1.93	1.20	0.24	1.25
P ₂ O ₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	95.85	92.01	92.19	89.52	98.35	88.71	96.13
(ppm)							
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Au	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Ag	0.50	1.00	2.00	1.00	1.00	2.00	0.50
Cu	59	38	425	280	47	800	132
Zn	88	115	3300	2200	113	338	73
Co	30	28	37	35	10	35	18
Ni	53	45	50	55	43	60	38
den	2.41	2.44	2.45	2.48	2.36	2.51	2.37

FeO: Total iron calculated as FeO

SPLINTER MEMBER, Waite Andesite Formation

	101-85	117-85	119-85	120-85	121-85	122-85	124-85
(wt%)							
SiO ₂	64.10	80.40	72.50	69.80	75.60	70.40	74.40
TiO ₂	0.65	0.44	0.47	0.54	0.45	0.63	0.69
Al ₂ O ₃	13.22	9.99	12.30	13.58	11.81	12.84	12.73
Feo	6.65	2.13	4.40	4.47	3.78	4.73	3.00
MnO	0.09	0.02	0.06	0.07	0.06	0.08	0.05
MgO	3.12	0.20	0.60	0.73	0.46	0.86	0.60
CaO	1.18	1.00	1.62	2.70	2.07	1.46	3.20
Na ₂ O	3.40	3.83	4.20	4.90	4.15	4.64	3.07
K ₂ O	0.48	1.25	1.54	0.48	0.87	0.96	1.88
P ₂ O ₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	92.89	99.26	97.69	97.27	99.25	96.60	99.62
(ppm)							
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Au	0.03	0.03	0.03	0.03	0.03	0.09	0.03
Ag	1.00	0.50	0.50	0.50	0.50	0.50	0.50
Cu	65	57	52	48	68	80	47
Zn	115	25	53	66	64	77	46
Co	33	10	33	38	25	30	27
Ni	50	33	37	40	35	45	33
den	2.46	2.33	2.38	2.40	2.37	2.40	2.38

FeO: Total iron calculated as FeO

SPLINTER MEMBER, Waite Andesite Formation

	235-86	238-86	241-86	242-86	392-86	393a-86	396-86
(wt%)							
SiO ₂	69.40	62.00	55.70	74.70	74.50	63.00	71.40
TiO ₂	0.60	0.71	1.20	0.23	0.72	1.01	0.34
Al ₂ O ₃	12.80	13.10	16.40	11.30	11.30	14.60	12.30
Feo	4.04	7.82	10.26	3.86	3.25	7.12	5.74
MnO	0.09	0.16	0.13	0.07	0.06	0.11	0.14
MgO	1.01	1.93	3.59	1.32	1.41	2.69	1.86
CaO	2.83	3.98	1.20	0.75	1.52	2.35	0.41
Na ₂ O	5.01	2.10	5.92	3.82	3.10	6.05	4.91
K ₂ O	1.25	2.61	0.23	2.03	1.93	0.12	0.72
P ₂ O ₅	0.20	0.27	0.47	0.03	0.26	0.36	0.07
LOI	2.77	5.00	2.93	1.54	2.08	2.08	1.54
Total	100.00	99.68	98.03	99.65	100.13	99.49	99.43
(ppm)							
Rb	30	100	10	60	60	<10	30
Sr	60	70	50	30	40	50	30
Y	60	50	50	60	40	40	50
Zr	220	210	180	300	150	210	300
Nb	20	40	30	20	20	30	40
Ba	310	410	130	500	500	110	300
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.40	2.49	2.55	2.37	2.37	2.48	2.41

FeO: Total iron calculated as FeO

SPLINTER MEMBER, Waite Andesite Formation

	397-86	398-86	399-86	392-86	1-87	2-87	3-87
(wt%)							
SiO ₂	70.40	72.90	70.80	63.60	73.30	69.10	66.20
TiO ₂	0.45	0.32	0.40	0.71	0.50	0.74	1.18
Al ₂ O ₃	12.90	11.10	12.30	13.40	11.95	14.82	13.93
Feo	4.63	4.70	5.36	9.00	4.60	2.98	5.50
MnO	0.07	0.18	0.32	0.12	0.10	0.06	0.11
MgO	1.77	1.29	2.78	2.10	1.40	1.45	1.70
CaO	0.84	1.71	0.44	2.92	1.87	1.34	2.18
Na ₂ O	4.13	2.42	2.88	4.00	4.10	6.10	5.12
K ₂ O	2.90	2.12	1.52	1.25	0.09	0.48	0.02
P ₂ O ₅	0.12	0.07	0.10	0.26	0.19	0.06	0.14
LOI	1.77	2.93	2.39	2.16	2.00	2.00	2.00
Total	99.98	99.74	99.29	99.52	100.10	99.13	98.08
(ppm)							
Rb	60	80	40	30	n.a.	n.a.	n.a.
Sr	30	50	<10	130	n.a.	n.a.	n.a.
Y	60	50	60	20	n.a.	n.a.	n.a.
Zr	270	230	260	210	n.a.	n.a.	n.a.
Nb	20	20	30	30	n.a.	n.a.	n.a.
Ba	620	600	530	300	n.a.	n.a.	n.a.
Au	n.a.	n.a.	n.a.	n.a.	0.01	0.01	0.01
Ag	n.a.	n.a.	n.a.	n.a.	0.07	0.03	1.00
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	6	7
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	35	54
Co	n.a.	n.a.	n.a.	n.a.	n.a.	11	15
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	7	9
den	2.39	2.39	2.41	2.50	2.40	2.38	2.44

FeO: Total iron calculated as FeO

SPLINTER MEMBER, Waite Andesite Formation

	4-87	7-87	8-87	12-87
(wt%)				
SiO₂	76.90	81.40	54.50	76.00
TiO₂	0.20	0.29	0.47	0.30
Al₂O₃	10.70	9.90	17.90	10.80
Feo	5.25	0.93	11.43	5.51
MnO	0.11	0.03	0.21	0.17
MgO	1.23	0.12	2.59	0.93
CaO	0.16	1.20	0.86	0.50
Na₂O	0.68	5.10	2.62	3.25
K₂O	2.19	0.95	5.32	0.86
P₂O₅	0.03	0.06	0.09	0.06
LOI	2.00	0.31	2.85	1.54
Total	99.45	100.29	98.84	99.92

(ppm)				
Rb	51	27	144	28
Sr	10	62	27	10
Y	58	70	79	50
Zr	257	188	380	227
Nb	14	12	23	26
Ba	637	274	1400	312
Au	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.
den	2.38	2.31	2.54	2.39

FeO: Total iron calculated as FeO

WAITE ANDESITE FORMATION, upper member

	41-85	42-85	43-85	44-85	45-85	48-85	56-85
(wt%)							
SiO₂	59.60	63.90	67.20	67.00	62.50	65.00	65.70
TiO₂	1.35	1.21	1.05	1.03	1.12	1.23	1.06
Al₂O₃	15.56	14.23	13.36	13.78	15.13	14.59	12.85
FeO	5.90	5.60	4.05	3.45	5.60	5.40	6.10
MnO	0.08	0.11	0.09	0.05	0.08	0.08	0.11
MgO	2.06	1.46	0.83	1.39	1.66	1.39	1.99
CaO	2.52	3.25	3.19	2.80	3.86	3.14	2.46
Na₂O	5.93	5.07	5.39	6.52	5.17	5.28	4.20
K₂O	0.27	0.67	0.63	0.14	0.14	0.58	0.53
P₂O₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	93.27	95.50	95.79	96.16	95.26	96.69	95.00
(ppm)							
Au	0.03	0.03	0.03	0.03	0.03	0.07	0.03
Ag	1.70	0.30	0.30	0.30	0.70	0.70	0.70
Cu	830	57	50	73	121	56	52
Zn	1440	330	410	353	360	248	900
Co	45	40	35	25	35	35	45
Ni	50	45	45	45	50	40	50
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.47	2.45	2.41	2.40	2.46	2.44	2.45

FeO: Total iron calculated as FeO

WAITE ANDESITE FORMATION, upper member

	90-85	113-85	114-85	115-85	116-85	123-85	125-85
(wt%)							
SiO ₂	52.90	78.60	57.50	82.30	63.80	61.00	55.40
TiO ₂	1.78	0.88	1.27	0.84	1.06	1.37	1.43
Al ₂ O ₃	15.05	9.87	16.37	9.00	13.91	14.75	16.02
FeO	9.08	2.43	6.37	2.20	6.55	5.23	6.43
MnO	0.12	0.03	0.11	0.03	0.10	0.09	0.09
MgO	3.90	0.46	2.40	0.20	1.52	2.45	3.85
CaO	4.25	2.18	2.40	1.62	1.57	6.33	2.80
Na ₂ O	2.43	3.40	5.50	4.00	4.64	3.24	4.74
K ₂ O	0.53	0.51	0.14	0.17	0.24	0.27	1.60
P ₂ O ₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	90.04	98.36	92.06	100.36	93.39	94.73	92.36
(ppm)							
Au	0.03	0.03	0.03	0.03	0.03	0.03	0.06
Ag	1.50	0.50	1.00	0.50	1.00	1.00	0.50
Cu	53	110	54	155	35	100	65
Zn	73	20	100	12	92	76	100
Co	70	18	48	25	60	55	65
Ni	65	48	55	43	40	60	25
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.58	2.35	2.49	2.33	2.45	2.49	2.50

FeO: Total iron calculated as FeO

WAITE ANDESITE FORMATION, upper member

	200a-86	202-86	204-86	211-86	216-86	217-86	222-86
(wt%)							
SiO₂	58.30	57.70	53.30	61.50	76.10	63.70	58.10
TiO₂	1.21	0.80	1.24	0.82	0.63	1.11	1.25
Al₂O₃	15.90	16.30	16.90	13.90	8.46	14.30	14.80
FeO	8.50	6.67	9.72	7.10	2.21	7.44	8.49
MnO	0.11	0.14	0.16	0.14	0.06	0.11	0.14
MgO	3.74	0.21	3.84	2.03	0.44	1.84	3.99
CaO	3.10	15.40	2.37	3.93	4.70	2.08	3.67
Na₂O	4.02	0.05	4.82	3.27	3.83	5.52	5.00
K₂O	1.23	0.15	1.36	1.99	0.41	0.72	0.09
P₂O₅	0.42	0.32	0.43	0.28	0.26	0.39	0.26
LOI	2.93	1.62	3.39	4.08	2.54	2.31	3.31
Total	99.46	99.36	97.53	99.04	99.64	99.52	99.10
(ppm)							
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Rb	50	30	50	70	10	50	<10
Sr	100	750	40	40	100	10	110
Y	50	20	40	50	20	20	40
Zr	240	130	240	220	110	200	140
Nb	20	20	20	40	20	20	20
Ba	390	40	470	400	160	200	120
den	2.53	2.58	2.56	2.48	2.36	2.47	2.54

FeO: Total iron calculated as FeO

WAITE ANDESITE FORMATION, upper member

	309-86	315-86	319-86	327-86	347-86	348-86	349-86
(wt%)							
SiO ₂	64.60	54.30	56.50	63.20	61.30	67.70	71.50
TiO ₂	0.92	1.38	1.46	1.12	1.02	1.04	0.91
Al ₂ O ₃	13.40	15.50	15.40	14.50	14.30	13.60	12.20
FeO	7.68	9.18	8.55	6.87	8.95	4.73	3.70
MnO	0.16	0.21	0.16	0.13	0.25	0.10	0.08
MgO	1.28	5.66	4.41	2.25	3.95	1.41	1.00
CaO	2.96	3.46	2.88	2.59	0.81	3.29	2.89
Na ₂ O	5.18	4.28	5.30	6.09	3.47	5.92	5.29
K ₂ O	0.21	1.44	0.34	1.01	0.70	0.18	0.53
P ₂ O ₅	0.36	0.21	0.21	0.39	0.41	0.37	0.36
LOI	2.00	3.08	3.23	1.61	3.31	1.31	1.16
Total	98.75	98.70	98.44	99.76	98.47	99.65	99.62
(ppm)							
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Rb	20	40	10	30	20	30	30
Sr	80	90	80	20	10	190	200
Y	40	40	30	50	50	40	40
Zr	200	130	110	200	190	190	150
Nb	40	10	20	30	50	20	20
Ba	160	470	180	260	250	140	260
den	2.47	2.57	2.54	2.47	2.51	2.43	2.39

FeO: Total iron calculated as FeO

WAITE ANDESITE FORMATION, upper member

	370-86	371-86	401-86	402-86	403-86	404-86	407-86
(wt%)							
SiO ₂	57.60	66.60	69.90	54.00	51.80	48.70	61.00
TiO ₂	1.07	0.97	0.87	1.26	1.62	1.46	0.98
Al ₂ O ₃	15.50	13.70	11.50	16.50	16.90	17.00	14.30
FeO	9.36	5.67	4.27	10.71	10.88	13.77	7.05
MnO	0.21	0.11	0.12	0.22	0.26	0.31	0.15
MgO	2.73	1.45	1.59	3.90	3.91	5.59	1.49
CaO	4.53	3.97	3.37	2.49	4.07	2.04	5.32
Na ₂ O	3.15	5.05	4.56	5.46	4.53	3.64	4.99
K ₂ O	1.57	0.50	0.66	0.09	0.55	1.22	0.72
P ₂ O ₅	0.39	0.36	0.31	0.44	0.57	0.44	0.36
LOI	2.77	1.47	2.62	3.00	3.39	4.16	3.16
Total	98.88	99.85	99.77	98.07	98.48	98.33	99.52
(ppm)							
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Rb	50	10	30	<10	20	30	20
Sr	130	160	70	40	80	10	170
Y	30	60	10	30	60	50	40
Zr	200	180	150	230	290	280	190
Nb	40	10	20	30	30	30	10
Ba	490	140	290	110	190	610	260
den	2.55	2.45	2.41	2.58	2.61	2.66	2.49

FeO: Total iron calculated as FeO

WAITE ANDESITE FORMATION

	309-86	394-86	401-86	402-86
(wt%)				
SiO ₂	65.10	54.40	70.30	54.50
TiO ₂	0.91	1.14	0.85	1.24
Al ₂ O ₃	13.30	14.80	11.20	16.50
FeO	8.01	9.63	4.32	11.25
MnO	0.16	0.55	0.11	0.21
MgO	1.27	7.07	1.53	3.94
CaO	2.85	2.27	3.16	2.40
Na ₂ O	4.90	3.90	4.10	5.30
K ₂ O	0.18	0.21	0.64	0.07
P ₂ O ₅	0.36	0.14	0.30	0.44
LOI	2.00	4.60	2.60	2.90
Total	99.04	98.71	99.11	98.75
(ppm)				
Rb	n.a.	n.a.	n.a.	n.a.
Sr	87	28	87	58
Y	48	n.a.	20	49
Zr	158	99	125	177
Nb	n.a.	n.a.	n.a.	n.a.
Ba	95	132	239	96
La	15	13	11	16
Ce	39	30	29	43
Nd	26	17	20	28
Sm	6.1	2.9	3.9	6.0
Eu	2.0	0.8	1.3	2.1
Gd	7.2	3.4	5.1	7.6
Dy	7.5	3.5	5.3	7.8
Yb	4.4	2.2	3.0	4.0
Th	1.7	1.5	1.1	1.6
Y	41	18	28	41
Hf	4	3	3	4
(La/Sm) _n	1.55	2.82	1.77	1.68
(La/Yb) _n	2.30	3.98	2.47	2.70
Eu/Eu*	0.94	0.78	0.93	0.95
La/Zr	0.09	0.13	0.09	0.09
Yb/Zr	0.03	0.02	0.02	0.02
Lab	GSC	GSC	GSC	GSC

Eu* calculated by linear interpolation between chondrite-normalized Sm and Gd.

	397-86	4-87
(wt%)		
SiO ₂	70.90	75.90
TiO ₂	0.46	0.18
Al ₂ O ₃	12.60	9.90
FeO	4.77	5.15
MnO	0.06	0.10
MgO	1.74	1.30
CaO	0.74	0.20
Na ₂ O	3.70	0.79
K ₂ O	2.80	2.15
P ₂ O ₅	0.10	0.01
LOI	1.70	2.40
Total	99.57	98.08
(ppm)		
Rb	86	n.a.
Sr	52	n.a.
Y	68	n.a.
Zr	223	n.a.
Nb	n.a.	n.a.
Ba	526	570
La	14	19
Ce	36	45
Nd	25	28
Sm	4.9	6.3
Eu	1.2	1.3
Gd	6.5	7.1
Dy	7.7	8.1
Yb	5.6	5.7
Th	2.0	n.a.
Y	44	46
Hf	6	n.a.
(La/Sm) _n	1.80	1.90
(La/Yb) _n	1.67	2.24
Eu/Eu*	0.65	0.43
La/Zr	0.06	n.a.
Yb/Zr	0.03	n.a.
Lab	GSC	GSC

Eu* calculated by linear interpolation between chondrite-normalized Sm and Gd

WAITE RHYOLITE FORMATION, flow unit 1

	316-86	317-86	324-86	326-86	361-86	362-86	368-86
(wt%)							
SiO ₂	76.30	71.40	74.10	73.10	77.50	81.30	70.50
TiO ₂	0.21	0.23	0.24	0.23	0.20	0.19	0.27
Al ₂ O ₃	10.80	11.70	12.10	11.40	10.20	8.56	13.30
FeO	3.57	4.46	3.80	3.44	3.29	1.15	6.48
MnO	0.06	0.17	0.12	0.09	0.09	0.09	0.08
MgO	0.25	0.83	0.52	0.75	0.68	0.18	0.32
CaO	1.24	2.81	1.33	2.51	0.65	1.70	0.26
Na ₂ O	4.11	5.02	5.44	4.02	3.86	4.26	4.16
K ₂ O	2.63	0.62	0.73	1.46	1.25	0.86	2.84
P ₂ O ₅	0.03	0.03	0.03	0.03	0.03	0.03	0.03
LOI	0.62	2.62	1.62	3.00	1.39	1.62	1.31
Total	99.82	99.89	100.03	100.03	99.14	99.94	99.55
(ppm)							
Rb	70	10	50	70	90	50	110
Sr	90	70	70	40	30	80	50
Y	50	80	70	70	70	70	50
Zr	280	320	330	300	270	230	390
Nb	30	30	20	30	30	20	30
Ba	450	200	220	330	330	230	540
den	2.35	2.40	2.37	2.37	2.35	2.31	2.40

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 1

	369-86	435-86	436-86	437-86	438-86	439-86	440-86
(wt%)							
SiO ₂	77.20	74.00	74.00	73.20	74.40	80.50	74.30
TiO ₂	0.21	0.24	0.20	0.24	0.20	0.21	0.19
Al ₂ O ₃	10.60	12.60	10.50	10.90	10.80	10.10	9.37
FeO	1.84	4.70	3.86	4.80	3.12	0.88	3.40
MnO	0.07	0.04	0.18	0.12	0.11	0.04	0.14
MgO	0.06	0.65	0.71	0.57	0.61	0.01	0.53
CaO	1.64	0.29	2.27	1.95	2.18	1.02	3.24
Na ₂ O	4.56	4.67	3.59	4.01	0.52	6.51	0.81
K ₂ O	2.20	1.16	1.31	1.61	4.22	0.11	2.78
P ₂ O ₅	0.03	0.04	0.03	0.03	0.03	0.03	0.03
LOI	1.47	1.23	2.62	2.31	2.77	0.62	3.62
Total	99.88	99.62	99.27	99.74	98.96	100.03	98.41
(ppm)							
Rb	80	50	60	40	160	<10	90
Sr	60	40	80	40	10	40	20
Y	50	50	60	60	60	50	60
Zr	260	310	260	330	270	290	250
Nb	10	30	20	20	10	30	20
Ba	490	290	310	340	560	130	390
den	2.33	2.37	2.37	2.38	2.36	2.31	2.37

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 1

	441-86	442-86	443-86	445-86	446-86	447-86	448-86
(wt%)							
SiO₂	76.80	75.90	80.90	64.30	75.50	70.80	73.70
TiO₂	0.24	0.19	0.21	0.30	0.23	0.24	0.26
Al₂O₃	11.80	10.00	10.30	15.80	11.50	13.60	13.00
FeO	2.54	1.93	1.04	7.77	2.72	4.54	3.35
MnO	0.04	0.13	0.05	0.18	0.09	0.09	0.07
MgO	0.34	0.17	0.10	1.05	0.26	0.71	0.48
CaO	0.68	2.73	0.63	0.75	0.89	0.83	0.63
Na₂O	3.59	2.25	5.63	3.42	2.68	0.77	5.51
K₂O	2.27	3.60	0.79	3.36	4.33	5.70	1.57
P₂O₅	0.03	0.03	0.03	0.03	0.03	0.03	0.03
LOI	1.23	2.54	0.62	2.39	1.31	2.16	1.08
Total	99.56	99.47	100.30	99.35	99.54	99.47	99.68
(ppm)							
Rb	100	90	40	120	100	160	50
Sr	30	50	40	40	30	30	50
Y	60	50	80	60	60	60	60
Zr	320	250	280	430	310	340	350
Nb	20	20	20	50	30	30	20
Ba	550	940	280	580	950	940	290
den	2.34	2.34	2.31	2.45	2.34	2.38	2.36

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 1

	457-86	459-86	460-86	464-86	498-86	508-86	510-86
(wt%)							
SiO ₂	75.80	78.10	68.40	76.80	73.50	74.50	74.40
TiO ₂	0.20	0.20	0.27	0.21	0.26	0.25	0.24
Al ₂ O ₃	10.30	11.30	14.30	10.60	12.10	11.70	12.10
FeO	3.73	1.02	6.46	3.00	4.11	4.00	3.73
MnO	0.16	0.04	0.05	0.10	0.07	0.05	0.04
MgO	0.25	0.13	0.74	0.30	1.29	0.63	0.90
CaO	1.55	1.21	0.97	1.66	0.63	1.15	0.64
Na ₂ O	4.19	5.74	4.21	4.40	4.23	4.86	3.74
K ₂ O	1.71	1.28	2.00	0.97	2.15	0.92	2.38
P ₂ O ₅	0.03	0.03	0.03	0.03	0.04	0.03	0.03
LOI	0.85	0.85	2.08	1.85	1.23	1.62	1.54
Total	98.77	99.90	99.51	99.92	99.61	99.71	99.74
(ppm)							
Rb	70	20	60	20	70	20	50
Sr	50	40	20	70	30	40	10
Y	50	70	70	60	70	90	70
Zr	260	250	370	290	310	330	310
Nb	40	30	30	20	20	30	20
Ba	360	200	410	230	570	250	570
den	2.36	2.31	2.42	2.35	2.37	2.37	2.36

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 1

	511-86	523-86	525-86	531-86	534-86	536-86	539-86
(wt%)							
SiO₂	72.30	76.80	77.90	74.40	75.60	72.60	74.10
TiO₂	0.27	0.22	0.23	0.22	0.23	0.22	0.19
Al₂O₃	12.50	11.10	10.90	11.30	11.50	11.50	10.30
FeO	5.37	3.86	3.59	4.00	3.48	4.39	4.53
MnO	0.15	0.07	0.02	0.10	0.08	0.11	0.14
MgO	0.53	0.65	0.33	0.66	0.29	0.51	0.35
CaO	0.95	0.25	0.27	1.51	1.36	1.81	1.69
Na₂O	3.43	5.07	4.65	4.59	5.51	4.94	1.42
K₂O	2.29	0.67	0.80	0.95	1.06	0.90	4.51
P₂O₅	0.03	0.03	0.03	0.03	0.03	0.03	0.03
LOI	2.00	1.23	1.08	2.00	1.54	2.31	2.16
Total	99.82	99.95	99.80	99.76	100.68	99.32	99.42
(ppm)							
Rb	70	30	30	40	20	50	80
Sr	30	20	20	30	60	50	30
Y	70	70	50	70	60	80	50
Zr	390	300	310	300	330	300	250
Nb	20	20	40	40	20	20	30
Ba	460	250	210	190	75	230	690
den	2.39	2.35	2.35	2.37	2.36	2.38	2.37

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 1

	540-86	542-86
(wt%)		
SiO₂	76.90	72.40
TiO₂	0.22	0.22
Al₂O₃	11.50	10.30
FeO	1.67	8.31
MnO	0.03	0.16
MgO	0.19	1.72
CaO	0.34	0.46
Na₂O	2.36	2.59
K₂O	5.99	1.51
P₂O₅	0.03	0.03
LOI	0.62	1.85
Total	99.85	99.55

(ppm)		
Rb	80	30
Sr	<10	10
Y	50	60
Zr	290	290
Nb	20	30
Ba	910	360
den	2.31	2.44

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 2

	47-85	50A-85	50B-85	50C-85	51-85	58-85	60-85
(wt%)							
SiO₂	76.40	82.20	69.80	70.40	77.20	74.20	75.00
TiO₂	0.34	0.30	0.42	0.35	0.36	0.38	0.34
Al₂O₃	9.40	8.36	13.41	11.92	11.13	11.08	9.87
FeO	4.65	2.07	3.08	2.00	2.87	3.17	2.90
MnO	0.06	0.05	0.04	0.05	0.07	0.03	0.10
MgO	0.93	0.20	0.83	0.66	0.23	1.59	1.76
CaO	1.46	1.23	0.34	1.29	1.01	0.95	2.24
Na₂O	3.40	3.93	2.10	0.11	4.31	3.77	2.37
K₂O	0.48	0.29	2.99	3.76	1.25	1.35	1.78
P₂O₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	97.12	98.63	93.01	90.54	98.43	96.52	96.36
(ppm)							
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Au	0.07	0.03	0.03	0.03	0.07	0.03	0.03
Ag	1.00	0.30	0.30	0.30	0.30	0.30	0.30
Cu	102	71	38	52	45	36	90
Zn	247	150	194	168	560	144	110
Co	30	20	15	15	15	25	25
Ni	40	35	30	25	30	25	40
den	2.38	2.32	2.36	2.35	2.34	2.36	2.37

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 2

	373-86	374-86	386-86	387-86	388-86	389-86	390-86
(wt%)							
SiO₂	74.00	75.30	82.70	71.50	76.50	80.80	71.80
TiO₂	0.24	0.22	0.19	0.26	0.20	0.18	0.27
Al₂O₃	11.50	10.90	8.80	12.70	10.90	9.26	14.20
FeO	2.86	4.14	1.03	4.61	3.57	1.21	4.12
MnO	0.07	0.11	0.05	0.07	0.08	0.05	0.03
MgO	0.22	0.86	0.05	1.42	0.69	0.07	1.02
CaO	1.84	0.50	0.91	0.32	0.83	1.34	0.39
Na₂O	5.27	2.41	5.23	2.89	3.97	5.71	0.13
K₂O	2.16	2.63	0.35	2.86	1.40	0.31	4.98
P₂O₅	0.03	0.03	0.03	0.03	0.03	0.03	0.03
LOI	1.62	2.70	0.85	2.08	1.77	1.31	2.77
Total	99.81	99.80	100.19	98.74	99.94	100.27	99.74
(ppm)							
Rb	40	90	20	90	50	20	150
Sr	50	10	30	40	50	30	<10
Y	50	70	60	80	60	30	60
Zr	320	270	240	360	280	220	360
Nb	30	20	20	30	20	30	20
Ba	480	280	150	570	290	130	630
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.35	2.36	2.30	2.38	2.35	2.31	2.37

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 2

	529-86	548-86	550-86	551-86	556-86	557-86	559-86
(wt%)							
SiO ₂	72.30	76.50	77.00	72.70	74.30	67.20	71.90
TiO ₂	0.21	0.23	0.21	0.23	0.22	0.30	0.26
Al ₂ O ₃	11.70	10.60	10.60	11.30	11.20	14.20	12.40
FeO	4.62	4.36	2.92	4.78	3.70	6.69	4.89
MnO	0.13	0.05	0.12	0.12	0.07	0.18	0.21
MgO	0.96	0.63	0.42	0.54	0.50	0.94	0.89
CaO	1.34	0.43	1.24	1.50	1.67	0.48	1.09
Na ₂ O	0.39	5.13	4.69	4.16	4.62	2.95	5.46
K ₂ O	4.59	0.39	1.09	2.19	1.04	5.10	0.82
P ₂ O ₅	0.03	0.03	0.03	0.03	0.03	0.03	0.03
LOI	3.00	1.16	1.39	2.00	2.23	1.54	1.77
Total	99.27	99.51	99.71	99.55	99.58	99.61	99.72
(ppm)							
Rb	160	10	30	60	40	110	30
Sr	10	50	40	50	60	30	70
Y	80	50	60	60	60	70	60
Zr	280	320	260	310	310	420	360
Nb	40	30	30	20	30	30	30
Ba	510	170	240	440	300	660	210
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.38	2.36	2.35	2.38	2.37	2.42	2.39

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 2

	562-86	563-86	573-86	579-86	580-86	604-86	610-86
(wt%)							
SiO ₂	73.70	73.50	75.10	71.90	73.60	74.70	72.20
TiO ₂	0.22	0.23	0.23	0.25	0.23	0.23	0.20
Al ₂ O ₃	11.00	11.50	11.40	12.60	11.20	11.70	10.30
FeO	3.96	3.71	4.89	4.00	6.42	3.61	3.73
MnO	0.10	0.10	0.08	0.11	0.13	0.09	0.17
MgO	0.54	0.63	0.81	0.68	1.14	0.67	0.19
CaO	1.92	1.96	0.50	1.52	0.32	1.33	2.88
Na ₂ O	2.98	4.01	4.78	5.44	1.69	5.51	4.67
K ₂ O	3.27	1.48	0.77	1.50	2.74	0.96	1.29
P ₂ O ₅	0.03	0.03	0.03	0.04	0.03	0.03	0.03
LOI	1.93	2.47	1.31	1.85	2.00	1.23	3.85
Total	99.65	99.62	99.90	99.89	99.50	100.06	99.51
(ppm)							
Rb	70	40	40	40	100	20	50
Sr	10	80	20	30	10	70	90
Y	60	60	50	80	60	80	70
Zr	300	290	310	330	310	320	270
Nb	30	20	20	20	20	20	20
Ba	670	270	220	350	490	390	280
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.37	2.37	2.38	2.38	2.40	2.36	2.37

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 2

	661-86	662-86	NED-9	NED-10	NED-14
(wt%)					
SiO ₂	73.60	76.40	64.80	70.50	78.50
TiO ₂	0.21	0.23	0.41	0.34	0.21
Al ₂ O ₃	10.10	11.10	14.40	11.30	10.00
FeO	3.89	2.62	4.78	6.98	2.16
MnO	0.17	0.07	0.14	0.07	0.07
MgO	0.36	0.39	1.11	2.19	0.85
CaO	3.32	1.22	1.59	1.62	1.33
Na ₂ O	2.18	5.70	5.34	0.66	0.27
K ₂ O	2.48	1.11	2.37	2.08	2.91
P ₂ O ₅	0.03	0.03	0.11	0.07	0.03
LOI	3.70	1.23	4.47	3.63	3.16
Total	100.04	100.10	99.52	99.44	99.49
(ppm)					
Rb	80	20	n.a.	n.a.	n.a.
Sr	80	20	n.a.	n.a.	n.a.
Y	70	60	n.a.	n.a.	n.a.
Zr	260	310	n.a.	n.a.	n.a.
Nb	10	30	n.a.	n.a.	n.a.
Ba	390	210	n.a.	n.a.	n.a.
Au	n.a.	n.a.	80	70	100
Ag	n.a.	n.a.	40	<10	20
Cu	n.a.	n.a.	60	40	60
Zn	n.a.	n.a.	290	260	310
Co	n.a.	n.a.	20	30	20
Ni	n.a.	n.a.	470	370	180
den	2.38	2.34	2.41	2.44	2.34

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 3

	645-86	647-86	649-86
(wt%)			
SiO ₂	76.10	65.00	75.60
TiO ₂	0.24	0.55	0.24
Al ₂ O ₃	11.60	12.10	11.90
FeO	3.62	4.94	2.36
MnO	0.04	0.21	0.09
MgO	0.20	1.99	0.28
CaO	0.33	3.37	1.17
Na ₂ O	5.06	4.30	4.93
K ₂ O	1.43	1.46	1.57
P ₂ O ₅	0.03	0.17	0.03
LOI	0.85	5.39	2.00
Total	99.50	99.48	100.17
(ppm)			
Rb	50	50	60
Sr	40	120	40
Y	100	60	60
Zr	340	270	330
Nb	30	20	30
Ba	280	380	420
den	2.35	2.43	2.34

FeO: Total iron calculated as FeO

NEW VAUZE ANDESITE MEMBER, Waite Rhyolite Formation, flow unit 4

	61-85	63-85	380-86	543-86	545-86	572-86	617-86
(wt%)							
SiO ₂	53.50	54.30	49.90	54.00	79.30	53.20	53.80
TiO ₂	1.24	1.28	1.29	1.45	0.19	1.56	1.36
Al ₂ O ₃	13.60	13.47	14.10	13.00	9.12	14.40	15.30
FeO	6.65	5.35	11.16	10.98	2.55	11.07	8.78
MnO	0.12	0.16	0.22	0.29	0.07	0.31	0.19
MgO	4.24	3.25	5.52	5.82	0.59	5.47	4.39
CaO	5.04	7.00	4.77	5.63	3.06	4.98	4.23
Na ₂ O	4.58	4.20	4.16	4.63	2.69	4.20	5.21
K ₂ O	0.10	0.55	0.33	0.35	1.15	0.39	0.14
P ₂ O ₅	n.a.	n.a.	0.46	0.56	0.03	0.61	0.48
LOI	n.a.	n.a.	6.54	1.93	0.93	2.85	4.54
Total	89.07	89.56	98.45	98.64	99.68	99.04	98.42
(ppm)							
Rb	n.a.	n.a.	20	10	40	20	20
Sr	n.a.	n.a.	120	60	110	140	70
Y	n.a.	n.a.	20	30	70	30	40
Zr	n.a.	n.a.	80	90	240	90	110
Nb	n.a.	n.a.	20	20	20	30	10
Ba	n.a.	n.a.	150	170	330	190	140
Au	0.03	0.03	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	1.00	1.40	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	70	66	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	142	365	n.a.	n.a.	n.a.	n.a.	n.a.
Co	65	55	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	130	135	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.54	2.52	2.64	2.62	2.38	2.62	2.57

FeO: Total iron calculated as FeO

NEW VAUZE ANDESITE MEMBER, Waite Rhyolite Formation, flow unit 4

	625-86	627-86	646-86	648-86
(wt%)				
SiO ₂	52.70	49.70	68.00	50.90
TiO ₂	1.35	1.42	0.67	1.38
Al ₂ O ₃	14.70	14.00	12.20	13.20
FeO	9.18	12.69	5.43	9.90
MnO	0.22	0.37	0.17	0.32
MgO	4.29	7.05	2.58	4.82
CaO	5.44	6.03	2.10	5.01
Na ₂ O	4.92	2.85	4.82	3.82
K ₂ O	0.07	0.19	0.97	0.73
P ₂ O ₅	0.53	0.51	0.21	0.53
LOI	5.47	3.47	2.47	8.08
Total	98.87	98.28	99.62	98.69
(ppm)				
Rb	30	10	30	30
Sr	40	90	60	130
Y	30	40	50	40
Zr	70	110	250	70
Nb	30	20	30	10
Ba	90	130	350	220
Au	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.
den	2.59	2.69	2.43	2.61

FeO: Total iron calculated as FeO

NEW VAUZE ANDESITE MEMBER, Waite Rhyolite Formation, flow unit 4

572-86

(wt%)

SiO ₂	53.10
TiO ₂	1.53
Al ₂ O ₃	14.40
FeO	11.43
MnO	0.30
MgO	5.41
CaO	4.84
Na ₂ O	3.90
K ₂ O	0.33
P ₂ O ₅	0.61
LOI	2.80
Total	98.65

(ppm)

Rb	19
Sr	148
Y	59
Zr	132
Nb	n.a.
Ba	161

La	11
Ce	28
Nd	21
Sm	4.3
Eu	1.8
Gd	5.3
Dy	5.2
Yb	2.4
Th	0.8
Y	25
Hf	2

(La/Sm) _n	1.61
(La/Yb) _n	3.09
Eu/Eu*	1.17
La/Zr	0.08
Yb/Zr	0.02

Lab GSC

Eu* calculated by linear interpolation between chondrite-normalized Sm and Gd

WAITE RHYOLITE FORMATION, flow unit 5

	378-86	381-86	382-86
(wt%)			
SiO ₂	74.50	73.30	74.80
TiO ₂	0.29	0.18	0.22
Al ₂ O ₃	13.00	10.30	11.50
FeO	2.56	3.97	3.34
MnO	0.03	0.18	0.07
MgO	0.47	0.84	0.65
CaO	0.39	2.84	0.97
Na ₂ O	4.99	4.29	4.25
K ₂ O	2.49	0.98	2.61
P ₂ O ₅	0.04	0.03	0.03
LOI	1.08	3.08	1.31
Total	99.84	99.99	99.75

(ppm)			
Rb	80	50	50
Sr	10	80	40
Y	90	90	70
Zr	390	310	350
Nb	30	30	20
Ba	480	220	480
Au	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.

den	2.34	2.38	2.35
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FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 6

	65-85	384-86	385-86	618-86	620-86	593-86	594-86
(wt%)							
SiO ₂	76.20	77.30	70.40	70.00	75.50	73.50	70.20
TiO ₂	0.34	0.25	0.29	0.61	0.22	0.20	0.23
Al ₂ O ₃	11.07	11.40	14.30	12.20	11.40	10.60	13.50
FeO	3.45	1.36	4.08	4.54	3.16	3.41	3.46
MnO	0.06	0.04	0.06	0.09	0.08	0.09	0.09
MgO	0.60	0.26	1.40	1.96	0.71	0.54	0.94
CaO	1.06	0.67	0.23	1.83	1.25	5.11	3.84
Na ₂ O	4.20	4.78	4.31	5.53	1.22	0.73	1.83
K ₂ O	1.45	2.92	3.11	0.29	3.61	2.20	3.17
P ₂ O ₅	n.a.	0.04	0.04	0.19	0.03	0.03	0.03
LOI	n.a.	0.93	1.70	2.00	2.23	2.54	2.54
Total	98.43	99.95	99.92	99.24	99.41	98.95	99.83
(ppm)							
Rb	n.a.	70	80	20	170	110	140
Sr	n.a.	40	30	80	100	330	200
Y	n.a.	80	120	70	90	70	90
Zr	n.a.	340	480	260	360	350	370
Nb	n.a.	30	30	30	20	20	40
Ba	n.a.	590	550	170	720	330	540
Au	0.03	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	0.70	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	50	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	175	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	20	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	40	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.36	2.32	2.38	2.40	2.35	2.39	2.39

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 6

	626-86	18-87	19-87
(wt%)			
SiO ₂	70.10	74.00	79.90
TiO ₂	0.21	0.25	0.21
Al ₂ O ₃	10.50	13.00	10.30
FeO	4.54	3.86	1.89
MnO	0.13	0.06	0.05
MgO	1.31	0.54	0.20
CaO	3.51	0.65	0.75
Na ₂ O	1.47	3.45	4.60
K ₂ O	2.42	2.20	1.07
P ₂ O ₅	0.03	0.03	0.03
LOI	4.16	1.85	1.00
Total	98.38	99.89	100.00
(ppm)			
Rb	100	85	30
Sr	60	66	55
Y	70	96	72
Zr	340	389	298
Nb	20	36	28
Ba	350	382	422
Au	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.
den	2.41	2.36	2.32

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 6

	626-86	18-87	19-87	NED-17
(wt%)				
SiO ₂	70.10	74.00	79.90	74.90
TiO ₂	0.21	0.25	0.21	0.20
Al ₂ O ₃	10.50	13.00	10.30	10.20
FeO	4.54	3.86	1.89	2.80
MnO	0.13	0.06	0.05	0.09
MgO	1.31	0.54	0.20	0.65
CaO	3.51	0.65	0.75	3.06
Na ₂ O	1.47	3.45	4.60	0.75
K ₂ O	2.42	2.20	1.07	2.90
P ₂ O ₅	0.03	0.03	0.03	0.03
LOI	4.16	1.85	1.00	3.85
Total	98.38	99.89	100.00	99.43
(ppm)				
Rb	100	85	30	n.a.
Sr	60	66	55	n.a.
Y	70	96	72	n.a.
Zr	340	389	298	n.a.
Nb	20	36	28	n.a.
Ba	350	382	422	n.a.
Au	n.a.	n.a.	n.a.	80
Ag	n.a.	n.a.	n.a.	20
Cu	n.a.	n.a.	n.a.	70
Zn	n.a.	n.a.	n.a.	330
Co	n.a.	n.a.	n.a.	<10
Ni	n.a.	n.a.	n.a.	400
den	2.41	2.36	2.32	2.36

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 7

	621-86	622-86	634-86	637-86	638-86	NED-16
(wt%)						
SiO ₂	68.10	75.30	74.90	75.50	76.00	73.30
TiO ₂	0.40	0.20	0.28	0.27	0.23	0.25
Al ₂ O ₃	16.10	7.64	11.30	10.80	9.42	10.20
FeO	4.38	3.28	3.07	2.75	4.99	3.43
MnO	0.07	0.18	0.07	0.08	0.13	0.13
MgO	0.62	0.33	0.30	0.25	1.42	1.36
CaO	1.08	4.84	1.30	1.14	1.16	2.82
Na ₂ O	2.99	0.68	5.15	5.39	1.93	1.31
K ₂ O	3.36	1.83	2.05	1.70	1.87	2.48
P ₂ O ₅	0.04	0.03	0.04	0.03	0.03	0.03
LOI	2.70	5.00	1.39	1.00	2.31	3.77
Total	99.84	99.31	99.85	98.91	99.49	99.08
(ppm)						
Rb	130	60	40	30	70	n.a.
Sr	30	90	30	20	10	n.a.
Y	50	60	60	70	60	n.a.
Zr	460	200	300	290	240	n.a.
Nb	30	10	30	20	30	n.a.
Ba	380	190	440	390	400	n.a.
Au	n.a.	n.a.	n.a.	n.a.	n.a.	90
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	50
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	30
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	250
Co	n.a.	n.a.	n.a.	n.a.	n.a.	20
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	340
den	2.39	2.38	2.35	2.34	2.38	2.38

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 8

	28-84	30-84	4-85	21-85	22-85	23-85	25-85
(wt%)							
SiO ₂	76.30	80.60	73.10	71.10	73.30	75.40	82.10
TiO ₂	0.39	0.37	0.40	0.51	0.41	0.45	0.37
Al ₂ O ₃	11.60	8.81	10.67	13.08	10.08	10.96	8.60
FeO	2.40	2.05	4.25	2.80	2.70	3.00	2.00
MnO	0.05	0.06	0.06	0.08	0.08	0.06	0.03
MgO	0.13	0.17	0.60	0.70	0.36	0.50	0.53
CaO	0.84	1.50	3.08	0.95	4.31	1.40	0.90
Na ₂ O	5.72	3.60	2.21	4.20	3.07	2.26	3.34
K ₂ O	0.45	1.30	1.21	2.14	2.34	4.29	0.70
P ₂ O ₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	97.88	98.46	95.58	95.55	96.64	98.32	98.57
(ppm)							
Au	n.a.	n.a.	0.03	0.03	0.03	0.03	0.03
Ag	n.a.	n.a.	0.03	0.70	0.70	0.70	0.30
Cu	n.a.	n.a.	60	56	220	60	51
Zn	n.a.	n.a.	228	187	136	235	125
Co	n.a.	n.a.	25	15	20	15	15
Ni	n.a.	n.a.	40	25	30	35	25
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.34	2.33	2.39	2.36	2.37	2.35	2.32

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 8

	27-85	28-85	29-85	30-85	31-85	33-85	35-85
(wt%)							
SiO ₂	71.70	72.80	75.70	83.10	82.00	77.60	75.80
TiO ₂	0.40	0.40	0.45	0.34	0.36	0.35	0.34
Al ₂ O ₃	9.94	10.74	12.31	7.97	9.33	9.67	9.56
FeO	3.65	3.00	2.55	1.75	1.90	2.70	2.75
MnO	0.07	0.08	0.03	0.03	0.05	0.08	0.10
MgO	0.60	0.60	0.30	0.13	0.10	0.10	0.13
CaO	3.70	3.58	0.39	0.59	0.84	2.02	3.98
Na ₂ O	3.07	1.89	0.22	3.02	1.13	2.43	2.26
K ₂ O	1.06	1.88	6.60	1.11	2.17	1.49	1.57
P ₂ O ₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	94.19	94.97	98.55	98.04	97.88	96.44	96.49
(ppm)							
Au	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Ag	0.70	0.70	0.30	0.30	0.30	0.30	0.70
Cu	50	58	71	50	40	38	32
Zn	120	165	138	110	154	250	160
Co	25	25	15	10	10	20	20
Ni	45	30	20	20	25	25	40
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.39	2.38	2.33	2.31	2.32	2.34	2.36

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 8

	36-85	329-86	334-86	335-86	338-86	339-86	356-86
(wt%)							
SiO ₂	76.90	73.80	73.20	73.20	71.90	75.00	74.00
TiO ₂	0.38	0.29	0.27	0.27	0.26	0.29	0.25
Al ₂ O ₃	10.80	12.40	11.80	10.40	11.20	12.10	12.40
FeO	2.90	3.51	4.25	5.78	4.18	2.94	3.66
MnO	0.06	0.05	0.07	0.12	0.09	0.07	0.04
MgO	0.30	0.50	1.58	1.25	0.83	0.38	0.51
CaO	1.34	1.16	1.85	1.87	2.15	1.25	1.17
Na ₂ O	3.13	5.79	3.14	2.86	4.50	5.19	5.12
K ₂ O	1.30	1.00	2.06	1.91	1.07	1.37	1.04
P ₂ O ₅	n.a.	0.04	0.04	0.03	0.03	0.04	0.03
LOI	n.a.	1.23	1.70	1.70	3.08	1.39	1.70
Total	97.11	99.77	99.96	99.39	99.29	100.02	99.92
(ppm)							
Au	0.03	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	0.70	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	47	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	183	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	15	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	30	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Rb	n.a.	30	80	70	50	50	40
Sr	n.a.	40	100	70	40	80	50
Y	n.a.	70	50	60	60	40	80
Zr	n.a.	330	310	300	290	320	330
Nb	n.a.	30	30	20	30	20	20
Ba	n.a.	290	190	340	250	380	270
den	2.35	2.36	2.39	2.40	2.38	2.35	2.36

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 8

	455-86	515-86	565-86	570-86	582-86	588-86	590-86
(wt%)							
SiO ₂	74.90	75.90	72.30	76.80	76.00	70.50	76.10
TiO ₂	0.21	0.23	0.27	0.25	0.26	0.23	0.26
Al ₂ O ₃	10.90	10.80	10.40	10.00	10.60	9.32	10.40
FeO	1.92	3.28	4.76	1.93	2.29	4.99	2.39
MnO	0.09	0.07	0.17	0.08	0.07	0.16	0.11
MgO	0.15	1.21	0.11	0.10	0.31	0.36	0.26
CaO	2.30	1.61	3.47	2.19	2.69	5.27	2.48
Na ₂ O	4.88	3.80	1.65	4.82	1.07	1.02	4.46
K ₂ O	2.14	1.30	2.11	0.80	2.91	2.08	0.99
P ₂ O ₅	0.03	0.03	0.04	0.04	0.03	0.03	0.03
LOI	2.23	1.16	4.31	2.70	3.47	5.77	2.47
Total	99.75	99.39	99.59	99.71	99.70	99.73	99.95
(ppm)							
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Rb	50	50	80	30	90	80	50
Sr	60	90	130	120	50	70	90
Y	80	70	70	60	60	50	50
Zr	290	290	280	250	270	230	270
Nb	20	30	30	20	20	20	20
Ba	400	340	360	240	340	300	190
den	2.34	2.36	2.40	2.33	2.35	2.42	2.35

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 8

	628-86	635-86	640-86	650-86	651-86	653-86	654-86
(wt%)							
SiO ₂	72.30	73.40	74.00	72.90	75.00	73.80	76.00
TiO ₂	0.23	0.28	0.26	0.28	0.26	0.26	0.25
Al ₂ O ₃	10.10	12.20	10.80	11.60	10.40	10.10	9.97
FeO	4.09	3.93	3.88	3.05	3.44	4.54	2.92
MnO	0.14	0.04	0.12	0.15	0.11	0.06	0.08
MgO	0.39	0.47	0.40	0.33	0.47	0.23	0.45
CaO	3.99	0.20	1.96	2.60	2.34	3.20	2.30
Na ₂ O	0.83	0.17	0.51	6.28	3.88	2.15	4.72
K ₂ O	2.73	7.47	3.81	0.36	1.28	1.97	0.55
P ₂ O ₅	0.04	0.04	0.03	0.04	0.03	0.04	0.04
LOI	4.62	1.54	3.93	2.39	2.47	3.47	2.47
Total	99.46	99.74	99.70	99.98	99.68	99.82	99.75
(ppm)							
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Rb	120	200	170	20	40	80	10
Sr	130	<10	100	70	90	50	60
Y	70	90	60	70	50	50	60
Zr	250	310	280	310	290	290	260
Nb	10	20	10	30	10	20	30
Ba	300	1480	530	160	370	330	160
den	2.39	2.35	2.37	2.37	2.36	2.39	2.35

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 8

	656-86	657-86	658-86	658a-86	660-86	666-86	667-86
(wt%)							
SiO ₂	81.00	69.90	71.60	74.20	77.60	79.10	75.00
TiO ₂	0.23	0.30	0.29	0.32	0.21	0.21	0.24
Al ₂ O ₃	9.26	12.50	11.80	13.20	10.50	10.00	11.30
FeO	0.65	4.38	3.76	3.50	2.70	1.93	2.48
MnO	0.04	0.13	0.09	0.06	0.10	0.08	0.12
MgO	0.05	0.51	0.55	0.16	0.39	0.47	0.37
CaO	1.70	3.29	2.98	0.42	1.42	0.84	2.23
Na ₂ O	4.53	2.49	2.71	1.96	2.96	5.04	5.00
K ₂ O	0.88	2.34	2.17	2.80	2.13	1.00	1.58
P ₂ O ₅	0.03	0.03	0.04	0.04	0.03	0.03	0.03
LOI	1.47	4.08	3.54	2.00	1.85	0.77	1.47
Total	99.84	99.95	99.53	98.66	99.89	99.47	99.82
(ppm)							
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Rb	20	60	70	100	70	20	30
Sr	50	20	20	50	50	20	30
Y	30	70	70	60	60	70	70
Zr	220	320	320	340	290	280	310
Nb	30	40	20	20	20	20	30
Ba	180	300	340	460	470	400	410
den	2.31	2.40	2.38	2.36	2.34	2.32	2.35

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 8

	668-86	669-86	670-86
(wt%)			
SiO ₂	76.40	75.10	77.00
TiO ₂	0.23	0.24	0.23
Al ₂ O ₃	11.10	11.30	11.30
FeO	2.57	2.53	2.54
MnO	0.07	0.12	0.08
MgO	0.43	0.37	0.45
CaO	1.20	2.24	1.23
Na ₂ O	4.12	4.84	4.08
K ₂ O	2.64	1.49	2.58
P ₂ O ₅	0.03	0.03	0.03
LOI	0.70	1.62	0.54
Total	99.49	99.88	100.06
(ppm)			
Au	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.
Rb	90	40	80
Sr	60	30	60
Y	70	70	60
Zr	290	320	290
Nb	20	30	20
Ba	910	400	970
den	2.34	2.35	2.34

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 9

	642-86	643-86
(wt%)		
SiO ₂	68.20	73.80
TiO ₂	0.63	0.60
Al ₂ O ₃	12.40	12.90
FeO	4.18	1.31
MnO	0.11	0.05
MgO	0.85	0.10
CaO	3.79	1.80
Na ₂ O	4.41	6.94
K ₂ O	1.15	0.72
P ₂ O ₅	0.13	0.12
LOI	4.16	1.62
Total	100.01	99.96
(ppm)		
Rb	60	40
Sr	100	<10
Y	40	30
Zr	250	270
Nb	20	<10
Ba	310	280
den	2.41	2.34

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION, flow unit 10

	566-86	574-86	587-86	663-86	14-87	15-87	16-87
(wt%)							
SiO ₂	68.60	68.20	68.00	67.90	74.50	75.20	81.00
TiO ₂	0.64	0.62	0.60	0.70	0.29	0.28	0.25
Al ₂ O ₃	13.50	13.30	12.90	13.40	11.80	11.30	10.20
FeO	4.68	5.47	4.45	4.18	4.08	3.00	0.68
MnO	0.11	0.20	0.10	0.09	0.08	0.07	0.02
MgO	1.17	1.90	1.09	1.20	0.77	0.55	0.14
CaO	1.57	1.09	2.31	2.04	0.62	1.25	0.39
Na ₂ O	5.35	5.01	5.49	6.48	5.02	5.91	4.55
K ₂ O	1.16	1.10	1.03	0.88	1.76	0.42	2.39
P ₂ O ₅	0.14	0.13	0.13	0.16	0.04	0.03	0.03
LOI	2.85	1.77	3.39	2.39	0.85	1.62	0.31
Total	99.77	99.79	99.49	99.42	99.81	99.63	99.96
(ppm)							
Rb	30	10	60	30	30	16	42
Sr	90	50	100	60	<10	90	50
Y	50	60	50	40	58	51	53
Zr	290	300	280	260	312	266	226
Nb	20	30	20	20	16	19	19
Ba	430	420	300	290	388	112	355
den	2.40	2.43	2.40	2.40	2.36	2.35	2.30

FeO: Total iron calculated as FeO

WAITE RHYOLITE FORMATION

	316-86	317-86	339-86	382-86	386-86	387-86	442-86
(wt%)							
SiO ₂	76.70	71.70	75.50	75.30	82.80	72.80	76.20
TiO ₂	0.20	0.22	0.28	0.22	0.17	0.25	0.19
Al ₂ O ₃	10.50	11.50	11.80	11.20	8.50	12.50	9.70
FeO	3.69	4.50	2.97	3.42	1.08	4.68	1.89
MnO	0.05	0.15	0.06	0.05	0.03	0.06	0.12
MgO	0.25	0.79	0.36	0.62	0.04	1.38	0.17
CaO	1.14	2.64	1.11	0.86	0.77	0.21	2.56
Na ₂ O	3.60	4.50	4.60	3.70	4.40	2.60	1.90
K ₂ O	2.52	0.57	1.31	2.49	0.31	2.77	3.53
P ₂ O ₅	0.02	0.00	0.02	0.02	0.00	0.02	0.00
LOI	0.45	2.70	1.40	1.30	0.78	1.80	2.60
Total	99.12	99.27	99.41	99.18	98.88	99.07	98.86
(ppm)							
Rb	58	10	35	39	n.a.	54	89
Sr	93	74	103	61	65	52	70
Y	61	34	62	50	56	46	65
Zr	250	255	261	299	197	282	231
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	378	132	315	417	91	411	837
La	23	20	23	31	18	23	18
Ce	58	51	59	73	43	58	44
Nd	35	33	36	44	25	37	28
Sm	7.8	7.9	8.3	9.8	5.2	7.6	5.2
Eu	1.9	1.4	1.7	2.0	1.3	1.8	1.2
Gd	8.1	8.7	8.4	10.0	6.1	9.1	6.0
Dy	8.3	9.9	8.4	11.0	6.9	11.0	6.3
Yb	5.1	6.3	5.0	7.5	5.0	7.5	4.4
Th	2.6	2.6	3.0	3.6	2.0	3.0	2.3
Y	41	55	38	64	42	63	35
Hf	7	8	8	9	5	8	6
(La/Sm) _n	1.85	1.59	1.74	1.99	2.18	1.90	2.18
(La/Yb) _n	3.04	2.14	3.10	2.79	2.43	2.07	2.76
Eu/Eu*	0.74	0.51	0.63	0.65	0.69	0.67	0.66
La/Zr	0.09	0.08	0.09	0.10	0.09	0.08	0.08
Yb/Zr	0.02	0.03	0.02	0.03	0.03	0.03	0.02
Lab	GSC	GSC	GSC	GSC	GSC	GSC	GSC

Eu* calculated by linear interpolation between chondrite-normalized Sm and Gd.

WAITE RHYOLITE FORMATION

	443-86	455-86	542-8	566-86	579-86	594-86	604-86
(wt%)							
SiO ₂	81.20	75.70	72.80	69.10	72.40	70.10	74.40
TiO ₂	0.20	0.21	0.20	0.61	0.23	0.21	0.21
Al ₂ O ₃	9.90	10.70	10.30	12.80	12.30	13.10	11.30
FeO	1.08	1.89	8.55	4.71	4.23	3.60	3.87
MnO	0.04	0.07	0.15	0.09	0.10	0.08	0.08
MgO	0.05	0.23	1.77	1.22	0.74	0.99	0.72
CaO	0.50	2.05	0.29	1.50	1.35	3.63	1.16
Na ₂ O	4.80	4.20	2.30	4.89	4.70	1.60	4.70
K ₂ O	0.75	2.08	1.43	1.11	1.41	3.02	0.89
P ₂ O ₅	0.02	0.02	0.02	0.14	0.03	0.02	0.03
LOI	0.63	2.50	1.60	3.20	1.70	2.20	1.20
Total	99.17	99.65	99.41	99.37	99.19	98.55	98.56
(ppm)							
Rb	10	36	73	n.a.	33	116	57
Sr	66	49	57	n.a.	40	172	60
Y	30	53	52	n.a.	65	82	52
Zr	228	290	320	n.a.	319	387	303
Nb	n.a.	24	13	n.a.	31	35	25
Ba	189	311	294	320	264	482	267
La	18	30	20	21	25	28	22
Ce	44	70	48	46	59	72	53
Nd	27	41	28	26	37	46	33
Sm	5.4	8.2	5.7	5.8	7.9	9.5	6.8
Eu	1.4	1.8	1.1	1.4	2.1	2.3	1.6
Gd	6.9	8.9	7.2	6.7	9.4	12.0	8.2
Dy	8.2	9.1	9.0	7.0	11.0	14.0	9.1
Yb	5.8	6.0	5.8	4.4	6.5	8.7	5.5
Th	2.3	2.4	2.1	n.a.	2.8	4.0	2.8
Y	49	51	49	40	58	78	51
Hf	7	7	5	n.a.	8	8	8
(La/Sm) _n	2.10	2.30	2.21	2.28	1.99	1.85	2.04
(La/Yb) _n	2.09	3.37	2.33	3.22	2.59	2.17	2.70
Eu/Eu*	0.70	0.64	0.53	0.56	0.75	0.66	0.66
La/Zr	0.08	0.10	0.06	n.a.	0.08	0.07	0.07
Yb/Zr	0.03	0.02	0.02	n.a.	0.02	0.02	0.02
Lab	GSC	GSC	GSC	GSC	GSC	GSC	GSC

Eu* calculated by linear interpolation between chondrite-normalized Sm and Gd.

WAITE RHYOLITE FORMATION

	637-86	650-86	660-86	14-87	15-87
(wt%)					
SiO ₂	76.80	73.40	78.40	74.10	75.40
TiO ₂	0.26	0.27	0.20	0.27	0.25
Al ₂ O ₃	10.60	11.40	10.40	11.20	10.70
FeO	2.88	3.15	2.88	3.97	3.06
MnO	0.07	0.13	0.09	0.07	0.07
MgO	0.33	0.40	0.46	0.85	0.64
CaO	0.96	2.35	1.10	0.66	1.24
Na ₂ O	4.60	5.50	2.50	4.72	5.11
K ₂ O	1.58	0.31	2.03	1.78	0.40
P ₂ O ₅	0.03	0.03	0.02	0.06	0.05
LOI	1.00	2.30	1.90	1.30	1.90
Total	99.11	99.24	99.98	98.98	98.82
(ppm)					
Rb	65	42	50	n.a.	n.a.
Sr	53	70	47	n.a.	n.a.
Y	47	55	52	n.a.	n.a.
Zr	289	289	294	n.a.	n.a.
Nb	28	25	14	n.a.	n.a.
Ba	339	80	370	350	40
La	20	23	22	26	24
Ce	52	54	53	62	54
Nd	32	36	33	38	31
Sm	6.6	6.6	6.2	8.8	7.2
Eu	1.6	1.7	1.6	2.1	1.7
Gd	7.6	8.1	7.0	10.0	8.0
Dy	8.3	8.6	7.4	11.0	8.2
Yb	5.6	5.6	5.2	6.5	5.4
Th	2.7	2.7	2.2	n.a.	n.a.
Y	44	47	41	61	45
Hf	7	7	6	n.a.	n.a.
(La/Sm) _n	1.91	2.19	2.23	1.86	2.10
(La/Yb) _n	2.41	2.77	2.85	2.70	3.00
Eu/Eu*	0.69	0.71	0.75	0.51	0.52
La/Zr	0.07	0.08	0.07	n.a.	n.a.
Yb/Zr	0.02	0.02	0.18	n.a.	n.a.
Lab	GSC	GSC	GSC	GSC	GSC

Eu* calculated by linear interpolation between chondrite-normalized Sm and Gd.

AMULET ANDESITE FORMATION

	332-86	470-86	471-86	474-86	475-86	477-86	478-86
(wt%)							
SiO ₂	52.30	50.40	51.70	54.50	47.70	55.10	51.80
TiO ₂	0.99	1.08	0.77	0.97	1.62	0.97	1.16
Al ₂ O ₃	17.30	20.10	17.80	16.10	14.90	17.50	18.70
FeO	8.48	7.81	8.94	7.38	12.15	6.81	7.32
MnO	0.20	0.15	0.17	0.16	0.20	0.14	0.18
MgO	6.21	5.16	6.73	4.82	5.69	4.23	5.35
CaO	6.29	5.36	4.52	7.99	11.50	7.61	6.39
Na ₂ O	3.66	5.20	3.96	4.41	1.44	4.73	4.93
K ₂ O	0.85	0.69	0.91	0.21	0.17	0.17	0.27
P ₂ O ₅	0.18	0.12	0.11	0.14	0.22	0.15	0.19
LOI	2.62	3.16	3.70	2.39	2.93	2.23	3.00
Total	99.80	99.23	99.31	99.07	98.52	99.64	99.29
(ppm)							
Rb	50	40	20	30	40	10	10
Sr	220	100	90	160	260	130	160
Y	20	10	<10	10	30	30	20
Zr	150	90	50	90	30	110	110
Nb	20	20	20	30	20	10	20
Ba	230	210	480	150	110	110	180
den	2.60	2.58	2.60	2.57	2.73	2.56	2.58

FeO: Total iron calculated as FeO

AMULET ANDESITE FORMATION

	480-86	490-86	491-86	492-86	493-86	494-86	495-86
(wt%)							
SiO ₂	52.90	51.00	53.40	47.40	62.00	63.60	58.00
TiO ₂	1.48	0.84	0.82	0.87	0.96	0.93	1.10
Al ₂ O ₃	16.70	16.40	16.20	16.30	14.80	13.20	16.50
FeO	6.78	12.42	8.12	14.58	7.37	7.80	8.16
MnO	0.15	0.14	0.13	0.14	0.17	0.14	0.14
MgO	3.55	4.99	3.39	6.20	1.62	1.50	1.81
CaO	10.60	2.13	3.96	2.15	4.42	6.11	5.88
Na ₂ O	3.11	1.79	2.23	1.90	5.13	2.82	5.12
K ₂ O	0.29	5.35	5.80	4.96	0.75	0.94	0.37
P ₂ O ₅	0.33	0.13	0.11	0.09	0.34	0.34	0.40
LOI	2.70	3.23	4.00	3.62	1.77	1.70	1.93
Total	98.59	98.42	98.16	98.21	99.33	99.06	99.41
(ppm)							
Rb	30	190	170	180	10	20	20
Sr	320	90	90	90	140	130	160
Y	20	<10	<10	20	40	20	60
Zr	130	90	90	80	180	180	240
Nb	10	20	20	20	20	30	20
Ba	200	340	290	840	200	390	150
den	2.59	2.60	2.53	2.67	2.49	2.51	2.53

FeO: Total iron calculated as FeO

AMULET ANDESITE FORMATION

	496-86	502-86	503b-86	504-86	505-86	506-86	507-86
(wt%)							
SiO ₂	55.20	53.50	58.40	55.90	51.20	55.50	50.90
TiO ₂	1.15	1.31	0.53	1.32	1.44	1.10	1.23
Al ₂ O ₃	17.20	16.10	15.20	14.10	15.80	17.50	17.30
FeO	8.90	6.60	6.58	7.51	8.84	5.93	7.83
MnO	0.14	0.50	0.43	0.99	0.92	0.40	0.34
MgO	3.63	4.21	4.56	4.85	5.80	2.64	4.06
CaO	2.46	8.30	4.04	5.58	5.19	7.93	8.84
Na ₂ O	4.75	3.72	5.45	5.02	4.36	4.16	3.31
K ₂ O	2.13	2.27	1.89	0.25	0.96	0.61	0.65
P ₂ O ₅	0.48	0.18	0.08	0.17	0.18	0.19	0.23
LOI	2.85	2.39	1.77	2.54	3.00	3.00	4.54
Total	98.89	99.08	98.93	98.23	97.69	98.96	99.23
(ppm)							
Rb	50	60	40	20	40	30	40
Sr	80	100	60	60	90	340	250
Y	50	10	10	<10	30	20	20
Zr	240	70	70	90	80	100	90
Nb	20	20	30	10	20	20	20
Ba	570	930	910	200	630	260	230
den	2.54	2.56	2.50	2.56	2.61	2.54	2.60

FeO: Total iron calculated as FeO

505-86

(wt%)

SiO ₂	52.10
TiO ₂	1.43
Al ₂ O ₃	15.80
FeO	9.36
MnO	0.92
MgO	5.82
CaO	5.15
Na ₂ O	4.20
K ₂ O	0.88
P ₂ O ₅	0.19
LOI	2.70
Total	98.55

(ppm)

Rb	52
Sr	112
Y	62
Zr	134
Nb	n.a.
Ba	632

La	9
Ce	23
Nd	16
Sm	3.3
Eu	1.2
Gd	4.1
Dy	4.4
Yb	2.2
Th	0.7
Y	22
Hf	2

(La/Sm) _n	1.70
(La/Yb) _n	2.73
Eu/Eu*	0.99
La/Zr	0.07
Yb/Zr	0.02

Lab GSC

Eu* calculated by linear interpolation between chondrite-normalized Sm and Gd

NEWBEC ANDESITE FORMATION

	5-84	6-84	7-84	8-84	9-84	10-84	12-84
(wt%)							
SiO ₂	56.20	56.90	54.90	61.20	55.40	58.70	54.20
TiO ₂	1.16	1.03	0.89	0.94	0.65	1.27	1.42
Al ₂ O ₃	14.15	17.98	17.16	16.99	16.63	13.99	14.93
FeO	6.55	5.68	5.34	5.29	6.74	7.49	7.90
MnO	0.09	0.13	0.19	0.14	0.11	0.17	0.19
MgO	5.42	3.03	2.02	2.76	5.41	5.89	5.66
CaO	3.14	6.33	10.75	6.44	5.32	3.75	4.87
Na ₂ O	3.18	4.26	3.02	4.37	4.64	4.64	5.12
K ₂ O	0.88	0.59	0.59	0.58	0.45	0.13	0.60
P ₂ O ₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	90.77	95.93	94.86	98.71	95.35	96.03	94.89
(ppm)							
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.52	2.52	2.54	2.49	2.54	2.54	2.56

FeO: Total iron calculated as FeO

NEWBEC ANDESITE FORMATION

	13-84	15-84	1-85	3-85	6-85	7-85	8-85
(wt%)							
SiO ₂	59.50	57.40	53.20	48.60	61.60	48.10	53.90
TiO ₂	1.57	0.96	0.78	1.30	1.25	1.39	1.23
Al ₂ O ₃	11.95	18.39	18.74	17.97	12.98	17.19	15.92
FeO	11.84	6.07	4.50	5.90	4.55	4.80	2.60
MnO	0.20	0.10	0.05	0.10	0.06	0.07	0.06
MgO	3.66	4.84	4.91	5.37	3.65	5.90	5.30
CaO	8.96	4.65	2.60	4.37	5.60	5.99	4.54
Na ₂ O	0.16	3.24	5.55	4.69	4.47	3.56	3.93
K ₂ O	0.02	1.68	0.31	0.36	0.19	0.63	2.65
P ₂ O ₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	97.86	97.33	90.64	88.66	94.25	87.63	90.13
(ppm)							
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Au	n.a.	n.a.	0.03	0.03	0.03	0.03	0.03
Ag	n.a.	n.a.	1.00	1.00	0.70	1.00	0.70
Cu	n.a.	n.a.	245	147	140	168	190
Zn	n.a.	n.a.	620	273	1060	350	175
Co	n.a.	n.a.	45	65	40	45	20
Ni	n.a.	n.a.	120	150	75	110	40
den	2.64	2.52	2.49	2.55	2.48	2.56	2.47

FeO: Total iron calculated as FeO

NEWBEC ANDESITE FORMATION

	9-85	10-85	11-85	14-85	15-85	18-85	24-85
(wt%)							
SiO ₂	59.90	53.00	49.60	60.10	58.10	54.30	51.70
TiO ₂	1.21	1.29	1.53	1.38	1.51	1.66	1.19
Al ₂ O ₃	13.39	15.12	16.20	14.66	14.64	16.86	15.06
FeO	4.60	5.70	6.70	5.55	6.40	3.55	5.35
MnO	0.07	0.08	0.14	0.10	0.11	0.09	0.07
MgO	3.58	4.71	4.64	1.72	3.05	4.18	5.97
CaO	7.84	5.74	6.16	4.70	4.98	4.59	2.49
Na ₂ O	2.53	3.72	3.40	3.23	3.18	3.67	2.32
K ₂ O	0.14	0.07	0.14	1.21	0.12	2.65	4.92
P ₂ O ₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	93.26	89.43	88.51	92.65	92.09	91.55	89.07
(ppm)							
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Au	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Ag	0.70	1.00	1.00	1.00	1.00	0.70	0.70
Cu	115	90	75	51	67	57	23
Zn	234	250	203	135	140	110	133
Co	50	55	65	40	50	40	55
Ni	75	80	140	75	70	75	135
den	2.51	2.54	2.58	2.48	2.52	2.48	2.50

FeO: Total iron calculated as FeO

NEWBEC ANDESITE FORMATION

	419-86	420-86	421-86	423-86	427-86	428-86	429-86
(wt%)							
SiO ₂	57.80	59.80	57.90	48.50	58.90	58.60	55.00
TiO ₂	0.84	0.88	0.79	1.35	1.26	1.11	1.29
Al ₂ O ₃	17.70	16.60	16.20	15.50	14.10	13.50	15.30
FeO	3.64	4.37	4.37	11.61	5.00	5.22	8.22
MnO	0.12	0.14	0.14	0.26	0.14	0.11	0.09
MgO	2.81	2.93	2.28	7.20	3.62	4.66	6.79
CaO	9.55	5.30	9.63	5.89	7.72	7.00	5.49
Na ₂ O	3.79	5.47	3.59	4.02	4.54	4.44	3.45
K ₂ O	0.09	0.45	0.15	0.22	0.14	0.25	0.17
P ₂ O ₅	0.11	0.11	0.11	0.15	0.16	0.14	0.19
LOI	2.85	3.31	4.31	3.23	3.08	3.62	3.23
Total	99.30	99.36	99.47	97.93	98.66	98.65	99.22
(ppm)							
Rb	10	40	10	20	10	10	20
Sr	80	250	140	50	160	80	110
Y	10	10	30	10	20	20	10
Zr	50	50	60	60	50	60	70
Nb	10	10	<10	20	20	30	20
Ba	80	200	80	110	130	120	110
Au	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.51	2.47	2.51	2.67	2.51	2.51	2.59

FeO: Total iron calculated as FeO

NEWBEC ANDESITE FORMATION

	430-86	431-86	432-86	433-86	434-86
(wt%)					
SiO ₂	53.80	51.40	55.40	54.80	54.50
TiO ₂	1.48	1.39	0.82	0.87	0.62
Al ₂ O ₃	16.20	14.40	17.50	18.00	16.20
FeO	7.09	10.26	5.87	7.30	7.57
MnO	0.23	0.24	0.07	0.12	0.17
MgO	6.91	6.61	5.11	4.98	6.11
CaO	3.67	7.63	7.56	2.95	8.94
Na ₂ O	5.25	3.33	2.82	3.19	1.84
K ₂ O	1.27	0.36	0.36	3.02	0.34
P ₂ O ₅	0.18	0.17	0.13	0.12	0.09
LOI	2.77	2.62	3.47	3.93	2.85
Total	98.85	98.41	99.11	99.28	99.23
(ppm)					
Rb	40	10	20	90	10
Sr	70	50	180	70	430
Y	20	30	20	20	20
Zr	70	80	60	70	70
Nb	20	10	30	10	10
Ba	550	180	120	740	130
Au	n.a.	n.a.	n.a.	n.a.	n.a.
Ag	n.a.	n.a.	n.a.	n.a.	n.a.
Cu	n.a.	n.a.	n.a.	n.a.	n.a.
Zn	n.a.	n.a.	n.a.	n.a.	n.a.
Co	n.a.	n.a.	n.a.	n.a.	n.a.
Ni	n.a.	n.a.	n.a.	n.a.	n.a.
den	2.55	2.65	2.55	2.53	2.60

FeO: Total iron calculated as FeO

	430-86
(wt%)	
SiO ₂	54.20
TiO ₂	1.46
Al ₂ O ₃	16.00
FeO	7.38
MnO	0.22
MgO	6.74
CaO	3.56
Na ₂ O	5.10
K ₂ O	1.21
P ₂ O ₅	0.17
LOI	2.60
Total	98.64

(ppm)	
Rb	n.a.
Sr	67
Y	n.a.
Zr	74
Nb	n.a.
Ba	479

La	9
Ce	21
Nd	15
Sm	3.5
Eu	1.3
Gd	3.9
Dy	4.0
Yb	1.9
Th	0.7
Y	19
Hf	2

(La/Sm) _n	1.56
(La/Yb) _n	3.09
Eu/Eu*	1.09
La/Zr	0.12
Yb/Zr	0.03

Lab	GSC
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Eu* calculated by interpolation between chondrite-normalized Sm and Gd

NEWBEC RHYOLITE FORMATION

	485-86	486-86
(wt%)		
SiO ₂	73.90	77.00
TiO ₂	0.21	0.17
Al ₂ O ₃	12.00	10.50
FeO	4.83	5.21
MnO	0.10	0.10
MgO	0.71	0.26
CaO	0.39	0.20
Na ₂ O	3.50	0.16
K ₂ O	1.95	3.16
P ₂ O ₅	0.03	0.03
LOI	2.00	2.70
Total	99.62	99.49
(ppm)		
Rb	60	90
Sr	<10	<10
Y	80	80
Zr	360	300
Nb	30	20
Ba	360	490
den	2.38	2.37

FeO: Total iron calculated as FeO

FISH ROE FORMATION

	2-84	3-84	414-86	416-86	425-86	484-86
(wt%)						
SiO₂	71.60	72.40	69.20	69.00	72.50	77.50
TiO₂	0.98	0.42	0.90	0.89	0.24	0.26
Al₂O₃	9.74	10.14	10.50	10.70	11.10	11.30
FeO	5.15	1.96	4.36	4.90	4.08	4.09
MnO	0.14	0.15	0.13	0.12	0.08	0.03
MgO	0.80	0.56	0.83	0.82	0.69	0.68
CaO	4.87	5.94	4.78	4.18	3.23	0.36
Na₂O	0.57	0.13	1.07	2.51	0.15	0.20
K₂O	2.46	3.28	2.47	1.81	3.27	2.98
P₂O₅	n.a.	n.a.	0.17	0.17	0.04	0.05
LOI	n.a.	n.a.	4.85	4.31	3.23	2.08
Total	96.31	94.98	99.26	99.41	98.61	99.53
(ppm)						
Rb	n.a.	n.a.	50	30	90	70
Sr	n.a.	n.a.	70	50	10	<10
Y	n.a.	n.a.	160	180	50	50
Zr	n.a.	n.a.	420	430	230	230
Nb	n.a.	n.a.	50	40	30	30
Ba	n.a.	n.a.	360	310	330	260
den	2.43	2.38	2.42	2.42	2.39	2.36

FeO: Total iron calculated as FeO

FISH ROE FORMATION

	416-86
(wt%)	
SiO ₂	69.20
TiO ₂	0.89
Al ₂ O ₃	10.40
FeO	4.86
MnO	0.11
MgO	0.80
CaO	3.94
Na ₂ O	2.20
K ₂ O	1.72
P ₂ O ₅	0.16
LOI	4.20
Total	98.48

(ppm)	
Rb	41
Sr	70
Y	143
Zr	357
Nb	17
Ba	232

La	31
Ce	85
Nd	63
Sm	16.0
Eu	3.0
Gd	19.0
Dy	21.0
Yb	13.0
Th	2.8
Y	110
Hf	11

(La/Sm) _n	1.22
(La/Yb) _n	1.61
Eu/Eu*	0.54
La/Zr	0.09
Yb/Zr	0.04

Eu* calculated by linear interpolation between chondrite-normalized Sm and Gd

D'ALEMBERT ANDESITE FORMATION

	408-86	410-86	412-86
(wt%)			
SiO ₂	56.20	57.10	51.90
TiO ₂	0.55	0.64	0.57
Al ₂ O ₃	13.60	14.70	17.10
FeO	5.87	5.82	7.13
MnO	0.17	0.12	0.10
MgO	5.08	6.50	6.09
CaO	14.00	5.79	3.65
Na ₂ O	0.20	4.93	4.59
K ₂ O	0.08	1.19	1.27
P ₂ O ₅	0.09	0.10	0.08
LOI	3.85	2.00	6.00
Total	99.69	98.89	98.48
(ppm)			
Rb	10	50	50
Sr	10	120	60
Y	10	<10	20
Zr	70	100	70
Nb	30	10	30
Ba	50	380	290
den	2.6	2.53	2.55

FeO: Total iron calculated as FeO

D'ALEMBERT ANDESITE FORMATION

410-86

(wt%)

SiO ₂	57.50
TiO ₂	0.64
Al ₂ O ₃	14.50
FeO	6.03
MnO	0.11
MgO	6.37
CaO	5.66
Na ₂ O	4.80
K ₂ O	1.12
P ₂ O ₅	0.08
LOI	1.70
Total	98.51

(ppm)

Rb	9
Sr	124
Y	n.a.
Zr	92
Nb	n.a.
Ba	335

La	12
Ce	28
Nd	16
Sm	2.9
Eu	0.7
Gd	3.5
Dy	3.7
Yb	1.8
Th	1.4
Y	18
Hf	2

(La/Sm) _n	2.60
(La/Yb) _n	4.50
Eu/Eu*	0.67
La/Zr	0.13
Yb/Zr	0.02

Lab GSC

Eu* calculated by linear interpolation between chondrite-normalized Sm and Gd

DIORITIC DYKES

	2-85	12-85	13-85	17-85	19-85	20-85	66-85
(wt%)							
SiO ₂	45.80	49.70	48.50	59.80	51.50	52.20	48.90
TiO ₂	0.97	0.94	0.97	1.03	1.20	1.23	1.17
Al ₂ O ₃	17.05	16.55	16.78	14.01	14.92	14.77	14.18
FeO	4.90	4.30	4.35	5.00	3.95	4.10	6.65
MnO	0.06	0.06	0.06	0.08	0.07	0.08	0.11
MgO	6.83	5.37	6.17	3.18	4.24	4.18	5.50
CaO	8.18	9.18	9.86	3.58	7.73	7.90	7.90
Na ₂ O	2.53	2.53	1.72	4.80	3.34	3.45	2.37
K ₂ O	0.36	0.05	0.39	0.27	0.65	0.63	0.10
P ₂ O ₅	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
LOI	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Total	86.68	88.68	88.8	91.75	87.6	88.54	86.88
(ppm)							
Rb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Sr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Y	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Zr	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Nb	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Ba	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.	n.a.
Au	0.03	0.03	0.03	0.03	0.03	0.03	0.07
Ag	0.70	0.70	1.00	0.70	0.70	1.00	1.00
Cu	178	58	108	31	50	54	154
Zn	312	185	141	163	122	107	152
Co	50	40	40	35	40	45	70
Ni	155	100	120	55	60	60	85
den	2.6	2.57	2.59	2.47	2.53	2.53	2.6

FeO: Total iron calculated as FeO

DIORITIC DYKES

	67-85	583-86	606-86
(wt%)			
SiO₂	54.60	45.60	53.70
TiO₂	1.67	1.10	1.22
Al₂O₃	11.90	14.90	14.50
FeO	11.10	10.80	9.27
MnO	0.13	0.25	0.15
MgO	3.12	4.70	5.50
CaO	4.59	8.06	4.74
Na₂O	3.40	1.12	3.71
K₂O	0.05	2.24	0.62
P₂O₅	n.a.	0.09	0.25
LOI	n.a.	10.10	5.47
Total	90.56	98.96	99.13
(ppm)			
Rb	n.a.	100	10
Sr	n.a.	140	70
Y	n.a.	20	80
Zr	n.a.	30	320
Nb	n.a.	10	20
Ba	n.a.	210	390
Au	0.03	n.a.	n.a.
Ag	1.40	n.a.	n.a.
Cu	95	n.a.	n.a.
Zn	136	n.a.	n.a.
Co	95	n.a.	n.a.
Ni	85	n.a.	n.a.
den	2.6	2.67	2.59

FeO: Total iron calculated as FeO

APPENDIX IV. METHOD OF CONSTRUCTION OF SPIDERGRAMS

**APPENDIX IV. METHOD OF CONSTRUCTION OF CHONDRITE-NORMALIZED
TRACE ELEMENT ABUNDANCE DIAGRAMS
(SPIDERGRAMS).**

Spidergrams are used to illustrate the content of lithophile and incompatible minor elements of igneous rocks. They can also be used to illustrate aspects of genesis and geochemical evolution of rocks.

The data are normalized to chondrite values (representative of undifferentiated earth composition) with the exception of K, Rb, and P. The normalization factors are listed in Table IV.1.

The order of the elements are after Sun (1980) and designed to give a smooth spidergram for average mid-ocean basalt (e.g. ENDV-86-BS). The elements are listed with increasing incompatibility from right to left.

The method of construction of spidergrams follows that of Thompson et al. (1983): The chondrite-normalized data were recalculated to make $(Yb)_n = 10$, using the following calculation:

Point on graph = [element content (in ppm)/its chondrite value] $\times 10 / (Yb/0.22)$

Oxides given in wt.% were recalculated to elemental values. This "over-simplification" minimized absolute differences in element abundance. Three elements (Ta, Tb, and Tm) were not shown on the spidergrams because they were not analysed.

Some elements such as Zr, Nb, Y, Hf, and Th have very low concentrations which approach the detection limits of the x-ray fluorescence technique. This analytical error is emphasized by the logarithmic scale of the diagrams, and may resulted in very irregular and rough spidergram patterns.

Table IV.1. Normalization factors used.

Ba	6.90	Nb	0.35	Nd	0.63	Hf	0.20
Rb	0.35	La	0.328	P	46	Ti	620
Th	0.042	Ce	0.865	Sm	0.203	Y	2.0
K	120	Sr	11.8	Zr	6.84	Yb	0.22

From Thompson et al. (1983).

APPENDIX V. MASS GAINS AND LOSSES

**APPENDIX V. MASS GAINS AND LOSSES (WT %) BETWEEN LEAST
ALTERED AND ALTERED VOLCANIC ROCKS**

Error in mass gains and losses.

Sources of error in calculation of mass gains and losses during alteration are 1) inhomogeneity in composition of altered and least altered volcanic rocks, 2) analytical errors including sample preparation (discussed in appendix I), 3) the choice of a protolith for the altered volcanic rocks, and 4) the choice of the position of the isocon. Volumes changes are affected by errors in determining rock density. Density was calculated with the help of a computer program assuming water-free basis at a pressure of 1 atm.

In using the graphical method of Grant (1986) to compute the alteration, a clustering of the ratios of individual elements in altered and least altered rocks usually occurs. In most cases, the best-fit isocon was chosen to intersect the Al_2O_3 point, and in some cases to lie between elements as Al_2O_3 and HFS that form a linear array through the origin. Preferentially, the choice of the isocon was base on species that are geochemically dissimilar. Taking into account the error on individual points in the diagrams, the position of the isocon may be traced anywhere within the envelope defined by the error bounds of the individual points. The error on the gains and

losses of individual components is probably around 20-25%. The error on component having a low detection limit and a small concentration is larger.

Least altered sample, # 579-86

Fig. V.1. Isocon diagram illustrating the graphical method of Grant (1986) to calculated mass and volume gains and losses during metasomatism. Major and trace elements in the least altered sample are plotted against the same component in the altered sample and each component is multiplied by the same factor. Major element oxides are in weight percent and trace elements are in ppm.

Table V.1. Mass gains and losses (wt%) between least altered and altered samples.

Sample #				
Altered	316	15	439	442
Least altered	579	579	579	579
SiO ₂	24.1	19.7	35.4	33.0
TiO ₂	1.9	24.9	11.2	5.0
Al ₂ O ₃	0	0	0	0
FeO	2.2	-16.8	-74.7	-43.0
MnO	-41.4	-19.5	-51.3	52.0
MgO	-60.4	-0.5	-98.4	-71.0
CaO	-1.1	5.6	-8.0	1434.0
Na ₂ O	-10.3	25.0	68.7	-49.0
K ₂ O	109.4	-67.4	-90.5	217.0
P ₂ O ₅	-21.9	91.6	21.8	100.0
Rb	105.9	-55.4	-63.0	242.0
Sr	172.4	234.5	21.8	122.0
Y	9.9	-28.9	-6.3	27.0
Zr	-8.2	-10.1	10.7	-8.0
Nb	b.d.	5.9	17.9	b.d.
Ba	67.7	-825.8	-40.0	302.0
Th	8.8	n.a.	n.a.	5.0
Hf	2.5	n.a.	n.a.	4.0
La	7.7	10.4	n.a.	-9.0
Ce	15.2	7.0	n.a.	-5.0
Nd	10.8	-3.7	n.a.	-4.0
Sm	15.7	4.8	n.a.	-17.0
Eu	6.0	-6.9	n.a.	-28.0
Gd	0.9	-2.2	n.a.	-19.0
Dy	-11.6	-14.3	n.a.	-27.0
Yb	-8.1	-4.5	n.a.	-14.0
V.vol.	18.6	16.4	25.0	29.0

Abbreviations: n.a. = not analyzed, V.vol. = variation of volume, b.d. = below detection limit, † = very large gain.

Table V.1. Cont.

Sample #				
Altered	637	650	446	666
Least altered	579	579	579	579
SiO ₂	23.1	9.4	15.0	39.0
TiO ₂	31.2	26.7	0.8	2.0
Al ₂ O ₃	0	0	0	0
FeO	-21.0	-20.0	-25.5	-39.0
MnO	-9.7	40.3	-10.4	-10.0
MgO	-48.3	-41.7	-58.1	-12.0
CaO	-17.5	87.8	-35.8	-30.0
Na ₂ O	13.6	26.3	-46.0	17.0
K ₂ O	30.0	-76.3	216.3	17.0
P ₂ O ₅	16.0	7.9	-17.8	0
Rb	128.6	37.3	447.8	-14.0
Sr	53.8	88.8	119.1	-14.0
Y	-16.1	-8.7	-17.8	11.0
Zr	5.1	-2.3	2.9	7.0
Nb	4.8	-13.0	64.3	25.0
Ba	49.0	-67.3	197.4	45.0
La	-7.2	-0.7	n.a.	n.a.
Ce	2.3	-1.2	n.a.	n.a.
Nd	0.3	5.0	n.a.	n.a.
Sm	-3.1	-9.9	n.a.	n.a.
Eu	-11.6	-12.6	n.a.	n.a.
Gd	-6.2	-7.0	n.a.	n.a.
Dy	-12.4	-15.6	n.a.	n.a.
Yb	-0.03	-7.0	n.a.	n.a.
V.vol.	18	8	11	23

Table V.1. Cont.

Sample #	362	19	36	442
Altered	534	579	579	534
Least altered				
SiO ₂	46.0	35.9	24.8	20.0
TiO ₂	11.5	2.8	77.3	0
Al ₂ O ₃	0	0	0	2.0
FeO	-57.0	-42.2	-15.4	-33.8
MnO	28.0	-44.4	-36.4	61.0
MgO	-13.0	-64.0	-48.5	-32.0
CaO	68.0	-39.6	-22.3	148.0
Na ₂ O	4.0	3.4	-32.9	-51.5
K ₂ O	11.5	-12.7	1.1	↑
P ₂ O ₅	n.a.	-8.3	n.a.	0
Rb	↑	-8.3	n.a.	↑
Sr	80.0	124.0	n.a.	0
Y	58.0	10.1	n.a.	0
Zr	-5.5	10.5	n.a.	-9.5
Nb	33.0	71.3	n.a.	16.5
Ba	↑	47.5	n.a.	↑
La	n.a.	n.a.	n.a.	n.a.
Ce	n.a.	n.a.	n.a.	n.a.
Nd	n.a.	n.a.	n.a.	n.a.
Sm	n.a.	n.a.	n.a.	n.a.
Eu	n.a.	n.a.	n.a.	n.a.
Gd	n.a.	n.a.	n.a.	n.a.
Dy	n.a.	n.a.	n.a.	n.a.
Yb	n.a.	n.a.	n.a.	n.a.
V.vol.	37	25	18	16

Table V.1. Cont.

Sample #				
Altered	439	15	661	317
Least altered	534	339	579	579
SiO ₂	21.0	10.1	27.7	5.9
TiO ₂	0	-1.5	4.8	2.3
Al ₂ O ₃	0	0	0	0
FeO	-72.5	13.6	21.3	13.8
MnO	-54.0	28.7	92.8	60.4
MgO	-100.0	96.0	-34.0	14.2
CaO	-15.0	23.2	172.5	109.2
Na ₂ O	39.0	22.5	-50.0	2.4
K ₂ O	98.5	-66.3	106.0	-56.8
P ₂ O ₅	0	175.7	-6.4	n.a.
Rb	-43.0	n.a.	149.5	-67.6
Sr	-28.5	n.a.	232.7	97.9
Y	-4.5	n.a.	9.2	-44.0
Zr	0	n.a.	-1.7	-14.5
Nb	69.0	n.a.	-37.6	n.a.
Ba	120.0	-86.0	39.0	-46.5
La	n.a.	15.1	n.a.	-1.4
Ce	n.a.	0.9	n.a.	-7.5
Nd	n.a.	-5.0	n.a.	-4.6
Sm	n.a.	-4.3	n.a.	7.0
Eu	n.a.	10.3	n.a.	-28.7
Gd	n.a.	5.0	n.a.	-1.0
Dy	n.a.	7.7	n.a.	-3.7
Yb	n.a.	19.1	n.a.	3.7
V.vol.	16	10	25	6

Table V.1. Cont.

Sample #				
Altered	14	660	660	387
Least altered	339	531	579	579
SiO ₂	3.4	14.5	28.1	-1.0
TiO ₂	1.6	-1.2	2.8	7.0
Al ₂ O ₃	0	-0	0	0
FeO	40.8	-21.8	-19.5	8.9
MnO	22.9	-2.2	6.4	-41.0
MgO	148.8	-24.3	-26.5	83.5
CaO	-37.4	-20.9	-3.6	-84.7
Na ₂ O	8.1	-40.8	-37.1	-45.6
K ₂ O	43.2	132.2	70.3	93.3
P ₂ O ₅	216.1	-27.6	-21.2	-34.4
Rb	n.a.	35.8	79.2	61.0
Sr	n.a.	70.2	39.0	27.9
Y	n.a.	-19.3	-5.4	-30.4
Zr	n.a.	6.4	9.0	-13.0
Nb	n.a.	-61.9	-46.6	b.d.
Ba	17.1	111.0	65.8	53.2
La	19.1	n.a.	4.1	-9.5
Ce	10.7	n.a.	6.2	-3.3
Nd	11.2	n.a.	5.5	-1.6
Sm	11.7	n.a.	-7.2	-5.3
Eu	30.1	n.a.	-9.9	-15.6
Gd	25.4	n.a.	-11.9	-4.7
Dy	38.0	n.a.	-20.4	-1.6
Yb	37.0	n.a.	-5.4	13.5
V.Vol.	5	10	20	-1.6

Table V.1. Cont.

Sample #			
Altered	642	440	14
Least altered	579	579	579
SiO ₂	-5.0	38.96	12.4
TiO ₂	150.0	2.2	28.9
Al ₂ O ₃	-1.0	0	0
FeO	4.5	14.3	3.0
MnO	0	71.1	-23.1
MgO	24.0	4.8	26.1
CaO	145.0	186.6	-46.0
Na ₂ O	-19.0	-80.0	10.3
K ₂ O	-24.5	149.2	38.6
P ₂ O ₅	†	0.8	120.0
Rb	49.0	n.a.	n.a.
Sr	†	n.a.	n.a.
Y	-51.0	n.a.	15.5
Zr	-24.5	n.a.	n.a.
Nb	0	n.a.	n.a.
Ba	-12.0	n.a.	45.6
La	n.a.	n.a.	14.2
Ce	n.a.	n.a.	15.4
Nd	n.a.	n.a.	12.8
Sm	n.a.	n.a.	22.3
Eu	n.a.	n.a.	9.8
Gd	n.a.	n.a.	16.8
Dy	n.a.	n.a.	9.8
Yb	n.a.	n.a.	9.8
V.vol.	0	30	10

Table V.1. Cont.

Sample #				
Altered	14	660	542	542
Least altered	566	339	579	531
SiO ₂	22.6	17.8	20.0	2.0
TiO ₂	-49.4	-18.95	3.8	0
Al ₂ O ₃	0	0	0	-5.8
FeO	-3.7	10.0	141.0	117.0
MnO	-11.1	70.2	79.0	0
MgO	-20.4	44.98	185.6	172.0
CaO	-50.0	12.4	-74.3	-69.0
Na ₂ O	10.3	-38.3	-41.6	-41.5
K ₂ O	83.3	75.8	21.1	65.0
P ₂ O ₅	-51.0	13.5	-20.4	0
Rb	n.a.	62.0	164.0	-21.5
Sr	n.a.	-48.2	70.0	-66.0
Y	n.a.	-4.8	-4.5	-9.8
Zr	n.a.	27.8	19.8	1.0
Nb	n.a.	b.d.	-49.9	5.0
Ba	25.0	33.3	33.0	96.5
La	41.5	8.5	-4.5	n.a.
Ce	54.0	1.9	-2.8	n.a.
Nd	67.0	4.0	-9.6	n.a.
Sm	73.4	-15.2	-24.4	n.a.
Eu	71.4	6.8	-37.4	n.a.
Gd	70.6	-5.4	-8.5	n.a.
Dy	79.6	-0.5	-2.3	n.a.
Yb	68.8	18.0	6.6	n.a.
V.vol.	16	14	16	6.5

Table V.1. Cont.

Sample #	594	594	594	620
Altered	382	339	579	579
Least altered				
SiO ₂	-20.4	-16.4	-9	16.1
TiO ₂	-18.4	-32.4	-17	-2.7
Al ₂ O ₃	0	0	-0.3	0
FeO	-10.0	9.2	-19.0	-12.7
MnO	36.8	20.1	-19.0	-19.6
MgO	36.5	147.7	23.5	15.4
CaO	261.0	194.6	152.0	-9.1
Na ₂ O	-63.0	-68.7	-68.0	-75.2
K ₂ O	3.7	107.0	101.0	166.0
P ₂ O ₅	-14.5	-9.9	-34.0	-17.1
Rb	154.0	198.0	230.0	369.7
Sr	141.0	50.4	303.7	268.4
Y	40.2	19.1	27.0	24.3
Zr	10.6	33.6	15.0	20.5
Nb	b.d.	b.d.	3.0	10.5
Ba	-1.2	37.8	72.0	127.0
La	-22.7	9.6	-5.0	n.a.
Ce	-15.7	9.9	34.0	n.a.
Nd	-10.6	15.1	5.0	n.a.
Sm	-17.12	3.1	15.0	n.a.
Eu	-1.7	21.8	17.5	n.a.
Gd	2.6	28.7	5.0	n.a.
Dy	8.8	50.1	0.8	n.a.
Yb	-0.8	56.7	19.5	n.a.
V.vol.	-16	-11	-6.5	12

Table V.1. Cont.

Sample #				
Altered	443	443	361	16
Least altered	579	534	534	579
SiO ₂	39.0	20.0	11.0	39.2
TiO ₂	3.0	0	0	23.5
Al ₂ O ₃	0	0	0	0
FeO	-68.0	-67.0	6.0	-79.0
MnO	-50.0	-45.0	1.0	-77.5
MgO	-91.6	-63.8	161.0	-74.6
CaO	-54.0	-50.6	-47.0	-68.3
Na ₂ O	26.9	14.0	-21.2	3.3
K ₂ O	-34.0	-19.5	32.5	96.8
P ₂ O ₅	-17.0	-17.0	0	-7.4
Rb	-62.0	123.0	†	29.7
Sr	105.0	-26.0	-44.0	105.8
Y	-43.0	50.0	32.0	-18.2
Zr	-11.0	-5.0	-8.0	-15.4
Nb	0	8.0	70.0	17.3
Ba	†	†	†	25.3
La	-10.5	n.a.	n.a.	n.a.
Ce	-7.0	n.a.	n.a.	n.a.
Nd	-9.0	n.a.	n.a.	n.a.
Sm	-15.0	n.a.	n.a.	n.a.
Eu	-17.0	n.a.	n.a.	n.a.
Gd	-9.0	n.a.	n.a.	n.a.
Dy	-7.0	n.a.	n.a.	n.a.
Yb	11.0	n.a.	n.a.	n.a.
V.vol.	28	14	13	28

Table V.1. Cont.

Sample #				
Altered	445	447	390	23
Least altered	579	579	579	579
SiO ₂	-28.7	-8.8	-8.5	20.6
TiO ₂	-4.3	-11.0	-1.0	106.9
Al ₂ O ₃	0	0	2.0	0
FeO	54.9	5.2	-7.0	-13.8
MnO	30.5	-24.2	-55.0	-37.3
MgO	23.1	-3.3	35.5	-15.5
CaO	-60.6	-49.0	-77.5	5.9
Na ₂ O	-49.9	-86.9	-98.0	-52.2
K ₂ O	78.6	252.1	89.2	288.8
P ₂ O ₅	-40.2	-30.5	-55.0	n.a.
Rb	378.5	641.0	565.0	n.a.
Sr	112.6	85.3	-70.0	n.a.
Y	-40.2	-30.5	-31.5	n.a.
Zr	3.9	-4.5	-1.0	n.a.
Nb	99.4	38.9	-9.0	n.a.
Ba	32.2	148.8	†	n.a.
La	n.a.	n.a.	n.a.	n.a.
Ce	n.a.	n.a.	n.a.	n.a.
Nd	n.a.	n.a.	n.a.	n.a.
Sm	n.a.	n.a.	n.a.	n.a.
Eu	n.a.	n.a.	n.a.	n.a.
Gd	n.a.	n.a.	n.a.	n.a.
Dy	n.a.	n.a.	n.a.	n.a.
Yb	n.a.	n.a.	n.a.	n.a.
V.vol.	-22	-7	-11	16

Table V.1. Cont.

Sample #				
Altered	455	455	566	455
Least altered	339	339	579	579
SiO ₂	10.6	11.0	-8.3	20.2
TiO ₂	-17.3	-19.0	154.9	4.9
Al ₂ O ₃	0	0	0	0
FeO	-29.8	-27.0	7.0	-48.6
MnO	28.7	42.5	-13.5	-19.5
MgO	-29.5	-56.0	58.4	-64.3
CaO	103.7	106.0	6.8	74.5
Na ₂ O	0.7	4.0	0	2.7
K ₂ O	75.1	75.0	-24.4	69.6
P ₂ O ₅	10.3	-19.0	348.0	-23.4
Rb	13.4	10.0	n.a.	25.4
Sr	-47.5	-12.0	n.a.	40.8
Y	-5.7	†	n.a.	-6.3
Zr	22.5	0	n.a.	4.5
Nb	b.d.	10.0	n.a.	-11.0
Ba	8.9	17.0	16.5	35.4
La	43.8	n.a.	-19.3	37.9
Ce	50.8	n.a.	-25.1	36.4
Nd	25.6	n.a.	-32.5	27.4
Sm	9.0	n.a.	-29.5	19.3
Eu	16.8	n.a.	-35.9	-1.5
Gd	16.8	n.a.	-31.5	8.8
Dy	19.5	n.a.	-38.8	-4.9
Yb	32.3	n.a.	-25.0	6.1
V.vol.	10.7	12	-4.7	17

Table V.1. Cont.

Sample #			
Altered	604	386	386
Least altered	579	579	604
SiO ₂	11.9	60.1	47.5
TiO ₂	-0.6	3.4	0
Al ₂ O ₃	0	-3.2	0
FeO	-0.4	-64.3	-64.5
MnO	-12.9	-58.0	-55.0
MgO	5.9	-92.4	-95.0
CaO	-6.5	-20.1	-9.5
Na ₂ O	8.8	31.1	24.0
K ₂ O	-31.3	-69.2	-55.5
P ₂ O ₅	8.8	0	-55.0
Rb	88.0	205.5	-100.0
Sr	63.3	127.5	41.0
Y	-12.9	24.9	47.5
Zr	3.4	-13.5	-13.5
Nb	-12.2	62.6	0
Ba	10.1	-51.7	-55.5
La	-4.2	0.8	-17.5
Ce	-2.2	2.0	-6.5
Nd	-2.9	-5.4	8.0
Sm	-6.3	-7.8	8.0
Eu	-17.1	-13.3	0
Gd	-5.1	-9.1	5.0
Dy	-10.0	-12.2	8.0
Yb	-7.9	7.7	0
V.vol.	9.7	40	36

Table V.1. Cont.

Sample #				
Altered	316	443	397	397
Least altered	317	442	579	394
SiO ₂	17.1	8.8	-4.4	53.1
TiO ₂	-0.4	7.4	114.0	-52.6
Al ₂ O ₃	0	0	0	-0.2
FeO	-0.1	-41.7	10.1	-41.8
MnO	-63.5	-66.0	-41.4	-55.9
MgO	-65.3	-70.0	129.5	-71.1
CaO	-52.0	-80.1	-46.5	-61.7
Na ₂ O	-12.4	157.8	-23.2	11.4
K ₂ O	384.0	-78.3	93.9	1466.0
P ₂ O ₅	b.d.	b.d.	225.4	-16.1
Rb	535.0	-88.5	154.4	b.d.
Sr	37.6	-3.8	26.9	118.1
Y	96.5	-5.3	-6.7	b.d.
Zr	7.4	-0.7	-31.8	164.6
Nb	b.d.	b.d.	b.d.	b.d.
Ba	214.0	-77.0	94.5	368.1
La	26.0	19.0	-45.3	26.5
Ce	24.6	-2.0	-40.4	41.0
Nd	16.2	-2.0	-34.0	72.7
Sm	0.08	-2.0	-39.5	98.5
Eu	48.6	-1.6	-44.2	76.2
Gd	2.0	5.9	-32.5	-10.2
Dy	-8.2	19.0	-31.7	3.4
Yb	-11.3	17.4	-15.9	198.9
V.vol.	9.5	2	3	17.5

Table V.1. Cont.

Sample #				
Altered	416	416	401	402
Least altered	579	382	394	394
SiO ₂	12.8	-1.0	70.8	-10.1
TiO ₂	356.6	335.0	-1.5	-2.4
Al ₂ O ₃	-0.2	0	0	0
FeO	35.6	53.9	-40.7	4.8
MnO	29.8	80.0	-73.6	-65.7
MgO	27.6	40.0	-71.4	-50.0
CaO	244.4	393.0	84.0	-5.2
Na ₂ O	-44.8	-35.0	38.9	21.9
K ₂ O	43.9	-26.7	302.7	-70.1
P ₂ O ₅	529.3	761.0	183.2	181.9
Rb	46.6	13.0	b.d.	b.d.
Sr	106.5	23.5	310.6	85.8
Y	159.6	208.0	b.d.	b.d.
Zr	32.1	28.5	66.8	60.4
Nb	-35.3	b.d.	b.d.	b.d.
Ba	3.7	-40.0	139.3	-34.8
La	46.3	7.6	11.8	10.4
Ce	70.0	26.5	27.7	28.6
Nd	100.9	54.0	55.5	47.7
Sm	138.9	74.0	77.7	85.6
Eu	68.6	61.5	114.7	135.5
Gd	138.5	104.6	98.2	100.5
Dy	125.3	106.0	100.1	99.9
Yb	136.0	86.7	80.2	63.1
V.vol.	19	8	42	-10

Table V.1. Cont.

Sample #			
Altered	309	222	114
Least altered	394	319	319
SiO ₂	35.0	7.0	-3.5
TiO ₂	-9.8	-10.9	-17.0
Al ₂ O ₃	1.5	0	0
FeO	-6.0	3.3	-31.2
MnO	-67.1	-8.9	-35.5
MgO	-79.7	-5.8	-47.2
CaO	41.9	32.6	-21.0
Na ₂ O	41.9	-1.8	-1.0
K ₂ O	-3.1	-72.5	-74.0
P ₂ O ₅	190.6	28.8	n.a.
Rb	n.a.	4.0	n.a.
Sr	251.0	43.1	n.a.
Y	n.a.	38.7	n.a.
Zr	80.3	32.4	n.a.
Nb	n.a.	4.0	n.a.
Ba	-18.7	-30.6	n.a.
La	30.4	n.a.	n.a.
Ce	46.6	n.a.	n.a.
Nd	72.8	n.a.	n.a.
Sm	137.7	n.a.	n.a.
Eu	182.5	n.a.	n.a.
Gd	139.3	n.a.	n.a.
Dy	142.1	n.a.	n.a.
Yb	126.0	n.a.	n.a.
V.vol.	17	4	-4

Table V.1. Cont.

Sample #				
Altered	251	371	370	349
Least altered	394	319	319	319
SiO ₂	33.5	12.0	1.2	59.5
TiO ₂	-0.1	-25.6	-27.2	-21.5
Al ₂ O ₃	2.1	-0.4	0	0
FeO	4.6	-25.7	8.8	-45.5
MnO	-65.3	-23.0	30.4	-37.0
MgO	-69.8	-63.2	-38.5	-71.4
CaO	72.8	54.4	56.3	26.4
Na ₂ O	39.3	6.7	-40.9	25.8
K ₂ O	93.9	64.7	358.8	96.4
P ₂ O ₅	159.3	92.0	84.5	116.0
Rb	-42.8	12.0	396.8	278.0
Sr	4004.0	124.0	61.5	215.0
Y	2188.0	124.0	-0.6	68.0
Zr	716.0	83.3	80.6	71.8
Nb	128.8	-44.0	98.7	26.0
Ba	-3.7	-12.9	170.5	82.0
La	n.a.	n.a.	n.a.	n.a.
Ce	n.a.	n.a.	n.a.	n.a.
Nd	n.a.	n.a.	n.a.	n.a.
Sm	n.a.	n.a.	n.a.	n.a.
Eu	n.a.	n.a.	n.a.	n.a.
Gd	n.a.	n.a.	n.a.	n.a.
Dy	n.a.	n.a.	n.a.	n.a.
Yb	n.a.	n.a.	n.a.	n.a.
V.vol.	19	16	1	34

Table V.1. Cont.

Sample #				
Altered	348	404	401	402
Least altered	319	319	319	319
SiO ₂	36.7	-21.6	65.7	-12.1
TiO ₂	-18.7	-9.0	-20.2	-20.6
Al ₂ O ₃	0	0.4	0	-1.4
FeO	-36.9	46.5	-33.1	15.2
MnO	-28.9	76.3	0.4	26.5
MgO	-63.5	15.3	-51.7	-18.6
CaO	30.4	-35.5	56.7	-20.5
Na ₂ O	27.5	-37.5	15.2	-5.2
K ₂ O	-39.6	226.5	159.9	-75.6
P ₂ O ₅	101.4	90.7	97.7	92.8
Rb	242.0	173.0	301.7	-81.6
Sr	171.0	-88.0	485.8	130.0
Y	52.0	51.6	-55.4	-8.0
Zr	97.1	131.6	82.6	92.4
Nb	14.1	36.5	33.9	38.0
Ba	11.2	208.4	115.7	-43.8
La	n.a.	n.a.	n.a.	n.a.
Ce	n.a.	n.a.	n.a.	n.a.
Nd	n.a.	n.a.	n.a.	n.a.
Sm	n.a.	n.a.	n.a.	n.a.
Eu	n.a.	n.a.	n.a.	n.a.
Gd				
* /P^Y3 . 8^]<				
^Dz[				
^A

INTRUSIVE ROCKS

20

Dioritic dyke

EXTRUSIVE FORMATIONS

Waite Andesite Formation

Upper member

WAu (b)

Andesite flow

WAu (a)

Massive and

Splinter member

WAs (c)

Rhyolite flow

WAs (b)

Siliceous lob

WAs (a)

Massive and

Lower member

WAI

Pillowed and

LITHOLOGY

V2 Rhyolite

V6 Andesite

INTRUSIVE ROCKS

2D

Dioritic dyke

EXTRUSIVE FORMATIONS

Waite Andesite Formation

Upper member

WAu (b)

Andesite flow breccia

WAu (a)

Massive andesite

Splinter member

WAs (c)

Rhyolite flow breccia

WAs (b)

Siliceous lobes in flow-banded rhyolite

WAs (a)

Massive and flow-banded rhyolite

Lower member

WAI

Pillowed andesite

LITHOLOGY

V2 Rhyolite

V6 Andesite

INTRUSIVE ROCKS

2D Dioritic dyke

2R Rhyolitic dyke

EXTRUSIVE FORMATIONS

Waite Rhyolite Formation

WR (d) Feldspar phyric rhyolite

WR (c) Quartz-feldspar phyric rhyolite
flow breccia with andesitic fragments

WR (b) Quartz-feldspar phyric rhyolite

WR (a) Feldspar phyric rhyolite

New Vauze Andesite member

WRnv (c) Andesite flow breccia

WRnv (b) Pillowed andesite

WRnv (a) Andesite flow breccia

LITHOLOGY

V2 Rhyolite

V6 Andesite

SYMBOLS

~FL Pillowed flow

Fbx Flow breccia

Fb Flow banding

QFP Quartz-feldspar phyric flow

FP Feldspar phyric flow

V2 FP (3-5%)
'a' (Qtz, Ep)
mass to Fb, Sil
Few Sil. lobes in Fb, Fbx

Sil. broken lobes
in Fb Fbx
Chl alt, loc Sil Fb

V2 Fbx, Fb FP
sil lapilli-sized frags
loc mottled Sil alt

V6 Fbx 'a'
Flow top bx
amoeb ribbon forms in
chloritized fragmental

- WRnv (b) Pillowed andesite
- WRnv (a) Andesite flow breccia

LITHOLOGY

- V2 Rhyolite
- V6 Andesite

SYMBOLS

- PFL Pillowed flow
- Fbx Flow breccia
- Fb Flow banding
- QFP Quartz-feldspar phryc flow
- FP Feldspar phryc flow
- Rhyolite lobe
- Flow breccia
- Outcrop
- Hydroline
- Sample number
- a / b Flow contact: a) defined, b) inferred
- a / b Facies contact: a) defined, b) inferred
- a / b Intrusive contact: a) defined, b) inferred
- a / b Fault: a) defined, b) inferred
- Strike and polarity of pillows

ABBREVIATIONS

"a"	Amygdular	Hem	Hematite
bx	Breccia	loc	Locally
Carb	Carbonates	mg	Medium-grained
Chl	Chlorite	ser	Sericite
Ep	Epidote	sil	Siliceous
fg	Fine-grained	Sil	Silicified
frags	Fragments	spher	Spherulitic

SYMBOLS

MFL	Massive flow
PFL	Pillow flow
Fbx	Flow breccia
Fb	Flow banding
FP	Feldspar phryic flow
●	Rhyolite lobe
▲	Flow breccia
○	Silicification
○	Outcrop
● 2-87	Sample number

a / b	Flow contact: a) defined, b) inferred
a / b	Facies contact: a) defined, b) inferred
a / b	Intrusive contact: a) defined, b) inferred
↖	Strike and polarity of pillows

ABBREVIATIONS

'a'	Amygdular	loc	Locally
alt	Alteration	mass	Massive
bx	Breccia	Qtz	Quartz
Chl	Chlorite	sil	Siliceous
Ep	Epidote	Sil.	Silicified
fg	Fine-grained	spher	Spherulitic
frags	Fragments

Fig.1.6

SPLINTER M
WAITE ANDESITE
NORANDA,

efined, b) inferred
defined, b) inferred
a) defined, b) inferred
of pillows

loc Locally
mass Massive
Qtz Quartz
sil Siliceous
Sil. Silicified
spher Spherulitic

Fig.1.6

SPLINTER MEMBER,
WAITE ANDESITE FORMATION,
NORANDA, QUEBEC.

SCALE 0 10 20 30 metres

S. PARADIS

March, 1989

Fig.1.4

SCALE

Fig.1.4

WAITE RHYOLITE FORMATION
NEW VAIZE AREA
NORANDA, QUEBEC

SCALE 0 10 20 30
metres

S. PARADIS
March, 1989

LEGEND

INTRUSIVE ROCKS

2R Rhyolitic dyke

EXTRUSIVE FORMATIONS

Waite Andesite Formation

Splinter member

WAs (c) Rhyolite flow breccia

WAs (b) Flow-banded rhyolite

WAs (a) Massive to flow-banded rhyolite

Lower member

WAI Pillowed andesite

"C" Contact Tuff

Tuffaceous exhalite

Amulet Formation, lower member

AI Rhyolite flow breccia

LITHOLOGY

V2 Rhyolite

V6 Andesite

Lower member

WAI

Pillowed andesite

"C" Contact Tuff

Tuffaceous exhalite

Amulet Formation, lower member

AI

Rhyolite flow breccia

LITHOLOGY

V2 Rhyolite

V6 Andesite

SYMBOLS

Fbx Flow breccia
 Fb Flow banding
 QP Quartz phytic flow
 ▲ Flow breccia
 ○ Silicification
 \ Outcrop
 ○ Drill hole
 --- Road
 • Sample number

a / b Formation contact: a) defined, b) inferred

a / b Flow contact: a) defined, b) inferred

a / b Facies contact: a) defined, b) inferred

a / b Intrusive contact: a) defined, b) inferred

a / b Bedding: a) inclined, b) vertical

ABBREVIATIONS

a'	Amygdular	mass	Massive
alt	Alteration	pill	Pillows
amoeb	Amoeboid	Py	Pyrite
bx	Breccia	Qtz	Quartz
Ccp	Chalcopyrite	Ser	Sericite
Chl	Chlorite	sil	Siliceous
cj	Columnar joints	Sil	Silicified
diss	Disseminated	spher	Spherulitic
frags	Fragments	Sul	Sulphides
hyalo	Hyaloclastite	tr	Traces
loc	Locally

Fig.1.5

SPLINTE

N

Fig.1.5

SPLINTER MEMBER, WAITE ANDESITE FORMATION
& "C" CONTACT TUFF
NEW VAUZE AREA, NORANDA, QUEBEC

0 10 20 30
SCALE metres

S. PARADIS
March, 1989

7

FOR INFORMATION ONLY
MicroD
MICROFILM TECHNOLOGY

D'ALEMBERT

D'ALEMBERT LAKE

NEW VAUZE - NORBEC AREA, NORANDA, QUEBEC

Fig.1.7. SAMPLE LOCATION MAP

Fig.1.7. SAMPLE LOCATION MAP

END

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FIN