**THE PARAGENETIC RELATIONSHIPS OF EPIDOTE-QUARTZ
HYDROTHERMAL ALTERATION WITHIN THE NORANDA VOLCANIC
COMPLEX, QUEBEC**

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the requirements for the degree of Doctor of Philosophy

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ABSTRACT

Epidote-quartz alteration is conspicuous throughout the central Noranda Volcanic Complex, but its relationship to the Volcanic-Hosted Massive Sulphide (VHMS) deposits is relatively unknown. A continuum of alteration textures exist that reflect epidote abundance as well as alteration intensity. The strongest epidote-quartz alteration phase is represented by small discrete “patches” of complete groundmass replacement that are concentrated in discrete zones. The largest and most intense zones are spatially contained in mafic volcanic eruptive centres, the Old Waite Paleofissure and the McDougall-Despina Eruptive Centre. Therefore, epidote-quartz alteration is regionally semi-conformable and is not restricted to the hangingwall or footwall of the VHMS deposits.

Epidote-quartz alteration is absent from the alteration pipes associated with sulphide mineralization. Early formed epidote-quartz alteration was confined to the eruptive centres, but became more widespread as mafic volcanism progressed and the hydrothermal system matured. Pervasive silicification was also produced as the system matured, but is overprinted by epidote developed during the latter stages of volcanism. Widespread epidote-quartz alteration also flourished during these latter stages along permeable conformable zones, such as the Rusty Ridge formation, deep in the volcanic sequence.

Large mass addition of Si, Al, Fe^{3+} , Ca, Mn, V, Cr, and Sr accompany depletion of Fe^{2+} , Mg, Na, K, Rb, Ba, and Zn in the epidote-quartz patches. Copper depletion is

erratic. Large enrichments in Mn, V, and Cr are related to the modal abundance of epidote versus quartz in the alteration patches and highlight the areas of strong alteration. Background alteration prior to epidotization sufficiently enriched hydrothermal fluids in whole-rock components that produced the alteration patches. Fluid:rock ratios of 75-100 correspond to the enrichment that produced the epidote-quartz alteration.

End-member epidote-clinozoisite compositions are prominent throughout the Noranda Cauldron, even at the micron-scale. At the patch-scale, iron-rich domains in epidote correspond to siliceous zones near the wallrock contact that reflect multiple episodes of hydrothermal alteration. At the cauldron-scale, Al-rich epidote is restricted to the eruptive centres where fluid circulation and temperatures are enhanced.

The metasomatic changes due to epidote-quartz alteration are related to high fluid fluxes and cannot be explained by metamorphic processes. Epidote in the Noranda Cauldron is similar to the patchy alteration described in ophiolites and may have formed at moderate fluid temperatures (220-300 °C). Epidote-quartz alteration zones in Noranda do not represent the extensive, high temperature (300-400 °C), metal depletion zones that characterize epidiosites deep in ophiolite sections. The Noranda Cauldron model closely corresponds to descriptions of epidote-quartz alteration in other VHMS districts.

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CHAPTER 1

INTRODUCTION

Purpose

The purpose of this study is to determine the spatial and genetic relationships of epidote-quartz hydrothermal alteration to Volcanic-Hosted Massive Sulphide (VHMS) mineralization in the Noranda Volcanic Complex, Quebec.

Scope

Hydrothermal alteration mineral assemblages associated with VHMS deposits in the Noranda Volcanic Complex (NVC) have been well documented by previous studies (e.g., Riverin and Hogdson, 1980; Parry and Hutchinson, 1981; Knuckey and Watkins, 1982; Galley et al., 1995). These assemblages are dominated by chlorite and sericite, or their metamorphic equivalents, and are generated by ore-forming hydrothermal fluids proximal to sulphide mineralization. Studies of the NVC stratigraphy have also included descriptions of more regionally developed alteration mineral assemblages (Gibson, 1979; Dimroth et al., 1982; Gibson, 1989; and Paradis, 1990), but only a few have considered the relationship of these alteration assemblages to sulphide mineralization (Gibson et al., 1983; Lesher et al., 1986).

Epidote-bearing assemblages are developed throughout the NVC, typically within mafic volcanic rocks. A distinct 'mottled textured' phase of semi-conformable epidote-quartz alteration was recognized within mafic volcanic flow units, but also locally concentrated in mafic flows proximal to some VHMS deposits, synvolcanic structures, and intrusions (Gibson et al., 1983, Gibson 1989; Gibson et al., 1993). In several other VHMS districts, semi-conformable alteration mineral assemblages are interpreted to be a product of regional hydrothermal fluid flow beyond the individual areas of sulphide mineralization (Iijima, 1974; MacGeehan, 1978; Osterberg et al., 1987; Vivallo, 1987; Galley, 1993; Skirrow and Franklin, 1994; Brauhart et al., 1998). Epidote-quartz assemblages as semi-conformable alteration have been commonly described in ophiolite-hosted VHMS districts (Richardson et al., 1987; Harper et al., 1988; Nehlig et al., 1994). Metasomatism associated with epidote-quartz alteration in ophiolites is intense and reflects locally concentrated hydrothermal fluid flow at high temperatures ($> 300\text{ }^{\circ}\text{C}$). These changes include metal depletion from the host mafic rocks deep within the ophiolite section, and thus epidote-quartz alteration has been interpreted to be genetically related to sulphide ore-forming hydrothermal systems.

This study combines field mapping and sampling with whole rock geochemistry and mineral chemistry to determine the paragenetic relationship of epidote-quartz alteration to the VHMS deposits in the NVC, particularly within the central part of the complex. Metasomatism by epidote-quartz alteration is quantified to predict the extent of exchange between hydrothermal fluids and the volcanic wallrocks. This study ultimately

presents a model for epidote-quartz alteration in the NVC with respect to the existing models of sulphide mineralization, semi-conformable alteration, and regional hydrothermal fluid flow. This new model emphasizes the scale and duration of hydrothermal fluid circulation required to generate the distribution of epidote-quartz alteration in the NVC. The new model also incorporates the general characteristics of epidote-quartz alteration in ophiolites and active seafloor hydrothermal settings to approximate the physical and chemical parameters of hydrothermal fluids associated with epidote-quartz alteration.

The geologic setting of the NVC, described in Chapter 2, provides a stratigraphic framework for this study and defines the relationships of several alteration mineral assemblages to the VHMS deposits. Chapter 3 describes the methodology and approach for this study. Regional alteration mineral assemblages are described in Chapter 4. Their spatial distribution within the NVC is considered in order to identify paragenetic relationships to volcanic stratigraphy as well as the relationships between the different alteration mineral assemblages. Field criteria to determine the intensity of epidote-quartz alteration are also presented in this chapter. Chapter 5 provides a detailed description in five different areas within the central NVC of the relationships between epidote-quartz alteration and: a) volcanic stratigraphy, b) lithology, c) silicification and d) chloritic alteration and VHMS deposits. Whole-rock geochemical changes associated with epidote-quartz alteration are calculated in Chapter 6 and demonstrate the scale of mass enrichment and depletion related to this alteration. In Chapter 7, compositional variations

in epidote at the microscopic scale are examined with respect to volcanic textures, lithology and volcanic stratigraphy. In Chapter 8, a model for the distribution of epidote-quartz alteration is presented in relation to the development of the volcanic succession in the central NVC. The whole-rock geochemistry and mineral chemistry data are combined with the alteration mineral paragenesis to illustrate the metasomatic changes accompanied by epidote-quartz alteration. Finally, a model of the hydrothermal system associated with epidote-quartz alteration in the central NVC is presented.

CHAPTER 2

GEOLOGIC SETTING

Volcanic Stratigraphy

The geology of the Noranda Volcanic Complex (NVC), Rouyn-Noranda, PQ has been under continuous study since the first discovery of massive sulphide mineralization at the Horne Mine in 1920. Numerous company maps of the different properties of the Noranda mining district were subsequently generated, and these provided the basis for the first integrated lithologic and stratigraphic maps of the area by Cooke et al. (1931), Wilson (1941), and Ambrose and Ferguson (1945). The first stratigraphic subdivision of the NVC to incorporate the massive sulphide deposits was proposed by Spence (1967) and later revised by Spence and de Rosen-Spence (1975). Subsequent mapping and research have been mainly directed at refining this stratigraphy and the volcanic reconstruction of the NVC.

The NVC is one of at least four distinct volcanic complexes within the Blake River Group of the Abitibi Greenstone Belt (Figure 2.1) (Dimroth et al., 1982; 1983). Each complex is considered a major volcanic centre recognizable by the concentration of felsic volcanic rocks (Goodwin, 1982). The NVC stratigraphy is subdivided into five distinct felsic volcanic zones separated by mafic volcanic units (Spence and de Rosen-Spence, 1975), which were later interpreted by Gibson (1989) as five mafic to felsic

volcanic cycles. Chemo-stratigraphic subdivision of the NVC also corresponds to this sub-division (Gelinas et al., 1982; Ludden et al., 1982). A lithologic compilation map has been generated for the central NVC during this study based on government mapping programs and university theses (Figure 2.2 and 1:25000 scale map in back pocket).

The most detailed work to resolve the NVC stratigraphy has concentrated on Cycle III, the “Mine Sequence”, and Cycle IV volcanic rocks which host most of the volcanogenic massive sulphide deposits in the Noranda area. Four distinct blocks of continuous volcanic stratigraphy of Cycle III and IV within the central NVC are separated by major faults (Spence, 1976). Interpretation that these faults are synvolcanic allowed for stratigraphic correlation between the blocks, but in some cases, the correlation is controversial due to the lack of distinctive marker units. The Cycle III volcanic rocks are a bimodal sequence of basalt-andesites and rhyolites in equal proportions (Gibson, 1989). The reconstruction of the Mine Sequence volcanic stratigraphy revealed distinct subsidence structures bound by synvolcanic faults and are considered as “cauldrons” (Gibson and Watkinson, 1990). The largest, the Noranda Cauldron, contains several eruptive centres which are identified by volcanic facies transitions and the locus of synvolcanic faults and dykes (Figure 2.3) (Gibson, 1989; Gibson and Watkinson, 1990; Setterfield et al., 1995). The Noranda Cauldron is structurally bound by the Hunter Creek Fault to the north and the Horne Creek Fault to the south. Synvolcanic faults and post-volcanic deformation have imposed a shallow dip on the Cycle III volcanic rocks exposing a west-facing stratigraphy.

Quartz-diorite dykes are widespread throughout the NVC. Many occupy shallow reverse faults and locally displace volcanic strata along previously developed subsidence structures. These dykes were once considered to be genetically related to massive sulphide mineralization by early workers; however, Cooke et al. (1931) and Wilson (1941) recognized the significance of the Flavrian-Powell Intrusion by similar granitoid compositions to the felsic volcanic rocks and suggested a volcanic origin for the massive sulphide deposits. Further investigation of the Flavrian-Powell Intrusion revealed its composite nature developed during synvolcanic intrusion into a cogenetic volcanic pile (Goldie, 1979; Paradis et al., 1988). The emplacement of the Flavrian-Powell Intrusion is also an important mechanism for regional hydrothermal fluid flow (Cathles, 1993). The Lac Dufault Granodiorite cross-cuts the entire NVC strata and post-dates massive sulphide mineralization in the area (Cooke et al., 1931; Spence and de Rosen-Spence, 1975). A hornfels-amphibolite metamorphic aureole is associated with this intrusion particularly along its western margin.

Volcanic-Hosted Massive Sulphide Mineralization

VHMS mineralization occurs throughout the NVC. Several deposits were discovered and mined prior to the interpretation of volcanic stratigraphy by Spence (1967), thus the designation of “Camps” was used by early workers to describe the distribution of the deposits (Figure 2.3). This designation is still useful, particularly in

areas where the interpretation of volcanic stratigraphy is contentious. The greatest concentration of deposits occurs in the Main Camp and most are correlated within the Mine Sequence at several stratigraphic intervals (Figure 2.4). Most of these deposits occur at major contacts between mafic and felsic volcanic rocks and are directly related to syn-volcanic structures cutting the volcanic strata (Gibson and Watkinson, 1990). These deposits range in size and shape as well as metal content with variable overall Cu-Zn-Au-Ag content (Gibson, 1989; Gibson and Watkinson, 1990). Deposits in East Camp are all felsic rock-hosted, in both the Cycle III and IV volcanic successions, and are particularly Zn-rich compared to the Main Camp deposits.

The largest VHMS deposit in the NVC, the Horne, lies within a separate fault block from the Mine Sequence. Stratigraphic correlation between the blocks has been subject of several studies and is still regarded as tenuous. The most recent published work places the Horne footwall volcanic section at a lower level in the Noranda volcanic sequence than the Mine Sequence, possibly in Cycle I or II, although the massive sulphides are interpreted to have formed over a time interval represented by the emplacement of the Mine Sequence (Kerr and Gibson, 1993). The volcanic rocks hosting the Aldermac deposit west of the Flavrian Intrusion are considered part of the Mine Sequence extending Cycle III volcanic rocks around the south margin of the Flavrian Intrusion (Hunter, 1979; Gibson, 1989). Across the Hunter Creek Fault, the lower and upper portions of the Mine Sequence are recognizable and are interpreted to have breached the north rim of the Noranda Cauldron (Spence, 1976; Camire, 1989; Gibson,

1989; Peloquin et al., 1989; and Paradis, 1990). The rocks are interpreted to extend northwest to Magusi River where they host the New Insko VMS deposits over 15 km away and outside of the central NVC (Gelinas et al., 1982; Dimroth et al., 1983).

Peloquin et al. (1990) also group these deposits within the Hunter Block.

Regional Hydrothermal Alteration and Metamorphism

Secondary mineral assemblages have been recognized throughout the Blake River Group volcanic rocks. These assemblages have been ascribed to both hydrothermal alteration as well as regional and contact metamorphism. The large-scale, regional distribution of these assemblages have been equated with syn-volcanic and syn-plutonic processes during the development of the Blake River Group sequence (Dimroth et al., 1983). Overall, the assemblages range from sub-greenschist to lower greenschist grades in the Blake River Group with locally elevated grades within the contact metamorphic aureole of some intrusions (Figure 2.5).

Sub-greenschist assemblages in the Blake River Group contain pumpellyite and prehnite typically as open-space precipitation in vesicles, cooling fractures and perlitic cracks although both minerals also occur as volcanic glass replacement. Textural evidence suggests that pumpellyite and prehnite have replaced precursor clay minerals, palagonite, and/or zeolites (Dimroth and Lichtblau, 1979). Locally, pumpellyite occurs with actinolite and is interpreted as a higher grade assemblage than the surrounding rocks (Powell et al., 1995). Around the Flavrian Intrusion, the metamorphic grade increases to greenschist facies with a predominance of chlorite in mafic rocks and sericite in felsic rocks with albite and quartz. Mafic volcanics also contain epidote and/or actinolite. Texturally, these minerals occur as groundmass replacement and overprint pre-existing open space filling minerals. Amphibole-dominated mineral assemblages are conspicuous

around the contacts of several granitoid intrusions throughout the area and were produced by thermal metamorphism. Higher metamorphic grades to the south are indicated by the presence of biotite and are considered post-volcanic (Dimroth et al., 1983).

Both the sub-greenschist and the greenschist assemblages are considered to have developed during subseafloor hydrothermal alteration processes and are considered syn-volcanic (Gelinas et al., 1982; Dimroth et al., 1983). The occurrence of predominantly greenschist facies assemblages within the Noranda Cauldron compared to the lower metamorphic grade in the Cycle I and II was interpreted by Dimroth et al. (1983) to reflect “primary”, higher temperature metamorphism within the core of the NVC related to concentrated volcanic activity.

Extrusive Rocks

- Cycle V - mafic volcanics
- Cycle IV - rhyolite, dacite
- Cycle IV - andesite
- Cycle III - Mine Sequence rhyolite
- Cycle III - Mine Sequence andesite
- Cycle II - rhyolite
- Cycle II - andesite

Intrusive Rocks

- gabbro
- syenite
- Lac Dufault Granodiorite
- Newbec Breccia
- quartz-diorite
- Flavrian-Powell Intrusion
- VHMS Deposits

Figure 2.2. Geology of the NVC (after Camire, 1990; Paradis, 1990; Gibson, 1989; Rive, 1986; and Spence, 1976). Major faults listed are considered syn-volcanic. A 1:25000 scale map of the NVC compiled during this study is given in the back pocket.

Figure 2.3. Eruptive centres within the Noranda Cauldron (after Gibson and Watkinson, 1990) and are numbered as: I - Old Waite Paleofissure, II McDougall-Despina, III - Cranston, IV - Waite Rhyolite, V - Quemont-Delbridge, and VI - Aldermac-Maconda. "Camp" designations within the CNVC are also marked. Section line A-B is used in Figure 2.4.

VOLCANIC STRATIGRAPHY

cycle IV	HCR Here Creek Rhy
	NBA Newbec And
	INR Insko Rhy
cycle III (Mine Sequence)	PWA Powell And
	AMA Amulet And
	UDR Upper Duprat Rhy
	WAR Waite Rhy
	MAR Millenbach Rhy
	QUR Quemont Rhy
	WAL Waite And
	MLA Millenbach And
	C Contact
	ARU Amulet Rhy (upper)
	ARF Amulet Rhy (F Shaft)
	ARB Amulet Rhy (Bedford)
	ARL Amulet Rhy (lower)
	LDA Lower Duprat And
	RRA Rusty Ridge And
	LDR Lower Duprat Rhy
	NWR North West Rhy
	JLR Joliet Rhy
	BRR Brownlee Rhy
	NVC Cranston Rhy
	FVA Flavrian And
	PCA Pre-Cauldron And

VHMS DEPOSITS ▲

AN Ansil	AA Amulet A
VZ Vauze	AU Amulet Upper A
NO Norbec	MB Millenbach
EW East Waite	CB Corbet
OW Old Waite	BD Bedford
AF Amulet F	QT Quemont
AC Amulet C	

SYNVOLCANIC FAULTS

HCF	Hunter Creek Fault
VCF	Vauze Creek Fault
BCF	Beauchastel Fault
HNF	Horne Creek Fault
cf	Cranston Fault
qf	Quesabe Fault
ff	F Shaft Fault
bf	Bancroft Fault

SYNVOLCANIC DYKES

andesite	
rhyolite	

Figure 2.4. Structural cross-section of the Noranda Cauldron with the stratigraphic distribution of massive sulphide mineralization (after Gibson and Watkinson, 1990). Abbreviations for the volcanic formation names are used for this study.

Figure 2.5. Regional hydrothermal alteration and metamorphic mineral assemblages in the Blake River Group (after Dimroth et al., 1983; Powell et al., 1995).

CHAPTER 3

METHODS

Regional Sampling and Alteration Mapping

Regional hydrothermal alteration mineral assemblages were identified and mapped at 1:20000 scale along twelve traverses within the CNVC. The location of the traverses, distribution of samples, and sample descriptions are provided in Appendix B. Traverses were oriented to transect the volcanic strata and sampling was conducted at 200 m spacing. In some places, sampling intervals were shortened to include lithologic and alteration mineral assemblage changes. In areas where alteration mineral occurrences were not previously mapped, volcanic formations containing andesitic rocks were closely examined for epidote-quartz alteration. Two andesitic rock formations, the Rusty Ridge and Amulet upper member, were sampled during several transects across volcanic strata from the Hunter Creek Fault to the Beauchastel Fault. In the Rusty Ridge formation, samples were collected in each volcanic flow unit containing epidote-quartz alteration. Representative samples of epidote-quartz alteration were collected from the Amulet upper member along traverses conducted with Paquette (1999).

Detailed Mapping Areas

Detailed mapping in the five areas described in Chapter 5 was conducted using previous outcrop maps and recent air photographs at 1:2000 and 1:1000 scale. In all map areas, the distribution of alteration mineral assemblages are represented at larger scales. Sampling in these areas was conducted to collect representative samples of alteration minerals and textures as well as examples of comparatively less altered volcanic wallrock. The distribution and description of samples are provided in Appendix C.

Whole Rock Geochemistry

Whole-rock geochemical analyses of crushed powders were performed by the Geological Survey of Canada (GSC) and Laurentian University Laboratories. The complete data set for all analyzed samples is given in Appendix D.

For altered samples, each was first carefully cut to remove the unaltered wallrock. For epidote-quartz alteration samples from the Rusty Ridge formation each was crushed in a small, ceramic-jaw crusher to 1 cm-sized chips. The chips were then hand-picked for portions of epidote-quartz alteration. Samples were then crushed to $< 150 \mu\text{m}$ size in a W-Mo crushing mill. Other analyzed samples were also crushed in a ceramic jaw crusher then further crushed without hand-picking. Samples analyzed by the Laurentian University Laboratory were crushed in a Cr-steel mill.

Whole-rock geochemical analyses for major elements (reported as oxides in Appendix C) and some trace elements were performed using standard X-Ray Fluorescence techniques at both the GSC and Laurentian University laboratories. For most samples, trace elements were analyzed using Inductively Coupled Mass Spectrometry techniques by the GSC laboratory. The analytical technique and reported precision for each element analyzed is given in Appendix D. The accuracy of the data was based on repeated analyses and in most cases < 10 relative % and is considered to be acceptable (Appendix D).

Whole-rock oxygen isotope geochemistry was performed by Dr. Bruce Taylor at the GSC using the remaining powdered material from selected samples analyzed by XRF and ICP-MS. The results are presently considered preliminary due to the difficulty of analyzing the epidote-quartz alteration samples and some require further analysis (Taylor, 1999; personal communication).

Mineral Chemistry

Mineral chemistry for all analyzed alteration minerals is provided in Appendix E. Most samples were analyzed using a Scanning Electron Microscope (SEM) under the supervision of Peter Jones at Carleton University. Measurement of elements by the JEOL 6400 SEM was made using a LINK-EXL L74 energy dispersive spectroscopy detector.

Chemical analyses were made at an accelerating potential of 20 keV, beam current at 0.80 nA during a live counting interval of 105 seconds. Backscattered electron images of epidote (Chapter 7) were generated at an elevated beam current of typically 3.00 nA. The precision of elements measured by the SEM is provided in Appendix E. Elements below detection limits (< 0.02 weight %) were not reported.

Other samples were analyzed at the Geological Survey of Canada using standard procedures on a Cameca-Camabax electron microprobe by Ingrid Kjarsgaard.

Comparison of chemical data for samples measured at the GSC and at Carleton University is good and reflects the high level of accuracy of all results (Appendix E).

CHAPTER 4

HYDROTHERMAL ALTERATION MINERAL ASSEMBLAGES IN THE NORANDA VOLCANIC COMPLEX

Intense epidote-quartz alteration, along with other mineral assemblages, distinguishes the CNVC from the other volcanic centres within the Blake River Group. In this study, the distribution of the main hydrothermal alteration mineral assemblages is based on outcrop and petrographic descriptions along sample traverses at 1:20,000 scale and from previous regional studies (Figure 4.1). Details are given in Appendix B. In several areas, the alteration assemblages exhibit a complex paragenetic relationship at the outcrop scale. Some of these areas were mapped in greater detail to establish the relationship of epidote-quartz alteration to the other mineral assemblages (Chapter 5).

A summary of the various mineral assemblages and their regional distribution is given in Table 4.1. The dominant alteration textures for each mineral assemblage are distinct and reflect a relative alteration intensity. The alteration intensity scale for the epidote-quartz assemblage is based on texture as well as the modal abundance of epidote at the outcrop scale. Background alteration encompasses the occurrence of several alteration minerals that are not mappable in the field, but are obvious petrographically. Previous studies of the Noranda area VHMS deposits have described chlorite-sericite alteration proximal to sulphide mineralization (Appendix A), thus only a general description of common textures developed regionally is provided here.

Background Alteration

Hydrothermal alteration minerals which cannot be readily identified by direct observation in outcrop or hand specimen are considered as “background” in this study. Petrographic studies reveal that to some extent, all volcanic rocks in the CNVC are hydrothermally altered. Most are characterized by: 1) the presence of pseudomorphic alteration minerals that replace primary minerals or volcanic glass and 2) the presence of secondary minerals that occur in low modal concentrations. In most cases, the background alteration minerals are not genetically related and their spatial distribution is still not well known, therefore, each mineral is described separately here.

Albite is one of the main alteration minerals of the mafic volcanic rocks in the NVC as small microlites and as phenocrysts (Plate 1A). In felsic volcanic rocks, albite microlites are less abundant, but are ubiquitous in crystalline massive flows. Albitization of feldspar phenocrysts in felsic porphyritic rocks is common (Plate 1B). The abundance of albite in both mafic and felsic volcanic rocks of the NVC is attributed to spilitization, a common process in submarine volcanic settings. Spilitization represents cation exchange reactions which include the removal of Ca from plagioclase and the addition of Na to form albite.

Chlorite occurs in both mafic and felsic volcanic rocks usually as a fine grained, massive part of the groundmass. In vitric rocks, chlorite abundance is attributed to the pervasive alteration of volcanic glass (Plate 1C). In breccia and hyaloclastite, glass shards are also completely replaced by chlorite. Chlorite in this form in the Noranda volcanic rocks does not accompany feldspar breakdown and corresponding Na depletion and is distinct from the chloritization of volcanic rocks associated with sulphide mineralization (Gibson, 1989).

Sericite is the dominant background alteration phase in felsic volcanic rocks. Minor quantities of sericite are found in all felsic volcanic rocks as isolated ‘clots’ in the groundmass or as pseudomorphic replacement of feldspar phenocrysts. This is not to be confused with the sericite-quartz assemblage described below which is volumetrically more significant and more widespread.

Actinolite occurs as small acicular crystals in most mafic volcanic rocks. Most commonly, it appears to replace albitized microlites in the rock groundmass, but also overgrows chloritized volcanic glass in vitric rocks (Plate 1D). Rare occurrences of actinolite are also found in amygdules with quartz, epidote and sulphide minerals. High concentrations (up to 15% modal volume) of actinolite occur in some mafic volcanic rocks, but due to its fine grain size, actinolite could not be reliably mapped in the field and could not be confidently related to volcanic textures or stratigraphy. The distribution

of actinolite in the NVC is currently under examination by Hannington et al. (1997; 1998).

Epidote is common within mafic volcanic rocks throughout the CNVC as isolated grains (called ‘matrix’ epidote in this study). Epidote typically overprints volcanic glass (chlorite) in the groundmass mesostasis and occurs as the replacement of plagioclase phenocrysts. Matrix epidote is relatively sparse in felsic volcanic rocks due to the low Ca concentration of the rocks.

Quartz, as a secondary mineral, is present in both mafic and felsic volcanic rocks in the CNVC. Most commonly, anhedral quartz grains occur in the volcanic groundmass, although the origin of this quartz may be primary. Open-space precipitation of silica, referred to as ‘silica dumping’ (Gibson 1989), is common throughout the CNVC. At the outcrop scale, silica dumping is concentrated near volcanic flow tops where volcanic fragments are completely cemented by fine grained quartz. At the hand specimen scale, fine grained quartz occupies open-spaces such as amygdules, cooling fractures, interpillow voids, hyaloclastite and flow breccia in both mafic and felsic flows. Chalcedony or chert has been preserved locally in amygdules and within the matrix of mafic hyaloclastite rocks.

Titanite occurs in mafic rocks in the absence of ilmenite. Its occurrence outside of the Lac Dufault Granodiorite metamorphic aureole may suggest its origin may be hydrothermal.

Carbonate Alteration

Most carbonate alteration does not extend beyond the outcrop scale and rarely exceeds > 5% groundmass replacement, thus is included in the background assemblage. Typically, carbonate minerals in the CNVC are present as fractures cutting the volcanic rocks and other alteration mineral assemblages commonly associated with gold mineralization and shear zones in the CNVC (Robert, 1990).

In some areas, carbonate minerals occur without an association to deformation structures and is likely synvolcanic. Carbonate minerals are largely confined to vesicle-infilling in mafic volcanic rocks. It is paragenetically late in relation to other vesicle-filling minerals such as quartz, chlorite and/or epidote, and typically occurs within the core of the amygdule. Carbonate alteration as volcanic rock groundmass replacement is rare in the CNVC, although, small disseminated grains occur locally in andesite as pervasive alteration (Plate 1E). The carbonate minerals do not appear to specifically replace any particular precursor mineral, but this type of carbonate alteration is more prevalent in mafic compared to felsic rocks, likely due to the abundance of Ca in the mafic rocks.

Widespread, pervasive carbonate alteration is conspicuous around the Delbridge deposit in the East Camp. Carbonate appears to overprint the sericitized felsic volcanics that host the deposit, but its paragenesis has not been fully considered. Carbonate alteration has been described as synvolcanic at the Mobrun deposit higher in the CNVC volcanic strata (Larocque and Hodgson, 1993) and semi-conformable carbonate alteration is common in other VHMS districts such as at Sturgeon Lake (Morton and Franklin, 1987). Alternatively, carbonate alteration may be related to late fluid migration along the Horne Creek Fault which forms gold mineralization at the nearby Donalda deposit. Thus, the carbonate alteration at the Delbridge deposit warrants further investigation.

Sericite-Quartz Alteration

A conformable sericite-quartz alteration assemblage occurs within thick successions of felsic volcanic rocks in the CNVC. This alteration is distinct from the fracture-controlled sericitic alteration discordant to several VHMS deposits by the absence of sulphide minerals and by the absence of penetrative replacement textures. Feldspar phenocrysts are preserved in this conformable-type of sericite-quartz alteration. In massive, crystalline flows, sericite typically accounts for 5-15 % of the rock by volume, and is prevalent along microfractures. In vitric flows, sericite replaces spherulites and the fine-grained groundmass mesostasis. The most intense conformable sericite-quartz alteration occurs in felsic volcanic breccias and affects both clasts and matrix

(Plate 1F). Sericite-quartz alteration in mafic volcanic rocks is rare and is typically associated with cross-cutting felsic dykes and does not extend beyond a metres from the dyke. Quartz that occurs in sericitized rocks is likely a residual alteration phase from the breakdown of felsic volcanic glass, but distinction of secondary from primary quartz in felsic rocks is not obvious.

Conformable sericite-quartz alteration is most widespread in the felsic volcanic rocks in the East Camp. No attempt has been made during this study to map the distinction between conformable sericite-quartz alteration and the diffuse, discordant sericitic alteration near the Delbridge deposit described by Boldy (1968). Rocks which have been most intensely sericitized are foliated parallel to major faults and parallel to the contact of the Lac Dufault Intrusion throughout the East Camp area. Thus, the origin for sericite-quartz alteration in this area could be attributed to metamorphism during late tectonic activity along these faults that were responsible for mesothermal gold mineralization as discussed above for carbonate alteration. More likely, conformable sericite-quartz alteration in felsic rocks represents an early alteration stage comparable to the timing of spilitization in the mafic rocks.

Chlorite-Sericite Alteration

Discordant chlorite-sericite alteration is invariably associated with sulphide mineralization in the CNVC and is distinct from chlorite and sericite in background

alteration by this association. Complete descriptions of this alteration mineral assemblage and its metamorphic mineral equivalents have been presented in studies of VHMS mineralization throughout the CNVC (Appendix A). Both chlorite and sericite occur in mafic as well as felsic volcanic rocks, although, chlorite-rich assemblages are better developed in mafic volcanic rocks and sericite-rich assemblages dominate felsic volcanic-hosted deposits. Regionally developed chlorite-sericite alteration includes both open-space infilling and volcanic groundmass replacement textures (Table 4.1) Weak to moderate chlorite-sericite alteration is characterized by vesicle-infilling with sulphide minerals or is fracture-controlled (Plate 1G). More intense alteration occurs as pervasive groundmass replacement by chlorite and sericite accompanied by sulphide mineralization (Plate 1H). Quartz is ubiquitous with this alteration and forms as a byproduct of the reactions that produce chlorite and sericite (i.e., both alteration minerals contain less silica than the precursor minerals). Prograde metamorphism of chlorite and sericite produces an assemblage of cordierite, anthophyllite, and biotite which defines the contact metamorphic aureole of the Lac Dufault Granodiorite (de Rosen-Spence, 1969). The ‘spotty’ nature of the anthophyllite and cordierite porphyroblasts has given rise to the field name ‘dalmatianite’ (Plate 1I).

Silicification

Silicification, as semi-conformable alteration, in the CNVC has been described elsewhere (Gibson et al., 1983; Gibson, 1989; Paquette et al. 1997; Paquette et al., 1998;

Gibson et al., in prep). The various textures related to silicification intensity are listed in Table 4.1.

Pervasive silicification of volcanic rock groundmass occurs both at the outcrop scale and the microscopic scale and but appears to have affected most of the volcanic rocks in the CNVC to varying degrees. Silicification is more readily identified in mafic volcanic rocks as isolated grains within the groundmass (Plate 1J). In felsic volcanic rocks, distinction between hydrothermal quartz and quartz grains as phenocrysts is often difficult, thus silicification is difficult to assess at the outcrop-scale. Outcrop-scale silicification is also more easily recognized in mafic volcanic rocks because of the light-coloured appearance of the silicified rocks (Plate 1K). The most intense silicification occurs as discrete masses ('patches') of fine-grained quartz up to 1 m in size (see F Shaft area; Chapter 5). Within these patches, primary volcanic textures are typically preserved. The intensity of alteration grades outward from the patches into more diffuse, pervasive silicification of the volcanic wallrock.

Epidote-Quartz Alteration

Epidote-quartz alteration in the CNVC is mappable at several scales. Epidote-quartz alteration most commonly occurs in mafic volcanic rocks, although the presence of epidote in felsic volcanic rocks in the CNVC has been locally recognized within the areas of strong epidote-quartz alteration. Several textural varieties have been recognized and are used to define the alteration intensity for this assemblage (Table 4.1). Epidote-quartz alteration textures correspond to intensity and reflect the modal abundance of epidote at the outcrop scale.

Weak alteration is distinguished by open-space infilling textures and is the most widespread occurrence of epidote in the CNVC. In amygdules, epidote may occur as the sole component of the vesicle-filling, although, quartz, chlorite, carbonate or sulphide minerals are also commonly present. Epidote-filled vesicles occur in both mafic (Plate 2A) and in felsic volcanic flows (Plate 2B). Volcanic cooling fractures within andesitic rocks are also commonly filled by epidote and typically possess narrow epidote-quartz alteration selvages. Epidote in amygdules and syn-volcanic fractures rarely exceeds > 5% volume of the rock at the outcrop-scale, except in some scoria-rich andesitic flow tops.

Vesicle-infilling for most other alteration minerals is considered as background (described above; Table 4.1). However, epidotized amygdules often form the nucleus of more pervasive, groundmass replacement alteration; thus is considered a more advanced

level of alteration intensity than matrix epidote. Amygdules containing epidote are not prominent in areas of background alteration (Figure 4.1), thus the occurrence of vesicle-infilling epidote is not related to matrix epidote. Prehnite and pumpellyite within amygdules have been reported in areas of background alteration (Powell et al., 1995; Stewart, 1998), thus epidote may have replaced these minerals during prograde hydrothermal alteration. Therefore, the presence of vesicle-infilling epidote represents more intense hydrothermal conditions (higher temperature, fluid:rock ratio) which is defineable by field mapping.

Moderate alteration is recognized by a combination of open-space precipitation and volcanic rock groundmass replacement textures. Moderate alteration intensity is characterized by > 5% epidote at the outcrop scale, but is largely confined to local areas of high permeability. This alteration can be readily mapped in the field (Figure 4.1). Mafic flows and breccias contain sufficient open space for epidote precipitation and also allow for groundmass replacement to occur. Interpillow hyaloclastites are often cemented by epidote and glass shards also may be completely replaced (Plate 2C and D). Volcanic breccias are similarly epidotized, particularly in andesitic flow-top breccia and within andesite interflow hyaloclastites. In these rocks, epidote occurs as matrix cement as well as a replacement of andesitic clasts (Plate 2E). Moderate epidote-quartz alteration is most pervasive in vitric andesitic flows. Individual variolites are selectively replaced by epidote at several scales (Plate 2F), but epidote rarely develops beyond 10-15% modal concentrations where this alteration texture is recognized.

Epidotization in rhyolitic breccias is rare. Groundmass replacement by epidote-quartz alteration occurs as distinct, rounded spots typically < 3 cm in diameter and usually centred on epidote-rich amygdules (Plate 2G). Groundmass replacement by epidote and quartz in rhyolite is complete and primary volcanic textures are not preserved within the spots. At the outcrop scale, epidote-quartz spots comprise 5-10% by volume of the rhyolites and thus are classified as moderate alteration intensity. At the regional-scale, epidote-quartz alteration in rhyolite typically connect more intense epidote-quartz alteration zones in andesite (Figure 4.1).

Strong alteration is characterized by groundmass replacement in isolated masses or “patches” of concentrated epidote and quartz in mafic volcanic rocks (Plate 2H). Epidote-quartz patches are variable in shape and size, although typically conform to the morphology of the mafic volcanic flow. Each patch ranges in size up to 2 m in diameter, although on average individual patches are < 0.5 m in diameter. A specific relationship between mafic volcanic flow morphology and the occurrence of patches is not apparent, thus, overall pillowed flows are equally epidotized compared to massive flows. The concentration of epidote within a single alteration patch typically exceeds the abundance of epidote as open-space infilling, thus the patches represent the most intense alteration at the outcrop-scale. Epidote-quartz alteration patches tend to occur in clusters of various dimensions, but typically beyond the outcrop-scale, and therefore they represent alteration zones developed at the regional scale.

Mineralogically, the epidote alteration patches are relatively simple, containing variable quantities of epidote and quartz with accessory illmenite, titanite and/or apatite. Primary volcanic textures within the patches are overprinted by epidote at the hand sample and microscopic scale and replacement of groundmass minerals is typically complete (Plate 2I). The epidote versus quartz content of individual patches is variable, even at the outcrop scale. At the regional scale, the epidote content of the patches is generally highest (70-80 % modal volume of the patch) in areas of intense alteration where patches are abundant. Outside of the patches, the volcanic groundmass is considerably less altered and is largely composed of minerals described in the background assemblage.

The alteration patches are typically developed with open space filling epidote, thus a genetic relationship between the different epidote-quartz alteration textures is implied. Most epidote patches contain epidote-filled vesicles and epidote-filled cooling fractures such that the patches appear as selvages (Plate 2J). A paragenetic relationship between matrix epidote and the epidote-quartz patches is not immediately apparent, but matrix epidote is most abundant within strong epidote-quartz alteration zones wallrock outside of the alteration patches. The contacts between epidote patches and the surrounding wallrocks may be either sharp (Plate 2K) or gradational (Plate 2L). These observations suggest epidote-quartz alteration patches form around one or several nucleation sites provided by previously developed epidote alteration.

Epidote crystallinity follows the macroscopic open-space or replacement textures observed in outcrop and hand specimen. In amygdules or as cement for volcanic breccias, epidote forms prismatic crystals as radial laths (“rosettes”; Plate 3A) or as euhedral rhombohedrons (“tombstone crystals”; Plate 3B). Epidote-quartz alteration patches are composed of anhedral masses of epidote grains interspersed with granular quartz (“aggregates”; Plate 3C). This aggregate-type texture of epidote is common to all patches regardless of the epidote to quartz content of the patch.

The Flavrian/Powell Intrusion also contains epidote-bearing alteration mineral assemblages (Goldie, 1976; Kennedy, 1985; Galley, 1997). Epidote occurs mainly in mariolitic cavities with quartz, chlorite and/or actinolite, however, a few local areas of groundmass replacement of tonalite and leucotonalite (i.e., epidote patches) are also described. Epidote-rich veins are also common in the felsic phases of the Flavrian/Powell parallel to the 070 orientation of most synvolcanic structures in the overlying volcanics (Galley, 1997). Diffuse, but pervasive, epidote-quartz alteration also occurs in the mafic phases of the Intrusion. A spatial relationship between the occurrence of epidote in the Flavrian/Powell Intrusion and the epidote-quartz alteration zones mapped in the volcanic rocks is not apparent.

Late intrusions (post-volcanic) throughout the CNVC contain epidote alteration texturally distinct from the patches mapped during this study. Veins of epidote and quartz

occur in small, granodiorite dykes along the margins of the Lac Dufault Intrusion (Plate 4A). Similar epidote-quartz veins are also found within the quartz-diorite dykes that cross-cut the volcanic strata throughout the CNVC.

Composite sets of epidote-quartz veins have been described by previous workers in the vicinity of some massive sulphide deposits and are referred to as “grid alteration”. These veins also occur outside of the mineralized areas, but are spatially confined within the contact metamorphic aureole of the Lac Dufault Intrusion. In the Amulet Upper A area, these epidote-quartz veins trend north-south and east-west and are oblique to the regional trend of syn-volcanic structures (Gibson, 1989; Setterfield et al., 1995). Thus, grid alteration is likely post-volcanic and may be genetically related to the Lac Dufault Intrusion.

Proterozoic gabbro dykes throughout the CNVC also contain epidote-quartz alteration as replacement of intercumulate plagioclase with amphibole and magnetite (Plate 4B). This mineral assemblage is distinct from the epidote-quartz alteration that occurs in the volcanic rocks and suggests different chemical and physical conditions of hydrothermal alteration apart from the syn-volcanic varieties.

Contact metamorphism does not significantly affect the epidote-quartz alteration mineralogy or alteration textures in the volcanic rocks, unlike the chlorite and sericite assemblages forming dalmatianite. Within the metamorphic halo of the Lac Dufault

Intrusion, minor recrystallization of anhedral epidote in the alteration patches to prismatic forms may be a result of contact metamorphism, although this recrystallization only occurs locally and not throughout the entire aureole.

Stratigraphic Distribution of the Hydrothermal Alteration Mineral Assemblages

The distribution of the hydrothermal alteration mineral assemblages with respect to volcanic stratigraphy and VHMS mineralization in the CNVC is illustrated in Figure 4.2. Semi-conformable versus discordant relationships of the assemblages, as listed in Table 4.1, are most obvious in the section. Chlorite-sericite alteration is discordant and forms mappable zones that cross-cut stratigraphy. Silicification, sericite-quartz alteration, and epidote-quartz alteration are more widespread and are both conformable and discordant.

Chlorite-sericite alteration is rarely found at surface outside of the immediate deposit areas. Several large zones of discordant chloritization occur in the CNVC that extend beyond the deposits. Two important examples which are highlighted here contain 1) the Quemont deposit and 2) the Amulet F deposit (Figure 4.2). A continuous zone of chlorite alteration and sulphide mineralization can be traced over 1 km down section from the Quemont deposit which is roughly equivalent to more than 500 m of volcanic stratigraphy. Stringer sulphides within this zone have been mined at the Joliet deposit, mainly as flux ore. This zone is associated with the volcanic dyke swarm which feeds the

Quemont Rhyolite formation (eruptive center V; Figure 2.3). A second chlorite alteration zone is associated with the small volcanic centre which hosts the Amulet F deposit.

Chloritization appears as dalmatianite alteration which cross-cuts over 500 m of stratigraphy. Its distribution is controlled by syn-volcanic faults and dykes mapped in the area (Buck, 1984; Gibson, 1989).

Sericite-quartz alteration is widely distributed throughout the cycle IV volcanic succession and likely reflects the higher proportion of felsic to mafic volcanic compositions in Cycle IV versus Cycle III. Sericite-quartz alteration is prominent in the thick felsic volcanic flows south of Lac Dufault, but does not exhibit a particular spatial association with the Delbridge VMS deposit outside of the mineralized zones. More local concentrations of sericite-quartz alteration occur in the felsic volcanic rocks in Cycle III, particularly in the New Vauze area (Paradis, 1990), but are not mappable at the scale shown here (Figure 4.2).

Silicification is prevalent in the Cycle III volcanic rocks compared to the Cycle IV rocks. The most intense and widespread silicification, mapped as discrete patches by Gibson (1989), is semi-conformable within the volcanic rocks of the Amulet and Waite Andesite Formations (Figure 4.2). The intensity of silicification increases toward VHMS deposits, eruptive centres, and syn-volcanic faults, particularly in the vicinity of the Amulet and the Millenbach deposits where it is interpreted to form a 'cap rock' to the active hydrothermal system (Gibson et al., 1983).

Epidote-quartz alteration is more widespread than silicification. The most intense zones overprint the main mafic volcanic eruptive centres within the Noranda Cauldron (the Old Waite Paleofissure, OWP, and the McDougall-Despina Eruptive Centre, MDEC; Figure 2.3). In the OWP, epidotization occurs in both mafic and felsic volcanic flows as well as in the volcanic feeder dykes cutting stratigraphy. Away from this dyke swarm, epidote-quartz alteration is absent from the felsic volcanic rocks, but persists within the mafic volcanic rocks. The number of individual alteration patches decreases with distance away from the OWP. As the number of dykes decreases towards the top of the OWP, strong epidote-quartz alteration grades into moderate alteration and silica dumping becomes more prominent. Epidote-quartz patches are sparse north of the Vauze Creek Fault and south of the F Shaft Fault which constrains the lateral extent of this alteration zone (Figure 4.1; 4.2).

Within the MDEC, epidote-quartz alteration is developed at the uppermost part of the volcanic stratigraphy where synvolcanic andesite dykes are abundant. Andesitic flows of the Millenbach Andesite and the Amulet Andesite formation volcanic flows are intensely epidotized within this eruptive centre, but the occurrence of epidote-quartz alteration patches decreases laterally away (Figure 2.4). South of the McDougall-Despina Structure, the andesitic flows are relatively unaltered and epidote-quartz alteration patches are absent, but small zones of weak, pervasive silicification occur near the contact with the Flavrian Intrusion. Semi-conformable epidote-quartz alteration in the CNVC is

also developed in the Aldermac eruptive centre (Figure 2.4), but was not mapped in detail during this study.

Epidote-quartz alteration outside these eruptive centres is more conformable in nature. Individual andesite flows in the Rusty Ridge and Flavrian Andesite formations contain abundant epidote-quartz alteration patches without an obvious spatial relationship to synvolcanic dykes and likely reflect lateral hydrothermal fluid flow away from these centres. In the East Camp, epidotization at any intensity in the Cycle III and IV mafic volcanic rocks is sparse. The most concentrated occurrence of epidote-quartz alteration persists throughout the South Bay Andesite formation as interpillow replacement (shown in Plate 2C). A relatively small zone of strong epidote-quartz alteration within the South Bay Andesite formation is spatially related to feeder dykes.

Background alteration has not been mapped systematically in this study. In general, albitization (spilitization) of plagioclase phenocrysts and microlites is ubiquitous as is background chloritization of volcanic glass. Carbonate alteration as vesicle-infilling and volcanic rock groundmass replacement is developed outside of the areas hosting VHMS mineralization, except in the Delbridge area in the cycle IV volcanics. Volcanic groundmass replacement by carbonate is weakly developed in the uppermost flows of the Amulet Andesite Formation, south of the Corbet mine site. Similar carbonate alteration occurs north of the Hunter Creek Fault in andesitic flows, but also includes locally well

developed carbonate as vesicle infilling. Carbonatized sections of the Waite Andesite Formation have also been noted in the New Vauze area (Paradis, 1990).

Summary

The occurrence of hydrothermal alteration mineral assemblages were mapped by outcrop and petrographic descriptions to identify the extent of epidote-quartz alteration in the CNVC. Five mineral assemblages were recognized in the CNVC which were spatially and genetically distinct: 1) Background alteration encompasses the occurrence of several alteration minerals (albite, actinolite, carbonate, chlorite, epidote, quartz, sericite, titanite) that are only obvious petrographically. In most cases, background alteration mineral have selectively replaced a precursor mineral or volcanic glass and most are the likely products of spilitization. Background epidote ('matrix') occurs as plagioclase phenocryst replacement and as an overprint of chloritized volcanic rocks dominantly in andesite. 2) Sericite-quartz alteration is ubiquitous in most felsic rocks in the CNVC typically as the replacement of feldspar. This assemblage is not spatially constrained to sulphide mineralization zones and is distinct from the fracture-controlled proximal quartz-sericite alteration present in the felsic-hosted massive sulphide deposits. 3) Chlorite-sericite alteration is typically discordant and occurs as a stockwork or pipe-shaped zone below the sulphide deposits ('pipe alteration'). Groundmass replacement is typically pervasive or clearly fracture-controlled and primary volcanic textures are rarely preserved. 4) Silicification of volcanic groundmass occurs both at the outcrop and the microscopic-

scale, but appears to have variably affected most of the volcanic rocks in the CNVC.

Silicification of andesite gives a bleached appearance to the rock, but most volcanic textures are preserved. Silicification does not coincide with particular precursor mineral or a specific volcanic texture and intense silicification is represented by patches.

The textural variations of epidote-quartz alteration define the alteration intensity. Weak alteration occurs as open-space infilling of vesicles and breccias by epidote. Moderate alteration is distinguished by selective volcanic groundmass replacement of varioles in andesites and fragments in volcanic breccia and hyaloclastite. Strong epidote-quartz alteration is represented by patches of complete groundmass replacement up to 1 m in diameter in andesite. Most primary volcanic textures within the patches are destroyed. These patches may be concentrated in clusters at the outcrop-scale and define large, intense alteration zones up to 1 km² in area. Epidote-quartz alteration in rhyolite as groundmass replacement is sparse, but typically occurs within the intense alteration zones. Epidote-quartz alteration in the Flavrian-Powell Intrusion occurs mainly as cavity-infilling and fractures with actinolite, but locally occurs as discrete groundmass replacement patches. Epidote crystal forms follow the alteration textures with the best developed crystals occurring as open-space infilling. Recrystallization of epidote in the Lac Dufault Intrusion metamorphic aureole is minor and illustrates the relative stability of this assemblage through contact metamorphism.

The distribution of the hydrothermal alteration mineral assemblages with respect to volcanic stratigraphy and VHMS mineralization in the CNVC illustrates the conformable versus discordant relationships of each assemblage. Chlorite-sericite alteration associated with sulphide mineralization is rarely distributed at surface outside of the immediate deposit areas, although, large discordant zones occur in the CNVC related to volcanic eruptive centres that host massive sulphide mineralization. Silicification and epidote-quartz alteration illustrate both a conformable and discordant distribution with respect to volcanic stratigraphy and are considered 'semi-conformable'. Intense silicification is confined mainly to the Amulet Rhyolite formation within areas of elevated volcanic activity. Intense epidote-quartz alteration occurs mainly in mafic-dominated eruptive centres (the Old Waite Paleofissure and the MacDougall-Despina Eruptive Centre) adjacent to and within synvolcanic dykes. Overall epidote-quartz alteration in the CNVC is more widespread than silicification. Epidote-quartz alteration in the cycle IV volcanics is limited to mafic volcanic rocks and is mainly conformable. Epidote-quartz alteration in the Flavrian-Powell Intrusion does not correspond spatially or genetically to the alteration zones in the overlying volcanic rocks.

Table 4.1. Summary of Alteration Mineral Assemblages and Textures within the CNVC.

MINERAL	TEXTURES		
ASSEMBLAGE	STRONG	MODERATE	WEAK
<i>Epidote-Quartz</i>	<u>groundmass replacement</u> patches/masses, primary textures destroyed > 15% epidote	<u>selective groundmass</u> <u>replacement</u> mafic breccias, interpillow hyaloclastite, variolites; "epidote spots" in rhyolites < 15% epidote	<u>open space infilling</u> amygdules, veinlets < 5 % epidote
Distribution (semi-conformable)	within mafic volcanic eruptive centres	conformable along flow units	ubiquitous
<i>Silicification</i>	<u>groundmass replacement</u> patches/masses; "ribbon texture"; pervasive	<u>groundmass replacement</u> pervasive > 5% modal silica addition	<u>groundmass replacement</u> pervasive < 5% modal silica addition
Distribution (semi-conformable)	local discordant zones typically within andesite breccias	conformable along flow units	ubiquitous
<i>Chlorite-Sericite</i>	<u>groundmass replacement</u> pervasive alteration, primary textures destroyed; includes sulphide mineralization	<u>groundmass replacement</u> pervasive alteration with relict primary textures, ± silica	<u>groundmass replacement</u> amygdules, pillow selvage, "spotted texture"
Distribution (discordant)	synchronous with synvolcanic faults; "feeder pipes" to massive sulphides	gradational with strong alteration	concentrated near andesite flow tops, pillow flows
<i>Sericite-Quartz</i>		<u>groundmass replacement</u> matrix replacement in spherulitic and hyaloclastite felsic flows	<u>groundmass replacement</u> pervasive replacement of felsic groundmass (< 10%)
Distribution (semi-conformable)		local development	typically in thick felsic volcanic units (West Camp - cycle IV)
<i>Background Alteration</i>			<u>selective groundmass</u> <u>replacement</u> isolated grains or microscopic masses
Distribution (conformable)			ubiquitous

Figure 4.1. The spatial distribution of hydrothermal alteration mineral assemblages in the central NVC (after Gibson, 1989; Paradis, 1990). White areas within the Main Camp and East Camp represent large, post-volcanic dioritic dykes. Other areas in white were not mapped. Where complex paragenetic relationships were observed, the latest phase of alteration was mapped. As a result, the distribution of alteration shown here reflects the cumulative hydrothermal history of the CNVC. Detailed map areas described in Chapter 5 are outlined in blue. Section line A-B is used for Figure 4.2.

Figure 4.2. Spatial distribution of hydrothermal alteration mineral assemblages within the Mine Sequence. Abbreviations for VHMS deposits, volcanic formation names, and synvolcanic faults are listed in Figure 2.4.

Plate 1. Representative textures of regional alteration mineral assemblages.

1A. Spilitization in andesite volcanic flows is evident by the abundance of Na-rich feldspar microlites (albite) .

1B. Feldspar phenocrysts in felsic porphyritic volcanic rocks are typically Na-rich and likely reflect background alteration processes.

1C. Background chlorite alteration as the pseudomorphic replacement of volcanic glass.

1D. Actinolite, as background alteration, overprints chloritized volcanic glass in andesite volcanic rocks.

1E. Carbonatization (cb) in rhyolite flows as pseudomorphic replacement of plagioclase phenocrysts.

1F. Pervasive sericite-quartz alteration as replacement of rhyolite clasts in felsic volcanic breccia.

Plate 1. Representative textures of alteration mineral assemblages in the cNVC.

1G. Chlorite-sericite selvages developed on sulphide stringers within columnar cooling joints (outlined) in massive rhyolite flows represent permeability-controlled alteration.

1H. Pervasive chloritic alteration (chl) replaces the groundmass and outlines relict plagioclase (ab) phenocrysts.

1I. Metamorphic overprint ('dalmatianite texture') of pervasive chloritic alteration evident by round cordierite porphyroblasts (white arrows) developed here with sulphide stringer mineralization (pyrrhotite and chalcopyrite).

1J. Weak silicification of mafic volcanic rocks as isolated grains within the groundmass.

1K. Bleached appearance to andesite pillow interior due to pervasive silicification contrasts with the dark chloritic pillow margin and selvage.

Plate 2. Representative epidote-quartz alteration textures from regional traverses.

2A. Large epidote-quartz amygdules surrounded by smaller chlorite-rich amygdules in weakly altered massive andesite flow.

2B. Large epidote-quartz amygdules in massive rhyolite flow.

2C. Pervasive epidote-quartz replacement of pillow selvage (outlined). Pillow groundmass contains isolated epidote grains.

2D. Concentrated epidotization by replacement of interpillow hyaloclastite. Epidote-quartz alteration partially replaces the chloritic pillow rim.

2E. Matrix replacement by epidote-quartz in andesite flow top breccia. Andesite clasts are mainly silicified with epidote developed on the clast margin (white arrow).

2F. Selective groundmass replacement in andesite by epidote-quartz alteration centred on varioles.

Plate 2. Representative epidote-quartz alteration textures from regional traverses.

2G Epidote-quartz alteration as distinct spots of groundmass replacement in rhyolite.

2H. Strong epidote-quartz alteration as isolated patches within the groundmass of andesitic rocks.

2I. Epidote-quartz patches developed parallel to primary cooling fractures and also centred on large amygdules ('gas cavities') in andesite.

2J. Epidote-quartz alteration patch in sharp contact with andesitic wallrock.

2K. Epidote-quartz alteration patch with gradational andesitic wallrock contact.

2L. Epidote as background alteration ('matrix') typically occurs as the replacement of chloritized glass in andesite.

Plate 3. Textures of epidote as open space-filling and groundmass alteration.

3A. Prismatic epidote typically occurs as radial laths within open spaces (e.g., vesicles, pillow selvages).

3B. Euhedral epidote crystals formed in amygdules are characteristic of open space mineralization and may also occur with prismatic epidote.

3C. Fine grained epidote (ep) as groundmass replacement in alteration patches occurs as anhedral aggregates without obvious grain boundaries. Quartz (qtz) is typically more coarse grained than epidote in the patches.

Plate 4. Epidote-quartz alteration associated with late intrusions.

(A) Epidote-quartz alteration (at arrows) developed as selvages along felsic dykes in andesite near the margin of the Lac Dufault Granodiorite.

(B) Massive epidote overprint of intercumulus plagioclase (white areas) with isolated grains of magnetite (mag) in a Proterozoic gabbro dyke. Elongate prismatic crystals of amphibole (arrows) also occur with epidote.

CHAPTER 5

DETAILED RELATIONSHIPS OF EPIDOTE-QUARTZ ALTERATION IN THE NORANDA MINE SEQUENCE

Five specific areas in the CNVC were chosen to examine the spatial and paragenetic relationships of epidote-quartz alteration to: a) volcanic stratigraphy, b) lithology, c) silicification and d) chloritic alteration and sulphide mineralization (Figure 4.1). Four areas were mapped in detail at 1:100 to 1:2000 scale. A fifth area, the Old Waite-Norbec Mines area, was not mapped, but reconnaissance traverses through this area and detailed sampling were completed for comparison with of previous mapping (Gibson, 1989). A summary of the volcanic stratigraphy, alteration mineral assemblages, and epidote paragenesis for each area is provided in Table 5.1.

This chapter also considers previous descriptions of epidote-quartz alteration within the Noranda VHMS deposits with respect to the paragenetic relationships determined by this study. Epidote-quartz alteration in the Ansil deposit area was re-examined during this study.

Lac Duprat South Area

The Lac Duprat South area represents regionally intense epidote-quartz alteration developed along the periphery of the Old Waite Paleofissure at a low stratigraphic level

within the Mine Sequence. The map area contains the most intense epidote-quartz alteration developed in rhyolite in the entire CNVC, therefore, a comparison of epidote-quartz alteration textures between andesites and rhyolites was also made. Alteration mapping in this area examined the relationship between epidote-quartz alteration and: (i) andesite flow morphology, (ii) andesite flow thickness, (iii) silicification within andesite flow top breccia, and (iv) rhyolite flow morphology. Figure 5.1 illustrates the distribution of epidote-quartz alteration as well as other mineral assemblages mapped in the area at 1:2000 scale.

Volcanology in the area has been studied in detail and various flow morphologies in all the volcanic rocks have been well documented by Gibson (1989). Individual flow units within the Rusty Ridge formation can be mapped on the basis of flow-top breccias, amygdule distribution, and relative grain size variations. Within the Lac Duprat South area, andesite flows are mainly massive with a few containing well developed pillow structures. All andesite flows in the area are vesicular, with an average amygdule content of 2-5%, increasing up to 10% near the flow tops. Large gas-cavities, up to 20 cm in diameter, occur in the massive andesite units within the centre of the flow. Most flows are hyalophitic, but locally, plagioclase microlites are dominant in the groundmass. Feldspar phenocrysts in the andesite volcanic rocks generally comprise < 5 % of the groundmass. Where present, the phenocrysts are small, < 2 mm, and are more prevalent in pillowed flows. The overlying Amulet formation lower member, is composed mainly of rhyolite lobate flows characterized by massive lobes 2-3 m in size surrounded by spherulitic

hyaloclastite. The massive lobes are texturally diverse with locally well developed flow banding, locally concentrated amygdules, and porphyritic sections. Both andesite and rhyolite dykes cross-cut strata in the area and form part of the Old Waite Paleofissure.

Silicification in the map area is not prominent, but is most evident within the massive rhyolite lobes resulting in a light-coloured appearance in outcrop. In the Rusty Ridge formation andesitic flows, silica dumping is widespread in the flow top breccias as matrix cement and in cooling fractures, but silicification is confined to fine-grained quartz as replacement of andesite lithic clasts in breccias (Plate 5A). Spherulitic rhyolite hyaloclastite is pervasively sericitized, but only contains 2-3 % sericite by volume. In general, the hyaloclastites are considered relatively unaltered.

Chlorite mainly occurs as background alteration in both andesite and rhyolite. Chlorite-rich amygdules occur in massive rhyolite lobes with thin chlorite-quartz alteration selvages. Chlorite replacement of rhyolitic hyaloclastite matrix is locally developed. Chloritic alteration within the Rusty Ridge formation in this area is particularly concentrated in the pillowed flows as vesicle-infilling and replacement of pillow selvages. Interpillow chloritic alteration in the R12 flow is accompanied by disseminated pyrite and minor chalcopyrite.

Epidote-quartz alteration as patches had been previously recognized by Gibson (1989). The complete range of epidote-quartz alteration textures and intensities is

represented in the Lac Duprat South map area. Epidote infilling of vesicles is widespread in both mafic and felsic volcanic flows; the most prominent areas are highlighted in Figure 5.1. Large, prismatic epidote crystals are conspicuous in gas cavities developed in the massive andesite flows (Plate 5B), particularly in the R11 flow. Silicified flow-top breccias within the Rusty Ridge formation contain epidote as a fine-grained alteration of andesite lithic clasts and as prismatic crystals with quartz within the breccia matrix (Plate 5C). Strong epidote-quartz alteration in the Rusty Ridge formation occurs as relatively small, well-rounded, replacement patches, typically less than 30 cm in diameter (Plate 5D). In the Amulet Rhyolite formation, epidote-quartz occurs mainly as rounded spots of groundmass replacement within the massive lobes (shown in Plate 2G). Individual spots are 1-3 cm in diameter and are characterized by diffuse alteration contacts with the rhyolite wallrock. This spotty alteration in rhyolite increases in abundance up section from the map area, to the east. Epidote-quartz replacement patches are sparse in andesite dykes in the area and rhyolite dykes are relatively unaltered.

Comparison between the alteration patches in andesite and the spots in rhyolite illustrates several similarities: both are mainly composed of epidote and quartz with minor titanite, both are fine grained, and neither contain relict minerals or primary textures. The only differences occur in size and abundance. These observations suggest hydrothermal fluid conditions in rhyolite and andesite are similar (i.e., similar temperature, acidity, oxidation state).

Distribution of epidote-quartz patches in andesite at the map-scale is mainly related to flow morphology and flow thickness. Epidote-quartz patches are particularly concentrated within the massive andesite flow units compared to the pillowed andesite flows. Overall, individual massive flow units contain up to 20% epidote by volume, although, the distribution of epidote-quartz patches is variable with most patches concentrated in clusters (Plate 5E). Outside of these areas, the massive andesite is relatively unaltered and contains background chlorite, albite, epidote, quartz and actinolite. The most intense epidote-quartz alteration occurs in relatively thick massive andesite flows (e.g., R4). Clusters of epidote-quartz patches have developed in the centre of these flow units rather than toward the flow-tops. In rhyolitic flows, the alteration spots are confined to the massive lobes, but a spatial relationship to syn-volcanic structures or open-space infilling structures is not evident within this area.

The distribution of epidote-quartz patches within individual andesitic flows at the outcrop-scale is often variable. In some units (e.g., R11b) the abundance of patches is directly related to the concentration of large vesicles, with epidote-quartz alteration forming a selvage of groundmass replacement around the vesicle (Plate 5B). In other units, epidote-quartz patches form independent of nearby gas cavities (Plate 5F). Elsewhere, epidote-quartz patches develop around small epidote-quartz-chlorite amygdules, although this association is not always apparent. The relationship between patches and vesicles in andesite is further considered at a more detailed scale.

A three-dimensional view of an individual flow tube within the R4 unit illustrates the relationship between epidote-quartz patches and vesicles in the thick andesite flows (Figure 5.2). Along the surface of the tube, the patches appear variably distributed, but are generally elongated parallel to the flow contact and cooling joints. In section, trails of epidote-quartz amygdules are apparent parallel to the cooling joints within the flow tube. The patches are formed outside of these vesicular zones where the andesite groundmass is massive and volcanic glass is concentrated. This relationship suggests that the patches have developed as the selective replacement of glass and that macroscopic primary permeability (i.e., vesicles) may not be the only control of epidote distribution. This also may explain the relative absence of epidote-quartz alteration in the pillowed andesite flows in this area which are more porphyritic and contain less vitric material.

In summary, the Lac Duprat South area is characterized by epidote-quartz alteration in both andesitic and rhyolitic flows within a regionally developed zone. Alteration occurs as groundmass replacement in both andesite and rhyolite, although alteration patches are larger and more abundant in andesite illustrating the lithologic control of epidote-quartz alteration. Epidote-quartz patches in andesite are absent from flow-top breccias which have been cemented by silica dumping and suggest the patches formed well after extrusion. Most epidote-quartz patches occur in clusters within the centre of relatively thick massive andesitic flows and form as selvages around large vesicles and by the replacement of volcanic glass. This signifies the importance of heat

generated by the volcanic flows to generate epidote-quartz patches rather than the importance of open-space for fluid circulation.

Old Waite-Norbec Mines Area

The Old Waite-Norbec Mines area is contained within the Old Waite Paleofissure (OWP) at a higher stratigraphic level than the Lac Duprat South area (Figure 4.1; 4.2). Detailed mapping was not carried out in this area, however regional and reconnaissance traverses through the area revealed several important relationships between epidote-quartz alteration and: (i) synvolcanic dykes and (ii) silicification. The area spans several andesite volcanic formations and most hydrothermal alteration in the area is strong (Figure 5.3).

Synvolcanic dykes in this area are well exposed and have been mapped by Gibson (1989). Most dykes are andesitic in composition with some rhyolite dykes as a separate intrusive phase. Composite dykes occur near the Old Waite Mine with rhyolite cores and andesite margins. Individual dyke margins and contacts are evident west of the Old Waite Mine where dykes cross-cut the volcanic rocks. Up-section, the high proportion of andesitic dykes near the Old Waite Mine obscures the contact between the Amulet Andesite formation and the underlying Waite Andesite. In this area, the andesitic dykes grade into the surrounding massive flows of the Amulet Andesite formation and individual dyke contacts are not readily apparent. The proportion of dykes decreases up-

section toward the Norbec Mine site and the dykes appear to feed the surrounding massive andesite flows.

Silicification of the Amulet formation and Waite Andesite formation volcanic rocks is intense (Gibson, 1989). Massive andesite flows in the Amulet formation are pervasively silicified and most primary volcanic textures are obliterated by quartz replacement. Patches of intense silicification are also prominent in these massive flows. The Waite Andesite volcanic rocks are similarly silicified, although alteration is less intense than the underlying andesitic flows. Pillow outlines are preserved in the Waite Andesite flows despite silicification, but most pillow cores and margins are replaced by fine-grained quartz (Plate 6A). Intense silicification persists up-section in flow top breccias at the top of the Waite Andesite formation and is described in detail by Gibson (1989) and Paquette (1999). Mapping in this area by Paquette et al. (1997) illustrates the close association of silicification with volcanic structures and primary permeability.

Epidote-quartz alteration varies in intensity throughout the area. Weak to moderate epidote alteration as open-space infilling and selective replacement are widespread in the Amulet Andesite formation and are preserved in the intensely silicified andesitic rocks. Relict epidote-quartz±chlorite amygdules occur throughout the Amulet Rhyolite formation andesite flows and are up to 6 cm in diameter (Plate 6B). Pervasive silicification in the andesite groundmass is often absent around the epidote-filled vesicles.

Interpillow epidote-quartz alteration in the Waite Andesite flows is also preserved despite complete replacement of the pillow interior by later silicification (Plate 6C).

Strong epidote-quartz alteration in the andesite volcanics occurs the area as replacement patches similar to those described elsewhere in the CNVC (Plate 2). Epidote-quartz patches comprise up to 30% by volume of most outcrops near both the Old Waite and Norbec mines (Figure 5.3). Epidote-quartz patches also occur lower in the volcanic stratigraphy within the Amulet Rhyolite and Waite Andesite formations, but are less abundant than in the overlying Amulet Andesite formation. These patches are conspicuous owing to the colour contrast between epidote and the light-coloured appearance of the silicified andesites. Most patches develop around epidote-filled vesicles (Plate 6D), although some patches do not appear to be spatially related to amygdules. Epidote-quartz patches also locally occur in the breccias at the top of the Waite Andesite formation. Epidote-quartz have mainly replaced the siliceous matrix of the breccia, but also overgrow the large andesite clasts (Plate 6E). Epidote-quartz patches are absent within the chloritic alteration pipe that contains the Old Waite and East Waite massive sulphides.

Synvolcanic dykes in the core of the Paleofissure are also epidotized. In the mafic dykes, epidote-quartz alteration is typically diffuse throughout the dyke groundmass (Plate 6F), although distinct patches are also developed locally in both mafic and felsic dykes.

The distribution of epidote-quartz alteration spatially corresponds to the proportion of mafic dykes within the OWP (Figure 5.3). Away from the OWP, epidote-quartz patches decrease in abundance in the surrounding volcanic rocks. This spatial relationship implies a genetic association between the dykes and the patches in which syn-volcanic faults, now occupied by dykes, have provided conduits for hydrothermal fluids. Intrusion of the dykes has also likely provided the heat necessary for epidote-quartz alteration. The decreasing proportion of syn-volcanic dykes and paucity of epidote-quartz patches up-section from the Norbec Mine suggest epidote-quartz alteration terminated when volcanic dyke intrusion ceased.

The relationship of epidote-quartz alteration and silicification is best illustrated by the variable nature of alteration contacts of epidote-quartz patches within the OWP (Figure 5.4). Within the silicified andesite flows, epidote-quartz patches are siliceous and contain silicified andesite inclusions. This implies that epidote is an overprint on the silicification. Higher in the stratigraphy, in the Amulet Andesite formation above the Old Waite Mine, patches have gradational wallrock contacts with epidote concentration decreasing toward the contact. Overall these patches are epidote-rich. Toward the top of the OWP, east of the Norbec mine, epidote patches contain distinct quartz-rich halos and imply that epidotization and silicification may be coeval at the patch-scale.

In summary, epidote-quartz alteration occurs throughout the OWP within syn-volcanic dykes as well as within andesitic flows. Epidote-quartz alteration is absent from the discordant alteration pipe associated with the Old Waite massive sulphides and suggests the pipe alteration assemblage cuts previously formed epidote-quartz alteration and does not provide a favourable host for overprinting epidote-quartz alteration. The distribution of epidote-quartz patches is directly related to the proportion of dykes in the OWP which provide heat and pathways for high temperature hydrothermal fluid migration. Intrusive activity within the OWP cross-cuts the silicified andesites that comprise the Amulet formation and Waite Andesite formation and allow epidote-quartz alteration to overprint the pervasive silicification. As dyke proportions and epidote-quartz alteration wanes toward the top of the OWP, quartz concentrations within the patches increases and suggests silicification and epidotization may be coeval at the patch-scale.

Ansil Hill

The Ansil Hill area represents an intact section of andesitic flows within the Rusty Ridge formation away from the main eruptive centre (the Old Waite Paleofissure) and has not been disrupted by later faulting. The relationship between epidote-quartz alteration and andesite flow morphology was thus investigated in this area.

The volcanology of Ansil Hill has been mapped in detail and the section is interpreted to represent a small andesite pillow volcano within the Rusty Ridge Andesite

formation (Gibson, 1989). Four individual andesitic flow units have been recognized (Figure 5.5). Pillow morphology is well preserved and the relief at Ansil Hill provides a section through the R6 flow where pillows may be observed in three dimensions.

Volcanic breccias are locally developed within the pillowed flows. Large vesicles, up to 30 cm diameter, are concentrated near the top of the R4 massive flow and highlight the contact with the overlying pillowed flow. Flow direction is locally apparent by the orientation of these vesicles. A volcanic vent as a local source for andesite lava has also been identified in the area.

Epidote-quartz alteration is not strongly developed at Ansil Hill and represents the lowest alteration intensity within the Rusty Ridge formation. The wide variety of alteration textures at Ansil Hill closely corresponds to the andesite flow morphologies in the area (Figure 5.5) and represents an early stage of regional epidote-quartz alteration development.

Epidote-quartz alteration at Ansil Hill predominately occurs as open-space infilling and volcanic groundmass replacement is relatively minor. Epidote as vesicle-infilling is common throughout all of the andesitic flows at Ansil Hill. Gas cavities developed in the R4 as well as the R6 flow are all infilled by quartz and prismatic epidote. Few of these vesicles demonstrate an apparent alteration selvage of groundmass replacement. Epidote is also common within interpillow hyaloclastite in both the R5 and R6 flows. Epidote is not pervasive throughout the hyaloclastite, but typically occurs in

discrete zones at pillow junctions (Figure 5.6). Epidote mainly occurs within the matrix of the hyaloclastite, although wallrock fragments and chloritic glass shards are also partially replaced by epidote. Within the hyaloclastite matrix, epidote forms as euhedral prismatic crystals and locally as radial structures (see Plate 3A). Outside of these epidote-rich zones, silica dumping occurs within the pillow selvages and chloritic hyaloclastite shards are completely preserved. Concentric cooling joints within the pillows are quartz-rich and contain only accessory epidote. Small epidote replacement patches within the pillow interior are rare and form parallel to the concentric cooling joints.

Epidote-quartz patches are sparse in the area and mainly occur within the R4 massive flow. Individual patches are relatively small compared to those in the OWP within the Lac Duprat South area. Each patch is 10-20 cm in diameter and contains a diffuse contact with the andesite wallrock. The alteration patches in the R4 flow are constrained below the upper contact and have no association with the large epidote-quartz amygdules formed near the top of the flow. A relationship between the epidote alteration distribution and the volcanic vent shown in Figure 5.5 is also not apparent.

In summary, epidote-quartz alteration patches are relatively sparse at Ansil Hill despite the widespread occurrence of epidote in vesicles and interpillow hyaloclastite. The prismatic nature of epidote in vesicles and interpillow hyaloclastite suggests epidote crystallized relatively slowly and developed where hydrothermal fluids became trapped. The occurrence of open-space infilling epidote at Ansil Hill indicates these textures are

easily formed well away from a major eruptive centre and do not require significant hydrothermal fluid circulation; thus, likely represent the earliest stage of epidote-quartz alteration at the regional scale. Development of epidote-quartz patches away from the eruptive centre is independent of open-space infilling and occurs where thick andesitic flows have insulated and trapped hydrothermal fluids.

Amulet F Shaft Area

The Amulet F Shaft area provides an excellent example of the spatial and temporal relationships of semi-conformable alteration to sulphide mineralization and associated chloritic alteration. This area occurs within the contact metamorphic aureole of the Lac Dufault Intrusion, thus the discordant chlorite-sericite alteration assemblages are represented by cordierite, anthophyllite and biotite (dalmatianite assemblage). Previous mapping by Buck (1980) and Gibson (1989) was modified during this study by accentuating the occurrence and distribution of alteration mineral assemblages in the area (Figure 5.7).

Massive sulphide mineralization at the Amulet F deposit lies atop a small, rhyolite flow dome, known as the "F Shaft Flow", near the top of the Amulet formation (Buck, 1980; Gibson, 1989). Footwall stringer sulphides and discordant alteration are well exposed at surface and can be traced approximately 1 km below the massive sulphides. The discordant alteration is developed along synvolcanic fault structures, parallel to

composite andesite-rhyolite dykes. Away from these fault structures, semi-conformable epidote-quartz alteration and silicification are preserved in the footwall and hangingwall andesite volcanic flows (Gibson, 1989). Strong dalmatianite alteration occurs with stringer and disseminated sulphides and all primary volcanic textures have been destroyed (Plate 7A). Zones of dalmatianite without sulphide mineralization are prevalent in the hangingwall Millenbach Andesite formation and represent weak chloritic alteration. Hangingwall mineralization is limited to thin sulphide-rich, tuffaceous horizons that occur in the Millenbach Andesite formation.

Silicification is pronounced in both the andesitic and rhyolitic flows in the F Shaft area and is the dominant semi-conformable alteration phase (Gibson, 1989). Below the F Shaft Flow, massive andesitic flow lobes are pervasively silicified, but the intervening andesite hyaloclastite is chloritic, giving a patchy alteration texture (Plate 7B) which is characteristic for the Amulet formation (Gibson et al., 1983). Patches above the F Shaft Flow resemble ribbon-textured silicification described by Gibson (1989) elsewhere in the Main Camp, although the alteration here does not appear to be concentrated within brecciated volcanic rocks. Silicification in the rhyolitic flows is not as prominent as in andesite, but typically occurs as light-coloured haloes around quartz-epidote amygdules.

Epidote-quartz alteration is not prevalent in the Amulet F Shaft area (Figure 5.7). Epidote in the Millenbach Andesite formation flows above the deposit occurs as open-space precipitation, vesicle infilling, and as sparse groundmass replacement (< 2%

epidote; background concentrations). Small, epidote-quartz patches in the Millenbach Andesite are fracture-controlled (Plate 7C) and texturally distinct from other patches described in this study.

Interpillow epidotization is also common in andesite flows within the Amulet Rhyolite formation away from the discordant alteration and the silicification zones (Plate 7D). Vesicle-infilling by epidote and quartz is widespread in the Amulet Rhyolite formation andesitic flows and is preserved in the intensely silicified areas (Plate 7E). A unique association of epidotization and silicification occurs immediately below the F Shaft Rhyolite contact. Small, silicified andesite lobes at the contact resemble fragments developed on the top of andesite flows. Each lobe contains an epidote-rich core surrounded by a rim of intense silicification (Plate 7F). The matrix between the lobes is relatively unaltered. Thus, the formation of the epidote-quartz assemblage at the patch-scale appears to liberate silicon from the andesitic wallrock into hydrothermal fluids.

Epidote-quartz patches are rare in the Amulet formation, but locally are preserved away from zones of intense silicification, chloritization and sulphide mineralization (Figure 5.8). Small, epidote patches form within a single massive andesite flow unit and texturally resemble other patches described throughout the CNVC. At the outcrop-scale, epidote-quartz patches are absent in the intensely silicified andesite rocks. Close inspection of the epidote-quartz alteration patch contacts shows that small siliceous domains cut into the patch and suggest the patch has been replaced by the pervasive

silicification in this area. Chloritic alteration occurs along cross-cutting fractures and 'spotty' chlorite alteration replaces both silicification and epidote-quartz alteration.

In summary, epidote-quartz alteration is scarce in the Amulet F Shaft area.

Epidote as open-space infilling in andesitic and rhyolitic flows is preserved in the widespread silicification zones in the area, but is absent in the discordant chloritic alteration zones. Where present, epidote-quartz patches are replaced in andesitic rocks by pervasive silicification and suggests some epidote-quartz alteration had preceded the widespread silicification of the andesitic rocks in the Amulet formation. The scarcity of patches in the F Shaft area may be attributed to the pervasive overprint of silicification and chloritization that characterize this area.

Amulet Upper A Area

Epidote-quartz alteration in the Amulet Upper A area is well developed and at the outcrop scale contains the most intense epidote-quartz alteration exposed at surface in the CNVC. Both lithologic and alteration distribution were mapped by this study at 1:1000 scale. The volcanology and stratigraphic setting of this area is discussed in Appendix F. Several paragenetic relationships are represented in this area between epidote-quartz alteration and: (i) andesite volcanic flow morphology, (ii) andesite feeder dykes, (iii) chloritic alteration and sulphide mineralization, (iv) later intrusions, and (v) contact metamorphism. The Amulet Upper A area occurs at a high stratigraphic level of the Mine

Sequence, thus these paragenetic relationships are relatively uncomplicated by later hydrothermal events generating epidote-quartz alteration.

The Amulet Upper A area is contained within a volcanic structure parallel to the McDougall-Despina volcanic centre which hosts several VHMS deposits. Volcanic activity is evident by the abundant synvolcanic andesitic dykes in the area which feed the andesitic flows of the Amulet Andesite formation. Previous maps of the volcanic stratigraphy compiled by Spence (1976) and Gibson (1989) did not resolve the distribution of these dykes or their relationship to the surrounding andesite volcanic flows. The lithologic relationships in the area were re-mapped during this study (Appendix F).

The distribution of alteration in the Amulet Upper A area is shown relative to the lithologic contacts mapped during this study (Figure 5.9). Early workers noted the extensive discordant alteration zone ('alteration pipe') which hosts massive sulphide mineralization at the Amulet Upper A and continued at depth to the Amulet Lower A deposit (Suffel, 1948; Knuckey et al., 1982). The alteration zone is composed of the dalmatianite mineral assemblage and was recognized as the metamorphic overprint of chlorite-sericite alteration (Spence, 1969). Previous alteration studies in the area have documented the whole-rock geochemistry of the dalmatianite assemblages (Hall, 1982; Beaty and Taylor, 1982), but did not consider alteration outside of the alteration pipe.

Epidote-quartz alteration is widespread throughout the map area, although the distribution of replacement patches is variable (Figure 5.9). A semi-conformable distribution can be demonstrated even at this map-scale; evident by the occurrence of epidote-quartz patches in relatively thick andesitic flows (conformable) and by the abundance of patches adjacent to andesitic dykes (discordant).

Thick andesitic flows typically contain intense epidote-quartz alteration. In some areas, over 40% of the andesitic groundmass is composed of epidote (highlighted in Figure 5.9). In these intense zones, a wide range of patch sizes and shapes conform to the morphology of the flow. In massive flows, the patches are elongated with the most spectacular patches up to several meters in length developed in large flow tubes (Plate 8A). In pillowed flows, near-complete replacement of the entire groundmass is displayed (Plate 8B). Both clasts and matrix in pillow breccias are overgrown by epidote in these intense zones (Plate 8C). The concentration of epidote relative to quartz in most patches throughout the area is consistently high averaging 70-80% epidote by volume.

Epidote crystallization textures within replacement patches are also variable, but do not correspond to the distribution of the patches. In some patches, epidote occurs as anhedral masses, however, in most patches, plagioclase microlites are pseudomorphed by epidote preserving the primary sub-ophitic texture (Plate 8D). Mineralogically the alteration patches are similar to those elsewhere in the CNVC and are largely composed of epidote and quartz with accessory titanite. Hematite haloes are developed around the

epidote-quartz patches in the relatively thick massive andesite flow unit stratigraphically above the deposit (Plate 8E) and this is unique to the Upper A area. Weak silicification is also notable in the Upper A area by the replacement of epidote-quartz patches by small quartz grains (Plate 8F).

Synvolcanic andesitic dykes that cross-cut the flows in the Amulet Upper A area are relatively unaltered, even where the surrounding andesite flows contain abundant epidote-quartz patches (Plate 8G). A detailed inspection of the intense epidote-quartz alteration zones illustrates this relationship (Figure 5.10). Minor quartz is concentrated within cooling fractures in the core of the dykes. Along the dyke margins, a thin silicified selvage grades into the pillowed flows. Adjacent to the andesite dykes, epidote-quartz patches are developed within each pillow. This intensity of epidote-quartz alteration extends along this flow unit beyond the outcrop shown in Figure 5.10. Elsewhere, andesite dykes truncate epidote-quartz patches indicating intrusion into an existing alteration zone. Patches in andesite dykes occur near the Upper A tuffaceous horizon. In these patches, epidote is diffuse and primary textures in the groundmass are preserved.

The overall semi-conformable distribution of epidote-quartz alteration in the Amulet Upper A area reflects the nature of hydrothermal fluid flow. This can be illustrated by marking the transition of strong to moderate epidote-quartz alteration (shown by red arrows in Figure 5.9). Thick andesitic flows constrain hydrothermal fluid circulation to the core of the flow, indicated by the concentration of patches, and insulate

fluids from cold seawater. Cross-cutting synvolcanic dykes that cut the flows supply additional heat to hydrothermal fluids and provide conduits for discordant circulation.

Dalmatianite alteration which hosts sulphide mineralization in the Amulet Upper A area consists of an anthophyllite-cordierite-biotite mineral assemblage. The core of the alteration pipe is marked by the presence of anthophyllite, which characterizes the most intense chloritic alteration zones associated with sulphide mineralization (Hall, 1982). Strong dalmatianite alteration associated with disseminated and stringer sulphides obliterates most primary volcanic textures (Plate 8H). Relatively weak dalmatianite occurs adjacent to sulphide-filled vesicles and stringer sulphides as discrete spots that are dispersed throughout the andesitic groundmass. Amygdule minerals within the strong dalmatianite alteration zone are preserved and mainly composed of quartz, but are locally epidote-rich. Epidote-bearing vesicles also contain pyrite, sphalerite and chlorite. In these vesicles, epidote forms along the rims of the amygdule and is succeeded by chlorite and the sulphide minerals (Plate 8I).

Epidote-quartz patches within the dalmatianite alteration zones are relatively rare, but do occur above the deposit where pillows have been preserved. These patches are partially replaced by chlorite and metamorphic amphibole (Plate 8J). Patches developed immediately outside of the dalmatianite zone contain amygdules composed of chlorite, epidote, and sulphides (Plate 8K). Both of these relationships suggest epidote-quartz

alteration has continued after the development of chlorite-sericite alteration and sulphide mineralization.

Post-volcanic epidote-quartz alteration is also represented in the Amulet Upper A area. Quartz-diorite dykes which cut the volcanic strata and the dalmatianite alteration pipe contain diffuse epidote alteration as replacement of pyroxene phenocrysts. A clear association of this alteration with the epidote patches in the volcanic rocks is not apparent and so is considered unrelated. Quartz-feldspar phyric dykes which cut the andesite volcanic rocks do not contain epidote.

Contact metamorphism associated with the Lac Dufault Intrusion is not particularly evident within the epidote-quartz patches. In some patches, metamorphic hornblende occurs as euhedral grains and appear as porphyroblasts (Plate 8L). The absence of hornblende in other epidote-quartz patches in the CNVC suggests its occurrence in the Upper A area is related to contact metamorphism and not by regional metamorphic effects.

Epidote-quartz veinlets ("grid alteration") occur throughout the Upper A area, but are concentrated particularly near the dalmatianite alteration zone. These veins cut the dalmatianite alteration as well as the quartz-diorite intrusions in this area. Similar grid alteration occurs in other VHMS deposits such as the Amulet F and the Old Waite mines (Riverin, 1977), but is absent outside of the Lac Dufault Intrusion contact metamorphic

aureole. Conjugate pairs of grid alteration veins in the Upper A area trend north-south and east-west, roughly parallel and perpendicular to the contact of the Lac Dufault Intrusion and may represent extension during magmatic activity.

In summary, the distribution of epidote-quartz patches in the Amulet Upper A area reflects conformable alteration along thick andesitic flows and discordant alteration associated to synvolcanic andesitic dykes. The strong epidote-quartz alteration zones are not spatially related to the discordant alteration pipe that hosts the Amulet Upper A massive sulphides and can be traced outside of the map area into the underlying Millenbach Andesite formation rocks and up-section in the flows at the top of the Amulet Andesite formation. Thus, the relationships described here represent regional hydrothermal fluid flow within a mafic volcanic centre which contains VHMS mineralization and is thus noteworthy.

Epidote-Quartz Alteration in the Noranda VHMS Deposits

Epidote-quartz mineral assemblages are generally poorly developed within the chlorite-sericite alteration zones in the Noranda VHMS deposits. Epidote is notably absent in deposits hosted mainly by felsic volcanic rocks such as Quemont (Taylor, 1957; Cattalani et al., 1990), Delbridge (Boldy, 1968; Barrett et al., 1995), and Mobern (Caumartin and Caille, 1990; Barrett et al., 1992; Larocque and Hodgson, 1993). In

deposits hosted by mafic volcanic rocks, epidote-quartz alteration is present within areas of stringer sulphide mineralization and as a 'distal' alteration assemblage.

Epidote-quartz alteration related to sulphide-bearing veins has been reported at the Millenbach deposit and in the Horne orebodies, although the paragenesis of epidote in these orebodies is poorly understood. Alteration of the host rhyolite volcanic rocks at Horne is dominated by sericite, but epidote replacement of plagioclase has been noted as part of this alteration assemblage (Butterfield, 1934; MacLean and Hoy, 1991). In the gold-bearing siliceous flux ores, epidote is a minor part of the quartz-pyrite-chlorite ore veins (Price, 1934). Epidote is also an accessory mineral of the footwall chlorite alteration beneath the H orebodies (MacLean and Hoy, 1991). Sulphide stringers at Millenbach contain chlorite-sericite-epidote-carbonate selvages (Simmons et al., 1973), but their relationship to the massive sulphides is not reported. Massive zones of epidote-quartz alteration in the Millenbach Andesite have been documented by Riverin (1977), however the origin for this phase of alteration is unclear. The epidote alteration appears to overprint sulphide mineralization and is spatially related to quartz-diorite dykes, thus is interpreted to be metamorphic (Riverin, 1995 per. comm.). An association of epidote-quartz alteration to quartz-diorite dykes has not been observed elsewhere in the CNVC during this study, and therefore this alteration at Millenbach may be volcanogenic.

At Corbet, Gibson et al. (1993) have shown that epidote-quartz alteration is concentrated outside of chloritic and sericitic alteration zones in massive and pillowed

volcanic flows from the Flavrian Andesite formation (Figure 5.11). Epidote-quartz patches, similar to those described here, overprint spilitization developed in the andesitic flows and may have formed after sulphide mineralization (Gibson et al., 1993). At surface, several outcrops of andesitic flows within the Flavrian Andesite formation contain abundant epidote-quartz patches away from the Corbet deposits (Figure 4.2). Therefore, the patches at Corbet likely reflect the regional distribution of epidote-quartz alteration throughout the Flavrian Andesite formation similar to the distribution described in the Rusty Ridge formation (Chapter 4) and do not necessarily coincide with massive sulphide deposition.

Above the Ansil deposit, widespread epidote-quartz alteration is conspicuous in the Rusty Ridge Andesite Formation (Figure 5.11). Distinct epidote-quartz patches are concentrated within zones < 50 m thick where 2-5 % of the overall andesite groundmass is replaced. It is difficult to assess from the drill holes, whether these zones can be correlated, nevertheless, the zones tend to be localized in the upper portion of the Rusty Ridge formation. Epidote-quartz alteration is also locally developed in the footwall rhyolitic flows of the Northwest formation distal from mineralization. Some of the epidote-quartz alteration in the Rusty Ridge formation is spatially related to the whole-rock, Na depletion zone which envelops the Ansil deposit and includes the Decoeur-Garon sulphide showing (Riverin et al., 1990). The Na depletion zone is centred on the Snoop fault and is structurally controlled by other synvolcanic faults in the Rusty Ridge formation. The epidote-quartz alteration zones are more extensive than the Na depletion

halo and epidote is absent within the quartz-pyrite-sphalerite-chalcopyrite amygdules which dominate the Decoeur-Garon Showing, therefore the epidote-quartz alteration is not genetically related to the Na depletion zone. A more intense epidote-quartz assemblages is described by Galley et al. (1995) in the footwall of the Ansil deposit, and is interpreted to be part of the “skarn-type” hydrothermal system associated with a late intrusive phase of the Flavrian Intrusion.

Epidote-quartz alteration is not prominent at the Amulet F deposit (discussed above in Chapter 4) although the paragenetic relationships within sulphide mineralization and chloritic alteration are similar to those at the Corbet and Ansil deposits. Epidote-quartz alteration appears as an early hydrothermal phase in amygdules and patches that is overprinted by the chloritic alteration zones. Epidote-quartz patches are not spatially related to the silicification zones or sulphide mineralization in the area.

The intense epidote-quartz alteration zone at the Amulet Upper A deposit extends beyond the detailed map area described above. This zone can be traced at surface through the underlying Millenbach Andesite formation flows, but dissipates above the Dufresnoy Diorite (Figure 5.11). This epidote zone envelopes the mineralization and hydrothermal alteration pipe connecting the Amulet A and Upper A deposits through over 500m of volcanic stratigraphy (Knuckey et al. 1982). Epidote-quartz alteration in the Amulet Andesite formation decreases laterally away from the MacDougall-Despina eruptive centre.

Epidote-quartz hydrothermal alteration was noted at other VHMS deposits in the NVC, however the relationship to other alteration mineral assemblages and sulphide mineralization has not been investigated systematically during this study. Andesitic rocks above the Aldermac deposit contain epidote-quartz alteration patches of similar intensity to those developed in the Old Waite Paleofissure and in the Amulet Upper A area. The intensity of this epidote-quartz alteration is confined to the extent of the Aldermac eruptive centre (Figure 2.3), and decreases over a 1 km strike length away from the deposit. Adjacent to the Four Corners sulphide prospects, in the West Camp, epidote-quartz alteration is conspicuous throughout the area in both andesite and rhyolite volcanic rocks highlighting an area of over 1.5 km². Parry and Hutchinson (1981) describe epidote-quartz alteration as part of the “background” assemblage distal to sulphide mineralization, however, structural complexities complicate the stratigraphic relationships in the Four Corners area. In places, epidote-quartz alteration includes K feldspar as well as disseminated hematite which have been ascribed to later fennitization (Comba et al., 1981). Thus, the genetic association of epidote in the volcanic rocks to sulphide mineralization in the Four Corners area is presently unclear.

Typically, epidote-quartz alteration in all of these deposits is regarded as distal alteration developed outside of chlorite-sericite alteration assemblages which host sulphide mineralization. This study indicates that epidote-quartz alteration, as replacement patches, is genetically related to mafic eruptive centres beyond the scale of a

single deposit and reflects regional hydrothermal fluid circulation. Recognition of this alteration mineral assemblage may not be important at the deposit-scale for mineral exploration, but at the regional scale epidote-quartz alteration clearly identifies zones of hydrothermal fluid upflow in productive volcanic centres

Summary

Detailed mapping in five different areas within the CNVC examined the physical controls on the distribution of epidote-quartz alteration taking into account: (i) andesite versus rhyolite lithologic composition, (ii) flow morphology, (iii) vesicle distribution, and (iv) proximity to synvolcanic dykes within volcanic centres. Generally, rhyolites only contain epidote as open space infilling, but in the Old Waite Paleofissure, epidote-quartz alteration locally occurs as distinct spots in rhyolites. Regionally, epidote-quartz alteration is not specifically concentrated in either massive or pillowed andesite flows, but in some areas, epidote-quartz patches are most abundant in relatively thick, massive flows which act as hydrothermal aquifers. Amygdules typically form the locus of epidote-quartz alteration, but some patches are developed within the vitric groundmass. Epidote-quartz alteration is most intense (i.e., high abundance of patches) proximal to synvolcanic dykes and the intensity decreases less than 500 m from dyke swarms. The synvolcanic dykes typically do not contain epidote-quartz patches except where dykes are numerous and where dykes are relatively thick.

The detailed mapping also examined the paragenetic relationships between epidote-quartz alteration and: (i) silicification and (ii) sulphide mineralization and associated chlorite-sericite alteration. Epidote-quartz replacement patches form after quartz and epidote infilling of open spaces such as cooling fractures, flow breccias, hyaloclastites, and vesicles in andesite flows. In the Old Waite Paleofissure, epidote-quartz patches overprint the pervasive silicification in the Amulet Rhyolite formation. However, in weakly silicified areas, relict epidote-quartz patches are preserved in the Amulet Rhyolite formation and are likely related to an earlier hydrothermal event prior to silicification. Epidote-quartz patches are rare within the discordant chlorite-sericite alteration pipes that host sulphide mineralization and were likely replaced by the more pervasive alteration. The absence of patches in the discordant pipes, even in major hydrothermal fluid upflow zones such as the Old Waite Paleofissure, suggest epidote-quartz alteration did not form within the Fe- and Mg-rich volcanic rocks during later hydrothermal events. Epidote-quartz alteration is developed in active volcanic areas, but not necessarily within a single hydrothermal fluid flow conduit, thus is more widespread than the chlorite-sericite alteration assemblages.

Table 5.1. Summary of Detailed Map Areas (see Figure 4.1 for locations).

ALTERATION ASSEMBLAGES						
AREA	STRAT	silica	epi-qtz	chl-ser	EPIDOTE DISTRIBUTION	EPIDOTE PARAGENESIS
Lac Duprat South	RRA	*	***	*	flow interiors core of lava tube (conformable)	absent from chloritized flows
	ARL	--	**	--	massive lobes	
Old Waite-Norbec Mine	AMA	--	***	***	adjacent/within synvolcanic dykes (discordant)	cut by chlorite pipe alteration (Old Waite Mine)
	ARU WAL	***	***	--	interpillow alteration (conformable) adjacent/within synvolcanic dykes (discordant)	overprints silicification
Ansil Hill	RRA	*	*	--	open space infilling flow interiors (conformable)	
Amulet F Shaft	ARU	***	**	***	flow interiors (conformable)	overprinted by silicification and chloritization
	MLA	--	*	**		
Amulet Upper A	AMA	--	***	***	flow interiors; adjacent to synvolcanic dykes (conformable and discordant)	cut by chlorite pipe alteration (Amulet A); exclusive of pipe

Notes:

Stratigraphy: see Figure 2.4 for volcanic formation abbreviations.

Alteration Intensity: -- = absent; * = weak; ** = moderate; *** = strong;

Epidote Distribution: reflects outcrop -scale relationships (described in text).

Figure 5.1. The distribution of alteration mineral assemblages in the Lac Duprat South area. The figure represents mapping at 1:2000 scale. Lithology and stratigraphy from Gibson (1989). Areas of strong epidote alteration (> 20% patches) are highlighted. Large amygdules ('gas cavities') infilled by epidote and quartz are shown.

Figure 5.2. Distribution of epidote-quartz patches in a single andesite tube within the R4 flow (Figure 5.1). The top view of the tube illustrates the abundance of epidote patches along the flow margins. In section, patches formed in the core of the tube outside of vesicular areas.

Figure 5.3. Old Waite-Norbec mines area geology and alteration distribution (after Cousineau and Dimroth, 1982; Gibson, 1989; Gibson et al., 1997). The distribution of epidote-quartz alteration is largely schematic, but the two most intense zones are indicated where > 30 % of the outcrop area is composed of patches.

Figure 5.4. Epidote-quartz alteration patch contact relationships with andesites in the Old Waite-Norbec Mines area. (A) Epidote-quartz patch overgrowth of pervasively silicified wallrock (Waite Andesite formation). (B) Gradational contact with decreasing epidote abundance within the patch toward the wallrock (Amulet Andesite formation). (C) Sharp alteration contact with wallrock (Amulet Andesite formation). Epidote patch rim is quartz-rich and contains little epidote.

Mafic Volcanic Units

- Pillow Breccia (siliceous matrix)
- Ponded Massive Flow (R7)
- Pillow Lava; concentric jointing (R6)
- Pillow Lava; amygdaloidal (R5)
- Massive Lava (R4)

ALTERATION TEXTURES

- Quartz-Epidote Amygdules
- Epidote-filled gas cavities
- Interpillow epidote-quartz alteration; open-space infilling and hyaloclastite replacement
- Epidote-Quartz Patches

Figure 5.5. The geology of Ansil Hill (after Gibson, 1989). Epidote-quartz alteration distribution and textures were re-mapped for this study. Alteration patch symbols represent < 5% andesite replacement. The detailed sketch in Fig. 5.6 is shown by the large arrow.

Photo

Sketch

Figure 5.6. Representative epidote-quartz alteration relationships at Ansil Hill illustrating open space control in areas of weak regional epidote-quartz alteration. The location of the photo and sketch is shown in Figure 5.5.

Alteration Mineral Assemblages

epidote-quartz alteration

strong moderate weak

dalmatianite

silicification

strong weak

Textures

epidote-quartz patches

a epidote-quartz amygdules

silicification patches

Lithology

andesite flows

massive

lobe-hyaloclastite

pillowed

flow contacts

faults

rhyolite dykes

composite dykes

diabase dykes

Figure 5.7. The distribution of alteration mineral assemblages in the Amulet F Shaft area. Stratigraphy and lithologic mapping by Gibson (1989). Local epidote-quartz patch occurrence shown in detail in Figure 5.8.

Figure 5.8. Relationships of epidote-quartz alteration to pervasive silicification and chlorite alteration in the Amulet F Shaft area. Lithology from Gibson (1989). Sample from epidote-quartz patch is shown with petrographic descriptions.

Figure 5.9. The distribution of alteration mineral assemblages mapped in the Amulet Upper A area. Lithologic contacts and volcanic textures are described in Appendix F. The intensity of epidote-quartz alteration reflects the abundance of patches in each outcrop rather than the alteration texture. The most intense epidote-quartz alteration areas that are highlighted represent > 40 % patches within the outcrop.

Figure 5.10. The relationship of epidote-quartz alteration and syn-volcanic dykes shown by detailed mapping. The location of the isla outcrop is shown in Figure 5.9. In the intense epidote-quartz alteration zone (> 40 % epidote), patch shape and distribution reflect the shape and distribution of pillows.

Figure 5.11. The occurrence of epidote-quartz alteration within the VHMS deposits. Corbet underground section after Gibson (1989) and Gibson et al. (1993). Ansil section from drillhole logging by this study (after Gibson, 1989; Galley et al. 1995).

Plate 5. Alteration mineral assemblage relationships in the Lac Duprat South area.

5A. Andesite clasts in flow top breccia outlined by fine grained quartz in the matrix is representative of weak silicification ('silica dumping').

5B. Epidote-quartz infilling of an amygdule ('gas cavity') as the core of an alteration patch.

5C. Epidote infilling and alteration in an andesite flow top breccia. Prismatic epidote crystals form within the breccia matrix.

5D. Characteristic rounded epidote patch shape and size (< 30 cm diameter) in andesite flows.

5E. Intense alteration occurs as abundant epidote-quartz patches ('clusters') particularly in massive flows.

5F. Epidote-quartz patch developed outside quartz-filled gas cavities.

Plate 6. Alteration mineral relationships in the Old Waite-Norbec mines area.

6A. Widespread silicification in the area occurs as the replacement of andesite pillow core and chloritic margins.

6B. Relict epidote-quartz amygdules with intensely silicified selvages are preserved within pervasively silicified andesite.

6C. Silicified andesite pillow with widespread interpillow epidote-quartz alteration occurs throughout the Waite Andesite formation.

6D. Small epidote-quartz patches (arrows) within silicified andesite flows developed on relict epidote-filled vesicles.

6E. Epidote-quartz patches overgrow silicified andesite breccia clasts and matrix in the Waite Andesite formation, upper member.

6F. Epidote-quartz alteration is diffuse and pervasive (mottled appearance) in coarse-grained andesitic dykes rather than distinct patches.

Plate 7. Representative alteration textures in the Amulet F Shaft area.

7A. Dalmatianite alteration (dal) and sulphide stringers (outlined) near the F Shaft Showing. Primary volcanic textures are completely destroyed.

7B. Patchy silicification in massive andesitic flow lobes within chloritized hyaloclastite (hycl) below the F Shaft Flow.

7C. Fracture-controlled epidotization in the hangingwall Millenbach Andesite.

7D. Pillow breccia matrix partial replacement by epidote in the Amulet formation upper member andesitic rocks.

7E. Epidote-quartz amygdules in silicified massive andesitic flow lobes below the F Shaft Flow.

7F. Epidote-quartz alteration within silicified andesitic lobe fragments near the top of the flow.

Plate 8. Hydrothermal alteration mineral relationships in the Amulet Upper A area.

8A. Large epidote-quartz patch (outlined) as near-complete replacement of andesite pillow tube.

8B. Intense epidote alteration as near-complete pillow replacement. Photo is representative of strong alteration zone shown in Figure 5.9.

8C. Epidote replacement of pillow breccia matrix.

8D. Relict subophitic texture of randomly oriented plagioclase microlites preserved in epidote patch.

8E. Epidote patches with hematite halos locally developed in the thick massive andesite flow unit above the deposit.

8F. Weak silicification, as small rounded quartz grains, overprints anhedral epidote aggregates (epi agg) within patch.

Plate 8. Hydrothermal alteration mineral relationships in the Amulet Upper A area.

8G. Epidote patch developed in andesite volcanic flow adjacent to relatively unaltered synvolcanic andesite dyke. Dyke contact with flow is shown by dashed line.

8H. Pervasive dalmatianite alteration; primary texture destruction

8I. Preserved epidote-rich amygdules containing sphalerite and pyrite in strongly chloritized andesite within the deposit alteration pipe.

8J. Anhedral grains of chlorite and amphibole as replacement of massive epidote within patch above deposit.

8K. Pyrite and chlorite formed after epidote in amygdule within epidote patch outside of VHMS alteration pipe.

8L. Metamorphic overprint of fine grained epidote by euhedral hornblende grains.

CHAPTER 6

WHOLE-ROCK METASOMATIC CHANGES ASSOCIATED WITH EPIDOTE-QUARTZ ALTERATION

Whole rock geochemical data have been generated for over 300 samples collected during this study (Appendix D). The data were used to confirm alteration mineral assemblages mapped in outcrop as well as to establish geochemical variations associated with volcanic composition.

The data contain several samples of epidote-quartz alteration patches and the corresponding volcanic wallrock. A mass balance approach to these data is used to evaluate the metasomatic changes associated with epidote-quartz alteration. Using this approach, whole-rock components which have been gained or lost are identified and the degree of mobility is assessed for each component. Emphasis is placed on the enrichments and depletions of whole-rock components in the areas of intense epidote-quartz alteration described in Chapter 4 (Figure 4.1).

The mass balance calculations take into account the paragenetic relationships of the alteration assemblages since most areas in the central NVC have been altered by more than one hydrothermal event. In order to evaluate the mass changes for the epidote-quartz patches, mass changes associated with background alteration in the immediate wallrocks

are considered first. The mineral assemblages associated with background alteration are described in Chapter 4 and the mass balance results are discussed separately below.

Samples from two specific volcanic formations within the Noranda Cauldron are used to evaluate the net mass changes due to epidote-quartz alteration at the cauldron scale. Both the Rusty Ridge and Amulet Andesite formations are relatively thick successions of andesitic flows and both contain discrete zones of strong epidote-quartz alteration (Figure 4.2), thus the net mass changes can be mapped according to these strong alteration zones. Using the estimated thickness of andesitic flows that comprise the Rusty Ridge formation, absolute mass changes were also calculated.

Whole-rock analyses from detailed sampling across three separate epidote-quartz patches at different stratigraphic levels are also described in this chapter to observe the net mass changes at the patch-scale. Geochemical variations at the patch-scale likely reflect the evolution of hydrothermal fluids during epidote-quartz alteration. Thus, the hydrothermal conditions (e.g., temperature, pH, oxidation state, fluid:rock ratios) that produce epidote-quartz alteration can be inferred.

For this study, major elements are considered in oxide form as typically quoted by the analytical laboratories. Standard discrimination plots for volcanic rocks typically utilize the element oxide form; this form is also convenient for comparison between the

least altered volcanic rock compositions in this and other studies and allow for direct comparison with other alteration studies.

Mass Balance Calculation Method

Various methods of evaluating whole-rock geochemistry data for metamorphosed and/or hydrothermally altered rocks have been derived (Appleyard and Guha, 1991; Leitch and Lentz, 1994). Most recent approaches are versions of the mass balance method first described by Gresens (1967) utilizing density and volume. MacLean (1990) simplified this technique for mass balance calculations and his method used here. This technique compares altered rock compositions to an unaltered wallrock composition (precursor) and calculates mass gains or losses of chemical components during hydrothermal alteration. "Immobile" elements are identified to monitor the effects of dilution or concentration due to overall mass gain or loss in the altered rock. A ratio of the immobile element is used to recalculate the altered rock composition for each of the elements analyzed as follows:

$$RC = \% \text{ component, altered rock} * IM (\text{precursor}) / IM (\text{altered rock}),$$

where RC is the altered rock recalculated composition, and IM is the concentration of the immobile element (MacLean, 1990). The mass change is equal to the RC minus the precursor composition. For the purposes of comparison in this study, a relative mass

change is calculated to account for the range of abundance of each chemical component as:

$$\text{relative mass change} = \text{mass change} / \text{precursor composition} * 100$$

Conserved Elements

The elements that are most commonly conserved (or “immobile”) during hydrothermal alteration have been evaluated by several studies of VHMS alteration systems (e.g., MacLean, 1990; Appleyard, 1990). These studies compare concentrations of incompatible elements and high field strength elements to gauge the relative mobility of each element in the altered volcanic rocks. Typically, Ti, Nb, Zr, Y are used since these incompatible elements can be accurately measured by standard analytical techniques (X-Ray Fluorescence) and have a relatively high abundance in mafic and felsic volcanic rocks. Other incompatible elements such as Th, Hf, Ta, and the REE may also be used, when more complicated analytical techniques (Inductively Coupled Plasma-Mass Spectrometry) are used. Aluminum is also commonly used as an immobile element. All of these elements have limited solubility in fluids and require extreme fluid chemistry to be mobilized from the crystallized, solid state (i.e., high temperature, low pH, high fO_2).

The Rusty Ridge data set was used to evaluate the immobility of the typical conserved elements since complete sample coverage within the formation is available and an extensive suite of elements have been analyzed for these samples (Appendix G). Zirconium is used as the conserved element for all the mass balance calculations because of its immobility and because Zr has been measured for all samples in this and previous studies. Other conserved elements identified in the Rusty Ridge Andesite data set are Nb and Th. The REE show a minor degree of mobility; La and the LREE are mobile in some samples, but the HREE are relatively immobile. Al and Ti, show a wide range of mobility and reflect the predominance of epidote, ilmenite, and titanite in the alteration mineral assemblage considered by this study.

Similar trends for Zr occur in the Amulet Andesite formation data set (Appendix G). This supports the use of Zr as the immobile element monitor for the mass balance calculations.

Least Altered Andesite Compositions

Least altered volcanic rock compositions were derived for both the Rusty Ridge and the Amulet Andesite formations (Table 6.1). Using the whole rock data set in Appendix D, samples were geochemically identified as least altered andesite compositions using standard discrimination plots ($\text{Na}_2\text{O}+\text{K}_2\text{O}$ vs SiO_2 , Le Maitre, 1989; SiO_2 vs Zr/TiO_2 , Winchester and Floyd, 1977; Zr/TiO_2 vs Nb/Y ; Winchester and Floyd,

1977). Alteration effects were recognized using normative CIPW calculations for both the Rusty Ridge and Amulet Andesite data sets and compared to accepted andesite compositional ranges (e.g., Best, 1982). In particular, calculations of normative albite, corundum, diopside, and quartz were used to infer the presence of alteration minerals. Excess quartz and albite indicate alteration of the volcanic rocks by silicification and/or spilitization. High values of diopside in the norm suggest calcium metasomatism has occurred in the form of epidote and/or actinolite. The presence of normative corundum indicates excess Al_2O_3 likely due to the concentration of chlorite and/or sericite at the expense of plagioclase. Samples identified as least altered andesites were re-examined petrographically for the presence of hydrothermal alteration minerals.

Least altered andesite compositions from previous studies within the Noranda Cauldron are also provided in Table 6.1. A plot of the least altered andesite compositions for the Rusty Ridge and Amulet Andesite formations illustrates the overlap in primary compositions (Figure 6.1). The range of compositions within the andesite field does not correspond to particular andesitic flow units, thus the average of the least altered compositions for each formation is representative (Appendix H). The least altered composition for other andesites in the central NVC are also contained within this field and suggests the primary compositions within any of the andesite formations in the NVC may be considered homogenous.

Mass Balance Results

The mass balance results for all the samples used in this chapter are given in Appendix I. The trends from mass balance calculations for background alteration and epidote-quartz alteration are summarized in Table 6.2. The percent change relative to the least altered precursor composition is given so that major and trace elements may be directly compared. These are grouped into ranges which discriminate between major and minor mass gains or losses. The range from +10 to -10% is considered as conserved. This relatively conservative approach to the mass balance results accounts for inconsistencies in each altered rock calculation such as; conserved element mobility, sampling bias, mineral heterogeneity, analytical error, and primary volcanic compositional variations. The average value for the gains and losses of each element is does not accurately represent the mass balance trend, since a single high enrichment value can dramatically effect the average. Thus, the modal range for each element is considered. In most cases, the mode represents >50% of the data set, but in some cases, the mass balance results are variable.

Background Alteration

In the *Rusty Ridge formation*, andesitic rocks display widespread depletion in all major and trace elements (Table 6.2). Consistent depletion trends occur for Ti, Fe, Mn, Ca, K, P, Rb, Sc, Ga, and most metals, although mass gains exist for some elements

(Appendix I). The mass balance trends for Si, Al, Na and P are much more variable. Enrichments in Ca occur in andesite wallrocks where epidote-quartz patches are abundant, suggesting that minor concentrations of epidote in the volcanic groundmass are localized near the patches. Sodium enrichments are likely related to spilitization and correlate positively with Si enrichments. Enrichments in Al outside of epidote-quartz alteration zones are likely attributed to background chloritization and/or sericitization. Samples with Si enrichment are not spatially associated with epidote-quartz alteration zones and occur sporadically. Several samples fall within the conserved mass balance range for Si (Appendix I) and illustrate the irregular behaviour of quartz in the background alteration. The widespread depletion in all elements for background alteration may be partially related to the enrichments of Si which dilutes the other whole-rock components. Wholesale depletion of the base metals (Cu, Zn) also characterizes background alteration. The depletion trends of the base metals is among the most consistent observed and is widespread throughout the Rusty Ridge formation.

In the *Amulet Andesite formation*, whole-rock components illustrate an overall enrichment trend which contrasts the overall depletion trends displayed in the Rusty Ridge formation (Table 6.2). Mass changes in the Amulet Andesite are also more extreme compared to the Rusty Ridge with several samples showing major gains and losses in most elements (Appendix I). Consistent enrichment trends exist for Mn, V, Co, Zn and Sc, but other components may be either conserved or depleted. The modal range for K, Na, Rb, Ba, and Cu is not representative, but generally these elements display overall

depletions trends. The mass balance results for Mg, P, Sr, and Ga in the andesitic wallrocks are variable. Only Si has a similar behaviour in both the Rusty Ridge and Amulet Andesite formations reflecting the common occurrence of localized background silicification and quartz precipitation throughout the entire Noranda Cauldron. The erratic behaviour of some of the whole-rock components due to background alteration are spatially associated to the intense epidote-quartz alteration zones within the Amulet Andesite formation. Enrichments in Si, Al, Fe, Ca, V, Cr, and Sr, in particular, are directly associated with epidote-quartz alteration zones and reflect the background concentration of epidote in the andesite volcanic groundmass adjacent to epidote-quartz alteration patches.

Epidote-Quartz Alteration

Calculated gains and losses for epidote-quartz alteration patches are similar in the Rusty Ridge and the Amulet Andesite formations (Table 6.2). The similarities are likely attributed to the predominance of epidote and quartz within the patches and hence, the trends mainly reflect the compatibility of each whole-rock component within the epidote mineral structure.

Enrichments in Ca, Sr, Fe^{3+} , Si, Al, Mn, V, Ga and Sc correlate with epidote abundance. Of these, the most consistent enrichment trends are found for Ca, Sr, Fe^{3+} , V, and Sr (Figure 6.2), indicating significant enrichment by hydrothermal concentration.

Sodium, Fe^{2+} , Mg, K, Rb, and Ba are excluded from any of the cation sites available within the epidote mineral structure and therefore, are depleted on a whole-rock basis. The behaviour of base metals, which are characteristically depleted in epidote-quartz alteration in other volcanic settings, is variable for both the Rusty Ridge and Amulet Andesite data sets. Depletion in Zn and Ni are near-complete for both formations, although Cu and Co display both enrichment and depletion trends. Metal depletion in the epidote-quartz patches is further considered below within this chapter.

Both Ti and P behave as conserved components in the epidote-quartz alteration patches which contrasts from the trends in the background alteration. Titanium is contained within residual ilmenite or titanite present as accessory minerals in most epidote alteration patches. The presence of accessory apatite in the patches accounts for the conservative behaviour of P.

Positive correlations exist among all components which are enriched in the epidote patches (i.e., Si, Al, Fe, Ca, Mn, V, and Sr). The variations in mass gains between each patch largely reflects the relative concentration of epidote versus quartz in each patch rather than any other specific affiliation of any of these components (Figure 6.3). This is particularly apparent for mass gains in Fe, Al, Ca and Sr which correlate with either Si enrichment or depletion.

Fe^{3+} and Al^{3+} are mutually exclusive within the octahedral cation site within the epidote structure, thus variations in the Fe# (calculated as whole rock $\text{Fe}_2\text{O}_3 / (\text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3) * 100$) may reflect the abundance of the clinozoisite or epidote end-members in particular patches. Other Fe-bearing minerals in the epidote patches such as titanite do not effect the whole-rock Fe# since even 5% weight percent titanite in the patch would only affect the Fe# by 0.02 (or 0.05 %). Therefore, the composition of epidote is the main mineral component of the whole rock Fe#. Correlations between the Fe# and other enriched whole-rock components are few (Figure 6.4). Only V shows a particular association with the Fe# and illustrates the chemical affinity of V with Fe^{3+} . The lack of Fe# correlations suggests the bulk rock geochemistry data does not represent variations in the end member epidote mineral compositions.

Variable additions displayed by Si and Al reflect both metasomatic additions and the relatively high concentration of Si and Al in the andesitic wallrocks prior to epidotization. As a result, the absolute enrichment in Si and Al associated with epidote-quartz alteration appear minor compared to the large mass gains of Ca, Sr and Fe^{3+} . Also, the variable quartz content of the epidote alteration patches serves to concentrate or dilute the components such that siliceous patches only display minor enrichments in Fe^{3+} , Ca, Mn, V, and Sr compared to epidote-rich patches.

Enrichments in Fe^{3+} for most patches are conspicuous in light of depletions of Fe^{2+} and suggest the behaviour of iron reflects oxidation reactions during epidote-quartz alteration as well as addition from hydrothermal fluids.

Spatial Distribution of Gains/Losses (Cauldron Scale)

The variations in the mass gains and losses of each element can be examined by the spatial distribution of the samples within the Noranda Cauldron. Components such as Ca, Fe^{2+} , Fe^{3+} , Na, K, Rb, Sr, and Zn which illustrate consistent mass enrichment/depletion trends are obviously not spatially controlled, however. other components vary in relation to the most intense epidote-quartz alteration zones (the Old Waite Paleofissure and the McDougall-Despina Eruptive Centre) (Figure 6.5).

Silicon is typically depleted in both epidote-quartz alteration zones, owing to the concentration of epidote over quartz in the alteration patches. Outside of these zones, epidote-quartz patches contain subequal amounts of epidote and quartz and may be either enriched or depleted. *Manganese* is either depleted or conserved throughout the Noranda Cauldron, but the highest enrichments (> 100 relative %) all occur within the Old Waite Paleofissure. Similarly, enrichments in *vanadium* and *chromium* are also found in the Old Waite Paleofissure and in a single sample from the Amulet Upper A area where epidote-quartz alteration is intense. All three elements, Mn, V, Cr, are compatible with the epidote mineral structure and may substitute for Fe^{3+} and Al in the octahedral cation site.

However, a particular correlation of Mn, V, or Cr with either Fe^{3+} or Al is not evident (Figure 6.4). *Copper* mass gains/losses do not vary systematically with epidote-quartz alteration intensity. Elevated values for Cu in the epidote patches occur in the Amulet Upper A area and reflect the widespread distribution of sulphide mineralization in this area, but a particular spatial relationship to volcanic stratigraphy or to the chloritic alteration pipe which hosts massive sulphides is not apparent in this area.

The *iron ratio* ($\text{Fe\#}$) is also examined to determine if a particular enrichment of clinozoisite versus epidote compositions within the alteration patches occurs spatially. For most samples, the Fe number is relatively high and suggests the bulk composition of alteration patches throughout the Noranda Cauldron is Fe-rich. The magnitude of Al and Fe^{3+} enrichments due to epidote-quartz alteration largely reflect the modal abundance of epidote over quartz in the individual patches. The distribution of distinct Fe/Al epidote bulk compositions does not correspond to the epidote-quartz alteration zones, volcanic stratigraphy, or the mineralized areas at this scale. Epidote mineral compositions are examined in greater detail in Chapter 7.

Distribution of Mass Gains and Losses (patch-scale)

Variations in mass gains and losses associated with epidote-quartz alteration was also examined at the patch-scale. The similarities in mineralogy of most patches in the Noranda Cauldron permit examination of a few representative patches. Three epidote

patches have been sampled in detail to compare variations within individual epidote alteration patches. All three patches occur in strong epidote-quartz alteration zones (> 20% patches) at the outcrop-scale and are representative for each area. Each patch occurs at different stratigraphic levels within the Noranda Cauldron. Figure 6.6 illustrates the sample distribution within each patch as well as some petrographic details. The whole rock geochemical data and re-calculated data are given separately from the regional data in Appendix D

The mass balance results for each patch are summarized in Figure 6.7. All samples display a mass increase relative to the wallrock, but the variable abundance of epidote versus quartz in each patch is illustrated by the concentration of Si (Figure 6.7a). The highest Si values within patch #1 indicate a high proportion of quartz throughout this patch and largely reflect the highly silicified nature of the immediate andesitic wallrock. The mass gains and losses of Si are variable in the patch from the Amulet Andesite formation (patch #2) in which the andesitic wallrock was not silicified. These relationships imply a correlation between the Si content of the volcanic wallrock and the quartz content of the epidote patches. The relative mass changes of Si for each patch show that the inner cores of the patches are epidote-rich compared to the outer core of the patch (Figure 6.7b)

The bulk iron number (Fe#) is similar for all patches regardless of sample distribution (Figure 6.7c). Most samples have Fe# values around 36, which is consistent

with a stoichiometric end-member epidote composition. The high Fe# for the interpillow hyaloclastite epidote within patch#3 distinguishes this alteration texture from the groundmass replacement texture in the other samples. The single anomalous value of 47 from patch#2 from the patch margin reflects the inclusion of chlorite with epidote identified petrographically in this sample.

Whole-rock components that are generally enriched within the epidote-quartz alteration zones (Mn, V, and Cr) are variable at the patch-scale. Variations in V range from partially conserved to moderately enriched (Figure 7d). Similar variations occur for Mn and Cr. Depletion of Zn is common in all three of the patches (Figure 7e), similar to that observed at the cauldron-scale. The behaviour of Cu is erratic and is enriched in some samples (not shown in Figure 7). Enrichment of Cu does not reflect the association of epidote with Cu-sulphides in the individual sample, but is a product of the low Cu concentrations in the andesite precursor wallrocks (confirmed by the absence of sulphide mineral phases in petrographic investigations). Enrichments in Sr are evident in all patches (Figure 7f). The highest Sr values occur in the core of each patch and coincide with the modal abundance of epidote over quartz in the core. These Sr enrichments are enhanced by the relatively low precursor concentrations in the andesite wallrocks resulting from earlier background alteration. Apparent enrichments in Rb for sample AMA (not shown in Figure 7) reflect the low precursor concentration of Rb in the andesitic wallrocks.

The variations of mass gains and losses at the patch-scale are closely associated with the distribution of epidote versus quartz within the alteration patches.

Concentrations of Si occur at the patch margin and epidote is localized within the core thereby diluting whole-rock components along the margin. Variations at the cauldron-scale therefore may reflect the patch-scale distribution of epidote. The variations of typically enriched components (Mn, V, and Cr) are not resolved at the patch-scale and suggest concentration of these elements are controlled at a smaller scale (see Chapter 7).

Lithologic Trends

In this section, comparisons are made between the Rusty Ridge and Amulet Andesite data and alteration patches in rhyolite volcanic rocks as well as patches in andesitic rocks from other formations (Figure 6.8).

In rhyolite, epidote patches are rare even within the intense alteration zones. The two rhyolite samples used here for comparison are texturally similar with epidote-quartz replacement of the volcanic groundmass typically centred on amygdules, although, the two samples occur at different stratigraphic intervals within the Noranda Cauldron. The samples also represent different epidote alteration intensities at the outcrop scale. One is derived from the intense alteration zone within the Old Waite Paleofissure while the other occurs north of the Cranston Fault within a felsic-volcanic-dominated eruptive centre where epidote-quartz alteration intensity is moderate to weak. Despite these differences,

both samples exhibit similar gains and losses within the ranges observed for the andesitic rocks.

Enrichments in Fe^{3+} , Mn, Cr, and Sr are more extreme in the rhyolites than the andesite rocks. Depletions in Na, K and Rb in the rhyolites are not as pronounced as in the andesites. Concentrations of K and Rb within one alteration patch reflect the presence of minor sericite which replaces epidote. Enrichment in Fe, Mn, and V in one rhyolite sample suggests that allanite may be intergrown with epidote and clinozoisite within the alteration patch. These trends reflect the different primary concentration of these components within mafic and felsic volcanic rocks.

Samples of andesites from other formations were taken from within areas of strong epidote-quartz alteration intensity at the outcrop-scale. Three samples from the Amulet formation, upper member are shown in Figure 6.8b in comparison to representative samples from the Rusty Ridge and Amulet Andesite formations. Two of the samples are from the Old Waite Paleofissure are patches that overprint silicification in the andesitic wallrocks developed prior to epidotization while the other sample is of an epidote-quartz patch from the Amulet F Shaft area that formed before the onset of silicification. The different alteration histories in the Amulet formation samples do not appear to be significant in terms of the overall mass balance trends.

Epidote alteration in the Amulet Rhyolite formation upper member follows a similar pattern to that of the Rusty Ridge and Amulet Andesite formations. Typical epidote-enriched components such as Si, Al, Fe^{3+} , and Ca are anomalously high due to the overall mass gain in all these samples (evident by the apparent depletion of Zr in the alteration patches relative to the wallrock concentration). The observed behaviour of the metals is erratic, owing to the depletion of metals in the adjacent wallrock. Only Zn is consistently depleted within the epidote patches. Trace elements appear to be highly mobile and trends of Rb and Sr in these samples contrast with that of other andesite volcanic rocks. Rubidium enrichments are conspicuous and the Sr depletions are due to the overall low concentration of both elements in the andesitic wallrocks.

Comparison is also made using two andesite samples from the Aldermac Mine area, west of the Flavrian Intrusion. The Aldermac Mine volcanic sequence is interpreted to be stratigraphically equivalent to the Norbec Mine or Millenbach Mine sequence (Hunter and Moore, 1983). These samples are from the Aldermac Andesite formation which overlies the host rhyolitic volcanic sequence to the massive sulphides. The mass gains and losses in the epidote-quartz patches are similar in the two samples, but are somewhat unique compared to the trends from the Rusty Ridge and Amulet Andesite formations. Most notable are the enrichments in K and Na which can be attributed to the occurrence of alkali-feldspar throughout the Aldermac area. Several epidote alteration patches in the area have a pink-coloured halo caused by the presence of K feldspar. The K

feldspar is likely related to the late syenite intrusion nearby and to the widespread fenitization throughout portions of the West Camp (Comba et al., 1981).

Absolute Mass Changes

Due to the consistent behaviour of most whole rock components throughout the Rusty Ridge formation, it is possible to calculate absolute mass gains and losses for the entire formation. Using the absolute changes, epidote-quartz alteration in the Rusty Ridge formation may be evaluated as a potential reservoir for whole rock components, particularly metals, that are enriched within the alteration zones which host massive sulphide mineralization. The volume of volcanic rock in the Rusty Ridge formation has been reasonably well constrained by Gibson (1989) and the distribution of epidote-quartz alteration is well known and has been thoroughly sampled.

A complete description of the procedure used to calculate the total mass for volcanic rocks and epidote in the Rusty Ridge formation is provided in Appendix J. The calculations have been made in the five, fault-bounded sectors of the Noranda Cauldron defined by Gibson (1989) (Figure J1). The results are given in Table 6.3 and illustrated in Figure 6.9.

The total mass flux for whole-rock components measured in this study is calculated for background alteration as well as for epidote-quartz alteration. For both

background and epidote-quartz alteration the largest mass changes occur within the Waite-Dufault sector, mainly because of the greater thickness of the andesite succession in the Old Waite Paleofissure. Enrichment of Si in the Waite-Dufault sector is contrary to the overall depletion trend for the Rusty Ridge formation and reflects local silicification in the Old Waite Paleofissure as displayed in other andesite formations in the Noranda Cauldron (Gibson, 1989; Paquette et al., 1997). An overall mass gain in Ca is also apparent in background alteration within the Waite-Dufault sector and is attributed to the concentration of matrix epidote adjacent to alteration patches. Enrichment of Mg in the Amulet-Millenbach sector for background alteration can be attributed to widespread, diffuse chloritization typically found as pervasive volcanic groundmass replacement and coincides with the large Na depletion within this sector (Gibson, 1989).

The absolute mass changes for background alteration are larger than those for epidote-quartz alteration because of the pervasive nature and widespread distribution of background alteration in contrast to the patchy character of the epidote-quartz alteration (Figure 6.9a). Sufficient quantities of Si, Al, Fe^{3+} , Ca, V, Cr, and Sr are stripped from the rocks during initial cauldron-scale fluid:rock interaction (i.e., background alteration) to account for addition to the rocks in the most intensely altered epidote-quartz zones throughout the volcanic succession, although other sources of components such as magmatic fluids or seawater to form epidote-quartz alteration cannot be discounted based solely on the whole-rock data (see Chapter 8).

The relationship between mass gains and losses due to background alteration and epidote-quartz alteration is best displayed within the Waite-Dufault sector where epidote-quartz alteration is most intense (Figure 6.9b). Mass depletion in the andesitic wallrocks due to background alteration exceeds the mass enrichments in the epidote alteration patches in all components except for Ca. This suggests that fluid/rock interaction is not confined to the scale of an alteration patch and the immediate wallrock, but instead are related to larger cauldron-scale processes. The behaviour of iron during epidote-quartz alteration is also evident within the Waite-Dufault sector where Fe^{3+} mass enrichment is completely balanced by Fe^{2+} mass depletion. This implies that oxidation of iron is significant during epidote-quartz alteration and does not necessarily reflect the presence of an Fe-rich hydrothermal fluid. Metal depletion in the Rusty Ridge formation epidote-quartz patches is much less than the depletion related to background alteration. The total amount of metal liberated during epidote-quartz alteration in the Waite-Dufault sector is also much less than the total Cu and Zn within the overlying massive sulphide deposits (Vauze, Norbec, Old Waite, East Waite) Metal depletion is further considered below (Chapter 8).

Mass Additions by Hydrothermal Fluids

The mass gains and losses for epidote-quartz alteration calculated for this study imply a significant amount of fluid has interacted with the volcanic rocks. The compositions of fluids associated with seafloor hydrothermal processes are well known

and can be utilized to predict water:rock ratios for epidote-quartz alteration in the Noranda Cauldron. Representative fluid compositions are provided in Table 6.4. The fluid chemistry has been measured at several active seafloor hydrothermal centres where massive sulphides are being produced; most notably along the East Pacific Rise (Von Damm et al., 1985; Bowers et al., 1988) and along the Southern Juan de Fuca Ridge. Other fluid compositions have been generated by experimental studies that simulate seafloor hydrothermal systems to produce typical alteration mineral assemblages in these settings. In basalt-seawater experiments by Seyfried and Bischoff (1981), an assemblage of anhydrite, wairakite, smectite, and hematite was derived at 300 °C and at a water/rock ratio of 10 yielding a modified seawater composition distinct from the vent fluid compositions ('MS/B', Table 6.4). This assemblage closely approximates the background assemblage described in the CNVC in this study, thus MS/B is also a likely composition of fluids related to epidote-quartz alteration.

Water:rock ratios are calculated using the average mass changes from the andesitic wallrocks and the epidote-quartz patches in the Rusty Ridge formation (Table 6.4). Two of the most enriched components in the epidote-quartz patches, Si and Ca, are also concentrated within most hydrothermal fluids and are used for the calculations. Aluminum is also an enriched component in the alteration patches, but hydrothermal fluids and seawater are generally devoid of Al and are not a likely source for the enrichment. Total Fe is conserved through epidote-quartz alteration of andesitic rocks, but as demonstrated previously, the oxidation state is converted from 2+ to 3+ illustrating

the additional dependence of fO_2 on epidotization. Therefore, Fe-rich hydrothermal fluids, such as the EPR vent fluid, do not promote epidote-quartz alteration without oxidizing conditions and suggest the MS/B fluid composition may be more closely associated to the formation of the patches.

Assuming that volume is constant through alteration, a given mass of andesitic wallrock reacts to produce an equal mass of epidote and quartz. The water:rock ratios are then calculated for seawater, MS/B, and the EPR vent fluid using Ca are 179, 90.5, and 63.2 respectfully and using Si are 294 for MS/B and 74.0 for the EPR fluid. Enrichments in Si are difficult to assess due to the variable abundances of epidote and quartz at the patch-scale, thus the ratios obtained from the calculations using Ca are likely more accurate. A water:rock ratio of 50-100 in experimental studies are associated with Ca and Mg metasomatism, but at ratios above 100, only Mg metasomatism is dominant. Therefore, the ratios calculated for the Rusty Ridge formation epidote-quartz patches are consistent with the experimental results.

The calculated water:rock ratios reflect the mass of fluid required for an individual patch and therefore, can be used to predict the mass of fluid involved at a larger scale. In areas of strong epidote-quartz alteration within the Rusty Ridge formation, the Waite-Dufault Sector, the mass of epidote-quartz patches was estimated to be 5.97×10^8 tonnes (Appendix J). At a conservative water:rock ratio of 75 and assuming a fluid density of 0.7 g/cm^3 (Von Damm, 1993), the total volume of fluid associated with

epidote-quartz alteration in the Waite-Dufault Sector is $4.18 \times 10^8 \text{ m}^3$. This volume can be compared to areas with a lower alteration intensity in the Rusty Ridge formation, such as the Ansil Sector with 5.20×10^7 tonnes of altered rock (Appendix J), in which m^3 of fluid is involved. This represents an influx of almost 10 times the volume of fluid through the Old Waite Paleofissure compared to the volume of fluid associated with lateral fluid flow.

The similar ratios for the MS/B fluid and EPR vent fluid illustrate the consistent behaviour of Ca at temperatures greater than 300°C and may constrain the lower temperature range for epidote-quartz alteration in the CNVC.

Water:rock ratios for epidote-quartz alteration in rhyolite are not confidently calculated since only two samples were analyzed during this study. One rhyolite sample yielded an enrichment of Ca by over 12 g from the wallrock; approximately twice the enrichment displayed by the average andesitic rocks. As such, the water:rock ratio for epidote-quartz alteration in rhyolite would be over 200 using either hydrothermal fluid composition.

Preliminary Whole-Rock Oxygen Isotope Data for Epidote-Quartz Patches

Oxygen isotope geochemistry of volcanic rocks has been studied in several VHMS districts including the CNVC. Most data from these studies did not include

examples of epidote-quartz alteration, thus analyses were made during this study. The $\delta^{18}\text{O}$ data is considered preliminary due to analytical difficulties, but some results are presented here (Table 6.5). Comparison of the data here to other studies in CNVC and to studies of epidote-quartz alteration in other volcanic rock shows several similarities to these studies that reflect the overall good quality of the data in Table 6.5 (discussed further in Chapter 8).

Pairs of samples were analyzed to compare $\delta^{18}\text{O}$ within an individual epidote-quartz patch with the corresponding wallrock. Most samples are rocks from the Rusty Ridge formation within areas of strong epidote-quartz alteration, the Old Waite Paleofissure, with others from less intensely altered areas. Samples of strong epidote-quartz alteration from other andesitic rock formations and from rhyolitic rocks were also analyzed for comparison.

The $\delta^{18}\text{O}$ values for the epidote-quartz patches have a relatively wide range (0.76 - 9.95‰), but generally, $\delta^{18}\text{O}$ is depleted in the patches relative to the host volcanic wallrock. The average of the 13 patches from andesitic rocks (5.26 ‰) is within the range of values from epidote mineral separate analyses within the CNVC (3.5, 4.9, 5.7, and 5.8 ‰; Hoy, 1993; Paradis et al., 1993), but is slightly higher than whole-rock $\delta^{18}\text{O}$ values from epidotized mafic rocks in ophiolites (2.5 - 5.0‰; Harper et al., 1988; Schiffman and Smith, 1988).

The patches in the CNVC andesitic rocks reflect the $\delta^{18}\text{O}$ concentration of both epidote and quartz, thus the wide range is likely attributed to the variable $\delta^{18}\text{O}$ concentration of quartz since epidote is constrained to a relatively narrow range. The $\delta^{18}\text{O}$ relative enrichment in the patches from the Cranston Sector may be due to the relatively high quartz concentration within these patches and likely contain quartz with relatively heavy $\delta^{18}\text{O}$ values.

Epidote-quartz patches in the OWP display a general enrichment trend in $\delta^{18}\text{O}$ with increasing stratigraphic height from 3.73 - 4.79‰ in the Rusty Ridge formation to 5.93‰ in the Amulet lower member rhyolitic rocks to 6.94‰ in the Amulet Andesite formation. This trend excludes the single sample (RRA94023) that contains anomalous $\delta^{18}\text{O}$ values in both the epidote-quartz patch and the andesitic wallrock which may reflect localized hydrothermal fluid conditions. The enrichment trend in $\delta^{18}\text{O}$ within the epidote-quartz patches mimics a similar enrichment trend with respect to increasing stratigraphic height in the volcanic rocks (Paradis et al., 1993) and within the VHMS deposits (Hoy, 1993). Enrichment in $\delta^{18}\text{O}$ reflects the overall duration of the hydrothermal system and fluid:rock interaction.

The overall wide range for $\delta^{18}\text{O}$ in the CNVC epidote-quartz patches potentially reflects high values in epidote that have not previously been reported in CNVC or in alteration in similar volcanic settings. This is the subject of a current research study that

includes $\delta^{18}\text{O}$ analyses of epidote-quartz mineral pairs to further investigate mineralogical as well as hydrothermal controls on the whole-rock data reported here.

Summary

A mass balance approach was used to assess the whole-rock geochemical changes associated with epidote-quartz alteration. To perform the mass balance calculations, Zr was recognized as a conserved element and least altered volcanic rock compositions were determined. Data from the Rusty Ridge and Amulet Andesite formations were used mainly to constrain the mass changes in areas of strong and weak epidote-quartz alteration and at different levels within the volcanic stratigraphy. Mass changes associated with background alteration, which forms prior to epidote-quartz alteration, confirm a general depletion of most elements in both andesite formations. Epidote-quartz alteration is characterized by enrichments in Si, Al, Fe^{3+} , Mn, Ca, V, Cr, and Sr and by depletions in Mg, Fe^{2+} , Na, K, Rb, Ba, Co, and Zn. The mass balance results are consistent throughout the Rusty Ridge formation, but are more erratic for the Amulet Andesite formation. The uniform enrichments and depletions associated with epidote-quartz alteration lower in the volcanic strata are interpreted to reflect multiple episodes of fluid:rock interaction and a longer history of hydrothermal activity. The consistency of the results regardless of alteration intensity suggests the abundance of patches reflects the volume of fluid in a particular area rather than a product of specific fluid compositions or hydrothermal conditions. Strong enrichments of Mn, V, and Cr occur within certain areas

of intense epidote-quartz alteration at the cauldron scale and reflect the overall concentration of epidote over quartz in the individual patches in these areas. The whole-rock geochemical data did not resolve consistent enrichments or depletions of either Al or Fe at the cauldron-scale. Overall geochemical variations at the patch-scale reflect the same mass gains and losses as at the cauldron-scale, but reflect the specific concentration of epidote versus quartz in the cores of the patch. Mass gains and losses in rhyolites are similar to the andesites except for the greater magnitude of enrichment in Fe^{3+} , Mn, and Ca in the rhyolites. Comparison of the mass balance results for the Rusty Ridge and the Amulet Andesite formations to other andesites in the Noranda yield similar mass enrichments and depletions. The erratic behaviour of Cu at all scales and for all lithologies cannot be related to areas of sulphide mineralization. The absolute mass changes calculated for the Rusty Ridge formation illustrate that depletions due to early background alteration are sufficient to account for enrichments associated with epidote-quartz alteration. Although the relative mass changes due to epidote-quartz alteration are more extreme, the absolute mass changes related to background alteration are more significant owing to the larger volume of rock affected.

Table 6.1. Least Altered Compositions of Andesitic Rocks in the CNVC.

RUSTY RIDGE FORMATION (data from Gibson, 1989)														
No.	HG-	HG-	HG-	HG-	HG-	HG-	HG-	HG-	HG-	HG-	HG-	HG-	HG-	AVERAGE
	81193	83120	82088	81202	83070	81194	83266	83261	83006	83264	83265	83005	83263	
SiO2	56.77	54.70	57.42	57.19	56.30	58.21	54.20	55.90	54.00	52.60	53.60	52.80	53.30	55.15
TiO2	1.26	1.03	1.46	1.27	1.27	1.17	1.58	1.52	1.56	1.63	1.65	1.62	1.60	1.43
Al2O3	14.96	14.10	15.60	14.65	15.40	14.64	14.70	14.10	14.40	14.30	14.60	14.60	14.40	14.65
FeO*	10.21	9.41	8.81	9.59	8.91	9.60	11.10	10.30	11.50	11.20	11.40	12.20	11.70	10.46
Fe2O3														
FeO														
MnO	0.18	0.15	0.15	0.16	0.21	0.13	0.15	0.15	0.25	0.17	0.14	0.27	0.16	0.17
MgO	4.95	4.55	2.85	5.25	4.53	5.51	4.63	4.25	3.63	5.08	5.17	4.95	4.16	4.58
CaO	6.27	8.16	5.37	5.58	6.51	5.50	4.92	6.21	5.65	7.22	4.98	4.74	6.43	5.96
Na2O	4.21	3.68	4.50	4.29	4.69	4.01	4.69	4.30	4.36	3.57	4.46	3.98	4.49	4.25
K2O	0.08	1.04	0.07	0.05	0.29	0.09	0.37	0.21	0.28	0.16	0.20	1.00	0.49	0.33
H2OT														
P2O5	0.09	0.17	0.23	0.11	0.21	0.10	0.20	0.20	0.20	0.20	0.22	0.19	0.20	0.18
LOI	0.00	1.70	0.00	0.00	2.08	0.00	2.23	2.00	2.70	2.39	2.62	2.47	1.93	1.55
SUM	98.98	98.69	96.46	98.14	100.40	98.96	98.77	99.14	98.53	98.52	99.04	98.82	98.86	
V														
Cr	55	100	45	55	80	63	40	20	20	40	30	50	40	49
Co														
Ni	12		1	10		6								7
Cu						60								60
Zn	142		91	98		70								100
Be														
Ga														
Sc														
Rb		30			10		10	10	10	20	10	40	10	17
Sr	164	210	129	148	90	142	150	130	50	150	50	60	120	123
Ba	96		30	39		67								58
Cs														
Th														
U														
Nb	3		2	3		6								4
Zr	123	110	131	133	160	122	120	110	90	110	150	120	110	122
Y	33		37	41		31								36
Hf														
Ta														
La														
Ce														
Pr														
Nd														
Sm														
Eu														
Gd														
Tb														
Dy														
Ho														
Er														
Tm														
Yb														
Lu														

Table 6.1. Least Altered Compositions of Andesitic Rocks in the CNVC.

AMULET ANDESITE FORMATION

No.	NOR- 96095B	NOR- 96096A	NOR- 95028A	NOR- 95125A	NOR- 95128B	NOR- 95130A	NOR- 96003B	AVERAGE
SiO ₂	55.71	56.34	57.5	57.3	59.5	59.2	57.95	57.64
TiO ₂	1.18	1.18	1.20	0.87	1.18	0.92	1.23	1.11
Al ₂ O ₃	14.45	14.49	15.0	15.1	14.3	15.7	15.61	14.95
FeO*	15.61	14.51	8.9	10.7	8.6	7.5	8.27	10.6
Fe ₂ O ₃			0.1		0.0	0.0		
FeO			7.9		7.9	7.0		7.6
MnO	0.16	0.17	0.14	0.17	0.14	0.10	0.15	0.15
MgO	3.56	4.37	4.85	4.85	4.37	3.15	2.46	3.94
CaO	1.51	1.18	5.85	6.15	5.22	6.63	8.53	5.01
Na ₂ O	2.55	1.76	4.9	3.1	4.2	4.1	3.08	3.38
K ₂ O	0.12	0.52	0.81	0.84	0.31	0.53	0.37	0.50
H ₂ O ^T			1.8	2.2	2.4	1.8		2.1
P ₂ O ₅	0.16	0.19	0.15	0.44	0.10	0.14	0.28	0.21
LOI	4.73	4.89					1.67	3.76
SUM	99.74	99.6	101.1	101.72	100.32	99.77	99.6	103.29
V	321.8	330.1	260	210	74	140	203	220
Cr	28.6	24.2	59	64	27	66	30.5	43
Co	58.9	52.2	36	30	25	21	37.7	37
Ni	26.4	21.9	65	44	23	50	32.5	38
Cu	11.5	1.8	84	79	100	130	44.4	64
Zn	89	91	59	56	52	26	77.9	64
Be			0.6	0.5	0.8	0.5		0.6
Ga			17	18	19	13		17
Sc	23.7	20.1	27	25	23	18	25.3	23
Rb	3.5	12.9	33	28	30	31	8	21
Sr	57.3	30.7	133	129	214	171	226.4	137
Ba	58.1	245.8	286	121	139	130	106.5	155
Cs			0.16	0.41	0.36	0.34		0.32
Th			1.6	1.5	1.8	1.3		1.6
U			0.35	0.37	0.48	0.32		0.38
Nb	10.3	7.2	6.4	5.8	8.5	5.5	11.9	7.9
Zr	136.4	140.6	126	119	153	114	140.3	133
Y	30.8	22.9	25	22	39	19	29.3	27
Hf			3.0	3.3	4.1	2.9		3.3
Ta			0.4	0.4	0.5	0.3		0.4
La			13	11	17	12		13
Ce			29	25	40	25		30
Pr			3.9	3.1	5.3	3.3		3.9
Nd			17	13	23	14		17
Sm			3.5	3.3	5.7	2.9		3.9
Eu			0.84	0.97	1.70	0.82		1.08
Gd			3.9	3.5	6.7	3.0		4.3
Tb			0.62	0.57	1.00	0.46		0.66
Dy			3.8	3.5	6.1	3.0		4.1
Ho			0.79	0.71	1.30	0.58		0.85
Er			2.4	2.2	3.7	1.7		2.5
Tm			0.35	0.30	0.50	0.25		0.35
Yb			2.2	2.3	3.7	1.8		2.5
Lu			0.33	0.30	0.54	0.25		0.36

Table 6.1. Least Altered Compositions of Andesitic Rocks in the CNVC.

REFERENCE SAMPLES

No.	RRA-1	RRA-2	AMA-2	AMA-1		
n	24	1	2	1		
SiO ₂	57.72	56.27	52.85	54.89	RRA-1	Barrett et al., 1991.
TiO ₂	1.39	1.57	1.42	1.37	RRA-2	Ujike and Goodwin, 1987.
Al ₂ O ₃	15.54	14.3	16.4	16.94	AMA-1	Ujike and Goodwin, 1987.
FeO*	10.97	18.8	9.38	8.33	AMA-2	Shriver and MacLean, 1993.
Fe ₂ O ₃						
FeO						
MnO	0.26	0.2	0.30	0.15		
MgO	4.79	5.26	4.77	5.64		
CaO	5.3	1.32	9.24	5.44		
Na ₂ O	3.67	1.21	4.43	5.3		
K ₂ O	0.18	0.83	0.28	1.61		
H ₂ O ^T						
P ₂ O ₅	0.19	0.22	0.2	0.22		
LOI			1.27			
SUM	100.01	99.98	100.52	99.89		
V		362		300		
Cr		<5		13		
Co		30		35		
Ni		12		65		
Cu						
Zn						
Be						
Ga	19		16			
Sc		32		28		
Rb	4	11	8	41		
Sr	112	8	180	137		
Ba		350		552		
Cs		nd		<0.3		
Th		1.0		2.0		
U		1.0		0.8		
Nb	10		6			
Zr	152	108	97	190		
Y	37	28	20	31		
Hf		2.7		4.6		
Ta		0.4		0.6		
La		7.7		17.9		
Ce		15.2		37.3		
Pr						
Nd		10.7		26.6		
Sm		3.21		5.56		
Eu		1.53		1.73		
Gd						
Tb		0.65		0.82		
Dy						
Ho		1.02		1.44		
Er						
Tm						
Yb		3.01		3.62		
Lu		0.48		0.48		

Table 6.2. Summary of Mass Balance Results of Altered Andesitic Rocks from: (a) the Rusty Ridge formation and (b) the Amulet Andesite formation.

(a)

RESULT	MODAL RANGE	BACKGROUND	EPIDOTE-QUARTZ
ENRICHED	>+100%		Fe ₂ O ₃ , CaO, Sr, Ga
	+50 to +100%		
	+10 to +50%		SiO ₂ , Al ₂ O ₃ , V
CONSERVED	+10 to -10%		TiO ₂ , P ₂ O ₅
DEPLETED	-10 to -50%	SiO ₂ , TiO ₂ , Al ₂ O ₃ , FeO, MnO, CaO, Na ₂ O, P ₂ O ₅ ,	MnO, H ₂ O, LOI
	-50 to -100%	K ₂ O, Cr, Cu, Zn, Rb, Sr	FeO, MgO, Na ₂ O, K ₂ O, Zn, Ni
VARIABLE			Cr, Co, Cu, Rb

(b)

RESULT	MODAL RANGE	BACKGROUND	EPIDOTE-QUARTZ
ENRICHED	>+100%	K ₂ O, Co, Zn	CaO, Cu, Sr
	+50 to +100%	TiO ₂ , CaO, Sc	Al ₂ O ₃
	+10 to +50%	SiO ₂ , Al ₂ O ₃ , FeO, MnO, V, Ni	SiO ₂ , FeO, MnO, LOI, V, Sc
CONSERVED	+10 to -10%	Na ₂ O	TiO ₂ , P ₂ O ₅
DEPLETED	-10 to -50%	LOI, CO ₂ , Rb, Ba	Cr, Rb
	-50 to -100%	Cu	MgO, Na ₂ O, K ₂ O, Ni, Zn, Ba
VARIABLE		MgO, P ₂ O ₅ , Sr, Ga	Co

Note: Modal Range values reflect proportional mass flux relative to the wallrock concentration for each element (discussed in the text). Histograms of mass gains and losses for both the Rusty Ridge and Amulet Andesite formations are given in Appendix I.

Table 6.3. Absolute Mass Balance for the Rusty Ridge Formation. Values in tonnes.

BACKGROUND ALTERATION

SECTOR	1	2	3	4	5	TOTAL
SiO ₂	-3.371E+08	-3.424E+08	7.655E+07	-1.219E+08	-5.534E+08	-1.278E+09
TiO ₂	-2.195E+07	-8.419E+06	-3.351E+07	-8.410E+06	-1.879E+07	-9.107E+07
Al ₂ O ₃	-1.367E+08	-9.951E+07	-1.744E+08	-8.269E+07	-1.802E+08	-6.735E+08
Fe ₂ O ₃ T	-1.590E+08	-1.052E+08	-2.008E+08	-7.325E+07	-1.490E+08	-6.872E+08
Fe ₂ O ₃						
FeO						
MnO	-2.404E+06	-1.058E+06	-6.729E+06	-1.187E+06	-1.943E+06	-1.332E+07
MgO	-7.770E+07	-1.673E+07	-1.094E+08	-1.038E+07	8.297E+06	-2.059E+08
CaO	-1.076E+08	-1.502E+08	4.026E+07	-9.350E+07	-1.930E+08	-5.040E+08
Na ₂ O	-2.084E+07	-3.671E+06	-1.267E+08	-1.723E+07	-6.516E+07	-2.336E+08
K ₂ O	5.360E+06	1.753E+07	-2.033E+07	-5.023E+06	-9.844E+06	-1.230E+07
H ₂ OT	3.147E+07	8.817E+07	2.533E+08	5.150E+07	0.000E+00	4.244E+08
P ₂ O ₅	-1.283E+06	1.547E+06	7.696E+05	-6.862E+05	-2.107E+06	-1.759E+06
LOI	-6.904E+06	5.147E+07	2.966E+07	1.225E+07	4.521E+07	1.317E+08
V	-1.077E+06	-6.057E+05	-1.276E+06	-3.888E+05		-3.347E+06
Cr	-6.045E+04	-1.598E+04	-2.023E+05	-8.012E+04	-1.479E+05	-5.067E+05
Co	-6.885E+03	9.662E+04	7.889E+04	2.421E+03		1.710E+05
Ni	-1.491E+04	8.279E+04	6.471E+04	2.210E+04		1.547E+05
Cu	-1.754E+05	-3.247E+04	-3.122E+05	2.727E+04		-4.928E+05
Zn	-1.806E+05	7.808E+04	-5.155E+05	2.139E+04		-5.966E+05
Be	1.001E+03	2.458E+03	6.397E+03	1.163E+03		1.102E+04
Ga	-3.206E+04	-2.493E+04	1.680E+03	-1.428E+04		-6.958E+04
Sc	-7.304E+04	-1.242E+04	-8.725E+04	-2.256E+04		-1.953E+05
Rb	-9.823E+03	-3.738E+04	-1.373E+05	-2.852E+04	-4.103E+04	-2.540E+05
Sr	-1.949E+05	-3.707E+05	4.766E+05	-1.601E+05	-2.749E+05	-5.240E+05
Ba	-1.765E+05	0.000E+00	4.466E+05	-1.222E+05		1.480E+05
Cs	8.582E+01	4.040E+02	1.028E+03	1.661E+02		1.684E+03

EPIDOTE PATCH ALTERATION

SECTOR	1	2	3	4	5	TOTAL
SiO ₂	1.365E+06	1.336E+07	2.121E+07	1.363E+06	0.000E+00	3.730E+07
TiO ₂	1.062E+04	-1.609E+05	-5.950E+05	4.021E+03	0.000E+00	-7.413E+05
Al ₂ O ₃	5.514E+05	3.338E+06	2.305E+07	3.673E+05	0.000E+00	2.731E+07
Fe ₂ O ₃ T	-9.873E+04	1.487E+05	6.384E+06	1.851E+05	0.000E+00	6.619E+06
Fe ₂ O ₃	5.561E+05	3.569E+06	2.370E+07	7.136E+05	0.000E+00	2.854E+07
FeO	-5.775E+05	-3.035E+06	-1.925E+07	-4.702E+05	0.000E+00	-2.333E+07
MnO	-4.937E+03	-3.012E+04	-6.271E+04	-1.811E+03	0.000E+00	-9.957E+04
MgO	-1.095E+05	-1.506E+06	-1.618E+07	-3.987E+05	0.000E+00	-1.820E+07
CaO	1.108E+06	7.364E+06	5.889E+07	1.410E+06	0.000E+00	6.877E+07
Na ₂ O	-1.919E+05	-1.481E+06	-1.410E+07	-3.557E+05	0.000E+00	-1.613E+07
K ₂ O	-9.128E+03	-1.712E+05	-3.676E+05	-8.187E+03	0.000E+00	-5.562E+05
H ₂ OT	-5.961E+04	-4.330E+05	-5.311E+06	-1.123E+05	0.000E+00	-5.916E+06
P ₂ O ₅	4.657E+02	3.183E+03	-3.247E+05	1.884E+03	0.000E+00	-3.191E+05
LOI	5.030E+04	-1.153E+05	-5.169E+06	-6.629E+04	0.000E+00	-5.301E+06
V	7.172E+01	9.154E+03	2.033E+04	1.750E+03	0.000E+00	3.131E+04
Cr	1.397E+01	-2.991E+02	4.477E+02	-6.557E+01	0.000E+00	9.694E+01
Co	1.085E+03	3.239E+03	-3.470E+03	3.416E+02	0.000E+00	1.197E+03
Ni	1.397E+01	-1.051E+03	-4.929E+03	-1.395E+02	0.000E+00	-6.106E+03
Cu	1.397E+01	-2.638E+03	-7.078E+03	-3.213E+02	0.000E+00	-1.002E+04
Zn	-9.436E+02	-3.449E+03	-3.080E+04	-1.183E+03	0.000E+00	-3.638E+04
Be	1.164E+01	1.360E+01	2.101E+00	2.898E+00	0.000E+00	3.024E+01
Ga	2.925E+02	1.228E+03	7.786E+03	2.021E+02	0.000E+00	9.508E+03
Sc	4.750E+01	-2.994E+02	-2.362E+03	1.087E+00	0.000E+00	-2.613E+03
Rb	1.235E+02	-2.593E+02	-1.809E+02	-4.608E+00	0.000E+00	-3.213E+02
Sr	3.565E+03	3.434E+04	1.810E+05	8.134E+03	0.000E+00	2.270E+05
Ba						
Cs	2.832E+00	-9.651E-01	-2.068E+01	-4.202E-01	0.000E+00	-1.924E+01

Sectors: 1 = Cranston; 2 = Ansil; 3 = Waite-Dufault; 4 = F Shaft; 5 = Amulet-Millenbach

Table 6.4 Data for Water:Rock Ratio Calculations.

Fluid Compositions

	seawater	MS/B	EPR	SJDF_1	SJDF_2
	mm/kg	mm/kg	mm/kg	mm/kg	mm/kg
	(1)	(2)	(3)	(4)	(5)
T	25	300	355	329	270
pH	7.8	5.6	3.3	2.9	2.9
Na	468	477	489		
K	10.2	12.5	26.7		
Ca	10.3	20.4	29.2		
Mg	53.2	0	0		
Si	0.00	4.5	17.8		
Fe	< 0.001	0.063	4959	6150	10500
Mn	< 0.001	0.001	1378		
Al	< 0.001	0.014	--		
Sr (um)	--	--	108		
Zn (um)	0.01	--	--	380	455
Cu (um)	0.004	< 0.01	48	11.2	1.5

1 = seawater (Bruland, 1983; Von Damm et al., 1985)

2 = seawater/basalt reactant fluid at w/r = 10 (Seyfried and Bischoff, 1981)

3 = average of 6 vent fluids from the East Pacific Rise (Von Damm et al., 1985; Bowers et al., 1988)

4 = average of 4 vent fluids from the Southern Juan de Fuca Ridge (Trefrey, 1994)

5 = average of 4 vent fluids from the Southern Juan de Fuca Ridge (Trefrey, 1994)

Rusty Ridge Formation

	Andesite	Epidote Patch		
	average	std dev	average	std dev
	g/100g		g/100g	
Na	1.4	1.0	0.2	0.3
K	0.09	0.13	0.03	0.05
Ca	5.1	3.0	12.5	2.7
Mg	2.1	0.7	0.6	0.4
Si	23.8	5.6	27.5	3.6
Fe	3.1	0.8	3.6	0.8
Mn	0.09	0.03	0.08	0.03
Al	3.2	0.7	4.6	1.0
Sr	187	120	573	231
Zn	57	46	6	6
Cu	38	49	19	18

Table 6.5. Preliminary Whole-Rock Oxygen Isotope Data for Volcanic Rock-Epidote Patch Pairs

SAMPLE	LITHOLOGY	STRAT	AREA	FLOW #	d18O	CHANGE
RRA94002A	EPI-QTZ	RRA	OWP	R4	4.79	-2.10
RRA94002B	ANDESITE	RRA	OWP	R4	6.89	
RRA94010A	EPI-QTZ	RRA	OWP	R7	4.40	-0.16
RRA94010B	ANDESITE	RRA	OWP	R7	4.56	
RRA94018A	EPI-QTZ	RRA	OWP	R10	4.56	-0.29
RRA94018B	ANDESITE	RRA	OWP	R10	4.85	
RRA94020A	EPI-QTZ	RRA	OWP	R2	4.56	-4.53
RRA94020B	ANDESITE	RRA	OWP	R2	9.09	
RRA94023A	EPI-QTZ	RRA	OWP	R5	7.66	-5.84
RRA94023B	ANDESITE	RRA	OWP	R5	13.50	
RRA94026A	EPI-QTZ	RRA	OWP	R11	3.73	-2.21
RRA94026B	ANDESITE	RRA	OWP	R11	5.94	
RRA94035A	EPI-QTZ	RRA	L.Fourcet	Rb	0.76	-1.73
RRA94035B	ANDESITE	RRA	L.Fourcet	Rb	2.49	
RRA94037A	EPI-QTZ	RRA	L.Fourcet	Ra	3.38	-6.45
RRA94037B	ANDESITE	RRA	L.Fourcet	Ra	9.83	
RRA94050A	EPI-QTZ	RRA	Cranston	R6	5.96	2.39
RRA94050B	ANDESITE	RRA	Cranston	R6	3.57	
RRA94052A	EPI-QTZ	RRA	Cranston	R7	9.95	5.99
RRA94052B	ANDESITE	RRA	Cranston	R7	3.96	
NOR95105A	EPI-QTZ	MLA	UAA	--	5.82	0.50
NOR95105B	ANDESITE	MLA	UAA	--	5.32	
NOR95124A	ANDESITE	AMA	OWP	--	7.61	
NOR95124B	EPI-QTZ	AMA	OWP	--	6.94	-0.67
RRA94057A	RHYOLITE	ARL	OWP	--	5.32	
RRA94057B	EPI-QTZ	ARL	OWP	--	5.93	0.61

Notes:

STRAT: RRA = Rusty Ridge, MLA = Millenbach Andesite; AMA = Amulet Andesite;
ARL Amulet lower member

AREA: OWP = Old Waite Paleofissure, UAA = Amulet Upper A area.

FLOW#: from Gibson (1989)

Figure 6.1. Volcanic rock discrimination diagram derived by Winchester and Floyd (1977) with data from the Rusty Ridge and Amulet Andesite formations (data descriptions in Table 6.1). The diagram illustrates the compositional similarities between the two formations and within each formation.

Figure 6.2. Mass balance results for epidote-quartz alteration patches in: (A) the Rusty Ridge formation and (B) the Amulet Andesite formation. Shaded areas in A and B represent all samples analyzed for each formation. Representative samples reflect the modal ranges in Table 6.2. The positioning of each whole-rock component reflects the modal mass change listed in Table 6.2.

Figure 6.3. Correlation of mass gains and losses in the epidote-quartz alteration patches in the Rusty Ridge formation (diamonds) Amulet Andesite formation (squares) samples.

Figure 6.4. Recalculated trace element concentrations versus the iron number (Fe#) in epidote-quartz alteration patches. The iron number is calculated as $100 \times (\text{Fe}_2\text{O}_3 / (\text{Fe}_2\text{O}_3 + \text{Al}_2\text{O}_3))$. Diamonds represent the Rusty Ridge formation samples and squares represent the Amulet Andesite formation samples. Grey squares are from the Amulet Upper A area. Fe# equal to 33 depicts the endmember composition for epidote (shown by the dashed line).

Figure 6.5. Distribution trends of mass balance results for selected whole rock components within the Noranda Cauldron. The Rusty Ridge and Amulet Andesite formations are highlighted in green. Two additional samples from the Amulet formation upper member are also included to give a more continuous sample distribution within the Old Waite Paleofissure. Samples are plotted as circles and crosses according to the ranges used in Table 6.2. Red symbols reflect enrichment while grey symbols represent depletion. The largest red symbol corresponds to the range > +100 relative percent. Crosses represent the conserved mass balance range (±10 relative %).

Figure 6.5. (continued). For the Fe#, the three plotted ranges reflect stoichiometric epidote mineral compositions. The range 0-17 represents clinozoisite, 17-33 epidote, and 33 to 50 Fe-rich epidote.

Patch #1

Amulet Rhyolite Upper Member

- A. Contact - hematization in wallrock (rust stained)..
- B, C, D. Massive epidote with fracture-controlled quartz (mottled texture).
- E. Sharp alteration contact.
- F. Silicified, massive andesite wallrock with disseminated po+cp.
- G. Massive epidote-quartz.
- H. Silicified andesite wallrock at sharp contact with patch.

Scale bar = 20 cm.

Patch #2

Amulet Andesite

- A. Massive andesite; abundant po-cp amygdules.
- B. Andesite wallrock.
- C. Alteration patch contact (sharp).
- D. Alteration patch margin.
- E, F. Massive epidote patch core.

○ quartz-filled gas cavities

● sulphide-filled gas cavities

Scale bar = 40 cm.

Patch #3

Millenbach Andesite

- A. Andesite pillow wallrock.
- B. Massive epidote core.
- C, D. Epidote-replaced interpillow hyaloclastite. Coarse epidote crystals.
- E. Epidote patch margin (quartz-rich).
- F. Massive epidote (quartz-rich).
- ■ ■ cooling joints (quartz-filled)
- △ hyaloclastite (epidotized in white).

Scale bar = 20 cm.

Figure 6.6. Distribution and description of individual alteration patches used for whole-rock geochemistry comparison. Patch 1 is from the Old Waite-Norbec Mines area; patch 2 and 3 are from the Amulet Upper A area.

Figure 6.7. Recalculated concentrations of selected whole rock compositions. Symbols for the samples are: triangles = patch#1; squares = patch#2; diamonds = patch#3. (A) Total mass is the total recalculated mass considering all enrichments and depletions due to alteration. The distribution numbers in B-F (x-axis) correspond to individual sample locations shown in Figure 6.6: 1 = interpillow hyaloclastite; 2 = alteration patch/wallrock contact; 3 = alteration patch rim; 4 = alteration patch outer core; 5 = alteration patch inner core.

Figure 6.8. Recalculated composition of epidote alteration patches in different lithologies throughout the Noranda Cauldron. (A) Rhyolitic rocks (grey diamonds) are compared to representative andesitic samples from the Rusty Ridge (black circles) and the Amulet Andesite (white circles) formations. (B) Andesitic rocks from the Aldermac Andesite formation (grey squares) and the Amulet formation upper member (black squares).

A **B**

Figure 6.9. Absolute mass balance results for the Rusty Ridge formation. (A) Results from all sectors across the Rusty Ridge formation. Background alteration in grey; epidote-quartz alteration in black. (B) Results from within the Waite-Dufault sector.

CHAPTER 7

COMPOSITIONAL ZONING OF ALTERATION MINERALS

Variations in the chemical composition of the dominant alteration minerals associated with epidote-quartz alteration were examined. Samples from traverses across volcanic stratigraphy in the Old Waite Paleofissure and the McDougall-Despina Eruptive Centre and from the traverse along the Rusty Ridge formation were analyzed to determine the compositions of epidote and other alteration minerals in the Noranda Cauldron. The complete data set for the is provided in Appendix E. In this chapter, the epidote mineral compositions are first evaluated at the thin section scale and then in different samples across the cauldron.

Fe/Al Zoning in Epidote

In most cases, regardless of alteration texture or host rock lithology, epidote crystals exhibit strong Fe/Al zoning reflecting exchange between Fe^{3+} and Al^{3+} in the octahedral cation site between end member clinozoisite ($\text{Ca}_2\text{Al}_3\text{Si}_3\text{O}_{12}\text{-OH}$) and epidote ($\text{Ca}_2\text{FeAl}_2\text{Si}_3\text{O}_{12}\text{-OH}$) (Deer et al., 1992). Fe/Al zoning in epidote is evident in cross-polarized light using an ordinary transmitted light microscope, but distinct boundaries between Fe- and Al-rich epidote is easily discernible using the scanning electron microprobe. The difference in atomic mass between Al and Fe of the end member mineral compositions is recognized in electron backscattered images by a distinction in colour

intensity. End-members in each sample were identified based on these images. An example is given in Appendix E. The range of textures that characterize Fe/Al zoning in epidote for all the samples studied is shown in Figure 7.1.

Open-space infilling by epidote typically occurs as coarse, euhedral crystals that contain relatively simple Fe/Al zoning (Figure 7.1a). In amygdules, epidote crystals with Al-rich cores and Fe-rich rims are common, although, epidote crystals in some amygdules may be more complexly zoned (Figure 7.1b). In these cases, regular Fe/Al domains still appear to conform to the crystal shape and crystal rims are Fe-rich.

Epidote formed by the replacement of volcanic groundmass minerals is complexly zoned. In areas of relatively weak alteration, where plagioclase phenocrysts are pseudomorphed by epidote in andesite, a distribution of Fe/Al zones cannot be discerned (Figure 7.1c). Relict phenocryst rims and cores are both Fe- and Al-rich, although zoning is typically developed parallel to the precursor twinning planes. In more intense epidote-quartz alteration, individual crystals are not evident within the patches and individual Fe- and Al-rich domains are small ($< 100\ \mu\text{m}$) (Figure 7.1d). The individual Fe/Al domains within the patches are rarely interconnected and the shapes of each domain are irregular. This apparently random distribution of Fe/Al zones characterizes most epidote-quartz patches throughout the Noranda Cauldron in both andesitic and rhyolitic rocks.

The relict textures and precursor mineral boundaries that are preserved in epidote-quartz patches throughout the Amulet Upper A area (Chapter 5; Plate 8) were examined in detail to observe Fe/Al distribution. In some patches, plagioclase phenocryst outlines are preserved despite pervasive epidote replacement. Fe/Al zoning in epidote does not conform to the plagioclase crystal outline (Figure 7.1e). In other samples in the Amulet Upper A area, relict plagioclase microlite grain boundaries can be seen and the subophitic texture has been preserved. The Fe/Al zoning in the epidote pseudomorphs roughly corresponds to the microlite structure (Figure 7.1f). This relationship is similar to the Fe/Al distribution displayed within epidotized plagioclase phenocrysts (Figure 7.1c) and suggests the zoning may be controlled by the internal structure and the availability of Al within the precursor mineral. However, the absence of these relationships outside of the Amulet Upper A area suggests prolonged hydrothermal activity overprints these controls.

The apparent random distribution of the Fe/Al zoning in the epidote-quartz alteration patches was further investigated using a composite of backscattered images to enlarge the scale of observation. Three samples were used which all displayed good contrast of Fe/Al at the millimetre scale. Each sample represented: (i) the relationship of Fe/Al zoning to alteration contacts, (ii) the relationship of Fe/Al zoning to relict amygdules within the patch and (iii) an overall wide range of Fe- and Al-rich epidote compositions (Figure 7.2).

The most obvious relationship derived from the three samples was demonstrated by Fe/Al zoning with respect to siliceous zones within the patch (Figure 7.2a). The composite images from patch rim to the interior illustrate the concentration of Fe-rich epidote around quartz grains along the patch margin. The Fe-rich domains are developed sub-parallel to the alteration patch contact and appear to be interconnected up to 500 μm in length. Within the core of the patch, Fe-rich epidote domains are fewer and smaller in size ($< 100 \mu\text{m}$).

The variations of Fe/Al zoning in relationship to relict quartz amygdules within an alteration patch are not obvious (Figure 7.2b), although Fe-rich epidote is generally more abundant in proximity to the amygdule. Most Fe- and Al- domains in this samples are confined to less than 100 μm .

Some samples contain Al-rich domains that approach endmember clinozoisite compositions (Figure 7.2c). In this sample, the individual Fe and Al domains are small ($< 200 \mu\text{m}$) and do not coincide with the occurrence with quartz or other micro-textures. The Al-rich domains are typically located within the core of the anhedral epidote masses.

Overall, the fine-scale of Fe/Al zoning that is preserved in all epidote alteration types suggests that recrystallization by later metamorphism is not important. The zoning in euhedral epidote crystals is regular, but zoning in epidote that occurs by replacement is

complex which may reflect prolonged fluid:rock interaction during multiple episodes of hydrothermal alteration.

Epidote Compositions In Different Alteration Textures

A comparison of epidote alteration textures suggests that epidote compositions may be more closely related to texture (and crystallinity) rather than to lithology.

The pistacite (Ps) content ($100 \text{ Fe}/\text{Fe}+\text{Al}$) of epidote was compared for samples from the Rusty Ridge formation (Figure 7.3). Overall, over 30% of all the analyses lie within the relatively narrow range of $\text{Ps} = 25\text{-}30$, and over half of the analyses in the range of $20\text{-}30$. Mineralogically, this places most of the Rusty Ridge epidote compositions between end member epidote ($\text{Ps} = 33$) and the clinozoisite end member ($\text{Ps} < 10$). The mode for all of the different epidote alteration textures is between 20 and 30 and suggests these distinct alteration phases may be genetically related as suggested by petrographic analysis (Chapter 4).

Epidote compositions in the alteration patches range from $\text{Ps} = 10$ to 40, similar to the range for both amygdule and matrix epidote. The widest range of Ps ratios is exhibited by epidote which occupies the matrix in interpillow hyaloclastite. In addition, hyaloclastite-hosted epidote is highly enriched in Fe (up to $\text{Ps} = 50$) compared to the other alteration textures. This likely reflects a contribution of Fe from the hydrothermal

fluid compared to the Fe and Al concentration of the wallrock which constrains the epidote composition in the replacement-type textures (i.e. matrix epidote and patches). The Fe content of fracture-filling epidote is slightly higher than the other epidote occurrences, although the ranges overlap.

Figure 7.4 illustrates the compositional variations in epidote samples with distinct alteration textures that represent different alteration intensity. Samples in Figure 7.4a and b are from intense alteration zones in the Rusty Ridge formation within the Old Waite Paleofissure where the alteration patches are centred on epidote-filled amygdulites. In both cases, the Fe/Al ratios of epidote from the patches overlap with the amygdulite and matrix compositions. In areas within the Rusty Ridge formation where alteration patches are not developed, epidote formed within interpillow hyaloclastite exhibit extreme compositional variability (Figure 7.4c). The most Fe-rich compositions occur as hyaloclastite infilling and are the highest recorded in the Noranda Cauldron by this study. The sample shown in Figure 7.4d is from a moderately altered area of the Rusty Ridge formation outside of the OWP and shows a similar compositional relationship between matrix, amygdulite, and patch epidote. Amygdulites within and outside of the alteration patches overlap in Fe/Al contents. Similar relationships between epidote composition and alteration texture occur in other lithologies. In the Amulet Andesite formation, epidote compositions within patches correspond closely to amygdulite-filling and matrix epidote (Figure 7.4e). In rhyolites, epidote compositions have a relatively narrow range, but textural variations overlap as in andesite-hosted epidote alteration (Figure 7.4f).

Epidote Compositions in Different Lithologies

Samples from the Old Waite Paleofissure and from the McDougall-Despina Eruptive Centre are used to compare epidote compositions from different volcanic formations within the Noranda Cauldron. The ranges of pistacite compositions for the different formations are shown in Figure 7.5. A large proportion of the data lies in the pistacite compositional range of 18-24 and closely approximates to the overall range for the whole Rusty Ridge formation described above. Andesites from the Flavrian and Rusty Ridge formation contain epidote with a similar range (Ps between 9-24). Despite pervasive and intense silicification of andesite volcanic rocks in the Amulet Rhyolite formation upper member, epidote within alteration patches and amygdules also fall within this pistacite range. Epidote from the Amulet Andesite formation exhibits the widest range of compositions from 6.9 to 30.3 with the highest Fe values typically from the Amulet Upper A area. The few epidote analyses from the Millenbach Andesite formation lie outside of this pistacite range. Epidote in this one sample occurs as interpillow hyaloclastite-filling prismatic crystals which display distinct Fe/Al zones and may not be representative for the entire formation. Epidote in volcanic rocks from the Amulet Rhyolite formation occurs as groundmass replacement and vesicle-infilling and is compositionally similar to the epidotes from andesite volcanic rocks.

The Distribution of Epidote Compositions

Figure 7.6 shows the relationship between epidote compositions and stratigraphy. Samples from traverses through the Old Waite Paleofissure (Traverse#3; Figure 7.6a) and the McDougall-Despina Eruptive Centre (Traverse#5; Figure 7.6b) were analyzed to compare epidote mineral variations across stratigraphy and within the epidote-quartz alteration zones. Samples from a traverse along the Rusty Ridge formation (Traverse#10; Figure 7.6c) were used to document epidote mineral variations along a single stratigraphic horizon and across an epidote-quartz alteration zone.

The relatively wide range of epidote compositions within each sample demonstrates the complex Fe-Al zoning prevalent at the individual crystal-scale. Most pistacite compositions lie within the epidote mineral field (Ps range 10-33) particularly where epidote alteration is regionally intense. Samples within the epidote-quartz alteration zones consistently contain the lower pistacite range toward the clinozoisite endmember (Ps < 10). The most aluminous epidote in these traverses overprints the silicified andesites in the Millenbach formation (sample 95105; Figure 7.6b). Samples with pistacite compositions above the epidote range (Ps > 33) tend to occur outside of the epidote-quartz alteration zones near the top and bottom of the stratigraphic columns. Rhyolites within epidote-quartz alteration zones contain similar epidote compositions as the underlying andesitic volcanic rocks (sample 94057; Figure 7.6a). Andesite dykes within the Old Waite Paleofissure are equally epidotized compared to the surrounding

lava flows and epidote compositions in the different lithologies overlap (sample 95116; Figure 7.6a).

The relationships between epidote mineral compositions and the distribution of intense epidote-quartz alteration is more apparent within the Rusty Ridge formation (Figure 7.6c). Within the Old Waite Paleofissure, pistacite compositions are within the epidote mineral field. Away from this eruptive centre, higher values of Fe in epidote are obtained and the overall pistacite range is larger. The most extreme pistacite range occurs in epidote as hyaloclastite matrix in an area of weak epidote-quartz alteration from Ansil Hill (sample AH-002).

Although epidote compositions in the three traverses overlap, the extreme values in each sample appear to coincide with the most intense epidote-quartz alteration zones. The most aluminous epidote compositions occur within the epidote-quartz alteration zones and Fe-rich epidote occurs outside of these zones.

Trace Elements in Epidote

Few elements other than Ca, Si, Al, and Fe were detected in abundant quantities during the microprobe analyses. Manganese is the next most abundant element to be concentrated in the octahedral site of epidote after Al and Fe. A general enrichment trend in Mn occurs with the more Al-rich epidote compositions regardless of texture (Figure

7.7a) or lithology (Figure 7.7b). The highest Mn concentrations in andesite volcanic rocks occur in the Amulet Upper A area and confirm the mass balance results of high Mn enrichment that corresponds with the epidote-quartz alteration zones. Epidote in rhyolite rocks from the Amulet Rhyolite are similarly Mn-enriched. Epidote in rhyolites throughout the Noranda Volcanic Complex also tend to be REE-enriched (Hannington et al., 1998). Some analyses of epidote contain elevated concentrations of Ti (Figure 7.7c). Values above 0.02 cations for Ti are well above analytical detection limits and can be considered accurate. These enriched Ti concentrations in epidote are exclusive from any association with titanite or ilmenite and occur in the andesite volcanic rocks containing Fe-rich epidote. The trends for high concentrations of V above analytical detection limits are similar to those for Ti (Figure 7.7d). A positive correlation between high V and high Mn is particularly evident in the samples from the Amulet Upper A area and likely reflects the high epidote alteration intensity in that area.

Chlorite Mineral Compositional Variations

Chlorite mineral compositions were also determined by microprobe analyses, particularly where spatially associated with epidote. In particular, background chlorite which forms as the near-complete replacement of volcanic glass in both andesites and rhyolites was analyzed to determine the most dominant alteration mineral phase before the onset of epidote-quartz patch development. The chlorite mineral chemistry data is

provided in Appendix E and is shown relative to stratigraphy along the Old Waite Paleofissure and the McDougall-Despina Eruptive Centre (Figure 7.8).

The chlorite compositions are relatively well constrained throughout stratigraphy. All chlorites fall within the chamosite field of a standard chlorite composition plot (Hey, 1954) with Si concentration within the range of 5.6-6.2. Distinction of chlorites can be made according to the Fe/Mg ratio between pycnochlorite (Mg-rich chamosite) and brunsvigite (Fe-rich chamosite). Along both sections, most chlorite compositions correspond to the pycnochlorite range with only a few anomalous samples within the brunsvigite range. The Fe-rich varieties of chlorite cannot be related to lithology, but are confined to the lower portion of each section. The background chlorite compositions are distinct from those within the VHMS deposits which commonly have Fe/Mg values above 75 (MacLean and Hoy, 1990; Barrett et al., 1991; 1993).

Summary

The Fe/Al ratio of epidote is variable at several scales within the Noranda Cauldron. X-Ray backscatter images from the scanning electron microprobe demonstrate distinct Fe- and Al-rich zones within epidote at the micron-scale. Coarse, euhedral epidote developed within vesicles illustrate a general Al-rich core and Fe-rich rim zonation, although several Fe/Al zones may occur within a single crystal. Replacement-type epidote textures have variable Fe/Al distribution. Epidote-quartz patches are the most

complexly zoned with individual Fe- and Al-rich domains less than 50 μm in size. In most patches, the Fe/Al distribution appears random, although, in the Amulet Upper A area relict plagioclase microlite grain boundaries are highlighted by Fe/Al zones. In some patches, Fe-rich epidote corresponds to the occurrence of quartz along the margin of the alteration contact with the andesite wallrock. The preservation of these fine Fe/Al zones in coarse crystals and within the epidote-quartz patches reflects the lack of recrystallization due to later contact or regional metamorphism. The modal pistacite range for the different epidote alteration textures is relatively narrow (between 20 and 35) and suggests a genetic relationship between early-formed epidote (matrix and vesicle-filling) and epidote within the alteration patches. Hyaloclastite infilling epidote is relatively Fe-enriched compared to the other epidote alteration textures and may reflect the relative temperature of epidote formation or the high Fe concentration of the hydrothermal fluid. Similarly, pistacite compositions of epidote from different volcanic formations also overlap with the modal value for each formation between 18 and 24. At the cauldron-scale, Al-rich epidote occurs within strong alteration zones (the Old-Waite Paleofissure and the McDougall-Despina Eruptive Centre) regardless of the lithologic composition of the wallrock. Other elements are not particularly abundant compared to Fe and Al in the octahedral cation site of epidote in the Noranda area. Anomalous concentrations of Ti, Mn, and V have been detected. High concentrations of Mn typically correspond to Al-rich epidote, whereas enrichment in Ti and V typically occur with Fe-rich epidote. Background chlorite compositions do not vary appreciably throughout the Noranda Cauldron. Most background chlorite is Mg-rich particularly compared to chlorite that is

associated with sulphide mineralization. Thus, precursor chlorite compositions do not appear to be related to the Fe/Al concentration of later formed epidote.

Figure 7.1. X-ray backscatter SEM images of Fe/Al zoning in epidote.

(A) Euhedral epidote in amygdule showing simple Fe/Al zoning from crystal rim to core (NOR95111B). (B) Euhedral epidote in amygdule showing cyclic Fe/Al highlighting progressive precipitation stages of epidote growth. (RRA94052A). (C) Plagioclase phenocryst pseudomorph by epidote (matrix epidote). A crude core to rim Fe/Al zoning is apparent, but also appears intergrown. (UAA96912). (D) Typical complex distribution of Fe and Al in epidote within an alteration patch. Al-rich zones are shown by the arrows (dark areas). (RRA94012). (E) Relict plagioclase phenocryst (edge marked at arrow) within massive epidote-quartz patch. Fe/Al distribution appears disordered. (UAA94907A). (F) Relict plagioclase microlite texture preserved by Fe/Al zoning within an epidote alteration patch. Microlite outline shown with dashed line. Microlite pseudomorphs contain Fe-rich cores and Al-rich rims (UAA96912A).

Mineralogy

Figure 7.2. Composite of X-Ray backscatter images illustrating mm-scale Fe/Al variations. Mineralogy is identified by the greyscale colour variations. (A) Variations of Fe/Al zoning related to alteration patch contact. The arrow points toward the edge of the patch beyond the view of the images. (Sample NOR95124).

Mineralogy

Figure 7.2. Composite of X-Ray backscatter images illustrating mm-scale Fe/Al variations. Mineralogy is identified by the greyscale colour variations. (B) Variations of Fe/Al zoning in relationship to relict quartz amygdules within the alteration patch. (Sample RRA94050).

Mineralogy

Figure 7.2. Composite of X-Ray backscatter images illustrating mm-scale Fe/Al variations. Mineralogy is identified by the greyscale colour variations. (C) The distribution of Fe/Al zones with a wide range of compositions within the core of an alteration patch. (Sample RRA94020). Arrows highlight Al-rich domains that approach endmember clinozoisite compositions.

Figure 7.3. Pistachite ranges (Fe/Fe+Al octahedral cations) for epidote within the Rusty Ridge formation grouped according to alteration texture. The arrows indicate the modal range of pistachite composition for each textural variety. Overall the textural varieties overlap in composition, although the highest Fe values occur as hyaloclastite infilling.

Figure 7.4. Epidote mineral composition variation according to alteration texture within individual samples: (A) RRA94008/010 (hyaloclastite infilling/patch sample pair) within the OWP, (B) RRA94029 within the OWP, (C) ANH94002 from Ansil Hill (weak epidote alteration intensity), (D) RRA94052 sparse epidote alteration patch developed outside of the OWP, (E) NOR95127 from the Amulet Andesite formation near the Norbec Mine site (OWP); (F) RRA94057 epidotized rhyolite in the OWP.

Figure 7.5. Histogram of epidote pistachite composition for different volcanic formations in the Noranda Cauldron. The arrows indicate the modal range for each formation. Formation abbreviations: FLA = Flavrian; RRA = Rusty Ridge; ARL = Amulet Rhyolite lower member; ARU = Amulet Rhyolite upper member; MLA = Millenbach Andesite; AMA = Amulet Andesite; UAA; Amulet Andesite, Amulet Upper A area.

Figure 7.6. Epidote compositions through stratigraphy along sampling traverses. Volcanic stratigraphy is after Gibson (1989). In each section black triangles represent massive sulphide deposits and formation abbreviations are given in Figure 2.4.(A) Traverse #3 is along the Old Waite Paleofissure. Alteration symbols shown in (C).

Figure 7.6. Epidote compositions through stratigraphy along sampling traverses. Volcanic stratigraphy is after Gibson (1989). (B) Traverse #5 is along the McDougall Despina Eruptive Centre.

C

Figure 7.6. Epidote compositions through stratigraphy along sampling traverses. Volcanic stratigraphy is after Gibson (1989). (C) Traverse #10 is along the Rusty Ridge formation.

Figure 7.7. Epidote mineral chemistry variations for trace elements near analytical detection limits. (A) Overall positive correlation of Mn and Al in epidote from the Rusty Ridge formation. The correlation does not coincide with alteration texture. (B) Positive correlation of Mn and Al in all lithologies in the Noranda Cauldron. (C) Correlation of Ti and Fe³⁺ according to lithology. (D) Correlation of V and Fe³⁺ according to lithology. Formation abbreviations given in Figure 7.5.

Figure 7.8. Chlorite mineral chemistry variations through stratigraphy. Chlorite compositional names from Hey (1954). Stratigraphic column and alteration symbols to the left of the section as in Figure 7.6. (A) Traverse #3 is along the Old Waite Paleofissure.

Figure 7.8. Chlorite mineral chemistry variations through stratigraphy. Stratigraphic column and alteration symbols to the left of the section as in Figure 7.6. (B) Traverse #5 is along the McDougall Despina Eruptive Centre.

CHAPTER 8

DISCUSSION

Hydrothermal Versus Metamorphic Origin for the Alteration Minerals

The relationships identified during this study indicate that the epidote-quartz mineral assemblage can be ascribed to hydrothermal alteration processes and not metamorphic effects. Epidote-quartz alteration zones are cut by discordant chlorite-sericite alteration that is associated with the VHMS deposits. The wide range of $\delta^{18}\text{O}$ values for the epidote-quartz patches also discounts metasomatism by metamorphic fluids. A number of additional observations are consistent with a synvolcanic origin for the epidote-quartz assemblage: 1) The spatial relationship of this assemblage at the cauldron-scale to mafic eruptive centres and synvolcanic structures constrains the development of this assemblage to the time of active volcanism. 2) The variable distribution of epidote-quartz patches at the outcrop-scale reflects fluid circulation controlled by primary permeability and is not likely a product of regional metamorphism. 3) The selective replacement of vitric volcanic material by epidote in areas of relatively weak alteration is consistent with the early alteration of glass. 4) The mass gains and losses of chemical components from the epidote-quartz patches indicate that a significant amount of fluid was responsible for the complete replacement of the volcanic groundmass. 5) The fine scale, Fe/Al zoning in epidote is evidence that primary crystallographic features may have been preserved.

The origin of the minerals considered here as background alteration is less clear. A distinction between a hydrothermal or metamorphic origin for these minerals is difficult using only petrographic techniques particularly within the Mine Sequence where background alteration appears ubiquitous. In contrast to epidote-quartz alteration, it has been argued that regional greenschist metamorphism in the CNVC and the Blake River Group may have been responsible for the widespread background alteration, particularly where there is no obvious spatial relationship to sulphide mineralization or to post-volcanic intrusions (e.g., Jolly, 1978; Powell et al., 1995). However, the predominance of chlorite in the CNVC can be mainly ascribed to regional-scale hydrothermal fluid flow. In modern submarine volcanic settings, low temperature alteration of mafic volcanic glass produces minerals such as palagonite or smectite (e.g., Alt et al., 1986; Alt, 1997), which are altered to chlorite at temperatures $>300\text{ }^{\circ}\text{C}$ (Seyfried and Bischoff, 1981; Seyfried et al., 1988). Replacement of palagonite textures by chlorite in mafic pillowed flows in the South Camp (Dimroth and Rocheleau, 1979) and in the Main Camp (Gibson et al., 1999) confirms that background chlorite alteration in these areas was likely a product of hydrothermal fluid:rock interaction. The origin of background actinolite is still unclear. The occurrence of amphiboles is associated with the Lac Dufault Intrusion (deRosen-Spence, 1969), but the widespread distribution of actinolite throughout the NVC may be related to regional-scale hydrothermal alteration (Hannington, 1997).

Low temperature, calc-silicate alteration minerals such as prehnite or pumpellyite occur outside of the Main Camp, north of the Hunter Creek Fault as volcanic glass replacement (Gelinas et al., 1982; Dimroth et al., 1983; Powell et al., 1995; Stewart, 1998). The absence of these minerals in the Main Camp may reflect the replacement of these minerals by epidote during prograde hydrothermal alteration. Similar epidote-rich assemblages are found locally in prehnite-pumpellyite facies rocks outside the Main Camp (e.g., New Insko-Magusi River area). The presence of epidote in subgreenschist rocks highlights local areas of synvolcanic alteration that cannot be related to later regional metamorphism (Hannington et al., 1998).

Development of Alteration Mineral Assemblages in the Noranda Cauldron

The paragenetic relationships derived from regional sampling, detailed mapping and petrographic descriptions of the alteration mineral assemblages in Main Camp reflect the progressive development of the volcanic succession. The alteration paragenesis, shown in Figure 8.1, is illustrated on a simplified section of the Noranda Cauldron which corresponds a relative time scale. The alteration scale to the left of each mineral assemblage is a volume percent estimate for the entire volcanic formation. The mineral assemblages produced by contact metamorphism during post-volcanic intrusion are given on the right.

Background alteration minerals are ubiquitous and do not concentrate at any specific time interval. Both albite and chlorite are present in andesites and rhyolites and represent the first hydrothermal alteration phases, most likely developed as products of cooling of the volcanic rocks soon after extrusion at or near the seafloor surface. Early replacement-type alteration is represented by actinolite in andesites and by sericite in rhyolites and are likely the products of hydrothermal alteration well below the seafloor. Widespread matrix epidote may also be attributed to deep, sub-seafloor processes. In general, matrix epidote is concentrated in areas that also contain abundant alteration patches and it is likely that both are related to regional-scale hydrothermal fluid upflow. Carbonate, as background alteration, also represents sub-seafloor alteration in both mafic and felsic volcanic rocks, but its occurrence in the Mine Sequence outside of the volcanic centres suggests carbonate alteration signifies a lower intensity of hydrothermal alteration similar to the prehnite-pumpellyite assemblage.

The timing of discordant chlorite-sericite alteration is closely linked to occurrence of VHMS mineralization. The volume of chlorite-sericite alteration is proportional to the amount of massive sulphide mineralization at a particular stratigraphic interval; the largest chlorite-sericite alteration zone is associated with the largest deposit within the Noranda Cauldron (e.g., the Quemont deposit). Other, large chlorite-sericite alteration zones are not well exposed at surface, but are evident in section (Figure 4.2) and represent large hydrothermal fluid upflow zones associated with sulphide mineralization. Both the Waite Rhyolite and Millenbach Rhyolite lava domes contain large chlorite-sericite

alteration zones. Deep chlorite-sericite alteration zones were traced 500 m below the Millenbach and Norbec deposits which both occur at this stratigraphic interval (Pirie and Nicholl, 1981; Knuckey et al., 1982). VHMS mineralization at the top of the Millenbach-Waite Andesite Formation, represented by the Old Waite and the Lower Amulet A deposits, is also associated with large chlorite-sericite alteration zones at depth in the footwall of each deposit. VHMS mineralization at other stratigraphic intervals lower in the Noranda Cauldron, Ansil and Corbet, are enveloped by chlorite-sericite alteration zones that are truncated by the Flavrian Intrusion.

While each of these chlorite-sericite alteration zones are vertically extensive, discordant alteration is not typically developed laterally from the sulphide deposit area. Consequently, the total volume of altered rock is relatively small compared to semi-conformable alteration.

Semi-conformable alteration (epidote-quartz and silicification) encompasses much more of the volcanic stratigraphy and more of the alteration history compared to discordant chlorite-sericite alteration. Both have been shown to be related to major episodes of volcanic activity during the development of the volcanic sequence within the Noranda Cauldron and extend beyond the deposit-scale (Gibson, 1989; this study). Semi-conformable alteration is most intense (shown as “peaks” in Figure 8.1) during maximum volcanic activity and gradually decreases or abruptly terminates at the end of each volcanic event.

Silicification is prominent during two separate episodes of volcanism. A period of strong silicification developed during the extrusion of mafic volcanic rocks which formed the Amulet Rhyolite formation (Gibson et al., 1983). A second, less intense episode of silicification occurred near the top of the Waite Andesite formation (Gibson, 1989). Both silicification events correlate directly with massive sulphide mineralization in the Waite, Amulet and Millenbach deposits. The intense silicification is believed to be responsible for the containment of hydrothermal fluids and for focusing fluid flow (ground preparation) prior to massive sulphide deposition. Another minor episode of silicification appears toward the top of the Rusty Ridge formation within the Cranston eruptive centre and prior to the Amulet Rhyolite formation event. No known massive sulphide mineralization is associated with this silicification, and it may be related to later synvolcanic faulting and dyke emplacement that cuts the cycle III volcanics (Gibson, 1989).

Peaks of epidote-quartz alteration recur throughout the Mine Sequence and coincide with time-stratigraphic intervals of mafic volcanism. The intensity of alteration is directly related to the volume of mafic volcanism within the associated eruptive centre. The peaks appear enhanced due to the comparative paucity of epidote-quartz alteration in the rhyolitic rocks. The most widespread and intense epidote-quartz alteration is developed in the two thickest andesite units, the Rusty Ridge and Amulet Andesite formations. Both peaks represent the cumulative epidote-quartz alteration associated with

two separate mafic eruptive centres. The distribution and intensity of epidote-quartz alteration within the Rusty Ridge formation is largely a product of volcanic events within the Old Waite Paleofissure. Epidote-quartz alteration developed in the Amulet Andesite formation is related to mafic volcanic events in both the OWP as well as the McDougall-Despina eruptive centre. A third, large peak is inferred for the Flavrian Andesite formation despite sparse distribution of outcrops. Abundant epidote-quartz patches in the Flavrian Andesite rocks are developed well outside of the mafic eruptive centres and have been documented throughout in the footwall andesitic rocks around the Corbet deposit (Gibson et al., 1993). Smaller epidote-quartz alteration peaks are associated with the other andesite formations within the Mine Sequence. Epidote-quartz patches are widely developed in the Waite-Millenbach formation as well as in the silicified areas of the altered andesite flows in the Amulet Rhyolite formation.

The intensity of epidote-quartz alteration in different areas of the Noranda Cauldron reflects the cumulative effects of successive magmatic events (Figure 8.2). At the early stage of volcanic development, successive lava flows are extruded at the seafloor and subsequently buried. The hydrothermal system developed as fluids were trapped and heated within the pile during burial. Open space precipitation by secondary minerals was dominant at this early stage. Alteration of volcanic rocks was restricted to lava flow tops (mainly silica dumping) and local groundmass replacement within the eruptive centre (silicification and epidotization). Pervasive background alteration

occurred throughout the section near the seafloor. The relationships described at Ansil Hill represent this stage of the hydrothermal system.

As volcanic activity progressed, a thick volcanic succession accumulated and high temperature hydrothermal fluid circulation was promoted by the continued injection of synvolcanic dykes as feeders to the overlying flows (Stage 2, Figure 8.2). Burial of hot volcanic flows generated a high geothermal gradient. Subsidence and subsequent faulting in the eruptive centre allowed additional fluids to penetrate the volcanic rocks and promoted alteration. Epidote-quartz patches developed throughout the eruptive centre at this stage, particularly where earlier-formed epidote was already present, but strong alteration was concentrated deep below the seafloor. The development of epidote-quartz alteration outside of these centres was limited by the earlier stages of open-space silica dumping which effectively sealed the volcanic rocks from later hydrothermal fluid flow. These relationships are evident in the Lac Duprat South area where epidote-quartz alteration is locally intense, but not particularly widespread.

Silicification was most intense at this stage (the major peak in Figure 8.1) evident by the pervasive replacement of the volcanic groundmass by quartz. At this stage, silicification overprinted open space-filling epidote textures and earlier developed alteration patches as demonstrated in the Amulet F Shaft area.

At the final stage of volcanic development, cross-cutting synvolcanic dykes and faults allow hydrothermal fluids to penetrate the entire succession. Numerous synvolcanic faults outside of the eruptive centres are generated in response to cauldron subsidence (Gibson, 1989). Much of the strong epidote-quartz alteration is developed at this stage during the extrusion of a thick mafic volcanic flow succession at the top of the sequence (the Amulet Andesite formation). This stage of epidote-quartz alteration overprints earlier formed semi-conformable and background alteration at all stratigraphic levels below the Amulet Andesite formation throughout the sequence. Deep in the sequence, lateral fluid flow promotes the generation of alteration patches well outside of the volcanic centre. Andesitic formations, such as the Rusty Ridge and Flavrian Andesite, acted as major hydrothermal aquifers to this lateral flow. Slightly higher in the sequence, epidote-quartz patches overprint the intense silicification zones as illustrated in the Old Waite-Norbec Mine area, but are not well-developed in the silicified andesites outside of the eruptive centre. Near the top of the sequence, volcanic flows within the eruptive centre contain patchy epidote-quartz alteration, but are relatively unaltered outside of the centre (the Amulet Upper A area). The size of the epidote-quartz alteration peak in the Amulet Andesite formation (Figure 8.1) is related to the relatively thick sequence of mafic volcanism at this stage and to progressive Ca enrichment of fluids due to interaction with a now thick volcanic pile. However, extensive epidote-quartz alteration did not occur in the Amulet Andesite formation beyond the eruptive centres due to waning mafic volcanism at the end of cycle III.

The development of epidote-quartz alteration terminates at the end of cycle III as volcanic activity evolved to more felsic compositions. The overlying rhyolites in the cycle IV Here Creek formation do not contain significant epidote. Epidote-quartz alteration is not important in the cycle IV volcanic rocks due to the paucity of mafic volcanism. The local occurrence of epidote-quartz alteration in the cycle IV mafic volcanics is likely attributed to the early development of seafloor alteration (Stage 1; Figure 8.2) unrelated to the development of the Noranda Cauldron.

Chemical Reactions Associated with Epidote-Quartz Alteration

The alteration paragenesis associated with the development of epidote-quartz alteration patches in the CNVC can be simplified to basically two stages, based on the petrographic descriptions and geochemical data presented here:

- (1) background alteration of plagioclase and volcanic glass in “unaltered andesites” to 40 % chlorite, 45 % albite, 10 % quartz and 5 % epidote and/or actinolite and/or carbonate (“spilitic alteration assemblage”).
- (2) epidote-quartz alteration of background minerals to 70 % epidote and 30 % quartz.

The chemical reactions involved with each stage are given in Table 8.1.

Spilitization of mafic volcanic rocks in most geothermal and seafloor hydrothermal systems generates a mineral assemblage of albite, smectite, prehnite (or wairakite), carbonate, quartz, and Fe-hydroxide minerals (Bischoff and Dickson, 1975; Henley and Ellis, 1983; Reed, 1994; Alt, 1997). Hydrothermal fluids associated with spilitization are compositionally modified from seawater due to increased temperature and prolonged fluid:rock interaction (Table 6.4; Seyfried and Bischoff, 1981). In the CNVC, few of these minerals have been preserved, but are represented by the background assemblage described here.

Alteration of plagioclase in andesitic rocks by Na-rich fluids (Table 6.4) produces albite and quartz with excess Ca and Al that are both likely utilized in forming prehnite and smectite (reactions i, ii, and iii). Prograde alteration (increasing temperature) of both prehnite and smectite results in the formation of epidote and chlorite in the CNVC background assemblage without significant metasomatic effects (reactions v and vi). However, the relatively low abundance of matrix epidote in the CNVC andesites suggests hydrothermal fluids are enriched in Ca during this stage of alteration. Background chlorite compositions in the CNVC are typically Mg-rich (Chapter 7), indicating that Fe contributions from an evolved hydrothermal fluid were minimal.

The second stage of alteration involved the breakdown of the background minerals to form the epidote-quartz patches. Destruction of groundmass albite and

chlorite provided the necessary Al to form epidote and yielded Na, Mg, and Si to the hydrothermal fluids (reactions vii and viii; Table 8.1). The mass balance results demonstrate that additional Ca was added to form the epidote-quartz alteration patches, suggesting that the hydrothermal fluids were sufficiently enriched in Ca to drive this reaction (reaction ix; Table 8.1). The breakdown of chlorite also releases Fe, which may be incorporated in epidote. Silica in the hydrothermal fluids is partially conserved in the altered rocks as indicated by the widespread presence of quartz in the patches (reaction x; Table 8.1).

This reactions involved can be illustrated on an Al-Ca-Fe ternary diagram (Figure 8.3). The four ternary plots each represent slightly different lithologic and stratigraphic settings within the Noranda Cauldron, but the similarities between each plot indicate similar hydrothermal reactions involved in forming epidote. In all examples, the extent of background alteration is indicated by the relative abundances of chlorite and albite. For andesites, background alteration does little to the unaltered protolith composition as is indicated by the largely conservative behaviour of Al, Ca, and Fe during the formation of chlorite. The presence of background epidote (and/or actinolite) does not appreciably effect the overall Ca-Al-Fe distribution during spilitization and reflects the recycling of these components (reactions i, iii, iv, v; Table 8.1). This is particularly evident in the Rusty Ridge formation example (Figure 8.3a).

In the andesitic rocks, formation of epidote-quartz patches drives the whole rock composition toward the epidote compositional range. The addition of Ca during epidotization gives an apparent depletion in Fe and Al on the ternary diagrams, but the whole-rock mass balance results indicate both of these are added as well. Compositional variations in epidote within all the patches are also shown on the ternary diagrams to illustrate the relative concentration of epidote versus clinozoisite in each patch. Production of end-member clinozoisite requires significant metasomatic changes from the bulk rock composition and represents the most extreme hydrothermal alteration.

In rhyolite, the formation of epidote produces an Al-rich whole-rock composition that reflects the incomplete reaction of the volcanic rock (Figure 8.3b). Nevertheless, larger additions of Al and Fe are required in rhyolite compared to andesite to produce epidote. The small size of most patches in rhyolite are likely attributed to the availability of Fe and Al in the rocks. Thus, the enrichment factors associated with epidote alteration (and therefore fluid:rock ratios) is also likely higher in rhyolite compared to andesite.

A third reaction is evident in the andesite samples within the Lac Dufault Granodiorite contact metamorphic halo where epidote is locally overprinted by amphibole (Figure 8.3c and d). This reaction implies that metasomatism of Fe and Ca coincided with the contact metamorphism, at least at the mineral-scale, and the

suggestion of 'isometamorphic' conditions within the aureole' (e.g., Riverin and Hodgson, 1981) should be re-evaluated.

Epidote-Quartz Alteration and Regional Oxygen Isotope Patterns in the CNVC

The distribution of regional whole-rock oxygen isotopes has been extensively studied throughout the entire NVC (Cathles, 1993; Taylor, 1997). These studies have utilized whole-rock oxygen isotope signatures to infer hydrothermal fluid circulation associated with intrusive activity in the NVC. Cathles (1993) established oxygen isotope ranges that represented depletion ($\leq 6 \text{ ‰}$) and enrichment ($\geq 9 \text{ ‰}$) of the whole-rock composition due to hydrothermal alteration and identified several depletion zones that extended from the Flavrian-Powell Intrusion associated with fluid upflow and VHMS mineralization. Heavy oxygen isotope enrichment away from the Flavrian-Powell Intrusion is interpreted as zones of seawater recharge or areas of diffuse hydrothermal alteration. Taylor (1997) modified the shape of these zones based on the analyses of more samples (some of which were collected during this study).

The oxygen isotope patterns in the CNVC have been superimposed on the alteration mineral assemblage map from this study (Figure 8.4.). The oxygen isotope depletion zones associated with the Flavrian-Powell Intrusion were shown to be largely confined to below the C Contact horizon with small 'fingers' through the C Contact (Taylor, 1997).

One finger coincides with the Old Waite Paleofissure which also hosts strong epidote-quartz alteration. The termination of this finger at the East Waite deposit remains uncertain owing to a lack of analyzed samples near the Norbec Mine, where epidote-quartz alteration is widespread. However, preliminary data from this study (sample NOR95124A; Table 6.5) confirms that the isotopic signature is not continuous.

Another finger extends through the C Contact to the Vauze Mine and can be attributed to silicification and moderate epidote-quartz alteration in the area. Both alteration assemblages persist outside the zone of $\delta^{18}\text{O}$ depletion, suggesting that the isotopic anomaly may be limited by the sample coverage.

The third finger across the C Contact outlines the altered volcanic rocks above the Millenbach and D-68 massive sulphide deposits, but does not include the Amulet Upper A deposit area. The 6 ‰ isopleth for the third finger transects two andesite samples in the Amulet Upper A area which are the wallrocks to epidote-quartz patches (6.80 ‰ and 5.33 ‰). The wallrock andesite sample from this area analyzed during this study (5.32 ‰) is contained within the depleted zone. However, the enriched value in the andesitic wallrocks suggests the whole-rock oxygen isotope signature is independent of the obvious alteration patches and possibly that the signature records a separate fluid:rock interaction outside of the patches (spilitization).

A fourth finger exists south of the Beauchastel Fault and penetrates the cycle III volcanics above the Powell Intrusion. The area of oxygen isotope depletion corresponds to the rhyolite dyke swarm and chlorite-sericite alteration zone that extends from the Powell Intrusion to the Joliet and Quemont deposits, but the area of depletion also includes weakly altered Powell Andesite rocks and identifies isotopic alteration that does not correspond to a particular mineralogical signature.

The ^{18}O enrichment zones were interpreted as hydrothermal fluid recharge areas that occur stratigraphically above the discharge zones (Cathles, 1993; Taylor, 1997). Both areas of oxygen isotope enrichment adjacent to the Hunter Creek Fault coincide with areas of background alteration in andesitic and rhyolitic rocks. The enrichment zone in the East Camp includes the Delbridge deposit and may reflect the pervasive carbonatization that occurs throughout the felsic volcanics in that area. The zone of enrichment is also traced over the South Bay Andesite rocks that contain widespread, diffuse epidote-quartz alteration although these rocks were not included in the $\delta^{18}\text{O}$ studies.

The strong epidote-quartz alteration in the andesites above the Aldermac deposit does not appear to influence the oxygen isotope value of the wallrocks. Three samples of andesite wallrock adjacent to epidote-quartz patches have $\delta^{18}\text{O}$ values of 6.47, 6.65, and 5.76 ‰ and closely correspond to the range for unaltered andesites.

The preliminary $\delta^{18}\text{O}$ data from the epidote-quartz patches in this study demonstrate isotopic depletion from the volcanic wallrocks which is consistent with prolonged, high- temperature hydrothermal fluid interaction. Volcanic wallrocks to epidote-quartz patches retain the regional alteration $\delta^{18}\text{O}$ signature and suggest the alteration patches represent concentrated fluid:rock interaction that does not extend into the surrounding rocks. This is supported by the whole-rock geochemical data in which the largest mass gains and losses are confined to the patches and not in the surrounding rocks. Although the $\delta^{18}\text{O}$ data in this study is preliminary, the few epidote-quartz patch / volcanic wallrock pairs that display enrichment are similar to the values in epidiosites that represent hydrothermal recharge in the Josephine Ophiolite (Harper, 1988). Epidote-quartz alteration $\delta^{18}\text{O}$ enrichment also coincides with lower hydrothermal fluid temperatures ($< 300\text{ }^{\circ}\text{C}$) as indicated by the other isotopic studies in the CNVC.

An isotopic study of the VHMS deposits in the CNVC by Hoy (1993) utilized whole-rock $\delta^{18}\text{O}$ data, mineral separate $\delta^{18}\text{O}$ data, and the modal abundance of minerals in each whole-rock analysis to estimate the $\delta^{18}\text{O}$ value of epidote. An $\delta^{18}\text{O}$ range of -1 to 6 ‰ was estimated for epidote from the Corbet, Ansil, Norbec, Horne, and Mobrun deposits. A single epidote separate from the Horne Mine returned a value of 3.2 ‰. The range between the deposits is interpreted by Hoy (1993) to reflect increasing ^{18}O concentration in epidote with stratigraphic height (low $\delta^{18}\text{O}$ values were from Corbet and the high $\delta^{18}\text{O}$ from Mobrun). Temperature estimates from this $\delta^{18}\text{O}$ range were 150 to 350 $^{\circ}\text{C}$. Epidote separates from epidote-quartz amygdules and veins contain $\delta^{18}\text{O}$ values

of 4.9, 5.7, and 5.8 ‰ and correspond to temperatures of 229, 233, and 260 °C (Paradis et al., 1993). These data are consistent with the estimates from Hoy (1993) and suggest that most epidote formed in the CNVC at temperatures less than 300 °C. The mineral pairs obtained by Paradis et al. (1993) were derived from quartz-epidote amygdules which commonly reflect the lower temperature range for fluids in a hydrothermal system. The overlap in epidote mineral compositions regardless of alteration texture, as determined by this study, suggests that this temperature range may also apply to the epidote-quartz patches.

Epidote-Quartz Alteration and the VHMS Model

The Noranda Cauldron VHMS Model

Figure 8.5 depicts the architecture of epidote alteration in a simplified section of the Noranda Cauldron at the end of the first stage of volcanic development when massive sulphide mineralization was most widespread (Gibson and Watkinson, 1990). The model shows a single volcanic eruptive centre which can represent either the Old Waite Paleofissure (and the Old Waite, East Waite, Vauze, and Norbec deposits) or the McDougall-Despina Eruptive Centre (and the Amulet A, C, F and Millenbach deposits).

The distribution of epidote-quartz alteration in the Noranda Cauldron indicates that fluid flow is both conformable and discordant. The widespread and abundant

epidote-quartz patches in the Flavrian Andesite and Rusty Ridge formation represent a deep hydrothermal fluid aquifer that was produced by semi-conformable fluid flow. Silicification is also a product of semi-conformable fluid flow and the Amulet formation upper member represents another aquifer developed higher in the volcanic strata (Gibson et al., 1983). All three aquifers are generated in the intermediate to late stages of volcanic development (stage 2 and 3; Figure 8.2) and reflect extensive lateral fluid circulation.

Whole-rock oxygen isotopes in the Noranda Volcanic Complex show that hydrothermal fluid flow likely extends beyond the Noranda Cauldron even in areas that appear relatively unaltered (Figure 8.4; Cathles, 1993; Taylor et al., 1997). The Flavrian-Powell Intrusion has driven regional-scale fluid flow outside of the Noranda Cauldron (approximately 30 km away) and beyond the timing of most of the VHMS deposits. This demonstrates that subseafloor hydrothermal systems are active well away from the volcanic centres and ocean-floor spreading axes as indicated by some seafloor alteration studies (e.g., Alt et al., 1986).

The most intense epidotization in the Noranda Cauldron at the regional-scale occurs in the Old Waite Paleofissure, about 1 km below the Waite massive sulphide bodies. The epidote-quartz patches represent 30% of the exposures and are confined to an area of $< 1 \text{ km}^2$ and reflects only localized fluid:rock interaction. Nevertheless, the occurrence of this alteration zone below massive sulphide bodies suggests zones of

patchy epidote-quartz alteration also represent focused hydrothermal fluid flow that is associated with VHMS mineralization.

Major enrichment of Al, Fe^{3+} , Ca, Mn, Sr, and V and depletion of Fe^{2+} , Mg, Na, K, Rb, and Zn is required to produce the epidote-quartz patches in the Noranda Cauldron regardless of rock type. The metasomatism of metals due to epidote-quartz alteration is particularly important to the VHMS model. Removal of greater than 65% of Zn from the wallrock andesite occurs in most patches. A similar proportion of Cu is removed from some epidote-quartz patches, although the overall mass gains and losses of Cu are variable throughout the Noranda Cauldron. The total volume of epidote-quartz alteration in the Rusty Ridge formation is insufficient to generate all of the massive sulphides, even within the Old Waite Paleofissure. The absolute amount of base-metals removed from the Rusty Ridge formation andesites due to epidote-quartz alteration is estimated to be more than 7000 tonnes for Cu and over 30,000 tonnes for Zn (Table 6.3) compared to the total mass of metal within the massive sulphide deposits within the OWP of approximately 250,000 tonnes Cu and 290,000 tonnes Zn (represented by the Vauze, East Waite, Old Waite and Norbec deposits). Epidotization of the underlying Flavrian Andesite formation may double these estimates, but the amount of metal released still falls short of the amount of metal in the massive sulphides. These observations imply that a deeper, stratabound hydrothermal aquifer may have existed and has been removed by the later phases of the Flavrian Intrusion. Alternatively, depletion of whole-rock components, including the base metals, during background alteration deep in the volcanic succession

may be significant for the mass additions in the overlying volcanic strata. The amount of metal leached from the Rusty Ridge andesitic rocks during background alteration is comparable to the amount of metal within the OWP massive sulphide deposits and suggests this early stage of hydrothermal alteration may also be important for base metal mineralization.

The complete dissolution of Zn from the andesite rocks and the overall erratic Cu concentrations associated with epidote-quartz alteration suggest that temperatures of hydrothermal fluids were relatively low which is consistent with the temperature range of 230-260 °C indicated by oxygen isotope values of epidote-quartz pairs from the Noranda Cauldron (Paradis et al., 1993). Although preliminary whole rock oxygen isotope data on the epidote-quartz patches indicate an overall ^{18}O depletion, the ^{18}O enrichment observed in some samples indicate a range of temperatures below 300 °C.

The fluid:rock ratio of 75-100 calculated for the epidote-quartz patches in the Noranda Cauldron represents the net effect of hydrothermal alteration that has likely developed during multiple fluid:rock interactions. This ratio is likely highest for the Rusty Ridge formation patches which have been generated by numerous hydrothermal events. Epidote-quartz patches formed higher in the volcanic strata, such as those in the Amulet Upper A area, may have formed at lower ratios.

The occurrence of clinozoisite compositions within the eruptive centres may not only reflect higher fluid flow in these areas, but could also be indicative of higher temperatures compared to epidote-quartz alteration outside of these centres. In geothermal areas, a general relationship of Al-rich epidote corresponds with higher hydrothermal fluid temperatures compared to Fe-rich epidote, although Fe/Al zoning in epidote also partly reflects the host rock compositions (Bird et al., 1984; Shikanzono, 1984; Arnason and Bird, 1992). In mid-ocean ridge volcanic settings, epidote occurs over a wide range of temperature (150-350 °C) with clinozoisite compositions most common at the upper end of this range (Bowers and Taylor, 1985). Thus, the lateral zoning of epidote towards clinozoisite compositions from the periphery of the volcanic complex to the eruptive centre (Figure 7.6C) may reflect increasing temperature. Lower Fe/Al ratios in epidote might also result from Fe mobilization during further alteration of the epidote-quartz patches, and the micron-scale Fe/Al zoning in the patches may reflect multiple episodes of hydrothermal leaching.

The oxidation of Fe^{2+} to Fe^{3+} during the formation of epidote indicates that temperature is not the only control on epidote-quartz alteration in the Noranda Cauldron model. In particular, hydrothermal fluids associated with epidote-quartz alteration must have a relatively high oxidation state compared to the reduced-state of the volcanic rocks. (e.g., Seyfried et al. 1987).

This new hydrothermal model for VHMS mineralization in the Noranda Cauldron mainly depicts the relationships associated with the first stage of volcanism. Intense epidote-quartz alteration in the second stage of volcanism within the Amulet Andesite formation cannot be traced in the overlying, felsic volcanic-dominated cycle IV succession. Therefore, the evolution of hydrothermal alteration depicted in this model terminates with volcanic activity in the Noranda Cauldron.

The Noranda Cauldron model for epidote-quartz alteration could possibly be applied to other mafic-felsic volcanic hosted massive sulphide deposits. Similar spatial relationships of epidote alteration zones below massive sulphide deposits have been described for the Matagami district (Harrigan and MacLean, 1976; MacGeehan, 1978), the Snow Lake district (Skirrow and Franklin, 1994), and the Flin Flon district (Bailes and Syme, 1989; Syme et al., 1996). In most of these studies the extent of the epidote-quartz alteration zones has not been identified and the paragenetic relationship of epidote-quartz alteration and massive sulphide mineralization is not fully understood. However, similarities in the distribution and metasomatism associated with epidote alteration in all these districts highlight the significance of this alteration assemblage for regional VHMS exploration.

The Ophiolite-Hosted VHMS Model

Epidote-quartz alteration in relation to VHMS mineralization has been extensively studied in ophiolite-hosted deposits. A model that relates volcanic structure, sulphide mineralization and other alteration mineral assemblages to epidote-quartz alteration has been generated (Alt, 1997; Galley and Koski, 1997; Figure 8.6).

Studies of hydrothermal alteration in ophiolitic volcanic environments have referred to zones of massive epidote as '*epidosite*'. The most detailed studies of epidosites have focused on the Troodos Ophiolite, Cyprus which hosts several VHMS deposits. The epidosite rocks are typically confined to the sheeted diabase dykes within the centre of graben structures deep in the footwall of the VHMS deposits (Richardson et al., 1987; Schiffman and Smith, 1988). A similar distribution for epidosites has been described in other ophiolites: the Samail Ophiolite, Oman (Nehlig et al., 1994) and the Josephine Ophiolite, Oregon-California (Harper et al., 1988). The extent of epidotization is best described in the Troodos Ophiolite, where exposed areas of $> 1 \text{ km}^2$ have been mapped containing $> 80\%$ epidosite within the sheeted dyke complex of the Solea Graben of the Troodos Ophiolite typically 1-2 km below the sheeted dyke / mafic extrusive contact (Varga and Moores, 1985; Schiffman and Smith, 1988).

Sparsely distributed epidosite patches are also described higher in the ophiolitic strata within mafic extrusive rocks in the Josephine Ophiolite (Harper et al., 1988) and in

the Pindos Ophiolite, Greece (Valsami et al., 1994). The exact location of this patchy epidote alteration with respect to massive sulphide deposits in these ophiolites is not well understood, but in both areas it is considered to be genetically related to mineralization. Epidosites in the upper extrusive sequence of the Josephine Ophiolite are also spatially related to replacement masses of prehnite and pumpellyite where epidote is interpreted to represent a higher grade of hydrothermal alteration (higher temperature, $> 315^{\circ}\text{C}$) that overprints the prehnite and pumpellyite (Harper, 1995).

Minor groundmass replacement by epidote is prevalent in all mafic rocks in most ophiolites including the Betts Cove Ophiolite, Newfoundland (Coish, 1977) and the Trinity Ophiolite, California (Lecuyer et al., 1990). Similar groundmass epidote alteration has been recognized in active hydrothermal systems on ocean ridge spreading centres (Alt et al., 1986), but occurrences of epidosites have not been identified in these active systems.

In contrast to epidote alteration, *chlorite-dominated alteration* in most ophiolites occurs at an early stage of hydrothermal alteration as mafic rocks interact with cold seawater shortly after extrusion and subsequent burial near the seafloor (Humphris and Thompson, 1978; Mottl, 1983; Alt et al., 1986; Seyfried et al., 1988). These Mg-fixation reactions have been extensively studied in experiments with seawater and mafic rocks (Mottl et al., 1978; Seyfried and Bischoff, 1979; Hajash and Archer, 1980; Ghiara et al., 1993) and the hydrothermal fluid conditions are well constrained to low temperatures

(100-200 °C) and near-neutral acidity (pH = 5-6). This background alteration is thought to represent seawater recharge zones where fluids penetrated to depths of < 500 m (near-seafloor alteration) at slightly elevated water:rock ratios (< 10).

Mg-dominated background alteration is distinct from the *chloritization zones* ('pipe alteration') which host sulphides in ophiolite deposits (Lydon and Galley, 1984; Richards et al., 1986; Kuhns and Baitis, 1988). Evidence from modern seafloor deposits and VHMS deposits indicate that pipe alteration occurs at 250-350 °C, high acidity (pH = 3-4), and high fluid:rock ratios (> 100:1) and represents the discharge portion of the fluid circulation path (Hannington et al., 1995; Alt, 1997).

Epidosites are considered the products of deep hydrothermal fluid circulation and record the interaction of evolved seawater with the mafic rocks in a high temperature reaction zone (Seyfried et al., 1988; Alt, 1997; Seyfried et al., 1997). Cu and Zn are leached from the mafic rocks by the hydrothermal fluids and extreme base metal leaching in epidiosites is reported in the Troodos Ophiolite (Richardson et al., 1987), the Samail Ophiolite (Nehlig et al., 1994), and the Josephine Ophiolite (Harper et al., 1988). Fluid inclusion studies of contemporaneous quartz in epidiosites reveal a temperature range of 250-400 °C with a mode around 340-350 °C (Richardson et al., 1987; Schiffman and Smith, 1988; Bettison -Varga et al., 1995). Temperatures derived from oxygen isotope studies in epidiosites coincide with this temperature range (Harper et al., 1988; Schiffman and Smith, 1988). These conditions are also suggested by experimental studies which

indicate epidote-quartz alteration and metal depletion at temperatures $>400^{\circ}\text{C}$ (Seyfried et al., 1988; 1997). The relatively narrow pH range of 5-6 in which epidote is stable at these temperatures constrains the fluid acidity for metal dissolution (Berndt et al, 1989).

Mineral compositions in the epidiosites are also relatively well constrained. The pistacite composition of epidote falls within the range of 15-30 in most epidiosites (Schiffman and Smith, 1988; Nehlig et al., 1994). Epidote mineral compositions outside of the epidiosites in the surrounding mafic rocks also fall within this range regardless of the texture of epidotization (Gillis and Robinson, 1991). The similar compositions may indicate that epidote formed outside of epidiosites developed under similar hydrothermal conditions, but where fluid flow is more diffuse. This reduced fluid flow may also explain the presence of patchy epidote alteration in some ophiolite sections where permeability of the volcanic rocks was not permissive of focused hydrothermal flow. Lower pistacite compositions (0-18) for matrix epidote are found within the basal sections of some ophiolites and may be accounted for by changes in the hydrothermal fluid conditions, particularly $f\text{O}_2$ and temperature (Coish, 1977; Ghent and Stout, 1981; Lecuyer et al., 1990).

In order to produce the extreme metasomatic changes (addition of Fe, Al, and Ca; removal of Mg, Na, K, Cu and Zn) in the reaction zone, abundant fluid is required and fluid:rock ratios have been typically estimated as high as >100 . Harper (1995) predicted ratios much higher than 1000 for epidiosites due to the major influx of whole rock

components. Because of the typical patchy nature of alteration in some epidiosites, lower ratios of 20-50 may be more representative for the total volume of rock affected (Richardson et al., 1987). A fluid:rock ratio of approximately 20 is also consistent with epidote as the host for Fe^{3+} instead of hematite (Mottl, 1983). In most high temperature, seawater-basalt experimental studies a ratio of 10 has produced epidote-quartz alteration (Seyfried et al., 1988; Bettison-Varga et al., 1995). Regardless of the exact ratio, the epidiosites in ophiolites represent large zones of focused fluid upflow often leading to massive sulphide mineralization.

Whole-rock oxygen isotope analyses of epidote-quartz alteration have been carried out on epidiosites from a number of ophiolites. The epidiosites within the Troodos Ophiolite, Cyprus have $\delta^{18}\text{O}$ values of 2.8 to 5.0 ‰ and depict significant ^{18}O depletion relative to the surrounding mafic dykes (Schiffman and Smith, 1988). This isotopic composition corresponds to temperatures of 310-370 °C, similar to that obtained from fluid inclusion studies of these epidiosites (Richardson et al., 1987; Bettison-Varga et al., 1995). Epidote-quartz alteration in the sheeted dyke sequence of the Josephine Ophiolite, California have whole-rock $\delta^{18}\text{O}$ values of 4.0 and 4.3 ‰ compared to the 5.1 ‰ value for the least altered rocks (Harper et al., 1988). Epidote-quartz alteration in the overlying extrusive sequence has $\delta^{18}\text{O}$ values of 8.8 and 9.5 ‰ and are interpreted to represent hydrothermal recharge at lower temperatures and lower fluid:rock ratios.

Comparison between the Noranda and the Ophiolite Models of Epidote-Quartz Alteration

Despite the strong contrasts in volcanic rock compositions and in the tectonic settings between the CNVC and ophiolites, similarities between the alteration mineral assemblages and the alteration textures make a comparison inevitable. Hydrothermal fluid upflow in both the Noranda and the ophiolite model is largely confined to synvolcanic structures within the core of volcanic centres. In the ophiolite model, fluid flow is mainly discordant and is channeled by fractures and vertical dyke-emplacement within the core of graben structures. In Noranda, eruptive centres are also major conduits for discordant hydrothermal fluid upflow; however the presence of semi-conformable alteration such as the epidote-quartz assemblage and silicification indicates that lateral fluid flow is also an important component of fluid circulation. This significant contrast in fluid circulation between the Noranda and the ophiolite models results in differences in the extent and the intensity of hydrothermal activity associated with epidote-quartz alteration.

Epidosites in ophiolites are concentrated areas where fluid:rock interaction is near-complete and are a product of channelized fluid flow. The patchy nature of epidote-quartz alteration in Noranda indicates that fluid:rock interaction is more localized and that fluid flow is more diffuse. As a consequence, the volume of rock represented by epidosites in the ophiolite model is much greater than the areas of intense epidote-quartz alteration in Noranda.

Epidosites and epidote-quartz alteration in Noranda both record similar bulk rock changes in compositions and similar epidote compositions and suggest similar hydrothermal conditions are represented, at least at the patch-scale. As a result, the fluid:rock ratios calculated here for the Noranda epidote-quartz patches are comparable to the ratios predicted for epidosites. However, the metal depletion and the $\delta^{18}\text{O}$ depletion that characterize the epidosite zones in ophiolites are both inconsistent in Noranda. This suggests that the temperatures of epidote-quartz alteration in the Noranda Cauldron may be significantly different than those determined for epidosites in the ophiolite model. Most geochemical data for the epidote-quartz patches in the Noranda Cauldron point to < 300 °C fluid temperatures and are not the high temperatures prescribed for the ophiolite-hosted epidosites (> 350 °C).

Epidote-quartz alteration in Noranda may more akin to the patchy epidote alteration described within the upper extrusive sections in some ophiolites. Consequently, patchy epidote in ophiolites is also likely related to similar semi-conformable fluid flow along more permeable strata similar to Noranda. Thus, a more extensively developed fluid flow system may exist in ophiolites than depicted in the model which lend new importance to mineral exploration in ophiolitic terranes.

Table 8.1. Reactions Represented by Alteration Minerals in the CNVC.

Background Alteration

- (i) andesine plagioclase $\Rightarrow$ albite + quartz
 $\text{Na}_{2.5}\text{Ca}_{1.5}\text{Al}_{5.5}\text{Si}_{10.5}\text{O}_{32} + 6\text{H}_2\text{O} \Rightarrow 2.5\text{NaAlSi}_3\text{O}_8 + 1.5\text{Ca}^{2+} + 3\text{Al}(\text{OH})_4^- + 3\text{SiO}_2$
- (ii) glass + fluid $\Rightarrow$ smectite
 $(\text{Mg,Fe})^{2+} + 14\text{Al}(\text{OH})_4^- + 22\text{H}_4\text{SiO}_4 \Rightarrow 6(\text{Mg,Fe})_{0.167}\text{Al}_{2.33}\text{Si}_{3.67}\text{O}_{10}(\text{OH})_2 + 60\text{H}_2\text{O} + 12\text{OH}^-$
- (iii) glass + fluid $\Rightarrow$ prehnite
 $2\text{Ca}^{2+} + \text{Fe}(\text{OH})_4^- + \text{Al}(\text{OH})_4^- + 3\text{H}_4\text{SiO}_4 + 2\text{OH}^- \Rightarrow \text{Ca}_2\text{FeAlSi}_3\text{O}_{10}(\text{OH})_2 + 10\text{H}_2\text{O}$
- (iv) glass + fluid $\Rightarrow$ epidote
 $2\text{Ca}^{2+} + \text{Fe}(\text{OH})_4^- + 2\text{Al}(\text{OH})_4^- + 3\text{H}_4\text{SiO}_4 + \text{OH}^- \Rightarrow \text{Ca}_2\text{FeAl}_2\text{Si}_3\text{O}_{12}(\text{OH}) + 12\text{H}_2\text{O}$
- (v) prehnite $\Rightarrow$ epidote
 $\text{Ca}_2\text{FeAlSi}_3\text{O}_{10}(\text{OH})_2 + \text{Al}(\text{OH})_4^- \Rightarrow \text{Ca}_2\text{FeAl}_2\text{Si}_3\text{O}_{12}(\text{OH}) + \text{OH}^-$
- (vi) glass (smectite) + fluid $\Rightarrow$ chlorite
 $5(\text{Fe,Mg})^{2+} + 2\text{Al}(\text{OH})_4^- + 3\text{H}_4\text{SiO}_4 + 8(\text{OH})^- \Rightarrow (\text{Fe,Mg})_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_8 + 8\text{H}_2\text{O}$

Epidote-Quartz Alteration*Breakdown of Wallrock Minerals*

- (vii) albite: $\text{NaAlSi}_3\text{O}_8 + 8\text{H}_2\text{O} \Rightarrow \text{Na}^+ + \text{Al}(\text{OH})_4^- + 2\text{H}_4\text{SiO}_4$
- (viii) chlorite: $(\text{Fe,Mg})_5\text{Al}_2\text{Si}_3\text{O}_{10}(\text{OH})_8 + 8\text{H}_2\text{O} \Rightarrow 5(\text{Fe,Mg})^{2+} + 2\text{Al}(\text{OH})_4^- + 3\text{H}_4\text{SiO}_4 + 8(\text{OH})^-$

Formation of Epidote-Quartz Patches

- (ix) wallrock + fluid $\Rightarrow$ epidote
 $2\text{Ca}^{2+} + \text{Fe}(\text{OH})_4^- + 2\text{Al}(\text{OH})_4^- + 3\text{H}_4\text{SiO}_4 + \text{OH}^- \Rightarrow \text{Ca}_2\text{FeAl}_2\text{Si}_3\text{O}_{12}(\text{OH}) + 12\text{H}_2\text{O}$
- (x) fluid $\Rightarrow$ quartz
 $\text{H}_4\text{SiO}_4 \Rightarrow \text{SiO}_2 + 2\text{H}_2\text{O}$

Note: Reactions ii, iii, iv, vii, viii, ix, x from Arnasson et al., (1982). Compositions of andesine plagioclase, albite, chlorite, are from Deer et al., (1992). The prehnite composition is from Harper (1995).

Figure 8.1. Paragenesis of hydrothermal alteration mineral assemblages in the Mine Sequence. The Mine Sequence section is simplified from Gibson (1989) and Gibson and Watkinson (1990). The red triangles represent the total massive sulphide accumulation and associated chlorite-sericite alteration at each specific interval. The stratigraphic position of the detailed map areas described in this study are shown for the epidote-quartz alteration and silicification assemblages. The metamorphic mineral equivalents for each alteration assemblage within the Lac Dufault Granodiorite halo are given on the right. Small numbers within the epidote-quartz assemblage refer to the alteration stages in Figure 8.2.

Figure 8.2. Volcanic development and associated semi-conformable alteration in the Mine Sequence. The volcanic development has been greatly simplified to consider only mafic volcanism due to its influence and control on epidote-quartz alteration. These stages of hydrothermal alteration are represented in both the Old Waite Paleofissure and the McDougall-Despina Eruptive Centre.

Figure 8.3. Paragenesis of metasomatism resulting in to epidote quartz alteration. Whole rock data indicated by boxes (black = unaltered protolith; yellow = volcanic wallrock; green = epidote alteration patch). Smaller symbols represent mineral chemistry data highlighted by bars. (A) Rusty Ridge formation (RRA94026); (B) Amulet Rhyolite formation (RRA94057); (C) Amulet Andesite formation (NOR95121); (D) Amulet Andesite formation, Amulet Upper A area (UAA96008).

Figure 8.4. Regional whole-rock oxygen isotope distribution in the central NVC (after Cathles, 1993; Taylor, 1997). Oxygen isotope depletion and enrichment zones are superimposed on the alteration mineral assemblage distribution mapped by this study.

Figure 8.5. Noranda Cauldron VHMS deposit model for epidote-quartz alteration (after Gibson, 1989; Gibson and Watkinson, 1990). The model only applies to the mafic-volcanic rock dominated VHMS deposits. Data for alteration is mainly from this study and other references discussed in the text.

Figure 8.6. Ophiolite-hosted VHMS deposit model for hydrothermal fluid circulation and 'epidosite' alteration (after Alt, 1997; Galley and Koski, 1997). Data derived from other references are discussed in the text.

CHAPTER 9

CONCLUSIONS

Epidote-quartz alteration is an important semi-conformable hydrothermal mineral assemblage in large, mafic-dominated volcanic complexes which host massive sulphide deposits. Epidote-quartz alteration is easily recognized in the field and mappable at the outcrop scale. Intense epidote-quartz alteration occurs as patches of volcanic groundmass replacement. Major epidote-quartz alteration zones are represented by abundant (> 20%) patches in andesites and small 'spots' in rhyolites that typically extend beyond the outcrop scale and delineate relatively large areas of hydrothermal fluid:rock interaction (1-2 km² on average). Open-space infilling by epidote (amygdules, hyaloclastite infilling, interpillow precipitation) is widespread in subaqueous volcanic environments and depict large zones of hydrothermal fluid flow, over 10 km away from volcanic centres. The general association of the epidote-quartz patches with these infilling textures indicates these patches are developed by prolonged hydrothermal activity and metasomatism within the core of a large hydrothermal system.

The scale of metasomatism can be demonstrated utilizing both whole-rock geochemistry and mineral chemistry data in conjunction with the distribution of the epidote-quartz alteration zones. The whole-rock geochemistry of the epidote-quartz alteration patches is largely controlled by the compatibility and incompatibility of the individual elements in the epidote mineral structure. Enrichment of Ca, Al, Fe³⁺, Mn, V,

Cr, Ga, and Sr and depletion of Fe^{2+} , Mg, Na, K, Co, Ni, Cu, Zn, Ba, and Rb all correspond to substitution within or exclusion from the octahedral and cubic cation sites available within epidote. The greatest enrichments occur in patches developed in the most intense epidote-quartz alteration zones and are indicative of the higher epidote to quartz proportion within the individual patches.

Compositional zoning in euhedral epidote is well developed and reflect distinct fluid composition. Anhedral epidote in the alteration patches demonstrate complex Fe/Al zoning over the complete range of epidote-clinozoisite compositions. Early-formed epidote (matrix and open-space infilling) have similar compositions to epidote within the alteration patches that suggest a genetic relationship between alteration textures. End-member clinozoisite compositions coincide with the most intense epidote-quartz alteration zones and may reflect higher fluid temperatures compared to the Fe-epidote compositions in patches outside of these zones. Aluminium concentration in epidote may also be related to the relatively low Al concentration compared to Fe in the hydrothermal fluids that form epidote. Thus clinozoisite may form as a residual mineral phase under multiple fluid:rock interactions.

Epidote-quartz alteration zones are not spatially related to the massive sulphide deposits or with the associated chlorite-sericite alteration zones as either a hangingwall or a footwall assemblage at the deposit-scale. Discordant epidote-quartz alteration zones correspond to mafic eruptive centres adjacent to and within synvolcanic mafic dyke

swarms. Epidote-quartz patches are formed by hydrothermal fluids driven by mafic dyke intrusions particularly within thick andesitic flows which insulate these fluids and prolong fluid:rock interaction. Conformable epidote-quartz alteration zones develop deep within the volcanic strata along intervals of relatively high permeability and can be considered as aquifers to fluids mobilized by synvolcanic dyke intrusion and cauldron subsidence during the latter stages of volcanism. Metal depletion in the epidote-quartz alteration patches occurs throughout the NVC and the most intense zones underlie some of the VHMS deposits. Both relationships imply that the epidote-quartz patches are genetically associated with massive sulphide mineralization.

Epidote-quartz alteration in rhyolitic rocks is sparse compared to the widespread distribution of epidote in andesites. Whole-rock metasomatic changes and epidote compositions in the rhyolites are similar to those in the andesites and suggest the contribution of elements, particularly Ca and Fe, from the hydrothermal fluids is higher in the rhyolites compared to the andesites. The occurrence of epidote-quartz alteration in rhyolites within the core of mafic volcanic eruptive centres indicates that hydrothermal fluids forming epidote are strongly influenced by the mafic rock compositions even during relatively short periods of felsic volcanism.

The epidote-quartz alteration in the Noranda Volcanic Complex is not analogous to the extensive epidosites commonly described in the lower portions of ophiolitic volcanic sequences, but is similar to the 'patchy' epidote alteration developed in the

extrusive units of ophiolites. Similarities in whole-rock geochemistry and mineral chemistry of ophiolite-hosted epidiosites and the epidote-quartz patches in the NVC suggest hydrothermal fluid conditions are comparable. However, a lower temperature of formation for the Noranda epidote-quartz alteration seems likely (220 - 300 °C) compared to the higher temperature range (300-400 °C) for epidiosites. Complete oxidation of iron from Fe^{2+} to Fe^{3+} is critical to epidote formation, thus $f\text{O}_2$ is also an important factor for epidote-quartz alteration. This lower temperature range may not have been sufficient for complete metal leaching that characterize the reaction zones in the ophiolite sequences. The semi-conformable distribution of epidote in the Noranda Cauldron due to lateral hydrothermal fluid circulation indicates a more diffuse hydrothermal system compared to the ophiolite model.

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APPENDIX A

A REVIEW OF PREVIOUS HYDROTHERMAL ALTERATION STUDIES ASSOCIATED WITH THE NORANDA VHMS DEPOSITS

Hydrothermal alteration mineral assemblages in the Noranda VMS deposits have been included in the first descriptions of massive sulphide deposits in the area since 1920. Continual mineral exploration, detailed mapping and scientific research since then have established a good understanding of the distribution and paragenesis of these assemblages in most of the Noranda VHMS deposits (Figure A1). As a result, the chemical and physical conditions of hydrothermal fluids responsible for alteration in the NVC have been surmised and are widely accredited in ore deposit models for VHMS deposits.

Table A1 is a compilation of the various alteration mineral assemblages recorded in the Noranda VHMS deposits and includes information derived by this study. The occurrence of alteration minerals can be made according to the spatial and genetic relationship to sulphide mineralization designated in standard VHMS terminology by "Host", "Footwall" (FW), and "Hangingwall" (HW). "Distal" assemblages are loosely defined here as alteration occurrences outside of the immediate area of sulphide mineralization, either above, below, or lateral from the deposit. This loose definition is largely due to the overall cursory description of alteration minerals outside of the mined areas. In many cases, these mineral assemblages are considered as "background" to the mineral assemblages associated with sulphide mineralization without regard to their

paragenesis. The distribution and composition of some alteration minerals are variably controlled by the host volcanic rock compositions, thus are included in Table A1.

Metamorphism related to post-mineralization intrusions and faults (listed under “Lithology”) have affected the alteration mineral assemblages in some deposits; thus, the metamorphic mineral equivalents are given in Table A1.

Massive sulphide deposits occur at several stratigraphic intervals within the Noranda Volcanic Complex (NVC) succession and are the product of a long-lived hydrothermal system. The complex evolution of this hydrothermal system creates a unique sulphide depositional environment at each deposit and has complicated several alteration mineral relationships. Synvolcanic dykes and faults in the NVC have provided cross-stratal conduits for hydrothermal fluids that produce “stacked” massive sulphide orebodies in which the hangingwall alteration of one deposit forms the footwall of the overlying orebody. Nevertheless, several common alteration mineral assemblages and mineral distribution trends persist at the deposit-scale (Figure A2).

Host Mineral Assemblages

Regardless of volcanic rock composition, alteration mineral assemblages which host sulphide mineralization are dominated by chlorite and sericite in varying abundances, although sericite is most prominent in felsic volcanic rocks over chlorite. In

most cases, chlorite-sericite alteration of volcanic wallrocks is near-complete and primary volcanic textures are most often completely destroyed.

Very few correlations can be made between the sulphide mineralogy of the orebody and the alteration mineral assemblages aside from the lithologic control for some deposits. The felsic-hosted deposits in the East Camp contain massive sphalerite and are Zn-rich compared to the Main Camp. These deposits are also dominated by sericite-quartz alteration assemblages and contain less chlorite. An association between alteration and sulphide mineral assemblages has been made at the Ansil deposit where sericite-rich alteration is related to Zn mineralization and chalcopyrite-pyrrhotite mineralization is dominated by chloritic alteration (Galley et al., 1995).

Alteration minerals have not been considered in many of the studies of the 'exhalite' horizons present at several of the Noranda VHMS deposits. Hydrothermal alteration of the clastic component of the Main Contact Tuff near the Millenbach massive sulphides is dominated chlorite, sericite, and quartz with accessory epidote, ilmenite, rutile, and titanite (Kalogeropoulos and Scott, 1989). Rutile is directly associated with the ore zone mineralization.

Footwall Assemblages

Footwall alteration is also dominated by chlorite and sericite regardless of volcanic host rock composition. Chlorite, sericite and quartz form as alteration selvages to sulphide stringers in the footwall, thus distinction between footwall and host alteration is vague. Pervasive replacement of the volcanic groundmass by chlorite and sericite typically decreases away from the stringer sulphide mineralization zones. Stringer sulphide mineralization and footwall alteration are typically developed along synvolcanic structures such as faults and dykes that focus hydrothermal fluid circulation toward the seafloor in a “pipe-like” distribution. Thus the footwall alteration assemblages are often referred as “pipe alteration”. Within most of the footwall alteration pipes, chlorite is concentrated with sulphide stringers the core and grades into more sericite-rich alteration toward the margins of the pipe. This gradation has been interpreted to represent changing hydrothermal fluid conditions such as decreasing temperature and decreasing Fe and Mg activity (Riverin and Hodgson, 1981), but other alteration studies have shown that chloritization overprints sericitic alteration and represents a distinct stage of hydrothermal activity (Ikingura et al., 1989).

Other alteration minerals noted in the footwall assemblage are relatively rare. Carbonate minerals are identified in the deep portions of the alteration pipe at Vauze, but their relationship to other alteration minerals or sulphide minerals was not described (Spence, 1975). Silicification is also noted in the deep footwall of the Vauze deposit. Epidote occurs within the selvages of footwall sulphide stringers at the Horne (MacLean and Hoy, 1990) and the Millenbach deposits (Simmons et al., 1973), but the paragenesis

of epidote in relation to the other footwall alteration minerals was not determined at either deposit. The absence of epidote and carbonate minerals in the other VHMS deposits suggests both are likely relict minerals or have developed after sulphide mineralization.

The size of the host and footwall alteration zones associated with the Noranda sulphide deposits are variable without a direct relationship to the size of the orebodies, however, the true size of any particular chlorite-sericite alteration zone associated with a single massive sulphide deposit is not easily determined. In many cases, chlorite-sericite alteration assemblages extend across over 500m of volcanic stratigraphy where massive sulphide deposition has occurred at several horizons along synvolcanic structures. These “stacked” massive sulphide systems are well represented at the Amulet A, Millenbach, and Waite orebodies where each deposit contains several massive sulphide lenses (Suffel, 1948; Price and Bancroft, 1948; de Rosen-Spence, 1969; Riverin and Hodgson, 1980). The chlorite-sericite assemblages likely overprint early formed alteration mineral assemblages, thus footwall/ hangingwall mineral relationships are not easily assessed at these deposits. Post-mineralization intrusions have displaced and removed portions of: the massive sulphides (Horne; Millenbach) and the footwall altered volcanic rocks (Corbet; Ansil; Vauze; New Insko), thus the true extent of the chlorite-sericite alteration zones cannot be resolved in these deposits. A large quartz-sericite-chlorite alteration zone is described at the Horne Mine, however the Andesite Fault has removed some of the footwall volcanic rocks, thus an extensive alteration pipe below the Horne orebodies has only been postulated (Price, 1948; Kerr and Gibson, 1993). Similarly, the size of the

Quemont chlorite-sericite alteration zone is not well known since folding and faulting has complicated the volcanic stratigraphy and complete descriptions of the alteration mineral assemblages were not emphasized at the time of mining. Fracture-controlled chloritic alteration and stringer mineralization can be traced at surface across stratigraphy over 1 km away from the Quemont deposit and suggests this pipe alteration zone is extensive. At the Norbec deposit, a single massive sulphide orebody represents a simple depositional environment that was not affected by later intrusive or tectonic activity. Footwall alteration extends well below the massive sulphide horizon over a distance of approximately 500 m. The shape of the Norbec footwall alteration zone follows the pipe-like shape then changes to a near horizontal orientation and illustrates hydrothermal fluid circulation along synvolcanic faults as well as through volcanic rocks with relatively high permeability.

Hangingwall Assemblages

Hangingwall alteration has not been emphasized in most models of the Noranda VHMS deposits. The lack of hangingwall hydrothermal alteration is clearly illustrated at the small Moosehead massive sulphide showing, similar to other deposits along the C Contact stratigraphic unit. Removal of the hangingwall volcanic rocks at the Horne; East Waite; Gallen; and Aldermac deposits by post-mineralization intrusions also promotes hangingwall alteration assemblages to be excluded from Noranda VHMS models. Stacked massive sulphide orebodies such as the Amulet A and the Waite deposits contain

continuous pipe alteration and stringer sulphide mineralization that extends well below and above the massive sulphides that represent persistent hydrothermal fluid conditions. Descriptions of hangingwall alteration without massive sulphide mineralization have been recorded in some of the Noranda VHMS deposits which signifies more diffuse hydrothermal fluid circulation after sulphide deposition. At Corbet, sericite-chlorite-quartz alteration is developed over 50m into the overlying Northwest Rhyolite formation (Gibson et al., 1993). Similarly, hangingwall chlorite-sericite-quartz is locally intense at the Delbridge deposit (Boldy, 1968).

The most extensive hangingwall alteration system occurs at the Ansil deposit where whole-rock depleted sodium anomalies are due to feldspar-destruction by sericitization in both andesite and rhyolite volcanic rocks over a kilometre above the deposit (Riverin et al., 1990; Galley, 1994).

Distal/Semi-Conformable Assemblages

Alteration mineral assemblages which do not host massive sulphides have been noted at most of the Noranda VHMS deposits although in many cases, are considered as “background” or “distal” to mineralization. The genetic relationships between the distal mineral assemblages and the sulphide-associated assemblages in many cases are not well understood. Thus, for consistency, these assemblages are grouped in Table A1 as “Distal” without a paragenetic implication.

Mineral assemblages containing quartz, albite, chlorite, actinolite, epidote and carbonate are described in many of the Noranda VHMS deposits. This assemblage is often referred as “background alteration” since it is not preserved within the pervasive hangingwall or footwall alteration zones. This assemblage is derived from the interaction of seawater with the volcanic rocks during or shortly after extrusion (“spilitization”). These minerals are also formed in volcanic rocks due to regional greenschist facies metamorphism, thus their occurrence in the Noranda VHMS deposits and throughout the area is somewhat contentious.

Sericite-quartz alteration without chlorite is common in several felsic-hosted deposits and occurs well away from the center of sulphide mineralization. Pervasive quartz-sericite alteration forms a halo around the East Camp deposits and is likely a product of diffuse hydrothermal fluid flow at an early and late stage of hydrothermal activity outside of the main sulphide mineralization system and may be regarded as distal. The best example of distal sericitic alteration in the Main Camp is described by Galley (1994) at the Ansil Mine where disseminated sericite, quartz and sphalerite is pervasive throughout the Cranston Tuff away from the massive sulphides.

Some of the mineral assemblages listed as distal in Table A1 have been recognized as semi-conformable and are considered an early integral stage of hydrothermal activity prior to massive sulphide deposition (Hunter and Moore, 1983;

Gibson et al., 1983; Gibson, 1989). In particular, silicification and epidote-quartz alteration were derived during volcanic development and regional hydrothermal fluid flow beyond the scale of any one particular VHMS deposit (Figure A3). Intense silicification was developed in andesite along regional synvolcanic structures such as faults and dykes within volcanic centres and thus is considered as semi-conformable. Large zones of silicification underlie the Amulet, Waite, Aldermac and Millenbach deposits and are interpreted to be genetically related to hydrothermal activity that produced sulphide mineralization (Gibson et al., 1983; Gibson, 1989). The silicified andesites form an effective barrier to confine hydrothermal fluids and focus discharge to allow massive sulphide accumulation. Thus, for these deposits silicification may be regarded as deep footwall alteration has been well documented in many of the Main Camp deposits and considered an early integral stage of hydrothermal activity prior to massive sulphide deposition (Hunter and Moore, 1983; Gibson et al., 1983; Gibson, 1989). The gold-rich siliceous zones hosting disseminated sulphides as part of the Horne deposits are distinct from the widespread silicification described in the Main Camp and are likely formed during a separate hydrothermal stage from the massive sulphides.

Similar to silicification, epidote-quartz alteration forms within volcanic centres, but is largely confined to mafic volcanic rocks and is not spatially related to any single sulphide deposit or any single volcanic stage. Large epidote-quartz alteration zones occur relatively deep within the Turcotte Lake section (Figure A3) and are interpreted as hydrothermal alteration developed in the medial part of a shallow sub-seafloor fluid

aquifer (Gibson et al., 1983). Epidote-quartz alteration occurs deep in the footwall of some VHMS deposits (e.g., Corbet, Amulet Upper A) as well as in the hangingwall of some VHMS deposits (e.g., Ansil, Aldermac, Amulet Upper A) but is not considered as a distal assemblage to the massive sulphides. The occurrence of prehnite and pumpellyite at the New Inco deposit is thought to be a low grade metamorphic equivalent to epidote (Meyers and MacLean, 1983; Stewart, 1998). Silicification and epidote-quartz alteration at the Four Corners deposit is similar in appearance to the examples in the Main Camp, but the volcanic stratigraphy in this area is poorly understood, thus the relationship between regional alteration and the sulphide deposits has not been investigated.

Carbonate alteration has been identified at the Mobrun deposit and is considered similar to the semi-conformable phases at the Mattabi VHMS deposit near Sturgeon Lake, Ontario (Larocque and Hodgson, 1993). Carbonate alteration is also conspicuous near the Delbridge deposit, but its distribution and paragenetic relationship to the massive sulphides has not been determined.

Hematization of felsic volcanics away from massive sulphides is described at the Vauze and Four Corners deposits, but has not been systematically studied in either areas.

Metamorphism

Chlorite-sericite alteration at several deposits have been superimposed by later hydrothermal activity related to different intrusive phases which post-date sulphide mineralization. De Rosen-Spence (1969) separated these metamorphic mineral assemblages into: (i) cordierite-anthophyllite and (ii) skarn assemblages.

Early workers recognized the association of cordierite-anthophyllite assemblages to sulphide mineralization at the Waite-Amulet Mines (Cooke, 1929; Price, 1934; Wilson and Bancroft, 1949). This assemblage is locally referred as 'dalmatianite' by the early workers due to the appearance of cordierite as large, ovoid spots hosted by a fine-grained assemblage of anthophyllite, biotite and chlorite. These workers considered the presence of dalmatianite to support a metamorphic origin of sulphide deposition in the Noranda area. De Rosen-Spence (1969) was able to confirm by petrographic relationships that this assemblage represented the overprint of volcanogenic chlorite-sericite hydrothermal alteration as a result of contact metamorphism around the Lac Dufault Granodiorite. Cordierite-anthophyllite assemblages were later described at the Millenbach deposit by Simmons et al. (1973). Mineralogical zoning of dalmatianite alteration at the Amulet Upper A deposit (Hall, 1982) and in the Millenbach Mine (Riverin and Hodgson, 1980) shows that anthophyllite is particularly developed in the stockwork zones of sulphide mineralization as the overprint of the chloritic core present in most of the un-

metamorphosed deposits. Gahnite (Zn-spinel) occurs with this assemblage, but only directly within massive sulphide zones (de Rosen-Spence, 1969).

Skarn alteration mineral assemblage have also been recognized within the Noranda VMS deposits. Variable proportions of ferroactinolite, andradite, hedenbergite, epidote, and magnetite have been described at the Amulet A, C, F deposits and at the Norbec and East Waite deposits (de Rosen-Spence, 1969). The paragenesis of these minerals at these deposits is still not well understood, however de Rosen-Spence (1969) assigns them to a skarn assemblage and suggests most have formed during a separate phase of metamorphic activity from the Lac Dufault Granodiorite intrusion and are likely related to local intrusions. Magnetite and bornite mineralization at the Vauze deposit is related to large quartz-diorite dykes cutting the B2 massive sulphide orebody (Spence, 1975). Large quartz-diorite dykes cut the other deposits containing magnetite, thus a similar association may exist. A magnetite-dominated skarn assemblage has been well documented at the Ansil deposit which in part has replaced the massive sulphide deposits and the footwall alteration assemblage, but also extends into the hangingwall (Riverin et al., 1990; Galley et al., 1995). The development of the skarn alteration is attributed to high temperature fluids which may be derived from the Flavrian Intrusion (Galley et al., 1995). The presence of tremolite at the Aldermac deposit (Hawley, 1948) is likely a result of contact metamorphism during the intrusion of the Aldermac Syenite and is included in this assemblage.

Retrograde metamorphism has also been noted at the Millenbach deposit in which an albite-calcite-chlorite-epidote-garnet assemblage has overprinted the anthophyllite-cordierite-biotite assemblage. The presence of chlorite within the dalmatianite assemblage has been noted at several other deposits (Amulet A, F, Norbec, and Newbec) and is also likely developed by retrograde regional metamorphism.

Whole-Rock Geochemistry

Because of the virtually consistent alteration mineralogies for the Noranda VHMS deposits, the whole-rock geochemical signatures associated with hydrothermal alteration are also consistent. Mass balance calculations based on comparisons of altered and "least altered" whole-rock compositions have been done at most of Noranda VHMS deposits. Riverin and Hodgson (1980) have shown that contact metamorphism of the hydrothermal alteration assemblages at the Millenbach deposits is isochemical and have postulated similar mineral reactions for other locations of dalmatianite alteration in the Noranda area. The core of the alteration zone at Millenbach, is highly enriched in Mg and Fe, while at the margins is highly enriched in K following the distribution of chlorite and sericite. Sodium is strongly depleted throughout the alteration zone, but Ca is only strongly depleted within the core and sporadically conserved towards the margins and is attributed to the degree of volcanic rock replacement by chlorite and sericite. Silica, in the form of quartz, is conserved overall throughout the alteration zones and Al is also relatively immobile through the formation of sericite and chlorite from plagioclase.

Later whole-rock geochemical studies of alteration at other Noranda VHMS deposits also showed similar trends (Norbec, Pirie and Nichol, 1981; Amulet Upper A, Hall, 1982; New Insko, Meyer and MacLean, 1983). Strong Fe, Mg, and K enrichments in the core of the alteration zones are also complimented by increases in Mn, Rb, Cu, Zn, Ag and S. Wallrock depletion of Na and Ca also includes Sr, Ba, Cr and Ni. Immobile Al at these deposits is also shown to coincide with immobile Ti as well as V at the Amulet Upper A deposit. Whole-rock Si trends with respect to massive sulphide mineralization at these deposits are variable. Depletion of Si in mineralized zones are reported at New Insko, however at both the Norbec and Amulet Upper A deposits, Si is enriched and depleted without particular spatial distribution. Similar whole-rock geochemical trends are described for the H orebodies at the Horne Mine (MacLean and Hoy, 1991) with specific attention to element mobility relationships to alteration mineral assemblages. Iron additions within the core of the alteration zone hosting massive sulphides is largely attributed to chlorite as well as the minor concentrations of pyrite and magnetite throughout the zone. Siliceous zones within the H orebodies show conservation of most the major elements excluding Si. Other whole-rock geochemical studies of the Noranda VMS deposits at Ansil, Mobrun, Corbet, and Delbridge by Barrett et al. (1991; 1992; 1993a; 1993b) yield similar results for elements listed above, although these studies included alteration developed in the hangingwall of these deposits. Geochemical trends for hangingwall volcanic rocks are similar to those in the footwall, however depletions and enrichments are not spatially extensive and tend to be sporadic except for Na which is

consistently depleted in all the studied deposits. Barrett et al. include REE data for these four deposits. The REE are generally immobile regardless of alteration mineralogy, although light REE show moderate mobility with chloritic alteration and strongly negative Eu anomalies are common in the FW of the deposits also associated with chloritization.

Volume changes are not typically considered as a influence on the major and trace element variations in all of these whole-rock geochemical studies. Most studies estimate less than 10% change of volume occurs during hydrothermal alteration despite the wide range of molecular volumes displayed by the minerals listed in Table A1. Shriver and MacLean (1992) calculate a 10% volume increase in the Norbec alteration pipe and further postulate total mass gains and losses. A total of 0.5 Mtonnes is removed from the Norbec alteration in contrast to a total of approximately 11 Mtonnes added which is largely Fe and Si. Less than 4% of this total addition is accounted by Cu and Zn.

Most of the whole rock geochemical studies listed above relate the major and trace element mobility to the temperature of the hydrothermal fluids associated with alteration and massive sulphide mineralization. Riverin and Hodgson (1980) estimate 200 °C and 250 °C for the formation of sericite and chlorite respectively using thermodynamic models for the perceived mineral reactions accounting for the enrichments of Fe, Mg, and K at Millenbach. Other studies using oxygen isotope thermometry give similar temperatures for quartz-sericite alteration and a range of 250-300 °C for chloritic

alteration (Barrett et al., 1993a; 1993b). Chlorite compositions from the Horne Mine in quartz-sericite zones correspond to a temperature range of 230-275 °C and a range of 250-310 °C in chloritized zones (MacLean and Hoy, 1991).

The Noranda VHMS Model

The model for the Noranda VHMS deposits and hydrothermal alteration shown in Figure A2 slightly modifies previous schematic sections (Cattalani and Chartrand, 1990; Franklin, 1996). The model depicted here emphasizes the stacked orebody orientation to illustrate the control of long-lived hydrothermal fluid conduits on massive sulphide deposition and hydrothermal alteration. The deposit examples shown in Figure A2 represent portions of the model and do not imply a particular genetic relationship between these deposits. This model, as with previous models, does not represent the lithologic setting of the Corbet deposit (i.e., mineralization at an andesite-rhyolite contact), but the alteration distribution is similar to that shown for the Millenbach and Ansil deposits. The model shown here, as also with previous models, does not include the felsic volcanic rock-hosted deposits such as those in the East and South Camp despite the significantly larger size of the felsic-hosted deposits. The volcanic stratigraphy at the Horne and Quemont deposits is complicated due to faulting and post-mineralization intrusions, thus was not resolved at the time of mining. The distribution of chloritic alteration at surface near the Quemont deposit suggests a similar pipe-like orientation of the footwall assemblages associated with synvolcanic dykes as displayed in the Main Camp. A

distinct footwall alteration pipe is not recognized at the Horne deposits, but most of the footwall rocks have been removed by the Andesite Fault. Discordant chloritic alteration zones have been identified in the H orebodies at Horne and may reflect the presence of alteration pipes (Kerr and Gibson, 1993). The highly permeable nature of the footwall epiclastic rhyolite below the Horne massive sulphides is more conducive to a large, diffuse alteration zone as described for VHMS deposits in similar volcanic settings (Gibson and Kerr, 1993), thus an alteration pipe may not be present at Horne.

Epidote-quartz alteration and silicification are not shown in the model as continuous alteration assemblages since both occur as distinct 'patches' of groundmass replacement with an irregular distribution at the outcrop scale. The abundance of patches decreases away from the volcanic centres and the areas of massive sulphide mineralization. This distribution for both semi-conformable alteration styles suggests groundmass replacement is not only structurally controlled, which is dominant for chlorite-sericite alteration, but is also controlled by volcanic textures such as vesicles, variolites, spherulites, and cooling fractures.

The size of the alteration pipe at Norbec suggests hydrothermal fluid upflow is derived deeply below the sulphide deposits and that fluid circulation at the larger deposits such as Horne, Quemont, and Gallen must be on the order of a few kms². Thus, the vertical scale in the model shown here is likely a minimum. The presence of semi-conformable alteration characterizes a regionally developed hydrothermal system which

reflects lateral hydrothermal fluid flow and so the horizontal scale in this model can also be extended. Oxygen isotope geochemistry of the volcanic rocks in the NVC depicts a hydrothermal system developed over a 20 km² area that is represented partially by the semi-conformable alteration mineral assemblages (Cathles, 1993; Paradis et al., 1993).

Therefore, while the alteration model presented here may be conservative with respect to the extent of hydrothermal fluid circulation in the NVC, it incorporates the paragenesis of the most significant mineral assemblages that have been described within the Noranda VHMS deposits. Consideration of the chemical effects of the semi-conformable alteration mineral phases is currently being considered (this study; Paquette, in prep) to evaluate the gross effects of hydrothermal fluid:rock interaction in the NVC including massive sulphide deposition.

Table A1. Hydrothermal Alteration Mineral Assemblages in the Noranda VHMS Deposits.

DEPOSIT<---LITHOLOGY--><---ALTERATION ASSEMBLAGES-->

MAIN CAMP	HOST	FW	HW	HOST	FW	HW	DISTAL	REFERENCES
Corbet	and	1) and 2) [ton]	1) and 2) rhy	1) ch	1) ch-se	1) se	1) ep-qt 2) qt-ab-ch-ep	Knucky and Watkins, 1982 Gibson et al., 1993
Ansil	rhy + rhy tuff	1) rhy 2) and 3) [ton]	1) and 2) rhy	1a) sp-py-po-se-qt-ab 1b) po-cp-ch-qt	1) ch-se-qt 2) mt-ac-hd-gn-ep-ab-cp-py [skarn]	1) ch-se-qt-	1) sp-po-se-qt-ab 2) ep-qt	Riverin et al., 1990; Galley et al., 1995; this study
Bedford	dac	1) dac 2) and	1) dac 2) and	1) ch-se-qt	1) ch-se-qt	1) se-qt	1) sl	Atkinson and Watkinson, 1980
Vauze	rhy	1) rhy bx 2) and	1) rhy bx 2) and 3) [dio]	1) qt-ch	1) ch-se 2) sl 2b) cb	1) ch-py 2) sl 3) [mt-bn]	1) hm (rhy)	Gilmour, 1965 Spence, 1975
East Waite	rhy	1) rhy	1) and 2) [dio]	1) cd-ant	1) cd-ant-ch-se-bi-gn	not noted	1) Fe_act-mt-hd-gn-ep [skarn]	de Rosen-Spence, 1969 McConnell, 1976
Old Waite	rhy	1) rhy 2) and	1)and	1a) cd-ant-gh-bi-ch 1b) ch-se-qt-ep	1) cd-ant-gh-bi-ch 2a) ch-se-qt-ep 2b) sl	2) cd-ant-bi-ch	sl ep-qt	Price and Bancroft, 1948 Gilmour, 1965 Gibson, 1989
Norbec	rhy	1) rhy 2) and	1) and	1) cd-ant-bi-ch-gh 2) qt-se	1) cd-ant-bi-ch-gh	not noted	1) se 2) qt-ep 3) ac-hd-ep-Mn_gn-mt [skarn]	de Rosen-Spence, 1969 Pirie and Nicholl, 1981 Cattalani et al., 1992
Amulet F	and	1) and	1) and	1) cd-ant-bi-qt	1) cd-ant-bi-qt	1) ch-py-cp	1) sl 2) ep-qt	de Rosen-Spence, 1969 Gibson et al., 1983; this study
Amulet C	and	1) and	1) and	1) cd-ant-bi-qt	1) cd-ant-bi-qt	ch-py-cp	1) sl 2) ep-qt	de Rosen-Spence, 1969; Gibson et al., 1983
Amulet A	and	1) and	1) and	1) cd-ant-bi-qt	1) cd-ant-bi-qt	1) cd-ant-bi-qt ch	1) sl 2) ep-qt	Suffel, 1948 de Rosen-Spence, 1969 Gibson et al., 1983
Upper A	and	1) and	1) and	1) cd-ant-bi-ch-gh	1) cd-ant-bi-ch-gh	1) cd-bi-qt	1) ep-qt 2) ac-mt-gn-hd-ep-py [skarn]	de Rosen-Spence, 1969; Hall, 1982; Gibson et al., 1983; this study
Millenbach (Contact Tuff)	QFP dac tuff	1) QFP 2) and	1) and	1) ant-cd-bi-gn-qt qt-ch-se-ep-ti-ru-il	1) ant-cd-bi-gn-qt 2) ep-ch-se-cc	cd-bi	1) ac-qt 2) se-qt 3) ab-cc-ch-ep-gn	Simmons et al., 1973 Riverin and Hodgson, 1980 Kalogeropoulos and Scott, 1988
D-68	QFP	1) QFP 2) and	1) and	1) ch-qt 2) se-qt	1) ch-qt 2) se-qt	1) ch-qt 2) se-qt	1) ep 2) cc	Ikingura et al., 1989
Aldermac	rhy	1) rhy 2) and	1) rhy 2) and 3) [syn]	1) qt-ch-se	1) qt-ch-se [trm]	1) sl [trm]	1) sl 2) ep-qt-ch-se-py	Hawley, 1948 Hunter and Moore, 1983 Barrett et al., 1991
NEWBEC	and	1) and	1) QFP	1) ant-cd-bi-ch	1) ant-cd-bi-ch	not noted	not noted	de Rosen-Spence, 1969; Smith, 1983

Table A1. (continued)

DEPOSIT<---LITHOLOGY--><---ALTERATION ASSEMBLAGES-->

EAST CAMP	HOST	FW	HW	HOST	FW	HW	DISTAL	REFERENCES
Quemont	rhy	1) rhy + rhy bx	1) QFP	1) ch	1) ch-se-qt 2) sl	1) se-ch-qt	1) se-qt	Scott, 1957 Taylor, 1957 Gilmour, 1965 Cattalani et al., 1990
Delbridge	rhy bx	rhy bx + rhy	rhy bx + dac tuff	1) ch-se-qt	1) ch-se-qt	1) se-qt	1) se-qt 2) cb	Boldy, 1968 Barrett et al., 1993
Gallen	rhy-dac	rhy-dac	1) rhy 2) [grd]	1) se-qt	1) se-qt-ch	1) se-qt-ch	1) se 2) ac-ch-ep-cc	Watkinson et al., 1990
Mobrun (Main Lens) (1100 Lens)	rhy+ dac pyr rhy	rhy ± and rhy bx	1) rhy rhy + rhy tuff	1) se-ch 1) se-ch	1) se 1) se-qt-ch-cb	1) se 1) se-qt-ch	1) cb 2) ep-hm	Caumartin and Caille, 1990 Laroque and Hodgson, 1993

DEPOSIT<---LITHOLOGY--><---ALTERATION ASSEMBLAGES-->

SOUTH CAMP	HOST	FW	HW	HOST	FW	HW	DISTAL	REFERENCES
Horne (H orebodies)	rhy bx	1) rhy tuff + bx 2) and [And. Fault]	1) rhy tuff + bx 2) [dio]	1) se-ch-qt-ep-ab	1) se-qt-ch-ep-ab 2) ch-qt-ep-se-cb	1) se-qt-ch	1) sl 2) py-se-ch-ep	Cooke, 1929; Price, 1934; Butterfield, 1934; MacLean and Hoy, 1991; Kerr and Gibson, 1993
Horne (#5 orebody)	rhy tuff	1) rhy + rhy tuff 2) and [And. Fault]	1) rhy + rhy tuff 2) [dio]	1) se-ch-qt	1) se-ch-qt	1) se-qt-ch	1) sl	Sinclair, 1971 Cattalani et al., 1990 Kerr and Gibson, 1993

DEPOSIT<---LITHOLOGY--><---ALTERATION ASSEMBLAGES-->

WEST CAMP	HOST	FW	HW	HOST	FW	HW	DISTAL	REFERENCES
New Insco	rhy bx	rhy	bas	1) ch-se-qt	1) ch-se-qt	1) se-ch-qt	1) ch-pu-qt-ep-se	Meyers and MacLean, 1983; Stewart, 1998
4 Corners (MN Tuff)	rhy bx	rhy + rhy bx	rhy pyro	1) ch-se-qt	1) ch-se-qt	not noted	1) ep-qt 2) hm 3) sl 4) ab-qt-ac-	Parry and Hutchinson, 1981

Table A1. (continued)

Lithologic Abbreviations

and	andesite
bas	basalt
bx	breccia
dac	dacite
dio	diorite
grd	granodiorite
QFP	quartz-feldspar porphyry (flow)
pyr	pyroclastic
rhy	rhyolite (flow)
syn	syenite
ton	tonalite

Mineral Abbreviations

ab	albite
ac	actinolite
ant	anthophyllite
bi	biotite
cb	carbonate
cc	calcite
cd	cordierite
ch	chlorite
cp	chalcopyrite
ep	epidote
gn	garnet (andradite)
gh	gahnite
hd	hedenbergite
hm	hematite
il	ilmenite
mt	magnetite
po	pyrrhotite
pu	pumpellyite
py	pyrite
qt	quartz
ru	rutile
se	sericite
sl	quartz (as silicification)
sn	sphene
sp	sphalerite
trm	tremolite

Figure A1. Geology of the Noranda Volcanic Complex and location of VHMS deposits (after Spence and de Rosen-Spence, 1975; Spence, 1976; Rive, 1986; Gibson, 1989; Peloquin et al., 1992). The approximate boundary for the NVC is outlined in blue.

Figure A2. The Noranda VHMS model (after Chartrand and Cattalani, 1990; Franklin, 1996). The distribution of distal and semi-conformable alteration is after Gibson et al. (1983) and Gibson (1989). This model represents the general relationships for massive sulphides developed atop rhyolite flow domes and at andesite-andesite flow contacts and does not reflect relationships at the large felsic rock-hosted deposits (e.g., Horne and

Figure A3. The distribution of semi-conformable hydrothermal alteration assemblages (after Gibson et al., 1983). The section represents volcanic stratigraphy in the Turcotte Lake area.

APPENDIX B

DESCRIPTIONS OF SAMPLES COLLECTED ON REGIONAL TRAVERSES

Descriptions of all samples collected on these regional traverses were tabulated (Table B1; on provided diskette). Abbreviations used in the table are listed in Table B2. Each sample collected on the regional traverses was systematically described to make particular note of volcanic and alteration textures following a guideline developed by the Manitoba Department of Mines and Geological Survey of Canada geologists. Nearly 500 hand specimens have been described and most have been augmented by petrographic descriptions of mineralogy. Outcrop and hand sample photographs also represent most samples and are available upon request.

Figure B1 illustrates the distribution of the regional traverses conducted throughout the CNVC. Each sample station is represented by an alteration symbol that characterizes each outcrop. Additional samples from each station were collected to represent the presence of distinct lithologies and other alteration assemblages that were not characteristic for the outcrop. Most traverses were oriented to intersect volcanic strata previously mapped, but without detailed descriptions of alteration to extend the alteration maps previously made (e.g., Gibson, 1989; Paradis, 1990). In the East Camp, the samples described here are the first to depict regional hydrothermal alteration in this area.

Figure B1. Distribution of samples collected along regional traverses within the central Noranda Volcanic Complex. Each sample station is marked with a representative alteration symbol. Sample descriptions are given in Table B1. The alteration map for the cNVC (Figure 4.1) is mainly derived from these traverses.

APPENDIX C

DESCRIPTIONS OF SAMPLES COLLECTED IN DETAILED MAP AREAS

Sampling within the detailed map areas concentrated on the relationships of different alteration mineral assemblages without a particular regard to spacing. The distribution of samples from the Lac Duprat South area, Amulet F Shaft area, and the Amulet Upper A area are provided (Figure C1, C2, C3). Each sample was systematically described using the same guidelines used for the regional samples. Descriptions of samples from each of these three areas are provided on the accompanying diskette (Table C1, C2 and C3).

Andesite Flows

massive	lobe-hyaloclastite	pillow	flow contacts
rhyolite dykes	composite dykes	diabase dykes	faults

Figure C2. Sample distribution for the Amulet F Shaft area. Samples all contain FSH-designation and are described in Table C2.

APPENDIX D

WHOLE ROCK GEOCHEMISTRY DATA

Over 300 samples have been analyzed by standard whole-rock geochemical techniques. Several of these samples represent epidote-quartz alteration / volcanic wallrock pairs to characterize the geochemical changes due to epidotization. Other samples were used to identify the geochemical compositions of the relatively unaltered volcanic rocks throughout the Noranda Volcanic Complex and to characterize the whole-rock geochemistry of background alteration. The complete data set is provided on the accompanying diskette (Table D1).

Two separate analytical laboratories provided the analyses for major and trace element geochemistry (the Geological Survey of Canada and Laurentian University Laboratories). All data have been measured using standard X-Ray Fluorescence methods with some additional trace elements measured by Inductively Coupled Mass Spectrometry on selected samples. Repeated analyses were performed at both Laboratories and have returned comparable results (Table D2). Samples RRA94018 and RRA94037 were analyzed by the GSC Laboratory and consistently returned deviations of less than 5 relative percent. Sample UAA96915 from the Laurentian Laboratory demonstrated higher errors, but typically for elements with relatively low abundances. The accuracy of the data is sufficient for the calculations made throughout this study.

Table D2. Repeated Analyses for Whole Rock Geochemical Analyses.

SAMPLE	RRA94018a	repeat	error	RRA94037b	repeat	error	UAA96915	repeat	error
SiO ₂	54.3	54.5	0.00	62.5	62.7	0.00	51.66	54.76	-0.06
TiO ₂	1.02	0.99	0.03	1.29	1.33	-0.03	1.22	1.13	0.08
Al ₂ O ₃	15.7	15.8	-0.01	13.6	13.6	0.00	17.9	17.18	0.04
Fe ₂ O ₃ _T	9.2	9.2	0.00	8.9	8.8	0.01	9.47	7.51	0.26
Fe ₂ O ₃	8.0	8.0	0.00	1.4	1.3	0.08			
FeO	1.1	1.1	0.00	6.7	6.7	0.00			
MnO	0.11	0.11	0.00	0.15	0.15	0.00	0.14	0.14	0.00
MgO	1.01	1.02	-0.01	5.17	5.19	0.00	5.99	4.16	0.44
CaO	16.72	16.68	0.00	1.96	1.91	0.03	5.58	9.14	-0.39
Na ₂ O	0.0	0.0		4.3	4.4	-0.02	4.21	3.88	0.09
K ₂ O	0.00	0.00		0.11	0.13	-0.15	0.16	0.32	-0.50
H ₂ O _T	1.7	1.6	0.06	3.2	3.0	0.07			
P ₂ O ₅	0.15	0.16	-0.06	0.18	0.19	-0.05	0.18	0.17	0.06
LOI	0.9	1.8	-0.50	2.7	2.7	0.00	2.68	1.46	0.84
TOTAL	99.8	100.0	0.00	100.6	100.6	0.00			
V	250	250	0.00	220	230	-0.04	230	219	0.05
Cr	19	21	-0.10	15	13	0.15	153.9	172.3	-0.11
Rb	0.3	0.4	-0.03	1.1	1.2	-0.08	5.8	8.4	-0.31
Sr	390	390	0.00	57	61	-0.07	132.3	134.5	-0.02
Nb	7.0	7.0	0.00	8.2	8.8	-0.07	7.8	7.3	0.07
Zr	120	120	0.00	160	150	0.07	76.4	84.3	-0.09
Y	25	27	-0.07	32	35	-0.09	14.2	15.7	-0.10

Note: oxides in weight %; trace elements in ppm.

APPENDIX E

MINERAL CHEMISTRY

The data for mineral compositions measured during this study is provided in Table E1.

Compositional variations in epidote are clearly visible in electron backscattered images due to the range in density between Fe and Al. The relatively higher density of Fe-rich epidote coincides with relatively bright areas compared to Al-rich epidote. An example of this relationship is shown here (Figure E1; Table E2). This example represents typical Fe/Al extremes within a single sample (Fe# between 20-30). A few samples display a larger Fe/Al range and typically contain aluminous epidote compositions with Fe# less than 15.

A comparison has been made between the data collected using the electron microprobe at the Geological Survey of Canada (sample RRA94037) and the data collected using the scanning electron microscope at Carleton University (sample NOR95092; Table E3). The chemical data from both samples analyzed are comparable with similar cation totals in each. Variations in Al and Fe between samples (and within samples) reflect mineralogical variations not analytical. Elements such as Ba, Sr, Zn that are detectable using the electron microprobe are typically of very low concentration in the analyzed epidote samples thus their omission from the scanning electron microscope data does not affect the measured totals.

Table E2. Epidote compositions from Scanning Electron Microprobe analyses.

Element	point #1	point #2	point #3
Si	6.04	6.01	5.99
Al	4.49	4.66	4.26
Ti	0.00	0.00	0.00
V	0.00	0.00	0.00
Cr	0.00	0.00	0.00
Fe	1.47	1.34	1.74
Mn	0.00	0.00	0.00
Ca	3.99	3.99	4.00
Fe#	24.6	22.4	29.0

Note: Values are number of cations (based on 13 oxygen formula of epidote)
 Point locations are shown in Figure E1 (sample NOR95111B).

Table E3. Comparison of Data for Mineral Chemistry Analyses.

Sample Point	RRA94037 1 (wt %)	RRA94037 2 (wt %)	RRA94037 3 (wt %)	NOR95092 1 (wt %)	NOR95092 2 (wt %)	NOR95092 3 (wt %)
SiO ₂	34.984	35.891	34.932	39.52	38.45	39.10
TiO ₂	0.008	0.000	0.008	0.33	0.00	0.00
Al ₂ O ₃	19.903	24.319	20.814	22.59	25.11	23.68
Cr ₂ O ₃	0.000	0.018	0.018	0.00	0.00	0.00
Fe ₂ O ₃	17.008	10.954	15.881	13.07	11.99	12.33
MnO	0.013	0.108	0.044	0.12	0.00	0.24
MgO	0.010	0.000	0.005	1.12	0.24	0.76
BaO	0.000	0.000	0.000	nd	nd	nd
SrO	0.000	0.184	0.026	nd	nd	nd
ZnO	0.000	0.152	0.014	nd	nd	nd
CaO	22.425	22.559	22.239	22.71	24.10	22.63
Na ₂ O	0.075	0.047	0.000	nd	nd	nd
K ₂ O	0.025	0.020	0.025	nd	nd	nd
F	0.022	0.000	0.044	nd	nd	nd
Cl	0.028	0.023	0.015	nd	nd	nd
TOTAL	94.451	94.252	94.006	99.59	99.89	98.74
# of Ions						
Si	2.943	2.957	2.938	3.079	2.985	3.063
Al	0.057	0.043	0.062	0.000	0.015	0.000
Z =	3.000	3.000	3.000	3.079	3.000	3.063
Ti	0.001	0.000	0.001	0.019	0.000	0.000
Al	1.974	2.362	2.064	2.074	2.283	2.187
Cr	0.000	0.001	0.001	0.000	0.000	0.000
Fe	1.077	0.679	1.005	0.766	0.701	0.727
Mn	0.001	0.008	0.003	0.008	0.000	0.016
Y =	3.052	3.050	3.074	2.867	2.983	2.914
Mg	0.001	0.000	0.001	0.130	0.028	0.090
Ba	0.000	0.000	0.000	0.000	0.000	0.000
Sr	0.000	0.009	0.001	0.000	0.000	0.000
Zn	0.000	0.009	0.001	0.000	0.000	0.000
Ca	2.022	1.991	2.004	1.895	2.005	1.900
Na	0.012	0.008	0.000	0.000	0.000	0.000
K	0.003	0.002	0.003	0.000	0.000	0.000
X =	2.038	2.019	2.010	2.033	2.033	2.005
F	0.006	0.000	0.012			
Cl	0.004	0.003	0.002			
Fe #	0.353	0.225	0.328	0.272	0.235	0.253

Notes: Both samples of epidote-filled amygdules from outcrop in the Rusty Ridge formation.

Number of Ions are calculated based on an 13 oxygen formula for epidote.

Figure E1. X ray backscatter image from a scanning electron microprobe of coarse epidote crystals illustrating compositional variations. Relatively light grey areas are Fe-rich and darker areas are Al-rich (see Table E2).

APPENDIX F

VOLCANIC STRATIGRAPHY OF THE AMULET UPPER A AREA

Epidote-quartz alteration in the Amulet Upper A area (Figure 4.1) was mapped in detail (1:1000 scale) to determine the stratigraphic relationships of alteration within the Amulet Andesite Formation as well as to determine the spatial and temporal relationships to sulphide mineralization and the host alteration assemblages. Previous lithologic maps of the volcanic stratigraphy compiled by Spence (1976) and Gibson (1989) are at a larger scale, so the area was re-mapped for this study (Figure F1). The map area is dominated by a sequence of andesite massive flows and pillowed lavas of various sizes and morphology. Due to the lack of obvious flow-top indicators such as brecciated intervals, individual flow units have been delineated by pillow morphology following the terminology of Dimroth et al. (1978). As a result, contacts between the units are often not obvious in outcrop and are thus somewhat arbitrary within 1 metre on the map.

Lithologic Units

Andesite Massive Flows

Most massive flow units in the map area are mega-pillows up to several metres long and do not represent ponded flows as described elsewhere in the Mine Sequence (Gibson, 1989). The pillow morphology in these massive flows is apparent by local

pillow junctions and quenched glass pillow crusts, but these textures are rarely continuous over 0.5 m (Plate Fa). These discontinuous selvages are likely re-entrant structures formed during flow movement that have quickly quenched. The lack of these particular textures may reflect partial welding of these flows, common in the Mine Sequence (Dimroth et al., 1978). Lava tubes are also recognized in some massive flows by the shape and size of some of the epidote-quartz alteration patches which conform to the flow morphology (Plate Fb). A single, thick massive flow unit (U10) occurs in the area with sill-like properties and is texturally distinct from the other flows (described further below). Porphyritic textures are common in some massive flows similar to some pillowed flows, thus the presence or absence of plagioclase phenocrysts is not a particularly useful criteria for discriminating flow morphology in the Upper A area. Similarly, the vesicularity of the flows does not specifically correspond to either massive or pillowed flows.

Andesite Pillow Flows

Pillows morphologies vary within single units over a few 10s of metres, but often characterize specific flow units. Pillows range in size from 1 m in diameter to < 10 cm and shapes also range from “bun shaped” to “ameboidal-shaped” accordingly. Interpillow spaces also vary in size, typically according to the pillow morphology. Large pillows contain thick interpillow spaces and often display well developed selvages (Plate Fc). The smaller ameboidal-shaped pillows contain thin interpillow spaces and selvages are often

not discernible (Plate Fd). Pillow breccias are conspicuous in some units and appear to grade into larger pillows locally. Andesite fragments within the breccias have irregular shapes and locally appear as micro-pillows (Plate Fe). On fresh cut surfaces and in thin section a textural distinction between the fragments and matrix is not obvious. A similar distribution of pillow morphologies is described elsewhere in the Amulet Andesite formation in the Norbec Mine area by Cousineau and Dimroth (1982). These irregular-shaped flow morphologies have been suggested to represent high lava flow rates (Moore, 1975). Flow directions based on pillow re-entrant selvage textures are complex even within a single outcrop and suggests close proximity to the volcanic vent area.

Andesite Dykes

Andesite dykes are prolific in the area and cut most of the flow units mapped in the area. The abundance of andesite dykes in the area is considered to represent a separate volcanic feeder system to the Amulet Andesite than the Old Waite Paleofissure as part of the McDougall-Despina Eruptive Centre (Gibson, 1989). These dykes contain a micro-gabbroic grain texture distinct from the vitric nature of the massive and pillow andesite flows. As a result, the dykes weather to a dark grey colour and are easily distinguished from the brown weathering colour of the flows. All of the dykes in the area cut the flows at a shallow angle at surface, typically less than 20° , thus in some outcrops, the occurrence of dykes appears intermittent with the flows. Most dykes contain well developed concentric cooling fractures developed parallel to their margins (Plate Ff).

Locally, pipe vesicles also develop along the dyke margins (Plate Fg). The dyke contacts are often chilled and are not easily recognized in outcrop. The contacts have an irregular propagation between individual flow tubes and locally appears to engulf pre-existing pillows. Pillow buds emanating from these dykes are also present locally and suggest these dykes are feeders to the andesite pile. In the SW corner of the map area, the andesite dykes appear to flatten and likely feed the U8 flow.

Felsic Dykes

Felsic dykes cross-cut the andesite flows in the Amulet Upper A area. Most dykes appear highly siliceous and most are aphyric. The felsic dykes trend E-W to NE-SW. Trace element compositions of the felsic dykes are similar to the overlying felsic volcanic flows in the cycle IV sequence (Galley, 1998) which suggests these dykes are part of the feeder system to the overlying felsic succession.

Volcanic Stratigraphy

Based on the previous volcanic stratigraphy studies by Spence (1976) and Gibson (1989) a volcanic stratigraphy is constructed here for the Amulet Upper A area. Descriptions of the individual flow units shown in Figure F1 are given in Table F1. The Millenbach Andesite-Amulet Andesite formation contact in the area as designated by Gibson (1989) provides the basis for numbering the lithologic units. The unit at the base

of the Amulet Andesite formation has been described outside of this map area as pillowed and strongly feldspar porphyritic (Gibson and Walker, 1984) and roughly corresponds to the U1 flow designated here.

The lack of flow top breccias and distinctive flow textures makes designation of individual flow units in the Upper A area somewhat arbitrary. Unit U3 contains pillows with a wide range of sizes and shapes without a particular spatial distributions. This unit is also cut by numerous andesite dykes which obscure the upper contact. Unit U4 was mapped as massive, although is composed of large flow tubes (shown in Plate Fb). Unit U5 is particularly vesicular, especially compared to other pillowed flows in the area. The U5 unit is spatially constrained by the surrounding massive units, U4 and U6, and thus may be part of one of these flows. Units U6 and U8 also display a similar concentration of vesicles as the U5 unit. Unit U6 is distinct by the presence of abundant, small (< 2 mm) plagioclase phenocrysts. Unit U7 is subdivided into four sub-units. Although mainly pillowed, U7 also contains pillow breccias with fragments similar to micro-pillows (described above, Plate Fe). A thin massive flow is enveloped by the pillowed flows and is considered part of this unit. Interpillow tuff is conspicuous within the U7 unit and is finely bedded (Plate Fh). The amygdule minerals in U8 appear chemically stable despite the intense discordant alteration associated with sulphide mineralization (Plate Fi). This U8 unit contains the tuffaceous horizon of the Upper A deposit. Units U6, U7, and U8 may represent a single flow unit based on: the similar vesicular textures of U6 and U8, the presence of massive flows within the U7 unit, and the presence of andesite tuffs in

both the U7 and U8 units. Well developed, large pillows occur throughout the U9 flow that are distinct from the irregular shaped-pillows from U7, although near the open pit pillows are ameboidal-shaped. The thick massive unit, U10, contains poorly developed columnar joints within the map area, but well developed columnar joints have been observed in this flow immediately north of this area. The U10 unit is only weakly altered proximal to the open pit and appears to cut the altered flows which host the massive sulphides (Plate Fj). The thickness of this flow and the nature of the contacts suggests the U10 unit may be a later andesite sill intruded into the andesitic pile after sulphide mineralization. Other previous workers have also considered this unit as a sill-like body (Spence, 1976; Hall, 1982).

Faults identified by Spence (1976) in this area have been retained by this mapping despite the lack of significant displacement along either fault. The unnamed fault south of the Corbet Road is distinguished at surface by a sharp gap in the outcrops. The U2 unit does not extend south of this fault, but interpillow tuffs in the U7 unit occur on either side of the fault. Correlation of volcanic units across the Turcotte Lake Fault is not always possible. Units U2, U3, U4, and U5 do extend north of this fault. The conspicuous U10 unit also terminates at the fault and suggests this may have been a fault scarp developed at the time of active volcanism, although the McDougall-Despina Structure is displaced by this fault outside of the map area (Gibson, 1989). This suggests the Turcotte Lake Fault is more likely post-volcanic.

The volcanic stratigraphy presented here modifies the previous section derived by Spence (1976). A comparison of the section derived from the surface mapping here is shown in Figure F2. Gibson (1989) had recognized that flow units A1 to A5 from the Spence section correlated to the Millenbach Andesite formation, so that the chert horizon in the Spence section represents the Main Contact Tuff (Bluff Exposure). The chert horizon considered by Spence to be equivalent to the C Contact also correlates to the Main Contact Tuff atop the Millenbach Rhyolite formation. The Upper A massive sulphide horizon is not shown in the Spence section, although on the surface map is contained in the A9 flow, although stratigraphy near the orebody is complicated by the pervasive and intense chloritic alteration associated with mineralization. Some flow units mapped by this study correspond to the Spence sections. Units U3, U7, and U9 are equivalent to flows A7, A9, and A13 respectively. The large sill-like unit mapped here as unit U10 is considered by Spence (1976) to be pre-mineralization (A8) despite the lack of pervasive chloritization in this unit.

Table F1.

Table F1. Description of Amulet Andesite Formation Flow Units in the Amulet Upper A Area.

FLOW #	MORPHOLOGY	TEXTURE
U1	PLWD	PORPH; PG_PH
U2	MSV	FN_GR
U3	PLWD	SMP; LGP
U4	MSV	RB; LGP
U5	PLWD	VES
U6	MSV	VES; PORPH; PG_PH
U7a	PLWD	TKSEL
b	PBX	
c	MSV	RB
d	ATFF	FN_GR; GRBD
U8a	MSV	VES
b	FDDY	CS_GR; PG_PH
U9	PLWD	LGP; PBX
U10	MSV	PG_PH; VIT; COLJNT

Note: Texture abbreviations given in Appendix B.

Figure F1. Lithologic mapping in the Amulet Upper A area. This figure represents mapping completed by this study at 1:1000 scale. Outcrop shapes are drawn from air photographs and are represented by dark colours.

Figure F2. Stratigraphic sections in the Amulet Upper A area. Sections A-B are east-west in orientation (after Spence, 1976) Section A is through the Upper A area and section B is through the strata north of the Corbet mine shaft. Section C is from this study and includes the contacts of the Millenbach Rhyolite and Millenbach Andesite formations from Gibson (1989).

Plate F. Lithologic relationships and volcanic textures from the Amulet Upper A area.

Fa. Massive andesite flows containing fragments of quenched lava crusts. These isolated selvages likely reflect an autobrecciated pillowed texture.

Fb. Large lava tubes can be recognized by large epidote-quartz alteration patches (outlined) which conform to the shape of the tube.

Fc. Well developed, “bun-shaped” pillows with mineralized interpillow spaces.

Fd. Ameboidal-shaped pillows with thin interpillow spaces characterize the Upper A area.

Fe. Pillow breccia with rounded, irregular-shaped fragments appear as micro-pillows. Fragments are dark in colour compared to the weathered light colour of the matrix.

Ff. Cooling fractures (arrows) infilled by quartz developed parallel along the andesite dyke margins. The dyke contact with pillows is marked by the dashed line.

Plate F. Lithologic relationships and volcanic textures from the Amulet Upper A area.

Fg. Pipe vesicles (arrows) developed within andesite dykes at contact with pillows.

Fh. Fine grained, thinly bedded interpillow tuff concentrated at the top of the U7 unit.

Fi. Unit U8 is particularly vesicular with relict amygdule minerals stable within the discordant alteration zone containing the massive sulphide deposits.

Fj. The contact of the U10 unit is highlighted by the lack of chloritization and subsequent

APPENDIX G.

CONSERVED ELEMENTS DETERMINATION

Conserved ('immobile') elements are identified by this study using a conventional statistical approach similar to other studies of hydrothermal alteration in volcanic rocks (e.g., MacLean, 1990). Common incompatible and high field strength elements were compared to observe the relative mobility of each element due to hydrothermal alteration. Data from the Rusty Ridge and Amulet Andesite formations are used for this observation and for comparison. The relative mobility of each element was determined for background alteration mineral assemblages and for the epidote-quartz patches.

The correlation coefficients for the common incompatible elements are given in Table G1 to G3. For the rocks that contain background alteration mineral assemblages (Table G1 and G2), most elements have positive correlation coefficients that reflect a similar response to hydrothermal alteration by these elements. Negative coefficients occur for Al in all the andesitic rocks and for Ta in the Rusty Ridge formation rocks. The highest correlation values occur between Nb, Zr, Y and Hf for background alteration assemblages in all andesitic rocks. In the epidote-quartz patches (Table G3), high correlations also occur consistently for Nb, Zr, Y and Hf and further verifies the relative immobility of these elements during hydrothermal alteration. Small variations in Zr due to primary variations or analytical error are not significant compared to the relatively high concentration of Zr in andesite. Thus, Zr is a useful monitor for immobility compared to

Nb, Y, and Hf which all occur at much lower concentrations. The high correlation value between Hf and Zr is inherent since Hf and Zr are chemically similar (Group IVA on the periodic table) and hence are likely contained in the same mineral phase (likely zircon). The high correlation is also a positive indication of the quality of the chemical analyses especially since different analytical techniques are used in measuring Zr and Hf (XRF and ICP-MS respectively; see Appendix D).

The variations for the other incompatible and high field strength elements are illustrated in plots versus Zr (Figure G1 and G2). The plots show the positive relationship between Zr, Nb, Y and Hf which is interpreted to reflect the conservation of these elements. The plots also illustrate a similar positive relationship for Th and U despite less data for these elements compared to Zr, Nb, and Y. The slight scatter in some of the conserved elements is partially due to primary compositional variations. Andesites in the Amulet Upper A area are enriched in Nb compared to other compositions in the Amulet Andesite formation (Figure G1). Similarly, andesites from the Amulet Upper A area are Ti-rich compared to other rocks in the Amulet Andesite formation. This distinction for Ti concentrations related to different primary compositional variations explains the low correlation values of TiO_2 -Zr for the Amulet Andesite formation which is also inferred from the Rusty Ridge data (discussed further in Appendix H).

Hydrothermal alteration variations do not appear to mobilize either Zr, Nb, Y, Th, or U as shown in the Zr plots. Weakly silicified and weakly chloritized rocks in the

Amulet Andesite formation are from the Despina area and the concentration of these elements overlap with the rocks from the same area with only background alteration (Figure G1). Andesites from the Old Waite-Norbec area are the wallrocks to epidote-quartz patches which also overlap in concentration for these elements. Depletion of Ti, Zr, Nb, Y, Th, and U occurs in the epidote-quartz patches and represents the overall mass addition in the patches and the dilution of these elements. Titanium is concentrated in the epidote-quartz patches as small grains of ilmenite or titanite. Intense chlorite-sericite alteration was not sampled in this study, although alteration studies of the VHMS deposits also revealed that Ti, Zr, Nb, and Y were relatively immobile (Shriver and MacLean, 1993; Barrett and MacLean, 1994; Barrett et al., 1995). Zirconium shows an erratic behaviour in the intensely silicified andesites in the Amulet Rhyolite formation (Paquette et al., 1998) which demonstrates the complexity in interpreting lithogeochemical data due to multiple episodes of alteration in the NVC.

In both the Rusty Ridge and the Amulet Andesite formations, Al does not correlate to Zr or the other conserved elements. A low, positive correlation between Al_2O_3 and Zr occurs in the Rusty Ridge samples, but a negative correlation between Al_2O_3 and Zr is displayed by the Amulet Andesite samples, even for the least altered rocks. Aluminium is contained in most of the background alteration minerals (albite, chlorite, sericite, epidote) and thus is potentially mobilized during alteration (Figure G1). In the epidote-quartz patches, Al is highly enriched compared to the andesite wallrocks due to the concentration of Al^{3+} in epidote.

Correlation values of the REE with Zr, Nb, and Th are consistently high for both the Rusty Ridge and Amulet Andesite formation. The REE patterns for weakly altered rocks from both formations are relatively flat (Figure G2) and correspond to calc-alkaline affinities as other studies have indicated (Ujike and Goodwin, 1983). The REE patterns for epidote-quartz patches in both formations are also flat and reflect only minor mobility due to alteration. Representative samples from the Rusty Ridge formation illustrate the overall depletion of the REE in the patches compared to the wallrocks which is likely due to dilution effects from mass addition as displayed by the other conserved elements. A similar relationship in the REE occur for the epidote-quartz patches versus the wallrocks in the Amulet Andesite, although this relationship is not consistent for all samples. In both formations, the LREE are less mobile compared to the HREE. Europium is highly mobile compared to all the other REE and likely reflects the replacement of Ca^{2+} by Eu^{2+} in epidote which is common in several calcic minerals such as plagioclase and titanite.

Table G1. Correlation coefficients for typical conserved elements in the Rusty Ridge Formation

Andesite wallrock for epidote-quartz patches; N = 20

	<i>TiO2</i>	<i>Al2O3</i>	<i>Nb</i>	<i>Zr</i>	<i>Y</i>	<i>Hf</i>	<i>Ta</i>	<i>Th</i>	<i>U</i>	<i>La</i>	<i>Ce</i>	<i>Pr</i>	<i>Nd</i>	<i>Sm</i>	<i>Gd</i>	<i>Eu</i>	<i>Tb</i>	<i>Dy</i>	<i>Ho</i>	<i>Er</i>	<i>Tm</i>	<i>Yb</i>
<i>TiO2</i>	1.00																					
<i>Al2O3</i>	0.34	1.00																				
<i>Nb</i>	0.52	0.51	1.00																			
<i>Zr</i>	0.32	0.39	0.87	1.00																		
<i>Y</i>	0.52	0.31	0.73	0.58	1.00																	
<i>Hf</i>	0.52	0.43	0.83	0.88	0.78	1.00																
<i>Ta</i>	-0.14	-0.42	-0.09	0.00	-0.13	-0.14	1.00															
<i>Th</i>	0.68	0.28	0.77	0.62	0.84	0.79	-0.16	1.00														
<i>U</i>	0.46	0.03	0.57	0.40	0.64	0.48	-0.05	0.81	1.00													
<i>La</i>	-0.09	-0.02	0.52	0.49	0.59	0.45	-0.09	0.48	0.55	1.00												
<i>Ce</i>	0.08	0.11	0.70	0.61	0.74	0.58	-0.05	0.62	0.62	0.95	1.00											
<i>Pr</i>	0.14	0.13	0.75	0.68	0.76	0.67	-0.11	0.67	0.60	0.92	0.98	1.00										
<i>Nd</i>	0.30	0.24	0.81	0.71	0.85	0.75	-0.13	0.76	0.59	0.81	0.93	0.96	1.00									
<i>Sm</i>	0.37	0.31	0.80	0.65	0.88	0.78	-0.21	0.82	0.61	0.71	0.84	0.88	0.94	1.00								
<i>Gd</i>	0.39	0.18	0.78	0.64	0.88	0.74	0.02	0.78	0.56	0.64	0.79	0.83	0.90	0.92	1.00							
<i>Eu</i>	0.14	-0.06	0.38	0.29	0.70	0.44	0.06	0.63	0.71	0.53	0.62	0.63	0.63	0.66	0.71	1.00						
<i>Tb</i>	0.54	0.29	0.77	0.62	0.94	0.81	-0.12	0.91	0.64	0.54	0.70	0.76	0.86	0.93	0.93	0.70	1.00					
<i>Dy</i>	0.58	0.35	0.80	0.64	0.92	0.85	-0.16	0.88	0.57	0.50	0.66	0.73	0.83	0.91	0.93	0.65	0.97	1.00				
<i>Ho</i>	0.67	0.35	0.80	0.63	0.92	0.86	-0.20	0.91	0.63	0.46	0.62	0.69	0.79	0.89	0.89	0.62	0.96	0.98	1.00			
<i>Er</i>	0.65	0.38	0.81	0.68	0.92	0.87	-0.21	0.88	0.56	0.48	0.62	0.70	0.79	0.87	0.87	0.53	0.94	0.97	0.97	1.00		
<i>Tm</i>	0.58	0.42	0.80	0.66	0.93	0.83	-0.21	0.87	0.61	0.49	0.64	0.70	0.81	0.91	0.87	0.60	0.94	0.94	0.95	0.96	1.00	
<i>Yb</i>	0.68	0.53	0.84	0.69	0.89	0.87	-0.24	0.86	0.55	0.37	0.55	0.62	0.75	0.85	0.82	0.50	0.91	0.94	0.96	0.96	0.97	1.00
<i>Lu</i>	0.60	0.47	0.85	0.75	0.89	0.87	-0.17	0.84	0.55	0.41	0.58	0.64	0.78	0.85	0.84	0.51	0.90	0.91	0.93	0.93	0.97	0.98

Table G2. Correlation coefficients in the Amulet Andesite Formation

(A) All Andesites N = 60 for TiO₂, Al₂O₃, Nb, Zr, and Y ; N = 25 for all other elements

TiO2 Al2O3 Nb				Zr	Y	Hf	Ta	Th	U	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
TiO2	1.00																					
Al2O3	0.10	1.00																				
Nb	0.21	0.02	1.00																			
Zr	0.01	-0.22	0.53	1.00																		
Y	0.17	-0.13	0.51	0.71	1.00																	
Hf	-0.06	-0.30	0.81	0.91	0.61	1.00																
Ta	0.20	-0.20	0.88	0.87	0.67	0.82	1.00															
Th	0.11	-0.03	0.70	0.83	0.60	0.82	0.69	1.00														
U	0.03	-0.23	0.77	0.88	0.61	0.94	0.79	0.92	1.00													
La	0.05	0.05	0.71	0.57	0.43	0.46	0.49	0.52	0.52	1.00												
Ce	0.11	0.01	0.77	0.61	0.50	0.51	0.57	0.56	0.56	0.98	1.00											
Pr	0.16	0.02	0.76	0.58	0.51	0.45	0.54	0.50	0.49	0.96	0.98	1.00										
Nd	0.18	0.02	0.75	0.53	0.52	0.39	0.52	0.43	0.42	0.94	0.97	0.99	1.00									
Sm	0.18	-0.05	0.85	0.64	0.73	0.55	0.67	0.53	0.56	0.86	0.91	0.92	0.94	1.00								
Eu	-0.04	-0.20	0.61	0.58	0.51	0.55	0.46	0.48	0.55	0.54	0.58	0.58	0.57	0.67	1.00							
Gd	0.17	-0.16	0.84	0.67	0.93	0.61	0.72	0.59	0.62	0.65	0.71	0.72	0.74	0.91	0.60	1.00						
Tb	0.17	-0.18	0.78	0.64	0.96	0.59	0.73	0.57	0.60	0.52	0.58	0.58	0.60	0.81	0.50	0.97	1.00					
Dy	0.19	-0.18	0.80	0.68	0.98	0.62	0.73	0.62	0.63	0.48	0.55	0.57	0.57	0.77	0.49	0.95	0.98	1.00				
Ho	0.18	-0.17	0.77	0.66	0.99	0.62	0.70	0.64	0.64	0.44	0.51	0.52	0.53	0.74	0.47	0.94	0.97	0.99	1.00			
Er	0.17	-0.23	0.77	0.67	0.98	0.65	0.71	0.64	0.66	0.37	0.45	0.45	0.45	0.68	0.47	0.90	0.95	0.98	0.98	1.00		
Tm	0.21	-0.17	0.80	0.67	0.95	0.62	0.73	0.62	0.63	0.43	0.52	0.52	0.54	0.72	0.48	0.90	0.94	0.96	0.95	0.97	1.00	
Yb	0.04	-0.26	0.82	0.74	0.94	0.77	0.75	0.70	0.75	0.44	0.51	0.49	0.48	0.70	0.52	0.88	0.91	0.93	0.95	0.96	0.94	1.00
Lu	0.21	-0.21	0.81	0.71	0.93	0.70	0.73	0.65	0.69	0.38	0.47	0.48	0.47	0.68	0.53	0.86	0.89	0.93	0.94	0.96	0.96	0.96

(B) Least Altered Andesite N = 6 for TiO₂, Al₂O₃, Nb, Zr and Y; N = 4 for all other elements

[illegible]

Table G3. Correlation coefficients for elements in epidote-quartz alteration patches.

(A) Rusty Ridge Formation (N = 20)

	TiO ₂	Al ₂ O ₃	Nb	Zr	Y	Hf	Ta	Th	U	La	Ce	Pr	Nd	Sm	Gd	Eu	Tb	Dy	Ho	Er	Tm	Yb
TiO ₂	1.00																					
Al ₂ O ₃	0.24	1.00																				
Nb	0.72	0.33	1.00																			
Zr	0.77	0.17	0.85	1.00																		
Y	0.52	0.08	0.83	0.76	1.00																	
Hf	0.75	0.33	0.88	0.96	0.73	1.00																
Ta	-0.39	-0.48	-0.34	-0.47	-0.25	-0.48	1.00															
Th	0.85	0.24	0.83	0.82	0.60	0.84	-0.35	1.00														
U	0.69	0.48	0.84	0.61	0.63	0.73	-0.37	0.81	1.00													
La	0.26	0.19	0.54	0.50	0.62	0.55	-0.21	0.55	0.55	1.00												
Ce	0.31	0.24	0.61	0.61	0.68	0.64	-0.31	0.58	0.56	0.97	1.00											
Pr	0.37	0.18	0.65	0.67	0.75	0.69	-0.32	0.62	0.58	0.96	0.99	1.00										
Nd	0.40	0.17	0.70	0.71	0.82	0.73	-0.31	0.65	0.61	0.93	0.96	0.99	1.00									
Sm	0.50	0.16	0.81	0.75	0.92	0.76	-0.29	0.71	0.72	0.84	0.87	0.91	0.96	1.00								
Gd	0.51	0.12	0.81	0.73	0.96	0.73	-0.28	0.65	0.69	0.73	0.77	0.83	0.89	0.97	1.00							
Eu	0.13	0.24	0.45	0.15	0.64	0.22	-0.08	0.10	0.52	0.50	0.46	0.48	0.49	0.57	0.61	1.00						
Tb	0.55	0.16	0.87	0.78	0.97	0.78	-0.31	0.70	0.74	0.70	0.74	0.80	0.87	0.96	0.98	0.63	1.00					
Dy	0.55	0.17	0.88	0.79	0.97	0.78	-0.33	0.69	0.73	0.67	0.74	0.79	0.86	0.96	0.98	0.59	0.99	1.00				
Ho	0.54	0.23	0.89	0.75	0.97	0.76	-0.28	0.66	0.75	0.64	0.69	0.74	0.82	0.93	0.97	0.66	0.98	0.99	1.00			
Er	0.57	0.16	0.86	0.79	0.98	0.78	-0.28	0.67	0.72	0.65	0.70	0.76	0.84	0.94	0.97	0.62	0.98	0.99	0.99	1.00		
Tm	0.61	0.23	0.92	0.81	0.94	0.82	-0.26	0.71	0.78	0.58	0.63	0.69	0.77	0.89	0.91	0.59	0.95	0.96	0.97	0.97	1.00	
Yb	0.61	0.19	0.91	0.84	0.93	0.84	-0.25	0.70	0.73	0.55	0.60	0.67	0.74	0.85	0.87	0.55	0.93	0.93	0.94	0.95	0.98	1.00
Lu	0.63	0.19	0.91	0.83	0.91	0.83	-0.23	0.72	0.72	0.52	0.57	0.64	0.72	0.84	0.86	0.49	0.91	0.92	0.93	0.95	0.97	0.99

(B) Amulet Andesite Formation (N = 34 for TiO₂, Al₂O₃, Nb, Zr, and Y; N = 6 for all other elements)

	TiO ₂	Al ₂ O ₃	Nb	Zr	Y	Hf	Ta	Th	U	La	Ce	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb
TiO ₂	1.00																					
Al ₂ O ₃	0.26	1.00																				
Nb	-0.58	-0.25	1.00																			
Zr	-0.47	-0.53	0.55	1.00																		
Y	-0.24	-0.31	0.53	0.62	1.00																	
Hf	-0.69	-0.75	0.86	0.95	0.15	1.00																
Ta	-0.65	-0.27	0.82	0.61	0.46	0.75	1.00															
Th	-0.62	-0.87	0.45	0.82	-0.28	0.79	0.43	1.00														
U	-0.70	-0.76	0.45	0.77	-0.25	0.77	0.56	0.97	1.00													
La	-0.44	-0.09	-0.31	0.03	-0.56	0.03	0.13	0.49	0.62	1.00												
Ce	-0.58	-0.57	0.35	0.52	-0.07	0.60	0.64	0.82	0.91	0.74	1.00											
Pr	-0.17	-0.57	0.62	0.42	0.60	0.61	0.75	0.53	0.59	0.18	0.74	1.00										
Nd	-0.16	-0.55	0.75	0.48	0.71	0.67	0.79	0.45	0.50	-0.03	0.61	0.97	1.00									
Sm	-0.17	-0.64	0.81	0.57	0.69	0.73	0.76	0.50	0.51	-0.13	0.56	0.94	0.99	1.00								
Eu	0.60	0.44	-0.08	-0.61	0.79	-0.38	0.10	-0.63	-0.55	-0.31	-0.23	0.29	0.32	0.24	1.00							
Gd	0.10	-0.27	0.68	0.22	0.94	0.44	0.67	0.05	0.09	-0.36	0.25	0.82	0.91	0.89	0.63	1.00						
Tb	0.08	-0.20	0.68	0.19	0.94	0.41	0.70	0.02	0.07	-0.34	0.24	0.81	0.89	0.87	0.64	0.99	1.00					
Dy	0.18	-0.19	0.67	0.17	0.97	0.37	0.58	-0.08	-0.06	-0.53	0.07	0.70	0.82	0.82	0.65	0.98	0.98	1.00				
Ho	0.22	-0.07	0.53	0.00	0.96	0.23	0.60	-0.12	-0.06	-0.32	0.18	0.76	0.83	0.78	0.77	0.97	0.98	0.96	1.00			
Er	0.45	0.06	0.38	-0.19	0.99	0.02	0.37	-0.35	-0.31	-0.50	-0.08	0.58	0.67	0.63	0.86	0.90	0.91	0.93	0.96	1.00		
Tm	0.35	0.09	0.41	-0.17	0.98	0.06	0.46	-0.32	-0.26	-0.42	-0.01	0.62	0.70	0.65	0.87	0.92	0.93	0.93	0.98	0.99	1.00	
Yb	0.13	-0.09	0.59	0.08	0.95	0.33	0.64	-0.10	-0.03	-0.37	0.16	0.73	0.82	0.79	0.74	0.97	0.97	0.97	0.98	0.92	0.95	1.00
Lu	0.33	0.02	0.52	-0.04	0.99	0.17	0.44	-0.31	-0.29	-0.62	-0.13	0.54	0.67	0.66	0.78	0.92	0.92	0.97	0.94	0.97	0.96	0.95

Figure G1. Plots of the 'typical' conserved elements in the Rusty Ridge formation illustrating variations related to background alteration (diamonds) and epidote-quartz patches (open boxes). The arrow in each plot points toward trend in mass enrichment in patch compared to the wallrock. Circled wallrock-patch pair are dacitic compared to

Figure G2. REE patterns for background alteration and epidote-quartz alteration in the Rusty Ridge formation. (A) Background alteration. Sample from Ujike and Goodwin (1983) from Ansil Hill included to represent least altered pattern for the Rusty Ridge. (B) Epidote-quartz alteration patches. (C) Comparison of representative samples of andesite wallrock (open symbols) and corresponding epidote-quartz alteration patches (closed symbols).

APPENDIX H

LEAST ALTERED COMPOSITIONS FOR VOLCANIC ROCKS IN THE NORANDA VOLCANIC COMPLEX

Whole-rock geochemical data on the composition of volcanic rocks compiled from previous studies in the CNVC is given in Table H1 (on diskette). For both the andesitic and rhyolitic rocks throughout the CNVC, compositions are similar and suggest similar geochemical affinities for all the volcanic rocks.

APPENDIX I

MASS BALANCE RESULTS FOR EPIDOTE-QUARTZ PATCHES AND VOLCANIC WALLROCKS

The recalculated whole-rock compositions of the epidote-quartz alteration patches are provided in Table I1.

Mass gains and losses due to background alteration and due to epidote-quartz alteration were calculated for several samples by this study. The results for samples from the Rusty Ridge and Amulet Amulet formations are illustrated in Figures I1 and I2. The modal range for each element reported in Table 6.2 can be easily seen from the histograms shown in these figures.

Figure I1. Mass balance results for each whole rock component for epidote-quartz alteration patches in the Rusty Ridge (grey) and the Amulet Andesite (black) formations. Mass gains/losses for each element in each altered sample are compared to the relative concentration in the precursor rock.

Figure I1. Mass balance results for each whole rock component for epidote-quartz alteration patches in the Rusty Ridge (grey) and the Amulet Andesite (black) formations.

Figure I1. Mass balance results for each whole rock component for epidote-quartz alteration patches in the Rusty Ridge (grey) and the Amulet Andesite (black) formations.

Figure I2. Mass balance results for each whole rock component for background alteration relative to a least altered precursor composition for the Rusty Ridge (white) and Amulet Andesite (black) formations.

Figure I2. Mass balance results for each whole rock component for background alteration relative to a least altered precursor composition for the Rusty Ridge (white) and Amulet Andesite (black) formations.

APPENDIX J

CALCULATIONS OF ABSOLUTE MASS CHANGE DUE TO HYDROTHERMAL ALTERATION IN THE RUSTY RIDGE FORMATION

In order to quantify the mass balance calculations for the entire Rusty Ridge formation (Chapter 6), a total volcanic rock volume for the Rusty Ridge formation was determined first using data from Gibson (1989) and estimates from this study (Table J1). Gibson (1989) estimated the strike length and thickness of individual mapping flow units in five separate faults blocks (sectors) in which continuous stratigraphy could be observed (Figure J1). These were determined by 1:2000 scale mapping at surface and from diamond drill hole intersections along several sections. A width dimension for each sector was estimated based on an ovoid shape of the Noranda Cauldron prior to intrusion of the Lac Dufault Granodiorite. Thus, a total volume of volcanic rock could be calculated for each sector. A total mass was calculated assuming a uniform density for a mafic volcanic rock of 2.85 g/cc (Best, 1982).

With these total volcanic rock volumes, a volume of total epidote in each sector was calculated (Table J2). An estimate of the volume of epidote for each flow unit in each sector was determined along sampling traverses (Traverse #10; Appendix B) and detailed petrographic descriptions. The representative sample number collected during this study is given in Table J2. Mass is calculated from the volume and concentration of epidote

using an average density of 3.50 g/cc (Deer et al., 1985). Where epidote alteration patches are absent in the Rusty Ridge formation, petrographic concentrations of epidote ($< 1\%$) were found throughout as part of the background alteration mineral assemblage along with quartz, albite and chlorite and/or actinolite. This type of epidote alteration is not included in the total volumes and masses calculated, so that the totals are considered the “effective” results of alteration forming the epidote-quartz patches. As illustrated in Table E2, the predominance of the total epidote mass is from the Waite Dufault sector, specifically within the Old Waite Paleofissure, the thickest section of the Rusty Ridge formation, thus the effective mass value (and the subsequent mass changes discussed below) reflects the alteration effects in this area rather than the entire formation.

The mass balance values for both background alteration and epidote-quartz alteration in the Rusty Ridge formation are listed according to the Noranda Cauldron sectors (Table E3). An average value for each whole-rock component is calculated for both alteration mineral assemblages in each sector. For most components, the mass balance values are consistent toward depletion or enrichment trends, thus the average represents a reasonable mass flux estimate for the sector. However, for some components particularly SiO_2 , the mass balance values are variable, thus anomalous values which drastically deviated from the modal range for each whole-rock component were eliminated from all of the average value calculations as indicated in Table E3. Samples used as the least altered volcanic rock composition were also accounted for in the weighted average calculation where applicable in each sector.

Using the weighted mass balance average for background alteration as the mass flux in each sector and the total mass for volcanic rocks in the Rusty Ridge formation (Table J1), the mass change for each whole-rock component is calculated representing background alteration effects. Similarly for epidote-quartz alteration, the mass balance average for each component is multiplied by the total mass of “effective” epidote (Table J2) to give the mass flux in each sector. For the sectors outside of the Waite Dufault sector, the epidote-quartz alteration results are only based on a few samples due to the paucity of epidote-quartz alteration patches in these sectors. Nevertheless, the overall consistency of the data between the sectors reflects these few samples are representative of their respective sector area.

Figure J1. The fault-bound sectors of continuous volcanic stratigraphy within the Rusty Ridge formation identified by Gibson (1989). Total thicknesses of each andesitic flow unit was estimated by Gibson (1989) and used here to determine a total volume of andesitic rocks in each sector. Estimates of epidote-quartz alteration intensity determined during this study were used to calculate a total mass of epidote within the Rusty Ridge formation.