Mineralium Deposita (2003) 38: 393–422
DOI 10.1007/s00126-002-0298-z

ARTICLE

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Regional-scale hydrothermal alteration in the Central Blake River Group, western Abitibi subprovince, Canada: implications for VMS prospectivity

Received: 20 May 2002 / Accepted: 23 May 2002 / Published online: 19 July 2002

Abstract The Late Archean Blake River Group is a thick succession of predominantly mafic volcanic rocks within the southern zone of the Abitibi greenstone belt. It contains a number of silicic volcanic centers of different size, including the large Noranda volcanic complex, which is host to 17 past-producing volcanogenic massive sulfide deposits. The Noranda complex consists of a 7- to 9-km-thick succession of bimodal mafic and felsic volcanic rocks erupted during five major cycles of volcanism. Massive sulfide formation coincided with a period of intense magmatic activity (cycle III) and the formation of the Noranda cauldron. Hydrothermal alteration in these rocks is interpreted to reflect large-scale hydrothermal fluid flow associated with rapid crustal extension and rifting of the volcanic complex. The alteration includes abundant albite, chlorite, epidote and quartz (silicification), which exhibit broad stratigraphic and structural control and correlate with previously mapped whole-rock oxygen isotope zonation. The Mine Sequence volcanic rocks are characterized by abundant iron-rich chlorite (Fe/Fe + Mg t7$\geq$ 0.5), hydrothermal amphibole (ferroactinolite) and coarse-grained epidote of clinozoisite composition (< 10 wt% Fe_2O_3). Volcanic rocks of the pre-cauldron sequences, which contain only subeconomic stringer mineralization, are characterized by less abundant chlorite and mainly fine-grained epidote ($\geq$ 10 wt% Fe_2O_3) lacking the clinozoisite solid solution. Alteration in the Mine Sequence volcanic rocks persists along strike well beyond the limits of the main ore deposits (as far as several tens of kilometers) and can be readily distinguished from greenschist facies metamorphic assemblages at a regional scale. The lack of similar alteration in the pre-cauldron sequences is consistent with limited ^{18}O-depletion and suggests that the early history of the volcanic complex did not support large-scale, high-temperature fluid flow in these rocks. Comparisons with a much smaller, barren volcanic complex in nearby Ben Nevis township reveal important differences in the alteration mineralogy between volcanoes of different size, with implications for area selection during regional-scale mineral exploration. The Ben Nevis Complex consists of a 3- to 4-km-thick succession of mafic, intermediate and felsic volcanic rocks centered on a small subvolcanic intrusion. Alteration of the volcanic rocks comprises mainly low-temperature assemblages of prehnite, pumpellyite, magnesium-rich chlorite (Fe/Fe + Mg $\geq$ 0.5), iron-rich epidote ($\geq$ 10 wt% Fe_2O_3) and calcite. Actinolite $\pm$ magnetite alteration occurs proximal to the intrusive core of the complex, but the limited extent of this alteration indicates only local high-temperature fluid circulation adjacent to the intrusion. A distal zone of carbonate alteration is located 4–6 km from the center of the volcano. Although iron-bearing carbonates are present locally within this zone, the absence of siderite argues against a high-temperature origin for this alteration. These observations do not offer positive encouragement for the existence of a fossil geothermal system of sufficient size or intensity to have produced a large massive sulfide deposit.

Keywords Abititbi belt · Ben Nevis · Mineral chemistry · Noranda · VMS alteration

Editorial handling: R.J. Goldfarb

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Introduction

Two main types of hydrothermal alteration are commonly associated with volcanogenic massive sulfide (VMS) deposits: (1) discordant pipe-like alteration beneath the massive sulfides, and (2) semiconformable alteration zones that extend well beyond the deposits at or below the ore horizon. Whereas discordant alteration pipes are restricted to the immediate host rocks, large semiconformable alteration zones may be several hundred meters in thickness and are often mappable for tens of kilometers along strike (e.g., Gibson et al. 1983; Galley 1993). This alteration is a product of regional-scale fluid flow, driven by large thermal anomalies similar to those associated with modern volcanoes. The very large alteration volumes reflect the capacity of the geothermal system to produce large mineral deposits, in part as a source for the metals and also as a reservoir for the hydrothermal fluids. For example, in Canada, the average massive sulfide district occupies approximately 850 km^2 (roughly 30×30 km) and contains as many as 12 different deposits, for a total of 94 million tonnes of ore (Sangster 1980). To form this much massive sulfide, substantial volumes of hydrothermal fluid must be mobilized through volumes of rock exceeding several hundred cubic kilometers. The effects of this fluid flow should be evident throughout large parts of the host volcanic complex.

In metamorphosed terranes, such as the Abitibi greenstone belt, the recognition of regional-scale hydrothermal alteration is complicated by the fact that secondary minerals produced by syn-volcanic hydrothermal activity are essentially the same as those produced by later regional metamorphism. In mafic volcanic rocks, the calcic minerals (prehnite, pumpellyite, epidote, actinolite, titanite, calcite), in particular, are common to both syn-volcanic hydrothermal alteration and regional greenschist facies metamorphic assemblages. Where metamorphic temperatures have exceeded the thermal maximum of the original hydrothermal minerals, complex alteration assemblages tend to be converted to lower variance metamorphic assemblages that may be unimpressive in the field. In some cases, the effects of regional metamorphism may conceal large-scale hydrothermal alteration systems.

This paper examines regional-scale hydrothermal alteration in two volcanic complexes of the Late Archean Blake River Group in the western Abitibi Subprovince. The study compares alteration mineralogy associated with a large, productive volcanic center at Noranda with that of a much smaller, barren volcano in nearby Ben Nevis township. Mineralogical mapping is used to document the effects of large-scale fluid flow in both areas, and mineral–chemical studies provide a means of distinguishing regional-scale syn-volcanic hydrothermal alteration from regional greenschist facies metamorphism of essentially unaltered rocks.

Regional geology and metamorphism

The Blake River Group is a 10-km-thick succession of predominantly mafic volcanic rocks, extending for 140 km from Cadillac township in Quebec to Ben Nevis township in Ontario. The belt of volcanic rocks includes an area of anomalously low-grade regional metamorphism, centered on the Ontario–Quebec border (Fig. 1). The central part of the belt also contains several small to large, felsic to intermediate intrusions that are interpreted to be the centers to low-relief shield-type volcanoes (Dimroth et al. 1983a). The eastern half of the Blake River Group is dominated by the Noranda volcanic complex and adjoining volcanic centers to the north (Reneault, Montsabrais) and east (Clericy). The western half of the belt contains the small Ben Nevis and Clarice Lake complexes (Fig. 2).

The Noranda and Ben Nevis volcanoes formed during a period of intense magmatic activity between 2700 and 2696 Ma (Nunes and Jensen 1980; Mortenson 1987, 1993; Corfu et al. 1989; Corfu 1993). Chemostratigraphic analysis of the volcanic rocks in both complexes suggests that they were likely part of the same rift zone (Gélinas et al. 1978, 1984; Gélinas and Ludden 1984 ; Peloquin et al. 1995). An age of 2701 ± 2 Ma for porphyritic rhyolites of the Clarice Lake complex, in Pontiac township, is similar to the age of the pre-cauldron cycles at Noranda (Corfu et al. 1989; Corfu 1993), suggesting that the volcanism at both centers was contemporaneous. The volcanic rocks consist of tholeiitic to transitional tholeiitic to calc-alkaline basalt, andesite, dacite, and rhyolite. Slightly more calc-alkalic volcanic rocks at Ben Nevis may reflect increasing contamination by basaltic crust and an increasing arc-like signature to the west. However, the trace element chemistry of the Ben Nevis volcanic rocks overlaps with that of the Noranda subgroup (Barrie et al. 1993).

Primary volcanic textures are exceptionally well-preserved in both areas (e.g., relict palagonite and zeolite textures in hyaloclastite at Noranda: Dimroth and Licthblau 1979). The rocks at Ben Nevis lie entirely within the prehnite-pumpellyite subfacies,

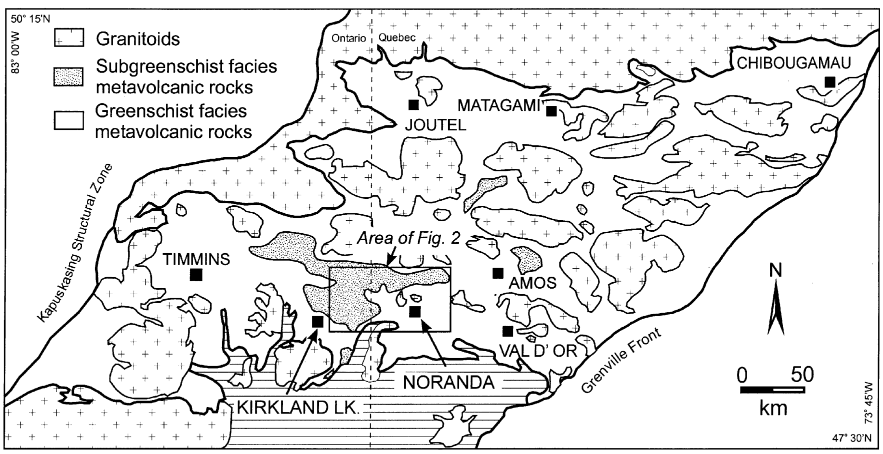


Fig. 1 Location of the study area, within the southern Abitibi greenstone belt (modified from Jolly 1978; Dimroth et al. 1983a, 1983b). Subgreenschist assemblages (*stippled areas*) are preserved in areas that were largely unaffected by the Kenoran orogeny

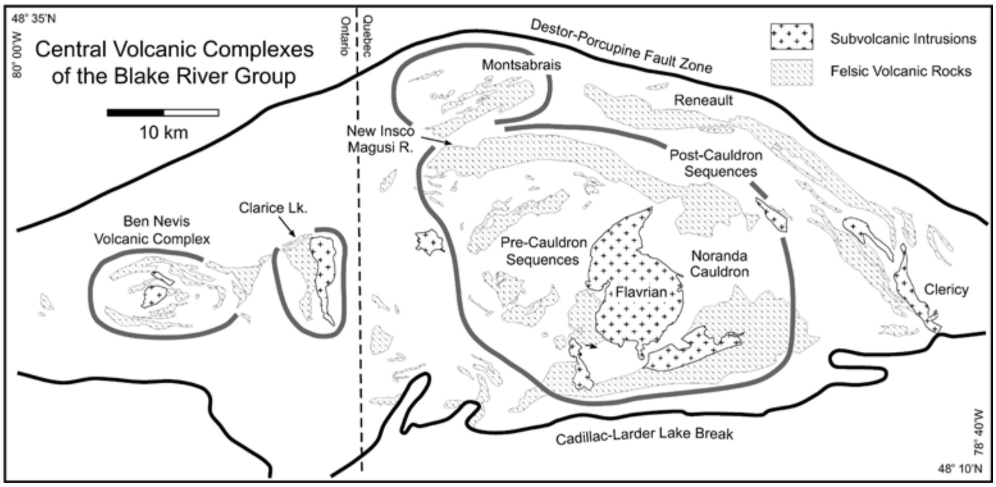


Fig. 2 Location of major silicic volcanic complexes of the late Archean Blake River Group (*bold outlines*). The volcanic belt extends for 140 km from Cadillac township in Quebec to Benoit township in Ontario and is bound by the Destor–Porcupine fault system in the north and Cadillac–Larder Lake fault system in the south. Volcanic rocks at the margins of the Ben Nevis and Clarice Lake volcanic complexes and the pre-cauldron sequences at Noranda are closely juxtaposed and may be in structural or stratigraphic contact

and a regional subgreenschist to greenschist metamorphic transition crosses the northwestern margin of the Noranda volcanic complex (Jolly 1978, 1980; Dimroth et al. 1983b; Powell et al. 1993, 1995). Hornblende-bearing rocks occur adjacent to the Larder Lake-Cadillac fault in the south and mark the regional greenschist-amphibolite transition.

Geology of the Noranda volcanic complex

The Noranda volcanic complex is interpreted to be a large shield volcano, approximately 35 km in diameter (Fig. 3). It consists of a 7- to 9-km-thick succession of bimodal mafic and felsic volcanic rocks erupted during five major cycles of volcanism (Spence and de Rosen-Spence 1975; Gibson 1989). The most important of these is cycle III, which includes the Noranda Mine Sequence. The Mine Sequence is a 3-km-thick succession of andesite, rhyolite, and minor volcaniclastic rocks erupted during a major period of rifting or cauldron subsidence. The boundaries of the cauldron structure are the Horne Creek fault in the south and the Hunter Creek fault in the north. Volcanic rocks of the Mine Sequence, which fill the cauldron, dip shallowly to the east at 35–60° and are underlain and intruded by the subvolcanic Flavrian pluton. Coeval volcanic rocks (included in the Mine Sequence) are also recognized to the north of the Hunter Creek fault and are thought to be related to eruptions that breached the north rim of the cauldron (Spence 1967; Camire 1989; Gibson 1989; Peloquin et al. 1989; Paradis 1990). These rocks extend northwest to Magusi River where they host the New Insco VMS deposit (de Rosen-Spence 1976; Gélinas et al. 1982; Dimroth et al. 1983a; Peloquin et al. 1990). Volcanic rocks to the west of the Flavrian pluton were described by Gibson and Watkinson (1990) as the ‘‘pre-cauldron sequences’’ and are products of effusive eruptions associated with early rifting. Although these rocks have been extensively explored, only subeconomic stringer mineralization has been found (e.g., in the Four Corners and Rob-Montbray areas; Parry and Hutchinson 1981).

The Flavrian intrusive complex is a 12-km diameter, sill-like tonalite body that was emplaced into its own volcanic pile during cauldron subsidence (Galley 2002). The nearby Powell intrusion is a faulted-off portion of the same composite body (Goldie 1976; Kennedy 1985). Multiple intrusive events have been responsible for a complex history of hydrothermal alteration in the overlying volcanic rocks, and whole-rock oxygen isotope data indicate that the Flavrian pluton was likely a driving force for hydrothermal circulation within the cauldron (Cathles 1993). The contact aureole of the intrusion is <1 km wide, presumably reflecting the efficient removal of heat by convective circulation of seawater. Intrusion of the younger Lac Dufault granodiorite caused local amphibolite facies contact metamorphism that overprints nearby VMS deposits (Riverin and Hodgson 1980; Hall 1982). Chloritic alteration pipes of several deposits adjacent to the Lac Dufault intrusion have been converted to cordierite–anthophyllite rocks. Additional dikes and sills, ranging from gabbro to quartz diorite, occur throughout the region.

Hydrothermal alteration and mineralization

The Mine Sequence volcanic rocks host 17 past-producing VMS deposits (Gibson and Watkinson 1990). Discordant pipe-like alteration zones occur immediately beneath each of the deposits and locally extends into the hanging wall (e.g., Atkinson and Watkinson 1980; Riverin and Hodgson 1980; Hall 1982; Knuckey and Watkins 1982; Ikingura et al. 1989; Barrett et al. 1990, 1991a, 1991b, 1992, 1993a, 1993b; Barrett and MacLean 1991; MacLean and Hoy 1991; Shriver and MacLean 1993). Larger, semiconformable alteration zones have also been mapped for tens of kilometers from the massive sulfides (Gibson et al. 1983; Galley 1993; Santaguida 1999). Five main alteration types have been identified at this scale, including regional spilitization (albite–chlorite alteration), chloritization, epidote–quartz alteration, and silicification (Gibson 1989; Paradis et al. 1993; Paquette 1999; Santaguida 1999). Silicification and epidote–quartz alteration are most conspicuous in the thick mafic flows of the Mine Sequence and increase in intensity toward the middle part of the cauldron where extensive dike swarms define several major eruptive centers and hydrothermal upflow zones. The most important of these is the Old Waite Paleofissure or Old Waite Dike Swarm, which is characterized by a well-defined zone of discordant epidote–quartz alteration (Santaguida 1999). Alteration of the Mine Sequence volcanic rocks outside the main camp has been described by Gélinas et al. (1978, 1982), Ludden et al. (1982), Meyers and MacLean (1983) and Liaghat and MacLean (1995).

Geology of the Ben Nevis volcanic complex

The Ben Nevis Noranda complex, located 50 km west of Noranda, consists of a 3- to 4-km-thick succession of mafic, intermediate and felsic volcanic rocks occupying a domal anticline that exposes the small subvolcanic Clifford stock (Fig. 4). Apart from the size of the intrusion and the thickness of the overlying volcanic rocks, there are several important differences between the Ben Nevis and Noranda complexes: (1) the volcanic rocks in Ben Nevis township are more evolved and are not strictly bimodal; (2) the structural setting of the volcanic complex is such that only the hanging wall stratigraphy above the intrusion is exposed (i.e., the volcanic basement is not exposed, as it is west of the Flavrian pluton); (3) no known

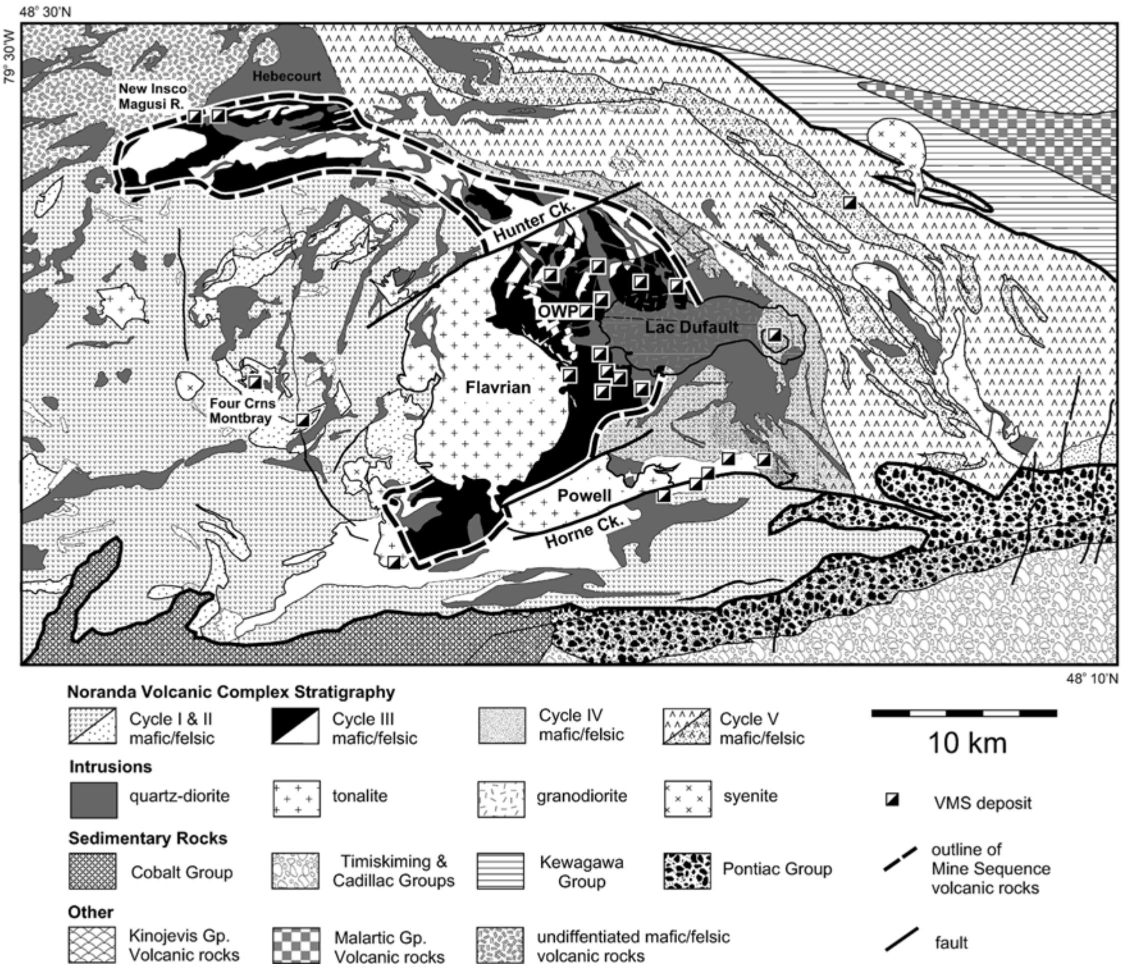


Fig. 3 Simplified geology of the Noranda volcanic complex after Spence (1967), Rive (1986), Camire (1989), Gibson (1989), and Paradis (1990). The Mine Sequence volcanic rocks and coeval volcanic rocks north of the Hunter Creek fault are outlined in *bold*. The approximate location of the Old Waite Dike Swarm or Old Waite Paleofissure is indicated by *OWP*. The main massive sulfide deposits (*squares*) are listed in Fig. 5

VMS deposits occur in the Ben Nevis area; and (4) the metamorphic grade is lower than in rocks elsewhere in the Blake River Group.

Low-iron tholeiitic basalt and calc-alkaline andesite comprise the bulk of the extrusive suite. These are mostly pillowed and brecciated flows, which have a shallow easterly dip. Felsic volcanic rocks are most abundant in the eastern half of the Ben Nevis area, and include massive dacitic flows and breccias and intercalated rhyolitic volcaniclastic units. The uppermost felsic units are as much as several hundred meters in thickness and comprise mainly dacite and rhyolite tuff with abundant tuff breccia. The greater abundance of pyroclastic material and the locally highly vesicular andesitic lavas in eastern Ben Nevis township have led to the suggestion that the volcanic succession is a shoaling upward sequence, with subaerial volcanic rocks exposed immediately to the east of the map area in Fig. 4 (Gagnon et al. 1995).

The intrusive core of the complex is the small Clifford stock, which has a diameter of less than 2 km. The sides of the intrusion are steep, and it has a narrow contact aureole, less than 200 m wide. The major part of the Clifford stock consists of equigranular to porphyritic quartz diorite and granodiorite. It partly intrudes earlier mafic volcanic rocks and is surrounded by a number of mafic dikes and quartz–feldspar porphyritic intrusions. Numerous faults on the eastern side of the Clifford stock have been interpreted as possible radial and ring fractures (Jensen 1975; Jensen and Langford 1985). As in Noranda, abundant quartz diorite bodies intrude the volcanic pile. These intrusions mainly post-date the Clifford stock and have an age of 2689 ± 2 Ma (Corfu and Noble 1992), similar to the age of the Lac Dufault granodiorite at Noranda.

Hydrothermal alteration and mineralization

A narrow zone of epidote–actinolite $\pm$ magnetite-bearing alteration surrounds the Clifford stock. This alteration is associated with a small, but notable, magnetic anomaly in the adjacent mafic volcanic rocks. A number of weakly mineralized zones also occur nearby in felsic volcanic rocks. This mineralization includes chalcopyrite-bearing quartz veins, porphyritic dikes with disseminated chalcopyrite and molybdenite, and minor associated Cu $\pm$ Au showings (e.g., Croxall occurrence: Fig. 4). These prospects have been extensively explored since the 1920s, but no economic discoveries were made. Rhyodacite, in the central part of Ben Nevis township, contains locally abundant quartz-, chlorite- and sulfide mineral-filled amygdules. However, discordant pipe-like alteration normally associated with VMS mineralization is not present in the Ben Nevis area.

Minor base metal-bearing veins (galena–sphalerite $\pm$ chalcopyrite $\pm$ silver) occur in the felsic fragmental rocks of easternmost Ben Nevis township. Most prospecting of these occurrences has been focused on the Canagau Mines property (Fig. 4). The mineralization consists of stockwork-like sulfide minerals, locally abundant disseminated pyrite in rhyolite tuff

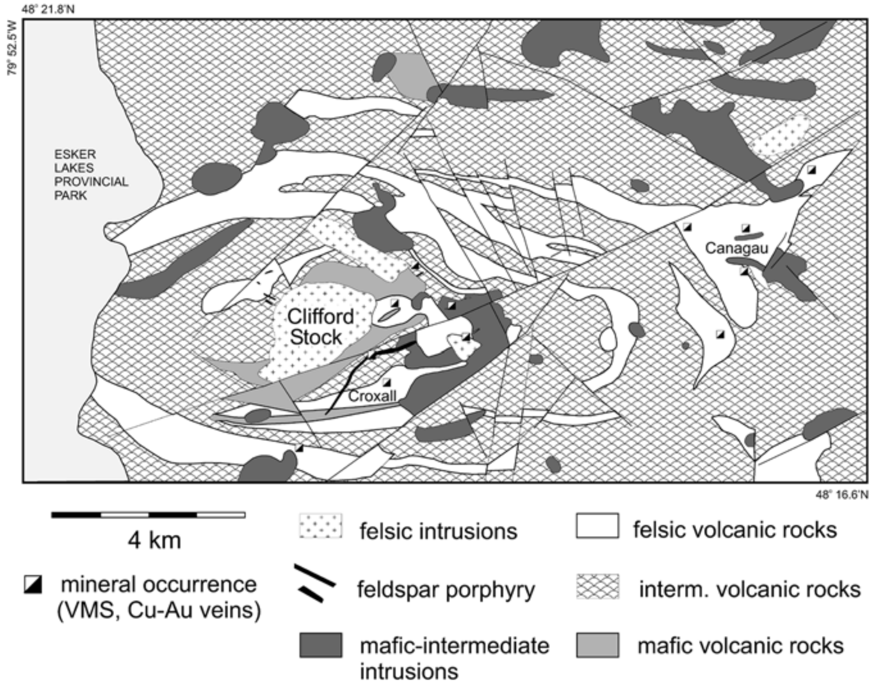


Fig. 4 Geology of the Ben Nevis volcanic complex after Jensen (1975). The map patterns reflect an east-trending domal anticline that is cored by the syn-volcanic Clifford stock

and breccias, and quartz- and calcite-filled veins in intensely sericitized and carbonatized fragmental rocks. The veins are thought to have formed contemporaneously with the volcanic rocks and may be part of a failed sub-seafloor stockwork or a shallow submarine epithermal system (Gagnon et al. 1995). A large zone of carbonate alteration in this area extends for more than 5 km, north and south of the Canagau occurrence (Grunsky 1986).

Methodology

More than 1,200 rock samples were included in this study. The samples cover areas of 35×50 km at Noranda and 7×15 km at Ben Nevis. The Noranda suite includes 500 samples from the oxygen isotope study of Cathles (1993), supplemented by an additional 120 samples collected for this study. Details of the sampling procedure are outlined in Cathles (1993) and the distribution of the samples is shown in Fig. 5. More than 600 samples from the Ben Nevis area were provided by the Ontario Geological Survey. These samples were collected between 1969 and 1981 by L.S. Jensen, W.J. Wolfe, and E.C. Grunsky (Jensen 1975; Wolfe 1977; Grunsky 1979, 1980, 1981, 1986, 1988; Jensen and Langford 1985). Their distribution is shown in Fig. 6. Mafic volcanic rocks represent about 85% of the sampled lithologies in both areas.

Mineral abundances were determined on whole rock powders by X-ray diffraction. These analyses were facilitated by a commercially available peak-stripping program (JADE), which is used

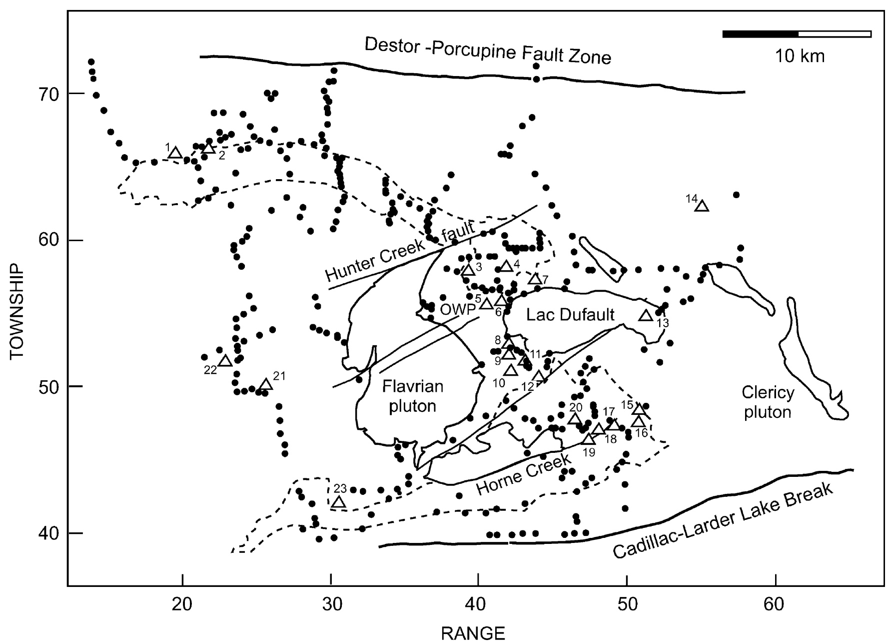


Fig. 5 Simplified map of the Noranda area showing the location of samples in the Cathles (1993) sample suite. The approximate location of volcanic rocks belonging to cycle III and including the Mine Sequence are indicated by the *dashed line*. The massive sulfide deposits are *1* Magusi R., *2* New Insco, *3* Ansil, *4* Vauze, *5* Old Waite, *6* East Waite, *7* Norbec, *8* Amulet E., *9* Amulet, *10* Corbet, *11* Amulet A, *12* Millenbach, *13* Mine Gallen, *14* Mobrun, *15* Deldona, *16* Delbridge, *17* Donalda, *18* Quemont, (*19*) Horne, *20* Joliet, *21* Four Corners, *22* Rob-Montbray, and *23* Aldermac

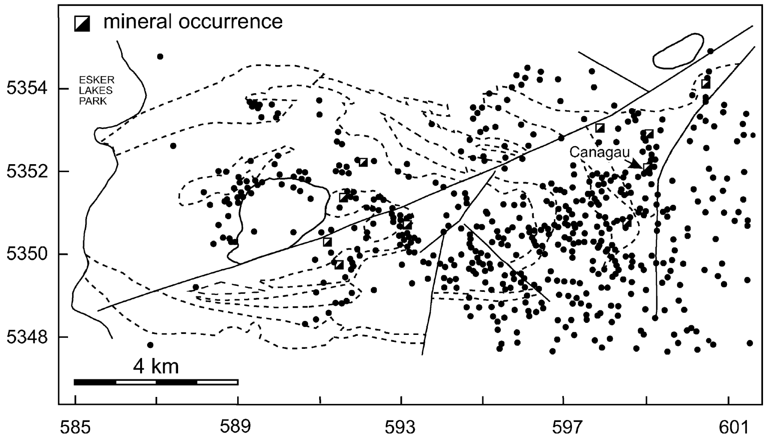
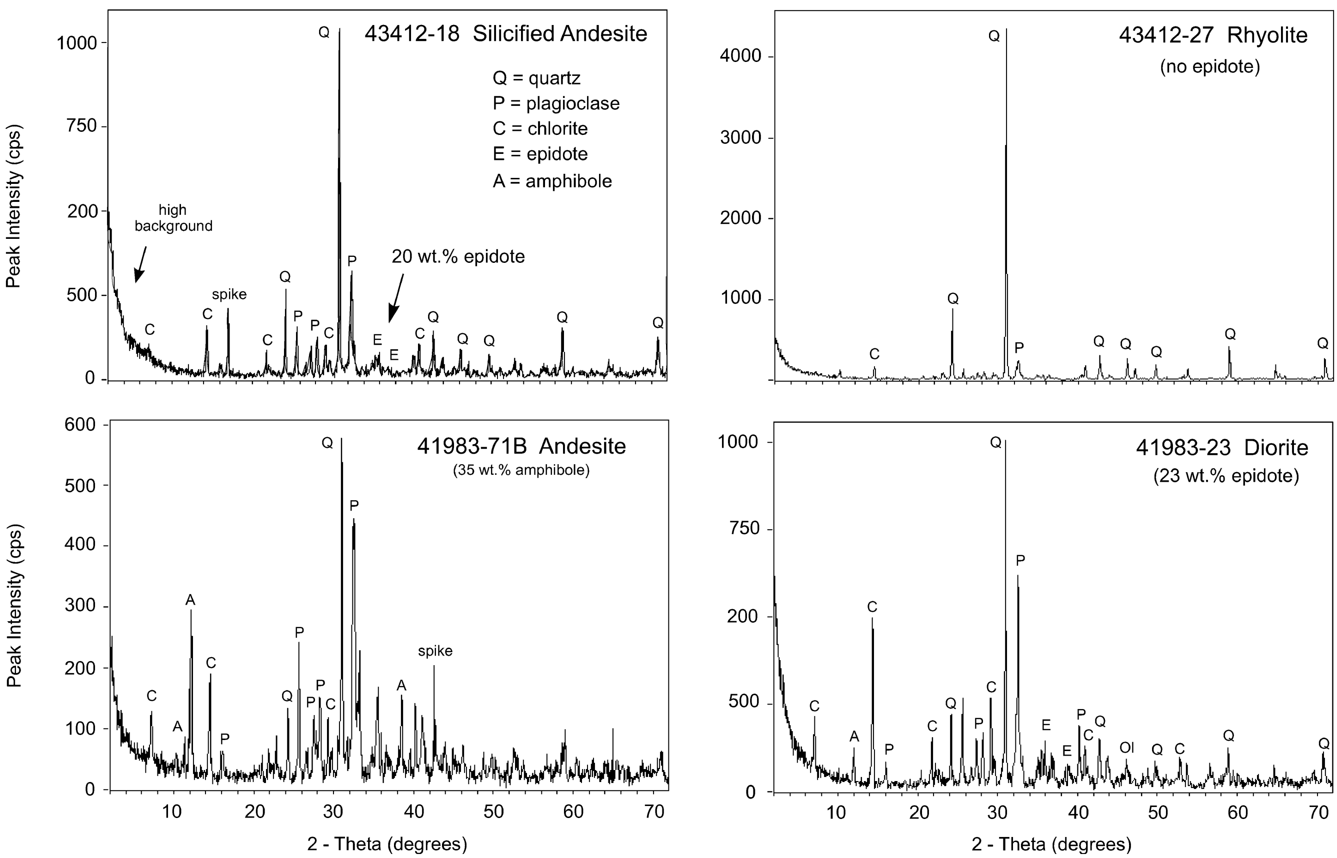


Fig. 6 Simplified map of the Ben Nevis area showing the location of samples in the Ontario Geological Survey (OGS) suite. Of 644 samples in the original OGS suite, 175 were selected for detailed microprobe analyses. The felsic volcanic rocks are indicated by *dashed lines*

to isolate peaks from the background and correct for interferences. Representative scans are shown in Fig. 7. The data are reported in weight percent relative to a whole rock standard, and the precision of the method is limited by the sensitivity of the X-ray detector; results cannot generally be reported with accuracy below 5 wt%.

A subset of 300 samples from Noranda and 175 samples from Ben Nevis was selected for electron microprobe study. More than 6,000 microprobe analyses were completed on the full range of secondary minerals including chlorite, sericite, prehnite, pumpellyite, epidote, actinolite, titanite, and carbonates. The complete dataset is available from the Geological Survey of Canada as Open-File D3560 (Hannington et al. 2001).

Fig. 7 Representative whole-rock, X-ray diffraction scans used for semi-quantitative mineral abundance determinations



Regional-scale alteration in the Noranda volcanic complex

Mafic and felsic volcanic rocks in the Noranda volcanic complex contain abundant secondary albite (after primary plagioclase), quartz, chlorite, epidote, actinolite, titanite, and calcite. Albite–chlorite alteration is widespread and is interpreted to be a product of early low-temperature seawater interaction (ca. 150 °C). This alteration is reflected in the bulk rock chemistry by coincident sodium enrichment and calcium depletion. Weak to moderate epidote alteration overprints the early albite–chlorite alteration in nearly all of the mafic volcanic rocks. In the Mine Sequence, large additions of calcium are evident (e.g., Santaguida 1999), and this is manifested as widespread epidote–quartz alteration. The chemistry of these rocks has been described by Gibson et al. (1983), Lesher et al. (1982), Paradis (1990), and Santaguida (1999). Most of the mafic volcanic rocks contain more epidote than can be accounted for without a substantial addition of calcium from a calcium-rich hydrothermal fluid. Many samples, including some rhyolites, contain >30 wt% epidote and indicate major additions of CaO.

The abundance of chlorite and epidote in all sampled lithologies of the Noranda and Ben Nevis volcanic complexes is shown in Fig. 8. At Noranda, the mafic volcanic rocks contain an average of 20 wt% epidote and at least 10 wt% chlorite. A large percentage of the samples contain more than 20 wt% chlorite, although true chloritite is rare. Of 350 strongly chloritized samples in the Cathles (1993) suite, only eight contained more than 30 wt% chlorite. The most strongly chloritized felsic volcanic rocks contain between 5 and 15 wt% chlorite.

The map distribution of secondary minerals in the Cathles (1993) sample suite is shown in Fig. 9. Chlorite and sericite are most abundant in Mine Sequence volcanic rocks within the Noranda cauldron, within a few kilometers of the main massive sulfide deposits. Except in the vicinity of known mineralization (e.g., at Four Corners), considerably less chlorite and sericite were found in volcanic rocks of the pre-cauldron sequences. Epidote is abundant throughout the Noranda complex; however, microprobe data show that clinozoisite compositions are notably lacking in the pre-cauldron sequences (see below). The locally abundant amphibole adjacent to the Lac Dufault granodiorite is related to contact metamorphism of hydrothermally altered mafic volcanic rocks. Pumpellyite is present in mafic volcanic rocks north of the Hunter Creek fault and is considered to be part of the regional greenschist to sub-greenschist metamorphic transition north and east of Noranda rather than a product of syn-volcanic hydrothermal alteration (Jolly 1980; Powell et al. 1993, 1995). However, secondary minerals typically associated with much higher temperatures (iron-rich chlorite, actinolite, and clinozoisite) are also present in these rocks.

The combined data for the most intensely altered rocks in the sample suite are shown in Fig. 10. Rocks containing abundant chlorite, sericite, and epidote of clinozoisite composition highlight major upflow zones within the Noranda cauldron and distinguish the altered volcanic rocks of the Mine Sequence from less productive volcanic successions higher and lower in the stratigraphy. Alteration typical of the Mine Sequence volcanic rocks persists along strike in coeval volcanic rocks north of the Hunter Creek fault and extends as far west as the New Insco–Magusi River area. This alteration terminates against the Horne Creek fault, at the southern margin of the Noranda cauldron, and is not found west of the Flavrian pluton. The lack of abundant chlorite, sericite or epidote of clinozoisite composition west of the Flavrian pluton supports the suggestion by Parry and Hutchinson (1981) that much of the alteration in the pre-cauldron sequences belongs to the regional background (e.g., early diagenetic effects or metamorphism of unaltered rocks). A previously unknown area of chlorite and epidote alteration also occurs north of the Mine Sequence volcanic rocks, along the eastern shores of Lac Duparquet (Fig. 10). This alteration may be related to the adjoining Montsabrais volcanic complex or the intrusion of the nearby Hébécourt diorite (Figs. 2 and 3).

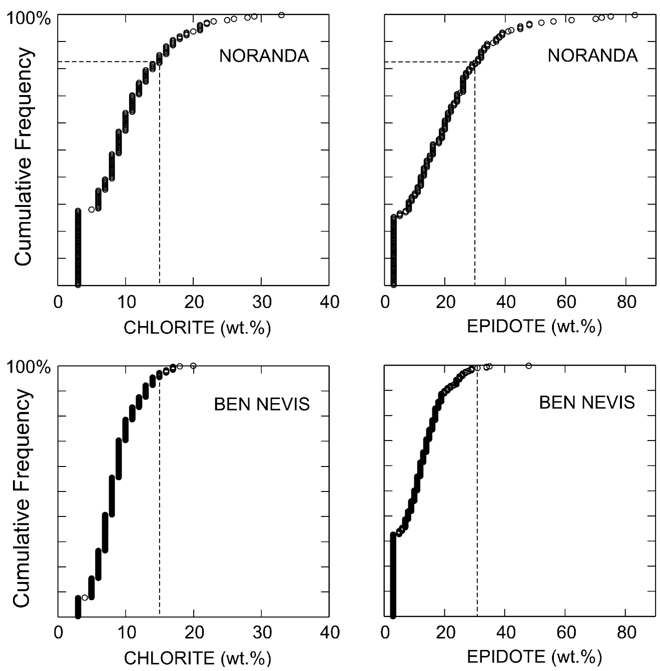


Fig. 8 Cumulative frequency plots of chlorite and epidote abundance in mafic and felsic volcanic rocks at Noranda and Ben Nevis. Mafic volcanic rocks represent about 85% of the sampled lithologies. Significant chlorite (>10 wt%) and epidote (>20 wt%) were found in almost half of the volcanic rocks in the Noranda area. Nearly 20% of the rocks contain more than 15 wt% chlorite and 30 wt% epidote. At Ben Nevis, the abundance of chlorite and epidote is much lower

Alteration mineralogy and mineral chemistry

Details of the mineralogy of regional-scale, syn-volcanic hydrothermal alteration at Noranda are summarized in Table 1 and discussed in the following sections.

Chlorite

Fine-grained chlorite typically replaces the glassy mesostatis in massive flows and glass shards in hyaloclastite and tuffaceous rocks throughout the Noranda complex. In more intensely altered rocks, abundant coarse-grained chlorite also occurs in amygdules, veinlets and

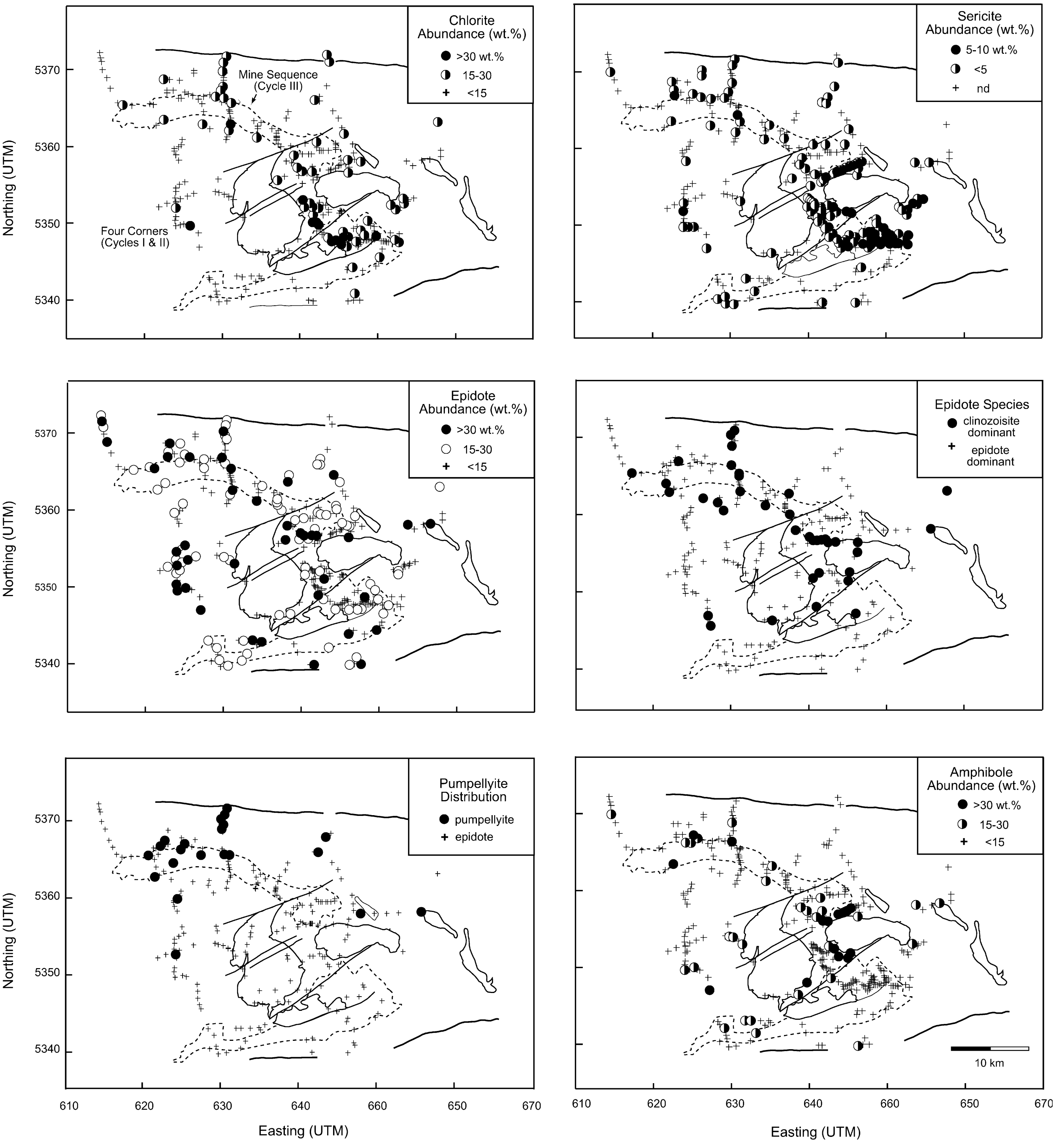


Fig. 9 Distribution of chlorite, sericite, epidote, pumpellyite and actinolite in mafic and felsic volcanic rocks of the Noranda area. Epidote species were determined by microprobe analyses (see text for discussion). Note that epidote is abundant throughout the map area, but clinozoisite compositions are mainly absent in the pre-cauldron sequences. The data for actinolite include the local occurrences of anthophyllite in areas of contact metamorphism adjacent to the Lac Dufault granodiorite (Fig. 3)

fractures. In the Mine Sequence volcanic rocks, chlorite is notably iron rich compared with the less altered volcanic rocks from Ben Nevis (e.g., Figs. 11 and 12). More than 40% of the analyzed samples have Fe/Fe + Mg ratios > 0.5 (Fig. 13). In general, the chlorite in felsic volcanic rocks is more iron rich than in basalts. Iron-rich chlorite, similar in composition to that in alteration pipes of the VMS deposits (e.g., MacLean and Hoy 1991), is found locally as far as several kilometers from the deposits. As much as 1 wt% MnO occurs in the most iron-rich chlorite, and, in the absence of other minerals with available sites for Mn^{+2}, this may be an important indicator of proximity to mineralization. Zinc is also

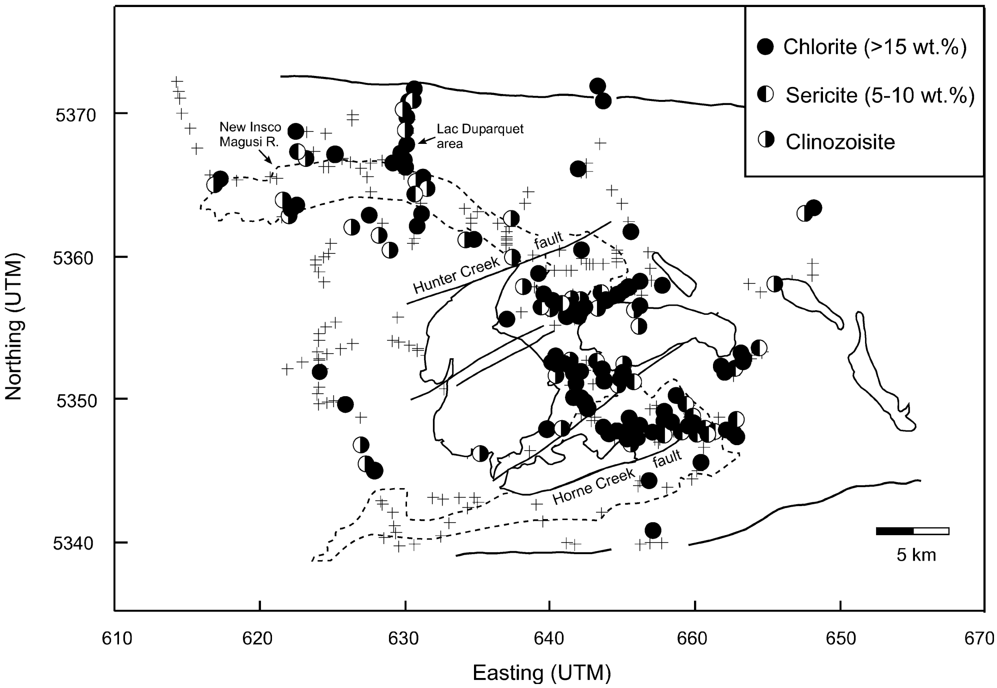


Fig. 10 Summary of alteration indicators in the Noranda volcanic complex. Overlapping chlorite, sericite, actinolite and epidote of clinozoisite composition highlight the major upflow zones at 1:50,000 scale and distinguish the altered volcanic rocks of the Mine Sequence from less productive volcanic successions higher and lower in the stratigraphy. Samples with less than 15 wt% chlorite, less than 5 wt% sericite, and no epidote of clinozoisite composition are indicated with (+)

Table 1 Comparison of regional scale, syn-volcanic hydrothermal alteration in the Noranda and Ben Nevis volcanic complexes

	Noranda Mine sequence	Ben Nevis volcanic complex
Albite	Common in least-altered rocks after primary plagioclase (spilitization); absent in high-temperature upflow zones (Na-depletion)	Common, after primary plagioclase
Chlorite	Abundant, replacing glass and ferromagnesian minerals and as coarse grains filling amygdules, veins and fractures. Samples with as much as 20 wt% chlorite are common, but true chloritite (>30 wt% chlorite) is rare. Fe-rich chlorite is common (Fe/Fe+Mg >0.5)	Abundant, replacing glass and locally filling amygdules, veins and fractures. Few samples contain significant chlorite (≤ 20 wt%). Uniformly Mg-rich (Fe/Fe+Mg ≤ 0.5)
Epidote	Common as coarse-grained aggregates, filling amygdules and in patches or quartz–epidote veins. Many samples with >30 wt% epidote. Complete replacement of mafic volcanic rocks occurs locally. Present locally in felsic volcanic rocks, especially allanite. Absent from VMS alteration pipes. Highly variable compositions, with abundant coarse epidote of clinozoisite composition (<10 wt% Fe_2O_3). Individual grains are strongly zoned. Epidote in pre-cauldron sequences is mainly fine-grained and lacking the clinozoisite solid solution	Widely distributed, but not abundant. Mainly fine-grained epidote replacing volcanic glass and its alteration products; locally in open spaces, filling amygdules and veins. Almost no samples with >30 wt% epidote. Absent in felsic volcanic rocks. Mainly Fe-rich (≥10 wt% Fe_2O_3). Coarse-grained epidote of clinozoisite composition (<10 wt% Fe_2O_3) is absent, except in epidote–actinolite ± magnetite alteration at the margins of the Clifford stock
Amphibole	Common and locally abundant, replacing ferromagnesian minerals and locally as coarse radial growths filling amygdules and veinlets. Fe-rich compositions are common (approaching ferroactinolite)	Locally as fibrous aggregates and coarse clots in a narrow zone of epidote–actinolite ± magnetite alteration adjacent to the Clifford stock. Ferroactinolite occurs in proximity to the Clifford stock; mainly tremolitic to magnesio-hornblende compositions elsewhere
Titanite	Widespread in mafic volcanic rocks from breakdown of ilmenite; locally abundant. Commonly Fe-rich (up to 5 wt% Fe_2O_3)	Minor constituent of mafic volcanic rocks; widespread, but not abundant
Carbonate	Rare to absent in the Mine Sequence volcanic rocks; locally abundant in later volcanic cycles	Widespread and locally abundant in amygdules of mafic rocks and replacing the matrix of felsic tuffs; late veins and fractures are common. Extensive carbonate zone 4–6 km from the Clifford stock. Mainly calcite; ferroan ankerite is present only locally, but siderite is absent. Fe-bearing carbonate contains ≤ 5 wt% MnO
Prehnite	Rare to absent; fine-grained aggregates locally with pumpellyite	Widespread and locally abundant as fine granular masses and colloform growths in amygdules. Typically Fe-poor (<5 wt% FeO), except in proximity to the Clifford stock
Pumpellyite	Locally abundant in subgreenschist rocks north of Hunter Creek Fault. Fibrous aggregates mainly filling amygdules. Typically Fe-poor (2–9 wt% FeO)	Common in amygdules after early Mg-chlorite. Absent within 1–2 km of the Clifford stock. Large compositional range, but commonly Fe-rich (≤ 13 wt% FeO)

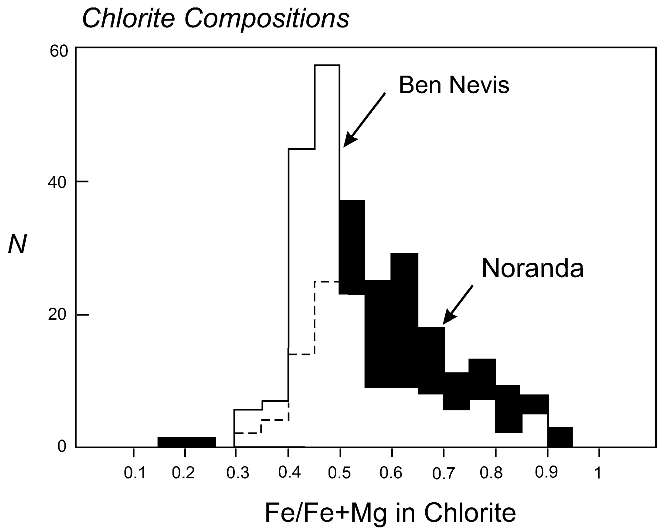


Fig. 11 Nested histogram of chlorite compositions in mafic volcanic rocks from Noranda and Ben Nevis. Most of the chlorite from Ben Nevis has a narrow range of low Fe/Fe + Mg ratios compared with the chlorite from Noranda

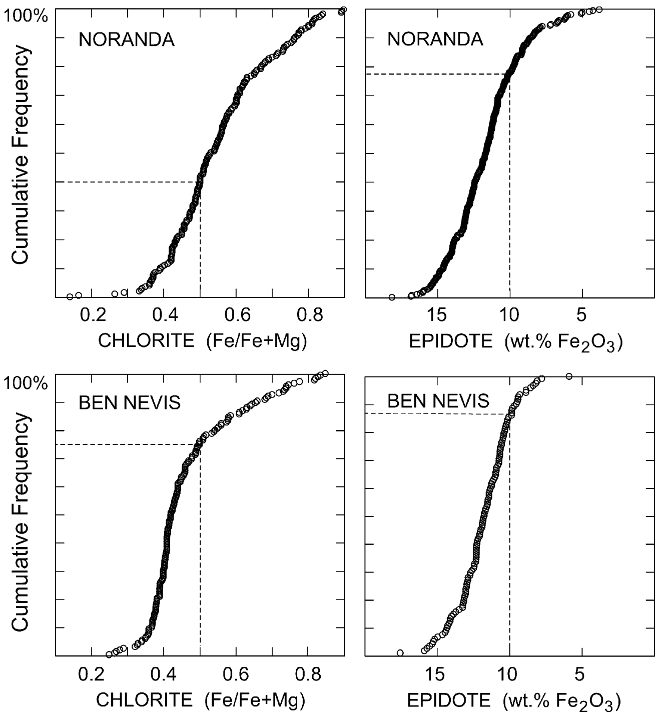


Fig. 13 Cumulative frequency plots of chlorite and epidote compositions (average values) in mafic and felsic volcanic rocks in the Noranda and Ben Nevis volcanic complexes. More than half of the chlorite at Noranda has Fe/Fe + Mg ratios > 0.5, and 20% of the epidote contains < 10 wt% Fe_2O_3. At Ben Nevis, most of the chlorite is magnesium-rich and nearly all of the epidote contains > 10 wt% Fe_2O_3

locally enriched in chlorite, especially in rhyolite samples from the vicinity of the Horne and Quemont deposits (≤ 0.5 wt% ZnO). A few samples of iron-rich chlorite were found in association with mineralized felsic volcanic rocks at Four Corners and Rob-Montbray, but overall chlorite is not abundant in the pre-cauldron sequences (Fig. 9).

Sericite

Sericite is most abundant in discordant pipe-like alteration zones surrounding massive sulfide deposits and especially in felsic volcanic rocks in the vicinity of the Horne and Quemont mines. Paradis (1990) also described intense sericitization in the New Vauze–Norbec area, which contains the highest proportion of felsic

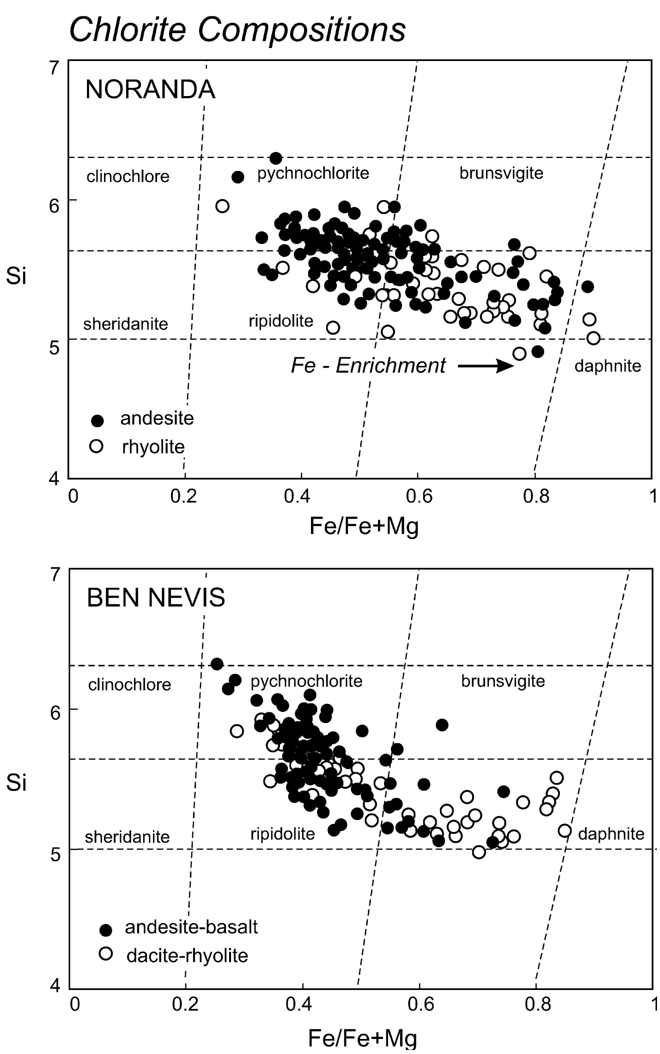


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Fig. 12 Chlorite compositions (average values) in mafic and felsic volcanic rocks from Noranda and Ben Nevis. Chlorite in the Mine Sequence volcanic rocks at Noranda shows a distinct iron-enrichment trend, thought to reflect high temperatures and anomalous fluid compositions (e.g., Saccocia and Seyfried 1995). Chlorite from Ben Nevis clusters at low Fe/Fe + Mg, which is typical of diagenetic chlorite formed in the early stages of low-temperature seawater–basalt interaction. Chlorite in felsic volcanic rocks from both areas tends to be more iron-rich than in coeval mafic volcanic rocks volcanic rocks in the Noranda cauldron. The sericite occurs mainly as groundmass replacement and along flow bands in massive rhyolite. It commonly occurs with fine-grained quartz or calcite, and the rocks that have been most intensely sericitized are often weakly foliated. The Fe/Fe + Mg ratios in the sericite correlate with that of coexisting chlorite and are generally higher in areas of known mineralization. In a number of samples the sericite is also enriched in fluorine, although the concentrations are low compared to sericite from more felsic rock-dominated VMS environments (e.g., Fig. 14).

Epidote

Fine-grained epidote (< 10–20 μm) occurs in all of the mafic volcanic rocks of the Noranda area, mainly as a replacement of volcanic glass and its alteration products. It is typically intergrown with fine chlorite, actinolite, and titanite. In more intensely altered rocks, coarse-grained epidote (100–500 μm) overprints the earlier fine-grained epidote in the matrix of the rocks and occurs as granular aggregates or patches, as radial growths filling amygdules or cooling fractures, and in networks of quartz- and epidote-filled veinlets. It commonly replaces relict plagioclase phenocrysts and occurs as distinctive halos or rims on chlorite- and epidote-filled amygdules. This coarse-grained epidote is interpreted to be mainly a product of high-temperature fluid–rock interaction and is most abundant in areas of enhanced primary permeability (i.e., flow contacts, flow-top breccias, and amygdule-rich zones: Santaguida 1999). Epidote is less abundant in proximity to the massive sulfide deposits and is usually absent from the discordant pipe-like alteration zones, where it is replaced by chlorite and sericite.

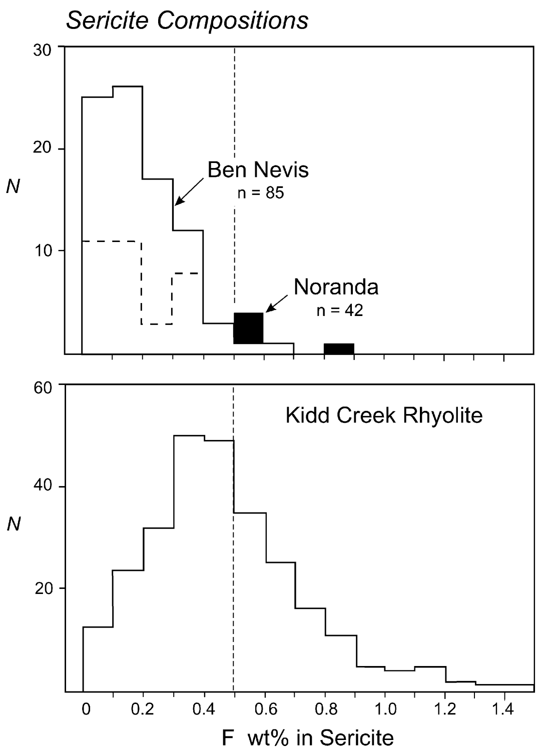


Fig. 14 Fluorine concentrations in sericite from Noranda and Ben Nevis. Fluorine concentrations are generally low compared with VMS deposits in felsic rock-dominated volcanic successions (e.g., Kidd Creek: M.D. Hannington, unpublished data)

Epidote is rare in rhyolite at Noranda, owing to the low initial calcium content of these rocks. Rhyolite accounts for about 15% of the sampled lithologies, but contains less than 5% of the epidote. Where it occurs, the epidote is commonly associated with disseminated sulfide minerals. In the intrusive rocks, epidote mainly replaces coarse-grained plagioclase and biotite. Abundant epidote also occurs in large miarolitic cavities and pipe vesicles in the Flavrian pluton (Galley 2002). Late-stage hydrothermal activity associated with the Lac Dufault granodiorite has caused local epidotization of mafic volcanic rocks in the contact zone, but this is distinguished from earlier epidote alteration by its very strong fracture control ("network" or "grid" alteration).

Microprobe analyses of epidote throughout the Noranda complex indicate a wide range of compositions from the epidote end member [$Ca_2(Fe^{+3},Al)_3$ Si_2O_{12} (OH)] to clinozoisite [$Ca_2Al_3Si_2O_{12}$(OH)] and REE-bearing allanite [$(Ca,Ce,Y)_2(Fe^{+2},Fe^{+3},Al)_3$ Si_2O_{12} (OH)] (Fig. 15). Fine-grained epidote in the matrix of the mafic volcanic rocks is typically iron-rich ($\geq$ 10 wt% Fe_2O_3) and is similar in composition to the epidote ascribed to the lower greenschist metamorphic overprint elsewhere in the Abitibi (e.g., 12–16 wt% Fe_2O_3: Powell et al. 1993). About 20% of the samples contain significant amounts of epidote having the clinozoisite composition (< 10 wt% Fe_2O_3) mainly within the Mine Sequence volcanic rocks (Fig. 13). This epidote is most abundant in zones of intense epidote–quartz alteration and is most common as coarse, often euhedral grains with distinctive pale blue to yellow birefringence that can be readily identified with a petrographic microscope. Similar epidote is notably absent in the pre-cauldron sequences west of the Flavrian pluton.

Epidote compositions from a 35-km-long traverse along the exposed length of the Mine Sequence volcanic rocks are plotted in Fig. 16. The traverse starts south of the Horne Creek fault, follows the Mine Sequence volcanic rocks through the Noranda cauldron, and extends as far west as the New Insco–Magusi River area. The lower part of the diagram shows epidote compositions from the traverse through the pre-cauldron sequences (see Fig. 5). Within the Noranda cauldron, clinozoisite compositions account for as much as 30% of the epidote. In coeval volcanic rocks north of the Hunter Creek fault, similar compositions account for about 20% of the epidote. Only two samples contained epidote of clinozoisite composition in the pre-cauldron sequences. A characteristic of epidote in the Mine Sequence volcanic rocks appears to be the extreme variability of

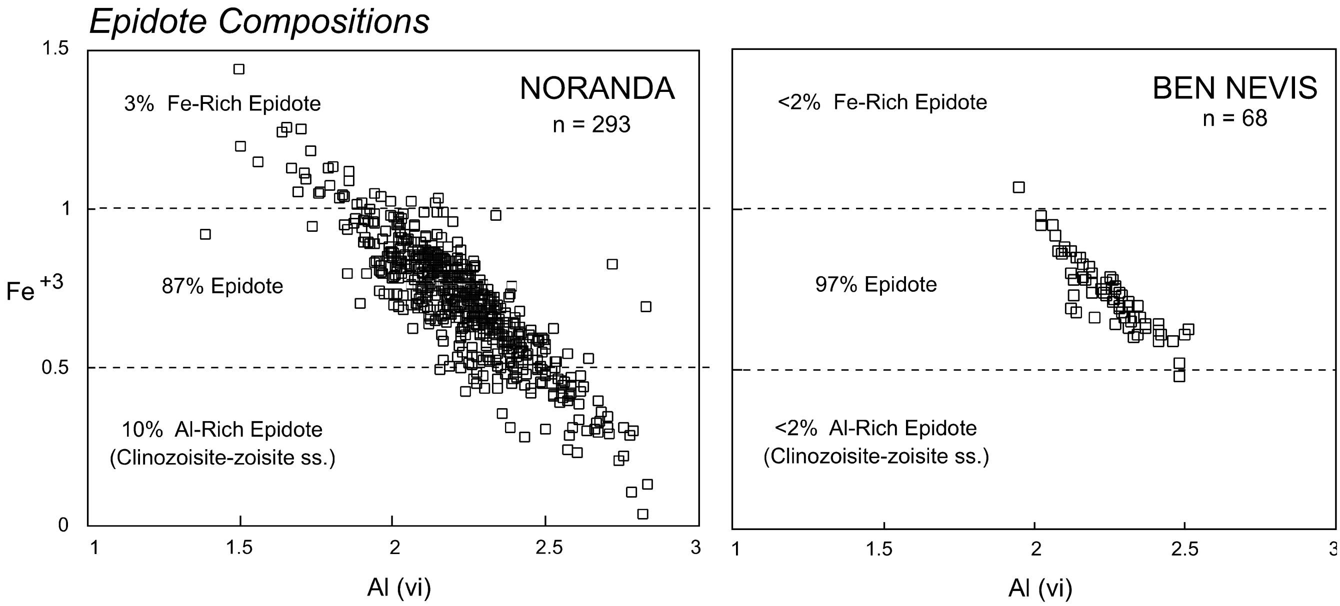


Fig. 15 Plots of Fe^{+3} versus Al in epidote (all analyses) from the Noranda and Ben Nevis volcanic complexes. Epidote compositions at Noranda span nearly the entire allowable range of solid solutions. The Fe–Al substitution reflects mainly temperature and redox conditions, with Fe-rich, Al-poor epidote indicating relatively low-temperature, oxidizing conditions and Fe-poor, Al-rich compositions (clinozoisite) indicating higher-temperature, reduced conditions (see text for discussion)

compositions, spanning the entire range of allowable Fe–Al substitutions. This juxtaposition of epidote with dramatically different compositions may be a key indicator of anomalous fluid flow, reflecting steep thermal and chemical gradients (e.g., within buried aquifers of the Mine Sequence volcanic rocks). Samples from the vicinity of the major dike swarms in the central part of the Noranda cauldron (e.g., Old Waite Paleofissure) all contain notable concentrations of epidote with clinozoisite compositions and most likely reflect high-temperature fluid flow adjacent to the dikes.

Individual epidote grains also commonly show significant compositional variability. Rims of clinozoisite composition with iron-rich epidote cores are particularly common. This may reflect changing Fe^{3+}/Al ratios resulting from progressive hydrolysis of plagioclase phenocrysts or, more likely, changing temperature and f_{O2} related to episodic hydrothermal pulses during the growth of the crystals (e.g., Bird et al. 1988; Arnason and Bird 1990; Bettison 1991). The presence of abundant clinozoisite filling open spaces, rather than replacing feldspars, implies that much of the compositional zoning is related to the chemistry of the hydrothermal fluid and not the alteration of a precursor mineral.

The major divalent cations substituting for Ca^{2+} in epidote (Fe^{2+}, Mn^{2+}, and Sr^{2+}) also show considerable variability. Strongly epidotized rocks are invariably enriched in strontium (Lesher et al. 1982; Ludden et al. 1982; Gibson et al. 1983; Santaguida 1999), and in general, the strontium content of the epidote increases with overall epidote abundance ($\leq$ 1 wt%). Epidote from the Mine Sequence volcanic rocks also contains between 0.35 and 0.7 wt% MnO and as much as 0.1 wt% ZnO. The MnO contents in epidote correspond closely to that of co-existing chlorite, similar to observations in several ophiolites (e.g., Herzig 1988; Beaufort et al. 1992; Plyusnina and Vysotsky 1994).

Allanite occurs almost exclusively in rocks of rhyolitic composition within the Mine Sequence volcanic rocks and is also abundant in the Flavrian pluton. It is rare or absent in the volcanic rocks of the pre-cauldron sequences, including the epidote-rich rocks at Four Corners. The best analyses indicate that allanite contains as much as 15 wt% total REE_2O_3 and, therefore, represents a significant repository for REE that were mobile during hydrothermal alteration. Because REE are more difficult to mobilize than elements such as manganese, the distribution of allanite may help to trace local high-intensity hydrothermal flow. Allanite is also the only member of the epidote group in which divalent transition metals (Fe^{2+}, Mn^{2+}) are an essential component, making it a potentially important indicator of metal-rich fluids. Allanite contains up to several wt% MnO (two to three times enriched over epidote in the mafic volcanic rocks), and manganese-rich allanite is locally abundant in the Amulet A-Millenbach area.

Actinolite

Fine-grained hydrothermal amphibole is common in the matrix of altered mafic volcanic rocks, although much of it has retrograded to chlorite. Secondary amphibole in these rocks has low Al_2O_3 and Na_2O contents (< 2 and 0.5 wt%, respectively) typical of regional metamorphic assemblages elsewhere in the Blake River

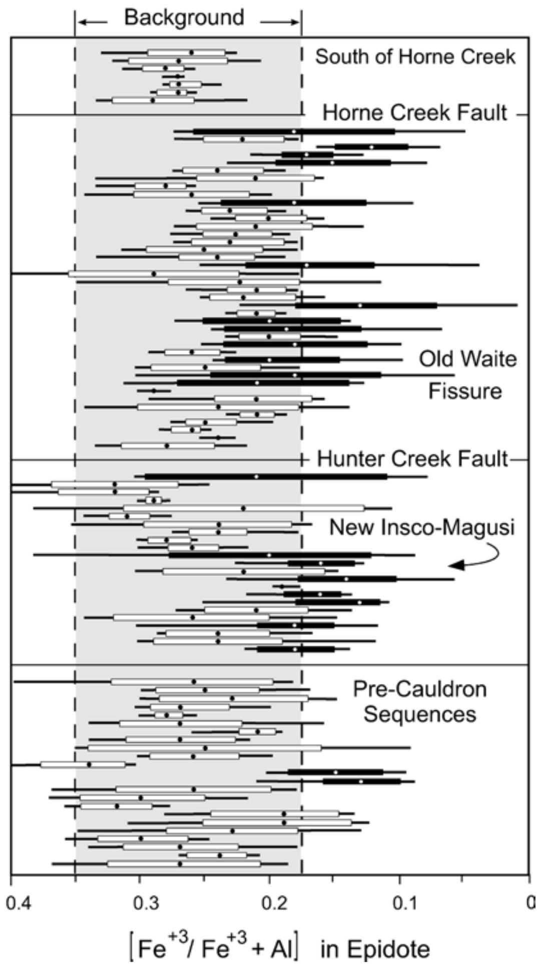


Fig. 16 Range of epidote compositions observed in samples of mafic volcanic rocks on a 35 km-long traverse across the Noranda volcanic complex. The traverse starts south of the Horne Creek fault and follows the Mine Sequence volcanic rocks through the cauldron and across the Hunter Creek fault, as far west as the New Insco-Magusi River area. Locations of samples in the pre-cauldron sequences are shown in Fig. 5. Epidote within the Mine Sequence volcanic rocks is characterized by highly variable compositions spanning the full range of allowable Fe–Al substitutions. This is thought to reflect anomalous hydrothermal fluid flow within the Mine Sequence rocks, compared with background epidote south of Horne Creek and in the pre-cauldron sequences. The *bars* represent 2σ ranges for multiple analyses of individual samples (minimum and maximum values are shown by the *lines*). *Solid bars* indicate samples that contained more than 50% epidote of clinozoisite composition

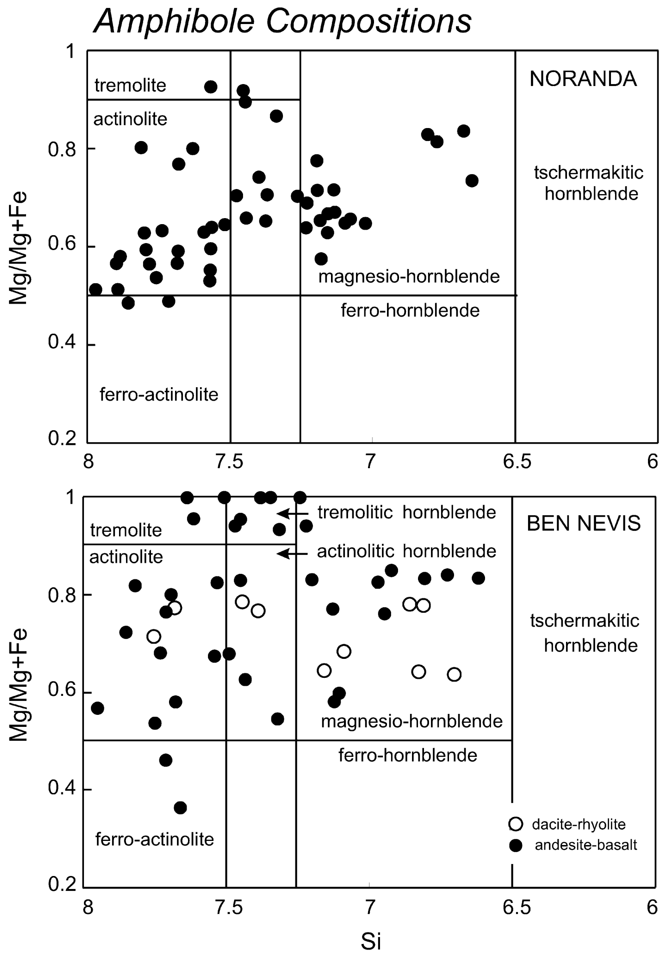


Fig. 17 Amphibole compositions (average values) in mafic and felsic volcanic rocks from Noranda and Ben Nevis. Secondary amphibole (actinolite) in the Noranda district shows a trend toward iron-rich compositions, similar to coexisting chlorite. Secondary amphibole at Ben Nevis is notably more magnesian

Group (e.g., Gélinas et al. 1982). Obvious hydrothermal amphibole, which occurs as coarse grains filling amygdules and veinlets, is usually the most iron-rich. Compositions approaching ferroactinolite are present in many of the samples (Fig. 17), consistent with locally reduced, high-temperature hydrothermal conditions. However, there is insufficient data to determine if iron enrichment reflects proximity to individual massive sulfide deposits. The most iron-rich amphibole is also enriched in MnO ($\leq$ 1.1 wt%) and TiO_2 ($\leq$ 1.5 wt%), similar to that observed in some other VMS districts (e.g., Ashley et al. 1988), but contains low ZnO ($<$ 0.2 wt%).

Prehnite and pumpellyite

Pumpellyite is locally abundant in the mafic volcanic rocks of the New Insco and Magusi River area. It occurs as distinctive sheaf-like aggregates filling amygdules and in fractures. Most of the pumpellyite has a narrow range of low FeO contents, from 2 to 9 wt% (Figs. 18 and 19), which likely reflects hydrothermal rather than metamorphic conditions (e.g., Beiersdorfer 1993). Prehnite, which was found locally in the same rocks, was too fine grained to analyze with confidence. Both minerals are texturally similar to epidote found elsewhere in the Mine Sequence volcanic rocks and may have been precursors to epidote alteration in the Noranda cauldron.

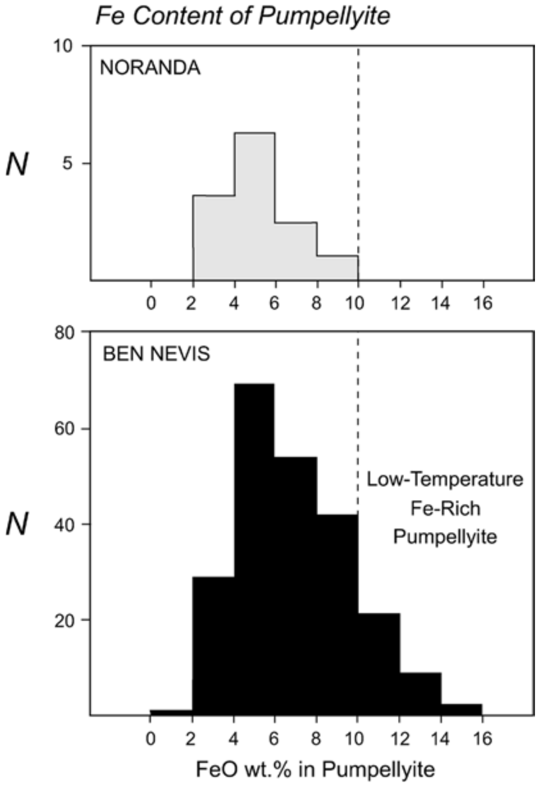


Fig. 18 FeO contents in pumpellyite from the New Insco–Magusi River area of Noranda and from Ben Nevis township. The somewhat higher iron contents in pumpellyite from Ben Nevis are similar to that observed in coexisting epidote

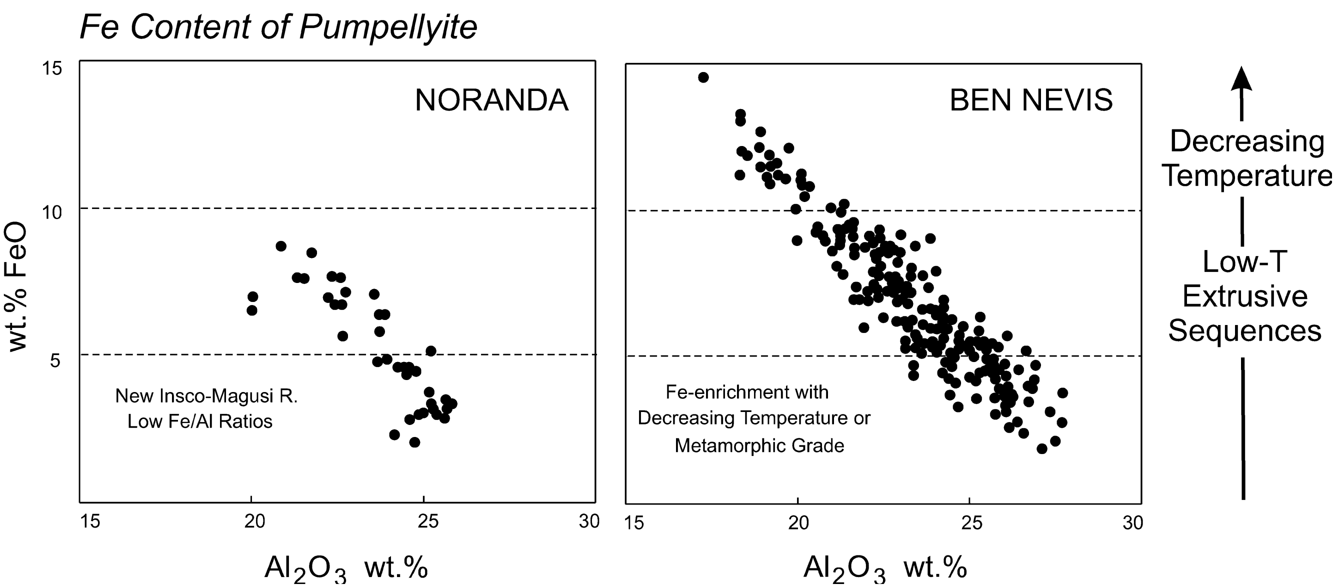
Carbonate

Calcite is not abundant in the volcanic rocks of the Noranda Mine Sequence. It occurs mainly in late microfractures and locally replaces pre-existing epidote. Dolomite and siderite are present locally in mafic volcanic rocks north of the Hunter Creek fault (e.g., in the vicinity of the New Insco and Magusi River deposits), but these minerals are rare. Widespread carbonate occurs in the volcanic rocks of Cycle IV, particularly in the Delbridge area. This carbonate overprints sericitized felsic volcanic rocks that host the Delbridge deposit (Santaguida 1999). Similar carbonate has been described from the Mobrun deposit in Cycle V (Larocque and Hodgson 1993). Low temperatures estimated from oxygen isotope data for calcite in the Norbec area are consistent with the carbonate in these rocks being mainly late-stage hydrothermal or metamorphic in origin (Paradis et al. 1993).

Titanite

Titanite is widespread as an alteration product in the mafic volcanic rocks, derived from the break-down of titanium-bearing igneous minerals during low-temperature syn-volcanic alteration. There is a general correlation between titanite abundance and epidote abundance, and the fine-grained titanite is often difficult to distinguish from fine-grained epidote in thin section. Titanite is generally less abundant in felsic volcanic rocks, but it is common in rhyolites that host the Horne and Quemont deposits. This titanite is locally enriched in FeO ($\leq$ 5 wt%), ZnO ($\leq$ 0.14 wt%), and MnO ($\leq$ 0.2 wt%). In the most intensely altered volcanic rocks, the titanite has broken down to rutile.

Fig. 19 Plots of FeO versus Al_2O_3 in pumpellyite (all analyses) from New Insco–Magusi River area, Noranda, and Ben Nevis township. The Fe–Al substitution in pumpellyite is similar to that observed in epidote and likely reflects similar temperature and redox controls (see Fig. 15). Higher iron in pumpellyite from Ben Nevis township is consistent with lower-temperatures, typical of seawater–basalt interaction following the initial emplacement and cooling of the volcanic pile (see text for discussion)



Alteration in the Ben Nevis volcanic complex

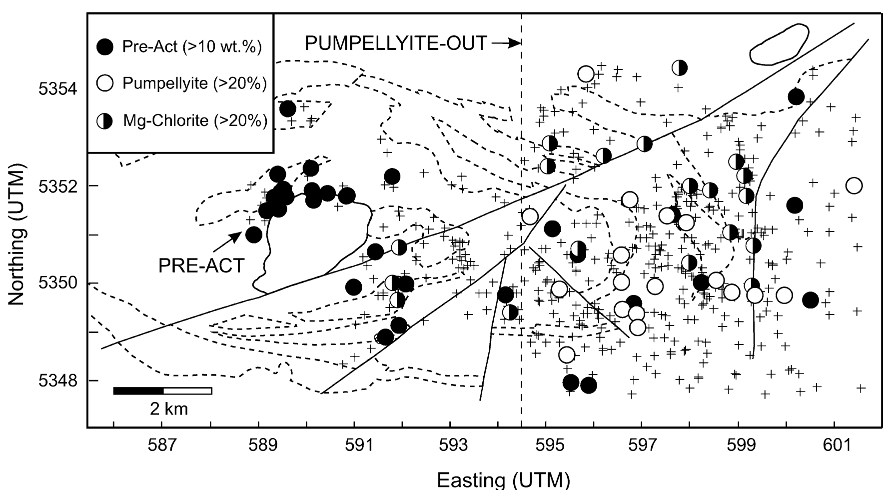
Both mafic and felsic volcanic rocks in the Ben Nevis area are affected by weak albite–chlorite alteration (spilitization) and magnesium enrichment, reflecting mainly low-temperature seawater interaction within the cooling volcanic pile (Jensen 1975; Jolly 1978). Whole-rock XRD reveals a nearly uniform distribution of prehnite, pumpellyite, epidote, magnesium-chlorite, titanite, and calcite throughout this complex. Fewer than 5% of the samples from Ben Nevis contain as much chlorite or epidote as in the Noranda Mine Sequence (Fig. 8). Primary plagioclase and augite phenocrysts in the andesites are commonly unaltered. This contrasts with the feldspar-destructive alteration throughout much of the Noranda volcanic complex. The secondary minerals mainly fill open spaces in the volcanic rocks, rather than replace the primary igneous phases, and the interiors of massive flows commonly contain few obvious alteration products. Large amygdules show essentially the same filling sequence in all cases: (1) early silica (microcrystalline quartz, cristobalite, or chalcedony) lining the vesicle walls, (2) fine-grained chlorite, progressing to fibrous or radiating chlorite, (3) pumpellyite or epidote after early chlorite in larger amygdules, and (4) late quartz or calcite filling the remaining open spaces. Quartz and calcite are the only widespread vein-filling materials, and they typically cross cut earlier quartz and chlorite-filled amygdules. Intense silicification and epidote-rich haloes surrounding the amygdules, common in Noranda, are rare or absent at Ben Nevis. This simple paragenesis contrasts sharply with the complex overprinting relationships observed in altered mafic volcanic rocks at Noranda (e.g., Santaguida 1999).

A dramatic decrease in the abundance of pumpellyite is evident in volcanic rocks within 1–2 km of the Clifford stock ("pumpellyite-out" in Fig. 20). The appearance of locally abundant actinolite at about the same stratigraphic position correlates with increasing temperatures at the base of the volcanic pile, proximal to the intrusive core. The narrow zone of epidote–actinolite ± magnetite alteration adjacent to the Clifford stock extends up to 200 m from the intrusive contact. This alteration is most likely related to weak, fracture-controlled hydrothermal circulation in the thermal halo of the intrusion.

Felsic pyroclastic rocks in eastern Ben Nevis township are the most intensely altered rocks in the area, containing locally abundant quartz, sericite, chlorite, and carbonate. Sericite is especially common in weakly mineralized pyroclastic rocks, whereas massive dacite and rhyodacite flows contain quartz-, carbonate- and chlorite-filled amygdules, similar to the mafic lavas. Chlorite–sericite alteration with obvious spatial and temporal relationship to mineralization is found only in the vicinity of the Canagau mineral occurrence. However, this alteration has limited continuity (occupying an area of less than 10 km^2) and shows no obvious relationship to synvolcanic faults.

Abundant carbonate occurs at the outer margins of the volcanic complex in an arcuate pattern 4–6 km distant from the Clifford stock (Fig. 21). Although the most intense CO_2-metasomatism defines a broad halo surrounding the Canagau occurrence, the carbonate zone has an apparent strike length of more than 5 km and is not confined to a particular stratigraphic unit. The presence of essentially unaltered volcanic rocks east of the carbonate zone suggests that this part of the volcano was well outside the thermal influence of the intrusive core. The absence of significant alteration of

Fig. 20 Distribution of prehnite, pumpellyite, and magnesium-rich chlorite in mafic and felsic volcanic rocks of the Ben Nevis volcanic complex. The magnesium-rich chlorite and pumpellyite are the dominant amygdule fill in volcanic rocks of eastern Ben Nevis township. The disappearance of pumpellyite west of Ben Nevis township (pumpellyite-out) records a subgreenschist to greenschist transition with depth in the volcanic pile. Actinolite occurs with prehnite in samples nearest to the intrusive core of the complex. Samples with less than 20 wt% pumpellyite, less than 20 wt% magnesium-rich chlorite, and less than 10 wt% prehnite or actinolite are indicated with (+)



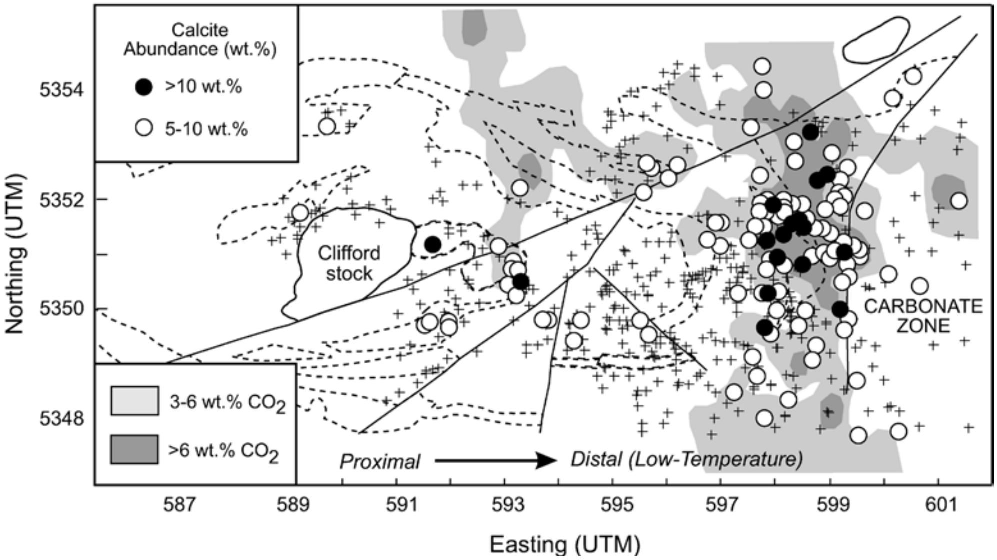


Fig. 21 Distribution of carbonate in the Ben Nevis volcanic complex. The abundance of carbonate correlates with a previously documented zone of CO_2-metasomatized volcanic rocks distant from the Clifford stock (Grunsky 1986). Calcite is the dominant mineral in both mafic and felsic volcanic rocks

any kind in some parts of this stratigraphy may also reflect subaerial conditions associated with possible emergence of the volcanic complex towards the east (e.g., Gagnon et al. 1995).

Alteration mineralogy and mineral chemistry

Details of the mineralogy of the regional-scale, synvolcanic hydrothermal alteration at Ben Nevis are summarized in Table 1 and discussed in the following sections.

Chlorite

Mafic volcanic rocks throughout the Ben Nevis complex contain about 10 wt% chlorite (Fig. 8). Only a small percentage of samples are strongly chloritized, and the most chloritic rocks contain < 25 wt% chlorite. True chloritites are absent. Some dacitic flows with sulfide-filled amygdules contain as much as 20 wt% chlorite, but this amount of chlorite is rare in the felsic rocks.

Amygdules in the mafic volcanic rocks are filled mainly by pale green, magnesium-rich chlorite. It is not uncommon to see chlorite-filled amygdules adjacent to completely fresh plagioclase, consistent with an early low-temperature origin. The earliest chlorite, which lines the walls of the larger amygdules, probably originated as cryptocrystalline smectite or smectite–chlorite mixtures, similar to that found in modern basalts. The composition of the chlorite in both the glassy groundmass of the flows and in the amygdules is similar, suggesting that they belong to the same generation of early chlorite. The chlorite compositions cluster within a narrow range of low Fe/Fe + Mg ratios (Figs. 12 and 22). Except in areas of known mineralization, the chlorite is rarely more iron-rich than its host rock. It is noteworthy that the highest Fe/Fe + Mg ratios are not always associated with the most abundant chlorite; some highly chloritized rocks contain only magnesium-rich chlorite.

As in Noranda, the chlorite in felsic volcanic rocks tends to be more iron-rich than in the mafic rocks. The most iron-rich chlorites are found in intensely altered felsic volcanic rocks immediately north of the Canagau mineral occurrence (Fig. 23). This chlorite also contains elevated ZnO and MnO (both $\leq$ 0.8 wt%). However, most of the MnO in these rocks is concentrated in coexisting iron-rich carbonates (see below).

Sericite

The distribution of sericite is closely related to the abundance of felsic rocks. It replaces the fine-grained, clay-rich matrix of altered pyroclastic units and locally replaces felsic clasts. At the Canagau occurrence, sericite is associated with intense carbonate alteration. The Fe/Fe + Mg ratios in the sericite correlate with those of coexisting chlorite and carbonate and are notably higher in areas of known mineralization.

Epidote

Large mappable zones of intense epidote alteration, similar to those at Noranda, are not found at Ben Nevis. Mafic volcanic rocks contain 10 wt% epidote, on average, and only a few samples in the area contained more than 30 wt% (Fig. 8). Fine-grained epidote (< 10–20 μm) is most common and occurs together with chlorite as a replacement of volcanic glass, filling amygdules, and in fractures and small veinlets (e.g., cooling fractures). Distinctive epidote patches or spots, typical of the epidote–quartz alteration at Noranda, are rare or absent. Vein-filling epidote occurs locally in mafic pillow breccias, but it does not define coherent zones of hydrothermal upflow. The felsic volcanic rocks do not

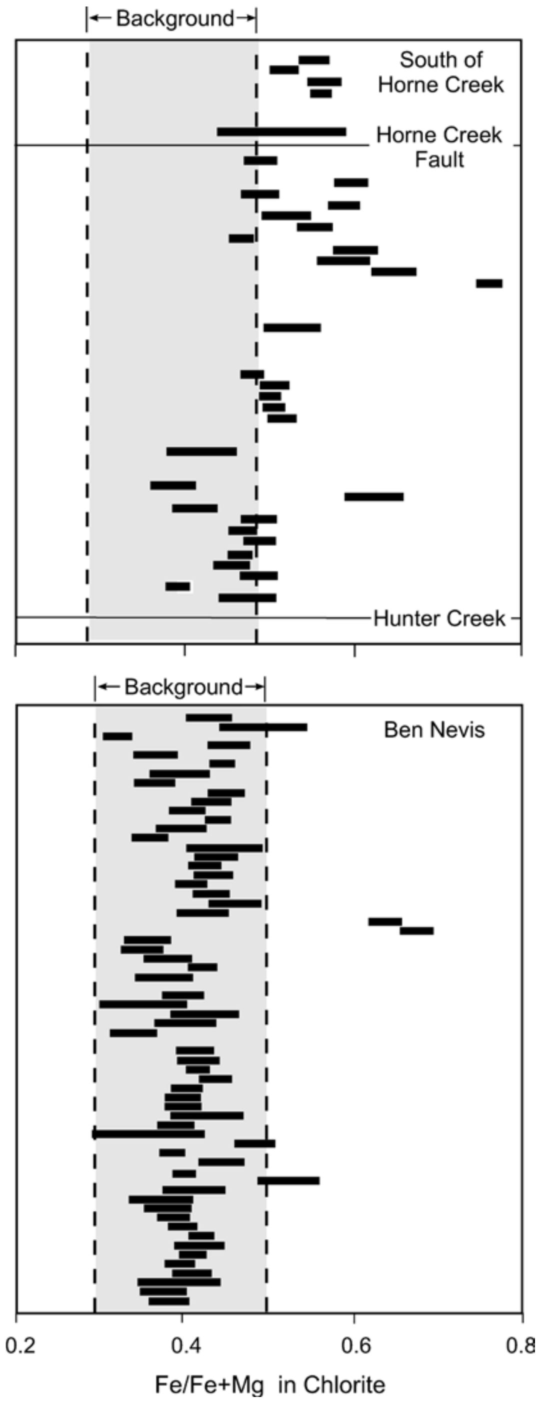


Fig. 22 Range of chlorite compositions in samples of mafic volcanic rocks from traverses through the Noranda and Ben Nevis volcanic complexes (see Fig. 16 for details). *Bars* indicate the range of Fe/Fe + Mg ratios in individual samples

contain any appreciable epidote, which contrasts with the locally abundant allanite found in rhyolites from Noranda. In the intrusive rocks, coarse-grained plagioclase is locally replaced by epidote. However, large miarolitic cavities and pipe vesicles containing epidote, similar to those in the Flavrian pluton, were not found in the Clifford stock.

Epidote compositions at Ben Nevis exhibit a narrow range of Fe/Fe + Al ratios, typical of the fine-grained epidote in mafic volcanic rocks throughout the Noranda area (Figs. 13 and 15), and there is no variation with depth in the volcanic pile. A traverse from the bottom to the top of the volcanic section in Ben Nevis township reveals nearly uniform epidote compositions compared to Noranda (Fig. 24). Most of the fine-grained epidote is characterized by Fe_2O_3 contents > 10 wt%, and only a few samples in the vicinity of the Clifford stock have Fe/Fe + Al ratios < 0.2, reflecting the higher temperatures adjacent to the intrusion. Zoning of individual epidote grains is common, but not as pronounced as in the Noranda camp, and distinctive coarse-grained epidote of clinozoisite composition was not observed outside the immediate contact zone of the Clifford stock. The MnO concentrations in the epidote are variable, but generally low (< 0.4 wt% MnO) compared with the epidote at Noranda.

Actinolite

Secondary amphibole occurs mainly in interstitial glass and as a replacement of clinopyroxene, but only rarely does it occur as coarse-grained fibrous or radial aggregates in amygdules. Tremolitic hornblende and magnesio-hornblende compositions are common, and most of the amphibole is notably more magnesian than in the Mine Sequence volcanic rocks at Noranda (Fig. 17). Iron-rich actinolite is present only in samples adjacent to the Clifford stock, consistent with the high-temperatures near the intrusion. This actinolite occurs in coarse clots associated with magnetite and rare epidote of clinozoisite composition. Enrichments in ZnO (≤ 0.2 wt%), MnO (≤ 0.9 wt%), and TiO_2 (≤ 0.8 wt%) are found in the most iron-rich actinolite.

Prehnite

Prehnite was found in 30–40% of the mafic volcanic rocks and 10–15% of the felsic rocks in the Ben Nevis area. The prehnite occurs in granular masses, cloudy or fibrous aggregates, and as colloform growths in amygdules and usually is poorly crystalline. Prehnite compositions are highly variable, with large variations in individual samples (e.g., < 1–10 wt% FeO). However, most of the prehnite contains less than 5 wt% FeO (Fig. 25), similar to that observed in low-grade metamorphic rocks elsewhere in the Abitibi (e.g., 0.8–4.3 wt% FeO: Powell et al. 1993). There is no observable difference in the composition of prehnite in mafic versus felsic volcanic rocks, and no significant concentrations of trace elements were found in any of the analyzed samples. Significant amounts of prehnite (≥ 20 wt%) were found within a few hundred meters of

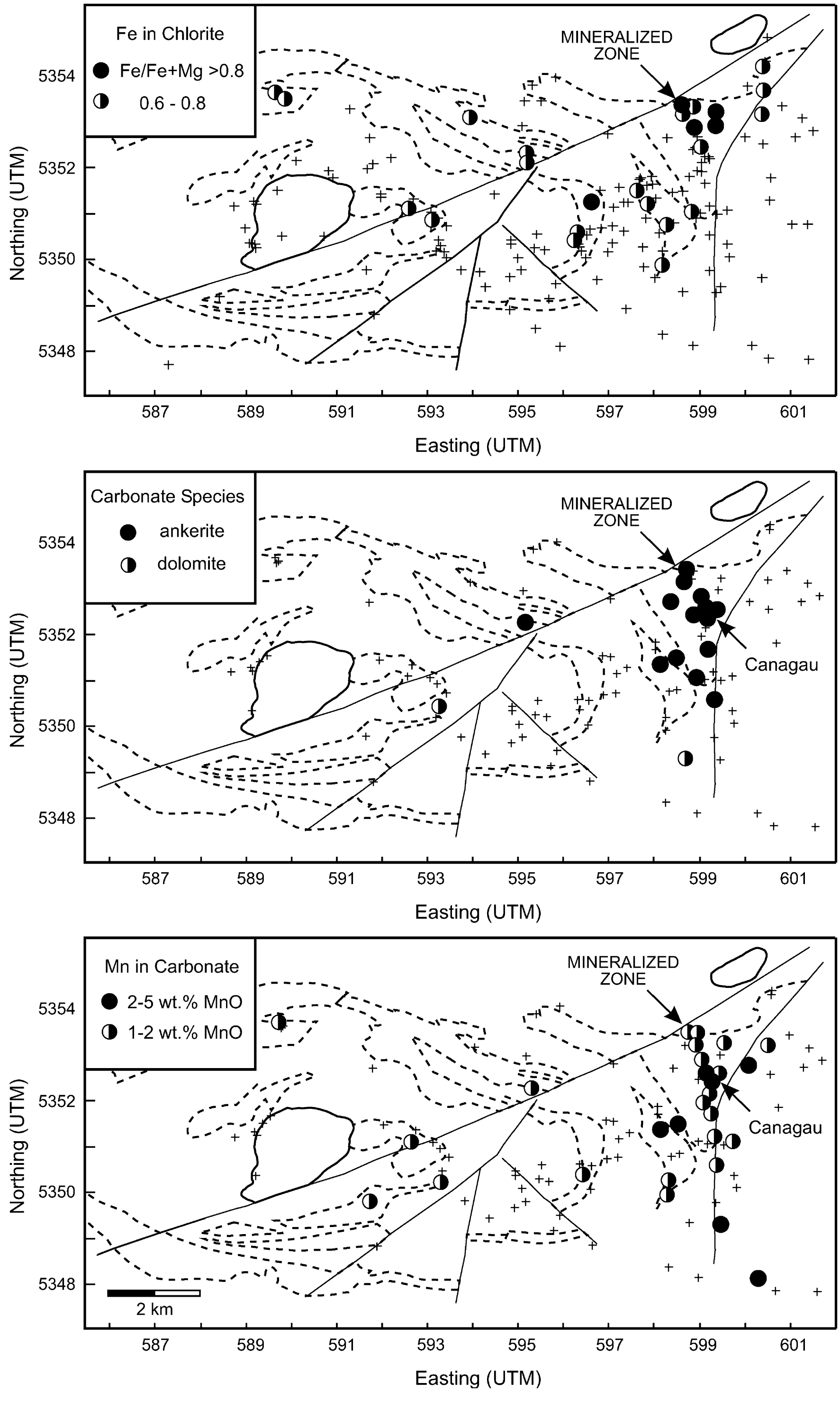


Fig. 23 Distribution of iron-bearing chlorite and carbonate in the Ben Nevis volcanic complex. The most Fe-rich chlorite and carbonate occur in intensely altered felsic volcanic rocks near the Canagau mineral occurrence (Fig. 4). In proximity to Canagau, manganese contents in carbonate are as high as 5 wt% MnO

the Clifford stock. Prehnite can persist to temperatures above 300 °C (Liou 1971; Bird et al. 1984), and this likely explains the abundant prehnite in actinolite-bearing rocks at the margins of the intrusion. This prehnite contains between 5 and 9 wt% FeO. The apparent increase in iron content with temperature is opposite to that of pumpellyite and epidote, as has been observed in ophiolites (Coombs et al. 1976; Evarts and Schiffman 1983; Liou et al. 1983; Beiersdorfer and Day 1995).

Pumpellyite

Pumpellyite is most abundant in massive vesicular lavas and fractured or brecciated flows, where it occurs

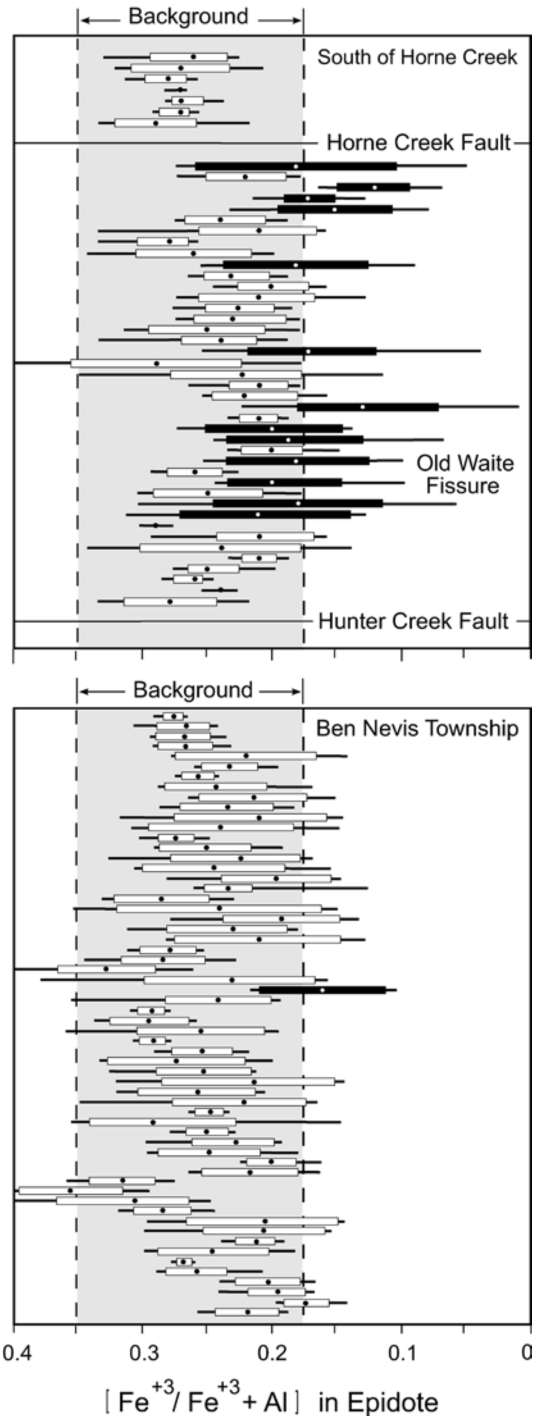


Fig. 24 Range of epidote compositions observed in samples of mafic volcanic rocks along an 8-km-long east–west traverse through Ben Nevis township (a portion of the Noranda traverse is shown for comparison). The Fe/Fe + Al ratios in all but one sample from Ben Nevis are well within the range of background epidote at Noranda. This epidote is similar in composition to epidote from regional greenschist facies metamorphic assemblages (Powell et al. 1993) Sample locations are the same as those shown in Fig. 22

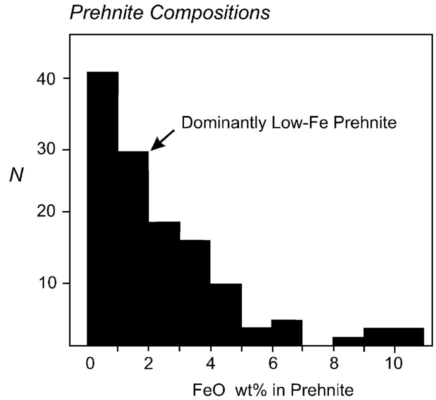


Fig. 25 Plot of FeO contents in prehnite from Ben Nevis township. Most of the prehnite at Ben Nevis is iron-poor, similar to that associated with low-temperature seafloor metamorphism. Iron-rich prehnite is found proximal to the Clifford stock and correlates with the distribution of iron-bearing actinolite (see text for discussion)

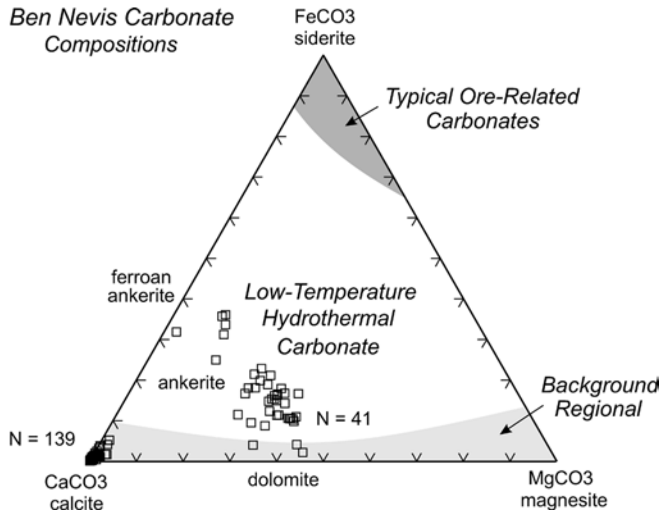


Fig. 26 Carbonate compositions in 70 samples from the Ben Nevis volcanic complex (180 analyses). The majority of the analyzed carbonates in the Ben Nevis volcanic complex are pure calcite. This contrasts sharply with the iron-rich carbonate typically associated with VMS. The presence of mainly calcite argues against a high-temperature origin and suggests that the regional carbonate alteration at Ben Nevis is unlikely to be related to a productive VMS-mineralizing system

as fibrous or sheaf-like aggregates in amygdules and filling open spaces. It typically occurs with small amounts of epidote, which exhibits a similar paragenesis. Some of the pumpellyite may be a replacement of pre-existing zeolites (e.g., laumontite, which is a common product of early diagenetic reactions in modern basalts).

The pumpellyite at Ben Nevis has a much larger compositional range (2–13 wt% FeO), at somewhat higher Fe/Fe + Al ratios, than pumpellyite from similar rocks in the New Insco–Magusi River area (Fig. 19). Both areas are within the prehnite–pumpellyite subfacies and, therefore, the observed difference in composition is unlikely to reflect a difference in metamorphic grade (see below). The high average iron content of pumpellyite at Ben Nevis (7.4 wt% FeO) is similar to that of pumpel-

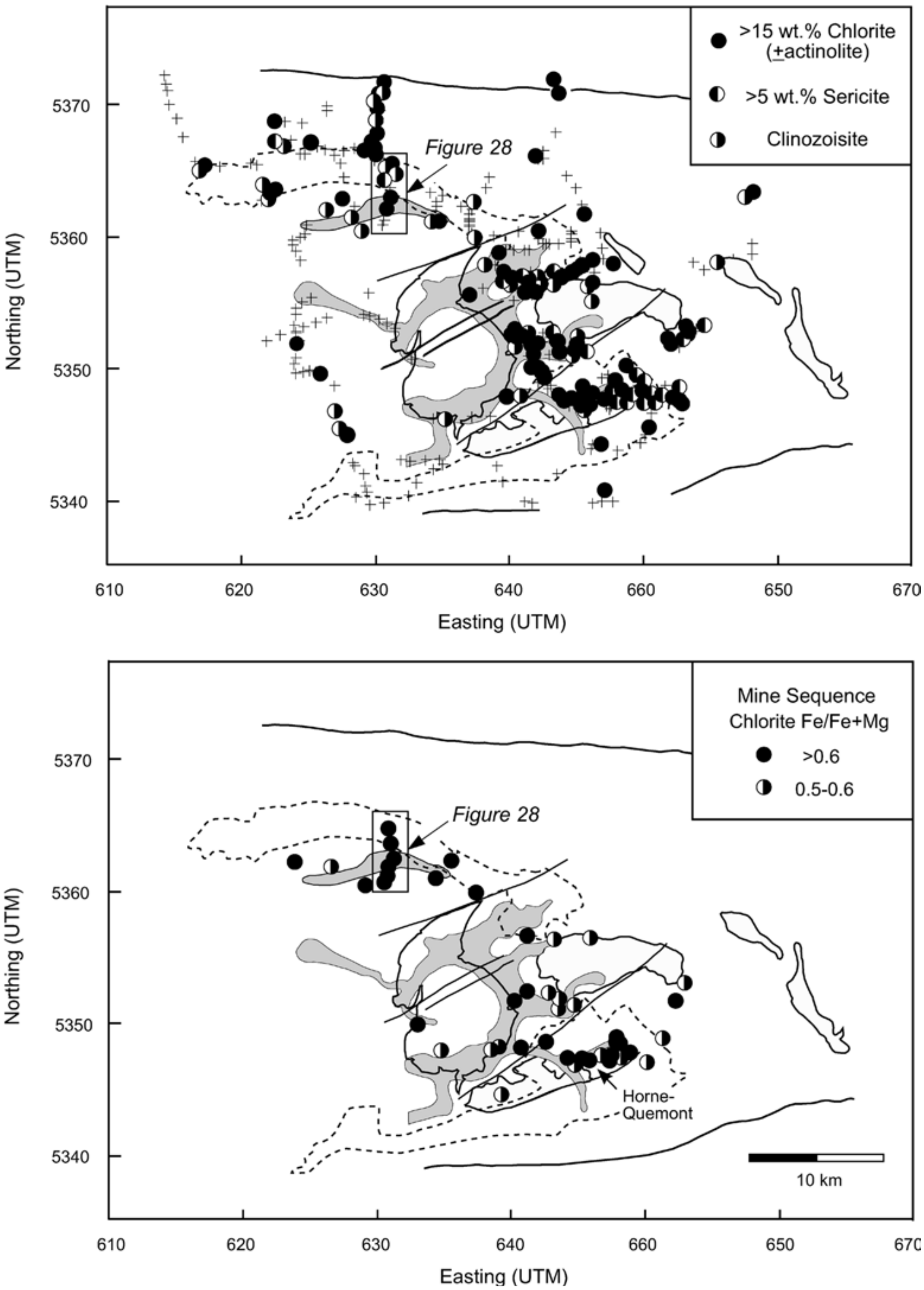


Fig. 27 Comparison of alteration mineralogy and whole-rock oxygen isotope zonation in the Noranda district. *Shaded regions* indicate rocks with significant ^{18}O depletion (< 6 per mil: Cathles 1993). A large zone of sericite alteration above the Horne and Quemont deposits (see Fig. 5) corresponds to an area of high ^{18}O. Chlorite compositions are shown for mafic volcanic rocks only

lyite in low-temperature alteration in ophiolites (Liou 1979; Harper 1995).

Carbonate

Carbonate is found in both mafic and felsic volcanic rocks throughout Ben Nevis township. In highly vesicular flows near the top of the section, the carbonate occurs in large amygdules and gas cavities after early quartz and magnesium–chlorite. In some felsic pyroclastic rocks, it nearly completely replaces the matrix, leaving only quartz phenocrysts behind. Elsewhere, the carbonate is clearly late and occurs in veins and fractures that cross cut earlier alteration.

Calcite is the dominant carbonate mineral in both mafic and felsic volcanic rocks; iron-bearing carbonates are restricted to a much smaller area in close proximity to the known mineralized zones (Fig. 23). This contrasts with the abundance of Fe–Mg carbonate associated with syn-volcanic hydrothermal alteration in other VMS environments (e.g., Morton and Franklin 1987). Of 70

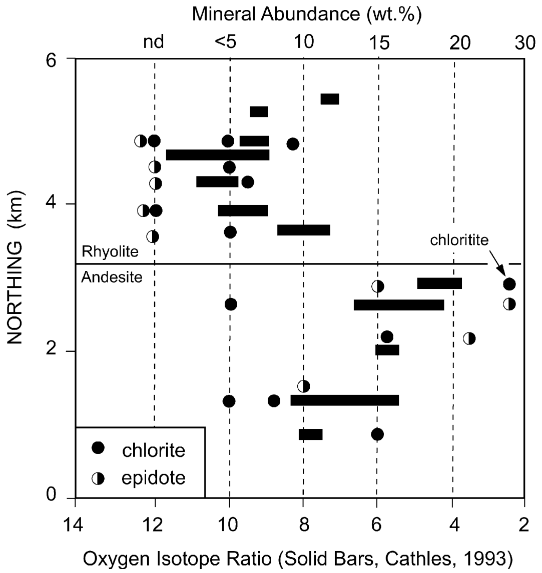


Fig. 28 Comparison of alteration mineralogy and whole-rock oxygen isotopes in a section of the Mine Sequence volcanic rocks north of the Hunter Creek fault (see Fig. 27 for location). The stratigraphy in this area is steeply-dipping (up to 80°) and exposes a vertical section through the volcanic pile. The samples correspond to a vertical section of ^{18}O-depleted andesites at the base of cycle III and ^{18}O-enriched rhyolites near the top of the sequence. The plotted isotopic compositions (*black bars*) are closely tracked by mineral abundances, with notable ^{18}O depletion occurring in samples with abundant chlorite and epidote of clinozoisite composition

samples from Ben Nevis township, only ten contained iron-bearing carbonate and only two samples showed significant iron enrichment (Fig. 26). The most iron-rich carbonate is ferroan ankerite from the Canagau occurrence, which contains 10–12 wt% FeO and as much as 5 wt% MnO (Fig. 23). Siderite was not found in any of the samples. The high manganese content of the carbonates is responsible for a distinct lithogeochemical anomaly associated with the mineralization (Wolfe 1977). However, the average MnO content of calcite elsewhere in the Ben Nevis area is less than 0.5 wt%.

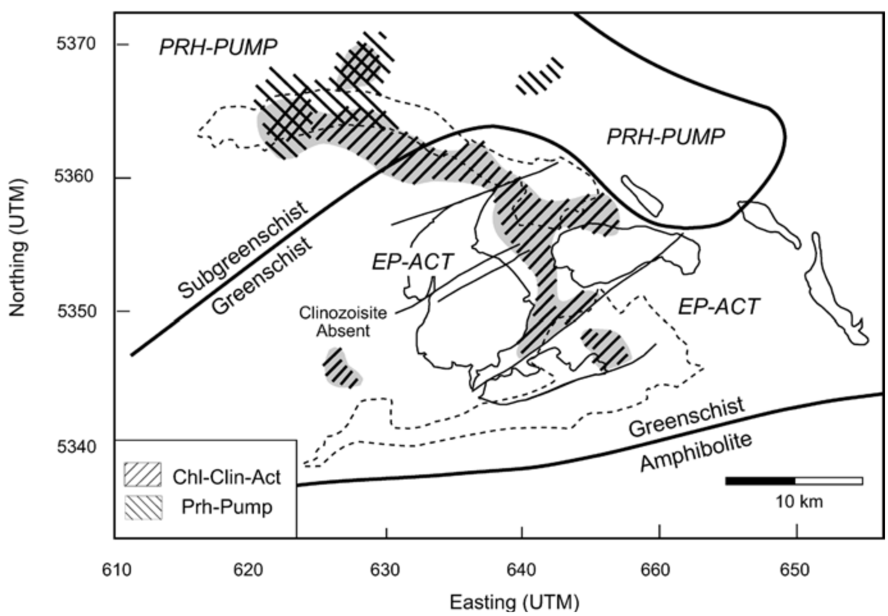
Other minerals

Although zeolites have not been found at Ben Nevis, the amygdules commonly contain abundant microcrystalline quartz (e.g., chalcedony or cristobalite) and calcite typical of the zeolite facies. Hydrogrossular, which occurs throughout the mafic volcanic rocks of Ben Nevis township, is also typical of zeolite-bearing assemblages in modern basalts. Titanite is a ubiquitous minor constituent of the mafic volcanic rocks. However, overall abundances of titanite are lower than in the Noranda camp, reflecting the slightly lower TiO_2 contents of the rocks and the less intense alteration.

Relationship of alteration mineralogy to isotope geology

The distribution of minerals associated with regional-scale, syn-volcanic hydrothermal alteration at Noranda correlates generally with the patterns of ^{18}O-depletion documented by Cathles (1993). Abundant chlorite and epidote of clinozoisite composition occur in the most depleted rocks above the Flavrian pluton and adjacent to the major dike swarms (Fig. 27). These zones also contain the most iron-rich chlorite. The strong mineralogical control on bulk rock ^{18}O is illustrated in Fig. 28, which shows chlorite and epidote abundance in samples from a traverse across a band of ^{18}O-depleted rocks north of the Hunter Creek fault. West of the Flavrian pluton, the absence of significant chlorite or

Fig. 29 Comparison of regional-scale, syn-volcanic hydrothermal alteration in the Noranda volcanic complex with previously mapped metamorphic isograds (*solid lines*: from Dimroth et al. 1983a, 1983b; Powell et al. 1993). The distribution of greenschist facies hydrothermal alteration (*shaded*) suggests that interpreted metamorphic zonation is at least partly a product of early syn-volcanic hydrothermal processes. Note that epidote and chlorite in the pre-cauldron sequences are distinct from those of the Mine Sequence volcanic rocks, even though they are well within the epidote–actinolite subfacies and have been metamorphosed at the same pressure and temperature (see text for discussion)



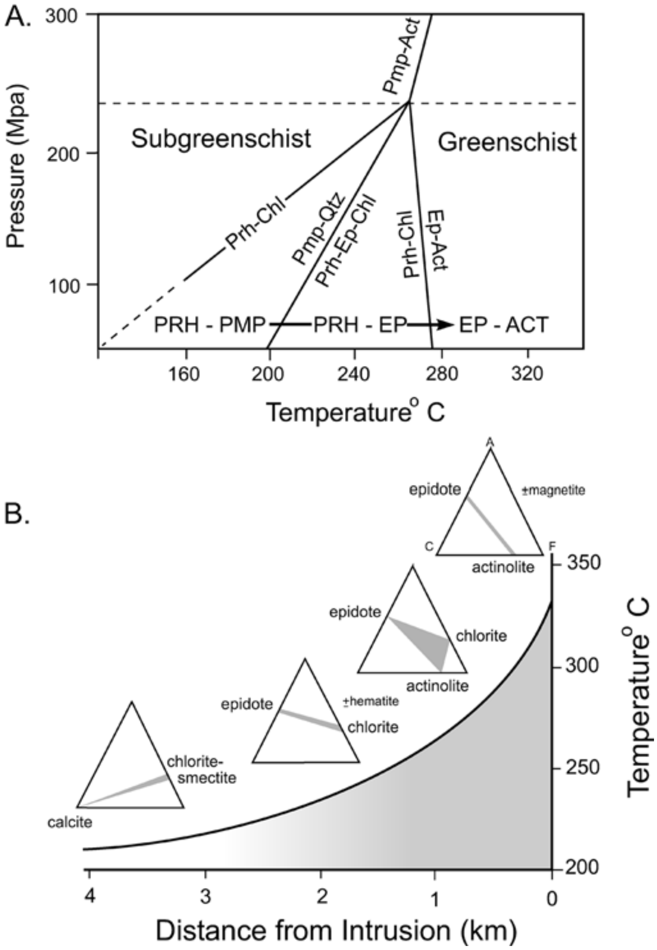


Fig. 30A, B Possible conditions of formation of syn-volcanic hydrothermal mineral assemblages in low-grade metamorphic rocks at Ben Nevis. **A** The low pressure assemblage of prehnite–pumpellyite near the top of the volcanic pile corresponds to temperatures of less than 200 °C. The disappearance of pumpellyite west of Ben Nevis township records a transition from prehnite–pumpellyite to prehnite–epidote at 200–250 °C. Actinolite-bearing assemblages proximal to the Clifford stock indicate temperatures in excess of 250 °C, but occupy only a small volume of rock (after Powell et al. 1993). **B** Mineralogical zonation with distance from a small cooling intrusion, similar to that of the Clifford stock (after Beaufort et al. 1992)

epidote of clinozoisite composition is consistent with the lack of ^{18}O-depletion in this area and suggests that large-scale, high-temperature fluid flow did not occur. Because the Flavrian pluton was intruded above the pre-cauldron volcanic succession, it could not have driven hydrothermal circulation in these rocks.

Oxygen isotope mapping in the Ben Nevis area was originally carried out by Beaty (1980). High ^{18}O values were interpreted to reflect mainly low-temperature seawater alteration during an early burial stage. Detailed oxygen isotope mapping of the Ben Nevis Noranda complex, in parallel with the present study (Taylor 1998), also provides little evidence for an organized hydrothermal system related to the Clifford stock. Local zones of ^{18}O depletion occur in areas of known mineralization (e.g., at the Croxall occurrence), but no coherent pattern of fluid flow was recognized within the map area. The most significant ^{18}O depletion coincides with the narrow zone of proximal epidote–actinolite ± magnetite alteration adjacent to the intrusion.

Significance of epidote chemistry

Much has been written about the significance of epidote composition, in terms of the physical and chemical conditions of its formation (see review by Beiersdorfer and Day 1995). There is considerable evidence that Fe/Fe + Al ratios in epidote decrease with increasing temperature or metamorphic grade. The temperature dependence is thought to be related to substitutional order/disorder in the M(1) octahedral site of the epidote structure. A metastable disordered state in epidote at low temperatures allows a larger proportion of Fe^{3+} to occupy the octahedral site (Bird and Helgeson 1980; Bird et al. 1988).

Depending on the assemblage of coexisting minerals, the composition of epidote is also known to be a strong function of f_{O2}, f_{S2}, or p_{CO2} (Holdaway 1972; Liou 1973; Bird and Helgeson 1980, 1981; Bird et al. 1988; Liou et al. 1983; Seyfried and Janecky 1985; Berndt et al. 1988, 1989; Caruso et al. 1988). Where epidote and quartz are the dominant minerals, an increase in f_{O2} can result in a large increase in the Fe/Fe + Al ratio in epidote, for example as the hydrothermal fluid cools or as seawater sulfate enters the reaction zone and creates more oxidizing conditions (Seyfried et al. 1999). Studies of altered metabasalts from the modern seafloor have established that alteration conditions in the cool, downwelling limb of a hydrothermal cell (low-temperature, relatively oxidized conditions) favor iron-rich epidotes, whereas epidote in proximity to the high-temperature upflow zones (temperatures of 250–450 °C and more reduced, low-pH fluids) is typically iron-poor (Stakes and O'Neil 1982; Alt et al. 1986; Delaney et al. 1987; Gillis and Robinson 1988; Bettison 1991; Gillis and Thompson 1993).

Epidote compositions in ophiolites also display a correlation with stratigraphic position, which has been interpreted to reflect increasing temperature with depth (Coish 1977; Evarts and Shiffman 1983; Richardson et al. 1987; Harper et al. 1988; Herzig 1988). In the epidote-bearing alteration zone beneath Agrokipia B in Cyprus, decreasing Fe/Fe + Al ratios in epidote (0.36–0.23) correlate with increasing temperatures determined from fluid inclusion and oxygen isotope geothermometry (Herzig 1988). Harper et al. (1988) and Harper (1995) also documented a systematic decrease in Fe/Fe + Al ratios, from 0.43 to 0.15, in the transition from the upper extrusive sequence to the base of the sheeted dikes in the Josephine ophiolite. Eastoe et al. (1987) noted similar aluminum-rich, iron-poor epidote close to the granite contact in the Mt. Read volcanic belt of Tasmania. In modern volcanic terranes, such as Iceland, epidote from the deepest parts of the volcanic pile (1–2 km) locally shows an appreciable decrease in Fe/Fe + Al that correlates with increasing temperatures (e.g., Viereck et al. 1982), whereas epidote in near-surface hydrothermal aquifers is typically iron-rich, reflecting the lower temperature and higher oxidation state of the near-surface fluids (Ragnorsdóttir et al. 1984; Sveinbjörnsdóttir 1992; Lonker et al. 1993). Similar observations have been made in other active geothermal systems such as the Salton Sea, Valles Caldera, and in Japanese geothermal fields (Keith et al. 1968; Bird et al. 1984; Shikazono 1984; Liou et al. 1985; Huelen and Nielsen 1986; Caruso et al. 1988).

By comparison with modern geothermal systems, the abundance of epidote of clinozoisite composition at Noranda is most reasonably interpreted in terms of large-scale hydrothermal fluid flow at high temperatures within the Mine Sequence volcanic rocks. The composition of epidote at Ben Nevis more closely resembles that of epidote in modern basaltic sequences that are far removed from high-temperature alteration (e.g., 11–19 wt% Fe_2O_3 in epidote from eroded volcanic complexes of eastern Iceland: Winkler 1974; Mehegan et al. 1982). High Fe/Fe + Al ratios in pumpellyite at Ben Nevis also suggest a low temperature of formation (Schiffman and Liou 1983; Cho and Liou 1987). Although epidote compositions are sensitive to bulk rock chemistry (e.g., Nakajima 1982; Terabayashi 1988; Shikazono et al. 1995; McCollom and Shock 1998), a difference in the composition of the mafic volcanic rocks at Noranda and Ben Nevis, which might explain the differences in epidote compositions, is not apparent from whole-rock analyses. The difference in epidote compositions is much larger than can be accounted for by a difference in FeO/Fe_2O_3 ratios of the volcanic rocks.

The coarse crystalline nature of the epidote at Noranda may also reflect high temperatures and high W/R within the hydrothermal aquifers of the Mine Sequence volcanic rocks (Seyfried and Bischoff 1981; Mottl 1983; Reed 1983). This is supported by studies of active geothermal systems in which epidote crystallinity has been used as a qualitative geothermometer (Patrier et al. 1990, 1991). Finer-grained epidote, typical of the alteration at Ben Nevis, is usually interpreted to reflect poor nucleation kinetics for this mineral at low temperatures.

Metamorphism versus hydrothermal alteration

The regional greenschist to subgreenschist metamorphic transition between Noranda and Ben Nevis, previously mapped by Jolly (1980) and Powell et al. (1993, 1995), raises the possibility that differences in the alteration mineralogy between the two volcanic complexes might simply reflect a difference in the depth of burial during metamorphism. However, several key observations suggest that the greenschist facies mineral assemblage in the Mine Sequence at Noranda is pre-metamorphic. Whereas regional metamorphic isograds have continuity across the volcanic complex, as well as across the major structural breaks (Fig. 29), mineralogical zonation associated with regional-scale hydrothermal fluid flow is generally fault-bounded and exhibits strong syn-volcanic control (e.g., in laterally extensive stratabound zones and adjacent to dike swarms: Gibson et al. 1983; Galley 1993; Santaguida 1999). The range of observed mineral compositions within the Mine Sequence volcanic rocks is also much larger than can be accounted for by the pressures and temperatures associated with regional metamorphism. For example, the composition of epidote spans nearly the entire range of allowable solid solutions, often within a single formation. The unusually iron-poor epidote found in the central part of the Noranda cauldron resembles epidote normally associated with amphibolite facies metamorphism (e.g., Nakajima et al. 1977; Nakajima 1982), although these rocks have never experienced metamorphic pressures and temperatures above lower greenschist conditions. On the other hand, the barren volcanic rocks west of the Flavrian intrusion are well within the epidote–actinolite metamorphic subfacies (Fig. 29), but have mineral compositions that are significantly different from those of the Mine Sequence volcanic rocks. If the secondary minerals reflected only the temperature of the latest regional metamorphism, then one would expect no difference in the compositions of these minerals across the Noranda complex.

The regional greenschist to subgreenschist metamorphic transition, which crosses the margins of the Noranda volcanic complex in the New Insco–Magusi River area, helps to constrain the depth of burial in this part of the volcanic complex. The abundant prehnite and pumpellyite in these rocks can only coexist at low pressures (less than 2–2.5 kbar), indicating relatively shallow burial. However, the mafic volcanic rocks at New Insco and Magusi River also contain a high-temperature assemblage of iron-rich chlorite, actinolite, and epidote of clinozoisite composition (Fig. 29). In a normal geothermal gradient of 35–50 °C/km, this assemblage would correspond to a depth of burial of about 7–8 km (Powell et al. 1995). In a near surface, low pressure environment these minerals could only have formed in a much enhanced geothermal gradient. Disequilibrium assemblages, such as these, indicate that the volcanic rocks in the New Insco–Magusi River area were exposed to hydrothermal fluids at temperatures considerably higher than any reached during subsequent metamorphism. A reconstruction of the volcanic pile at Ben Nevis by Jensen (1975) also suggests that the transition from prehnite–pumpellyite to epidote–actinolite in the lower part of the volcanic complex occurs well above the paleodepth at which this reaction is likely to have taken place during regional burial metamorphism. This mineralogical zonation is most reasonably interpreted in terms of the local thermal effects of the Clifford stock.

Origin of the alteration at Ben Nevis

Alteration of the mafic volcanic rocks at Ben Nevis is typical of low-temperature water–rock interaction during the initial emplacement and rapid burial of the volcanic pile (Moore and Schilling 1973; Humphris and Thompson 1978a, 1978b; Pritchard 1979; Alt 1999a). Hydration is the most significant of the chemical changes in the early history of the volcanic rocks, and this is reflected in their high H_2O content (Grunsky 1986). With the input of heat from below, the glassy material in the basalt alters quickly to magnesium-chlorite, and this is the most abundant mineral replacing hyaloclastite and infilling amygdules. However, the fact that these rocks still contain fresh plagioclase confirms that the alteration is part of their early diagenetic history and that temperatures did not exceed about 250 °C (e.g., the temperature at which plagioclase is destroyed in most Icelandic geothermal wells: Kristmannsdóttir 1982). Preservation of delicate radial growths and crustiform textures in amygdules and larger open spaces also indicates that little or no post-depositional recrystallization has occurred.

Two spatially separate, low variance mineral assemblages occur in the Ben Nevis Noranda complex: (1) prehnite–pumpellyite–epidote (+chl+qtz) in the upper part of the volcanic pile and (2) epidote–actinolite–prehnite (+chl+qtz) at greater depth. The prehnite–pumpellyite assemblage is located well away (>3 km) from the intrusive core of the complex and corresponds to temperatures of less than 200 °C (Fig. 30: Powell et al. 1993). The disappearance of pumpellyite west of Ben Nevis township records the transition to prehnite–epidote, which occurs in the temperature range of 200–250 °C. Although actinolite occurs in close proximity to the Clifford stock, consistent with steepening thermal gradients at the intrusive core of the complex, the heat loss and local hydrothermal circulation adjacent to the intrusion was not sufficient to drive high-temperature fluids to the surface.

The mineralogical zonation observed at Ben Nevis is similar to that of eroded Tertiary volcanoes in Iceland. The distal carbonate zone, in particular, resembles the outer "calcite halo" that surrounds many of the small silicic volcanic centers exposed in eastern Iceland (Walker 1960, 1974). Carbonate occurs mainly in calcite-filled amygdules and fractures that can be mapped at distances as far as 5 km from these volcanoes. Fluid inclusion evidence indicates that the calcite forms within a narrow temperature range of 150–200 °C, late in the cooling history of the volcanic pile (Mehegen et al. 1982). At Ben Nevis, the presence of Fe–Mg-carbonate minerals near the Canagau occurrence indicates locally anomalous geothermal activity in this part of the volcano. However, the absence of siderite as an iron-bearing species suggests that the fluids were probably not reduced or hot enough to carry significant base metals. Coincident iron-rich chlorite and iron-bearing carbonate occupy a relatively small area (e.g., a volume of rock no more than 10 km^3) and, therefore, do not indicate the presence of a fossil geothermal system of sufficient size to have produced a large deposit.

Origin of regional-scale hydrothermal alteration at Noranda

The development of the Noranda volcanic complex was characterized by major rifting, steep thermal gradients, and a permeability structure favorable for large-scale hydrothermal fluid flow. The thickness of the volcanic pile, the volume of rhyolite, and the abundance of dikes are all qualitative measures of a very large magmatic budget and corresponding high heat flow compared with Ben Nevis. The shield volcano at Noranda was built to a thickness nearly twice that of the Ben Nevis complex, and parts of the Mine Sequence comprise 30–50% dikes by volume, indicating major crustal extension during the growth of the volcano. At Ben Nevis, obvious cross cutting synvolcanic structures analogous to the Old Waite Paleofissure are absent, and the density of dikes surrounding the Clifford stock is small by comparison.

The regional-scale, syn-volcanic hydrothermal alteration at Noranda is similar to that found in a number of the large, high heat-producing geothermal systems in Iceland (Tomasson and Kritmannsdóttir 1972; Kristmannsdóttir 1975, 1979, 1982; Pálmason et al. 1979; Lonker et al. 1993), and likely formed under similar conditions. Hydrothermal fluid flow in these systems is driven by steep thermal gradients proximal to the intrusive cores of the volcanoes and essentially horizontal isotherms farther away. The scale and intensity of the alteration are proportional to the size of the thermal anomaly. Large volcanic complexes, such as Krafla and Hengill, have near surface thermal gradients of more than 200 °C/km, with high-temperature alteration occupying a volume of rock that can exceed 100–200 km^3 (Pálmason 1974; Robinson et al. 1982; Fridleifsson 1991). Comparisons with modern geothermal systems, as well as alteration in ophiolites, suggest that the most productive hydrothermal fluid flow occurs as much as 2 km below the paleo-seafloor (e.g., high permeability zones at the pillow-dike transition in ophiolites: Evarts and Schiffman 1983; Alt et al. 1986, 1999b). At Noranda, strong epidote–quartz alteration in the deep part of the cauldron sequence (e.g., in the Rusty Ridge andesite formation: Santaguida 1999) likely marks an important sub-seafloor aquifer at the time of massive sulfide formation. The conformable epidote–quartz alteration follows stratigraphy parallel to the main ore-bearing horizons and can be traced across a large part of the cauldron. The depth to this alteration zone is similar to that of deep hydrothermal aquifers in modern geothermal fields (Fridleifsson 1991; Lonker et al. 1993). A close spatial association of the most intense alteration with major dike swarms (e.g., the Old Waite Paleofissure) also suggests a link to dike emplacement within the reservoir zones, similar to that observed in modern oceanic crust (Bettison-Varga et al. 1995; Penwright et al. 1997).

Gibson et al. (1983) and Lesher et al. (1982) suggested that conformable epidote–quartz alteration at Noranda was the product of gradual sealing of hydrothermal aquifers within the Mine Sequence volcanic rocks. The resulting increase in temperature is thought to have been responsible for metal leaching from the aquifer (Gibson et al. 1983). Paradis et al. (1993) and Hoy (1993) also documented a pronounced decrease in the ^{18}O of altered rocks towards the base of the Mine Sequence. This trend was interpreted to reflect increasing temperature with depth and thermal stratification of the volcanic pile in response to the sealing of primary permeability. The observed shift in ^{18}O is similar to that observed in ophiolites and at modern mid-ocean ridges (Gregory and Taylor 1981; Stakes and O'Neil 1982; Bowers and Taylor 1985; Schiffman and Smith 1988; Stakes and Taylor 1992; Alt 1999b).

Equilibrium oxygen isotope temperatures for quartz–epidote pairs, recalculated using fractionation factors from Zheng (1993), indicate sustained aquifer temperatures as high as 300–350 °C in the Mine Sequence volcanic rocks (data from Maclean and Hoy 1991; Hoy 1993; Paradis et al. 1993). These temperatures are consistent with fluid inclusion studies of large-scale, epidote–quartz alteration zones in Cyprus (Schiffman and Smith 1988; Schiffman et al. 1990; Bettison-Varga et al. 1995) and are similar to that of epidote formation in modern geothermal fields, but they are lower than temperatures estimated for the deep root zones of submarine hydrothermal vents. The pure epidote–quartz rocks in the reaction zones of Cyprus-type hydrothermal systems (i.e., so-called epidosites) represent oceanic crust that has been exposed repeatedly to hydrothermal fluids at near critical pressures and temperatures. Fluid inclusions in quartz from these rocks contain high-salinity brines trapped near the critical point of seawater at temperatures in excess of 400 °C (Kelley and Delaney 1987; Cowan and Cann 1988; Kelley and Robinson 1990; Nehlig 1991; Nehlig et al. 1994). Such fluids do not appear to have been present in the aquifer zones of the Noranda volcanic complex. However, the formation of abundant epidote in these rocks implies that large volumes of highly-reacted seawater passed through the Mine Sequence volcanic rocks at high flow rates (cf., Richardson et al. 1987; Seyfried et al. 1988; Harper 1995). The formation of epidote–quartz rocks containing more than 20 wt% epidote would have required a massive influx of Ca^{2+} from seawater that had previously reacted with large volumes of basaltic rock. Various methods for estimating the volume of hydrothermal fluid involved all arrive at similar values (e.g., Barrie et al. 1999). For 50 Mt of massive sulfide in the Noranda cauldron, as much as 10^{15} kg of high-temperature hydrothermal fluid may have been required. At a W/R mass ratio of 1, a fully equilibrated hydrothermal fluid would have reacted with as much as 200 km^3 of rock at greenschist temperatures or higher (i.e., >300 °C: Fig. 30), similar to the alteration volumes associated with large silicic volcanic centers of Iceland.

Aquifer temperatures in the Noranda Mine Sequence were at least 100 °C hotter than the highest-temperatures at Ben Nevis, and the volume of altered rock is at least ten times larger. A comparison of the Ben Nevis alteration with secondary mineral assemblages in Tertiary volcanoes of eastern Iceland indicates a probable geothermal gradient of 50–70 °C/km in the upper part of the volcanic pile, steepening towards the intrusive core. A maximum thermal gradient of about 100 °C/km near the base of the volcanic pile (i.e., 200 °C at a depth of 2 km) is at least 50 °C/km higher than normal burial metamorphism, but much lower than the geothermal gradients associated with large silicic volcanic complexes such as Noranda.

Conclusions and implications for exploration

The results of this study confirm that alteration associated with convective hydrothermal circulation in a large district can be recognized well beyond the upflow zones of individual deposits and constitutes a potentially important exploration target at the regional scale. In the Mine Sequence volcanic rocks at Noranda regional-scale, syn-volcanic hydrothermal alteration is characterized by:

1. A complex paragenesis with evidence for multiple overprinting hydrothermal events.
2. An abundance of iron-rich chlorite ($Fe/Fe+Mg \geq 0.5$).
3. Anomalous, coarse-grained epidote of clinozoisite composition (<10 wt% Fe_2O_3).
4. Abundant REE-bearing allanite, especially in felsic volcanic rocks.
5. Hydrothermal amphibole with iron-rich compositions.
6. Locally iron-rich and manganiferous carbonates.

This alteration persists in coeval volcanic rocks for distances of as much as several tens of kilometers and can be readily distinguished from greenschist facies metamorphic assemblages at the regional scale. Large ranges in mineral compositions, such as those observed in epidote, are indicative of fluctuating permeability, temperature, and f_{O2} in areas of anomalous fluid flow and contrast sharply with the narrow range of mineral compositions typically associated with early diagenetic alteration or regional metamorphism of unaltered rocks. Map patterns based on mineral abundances and compositions highlight both conformable and discordant zones of hydrothermal fluid flow at the regional scale and correlate well with previously documented whole rock ^{18}O zonation. Although comparisons with less productive volcanic successions indicate that chlorite or epidote abundance alone may be significant in terms of identifying anomalous fluid flow, the conditions of alteration are difficult to assess without reference to the mineral compositions.

The formation of large VMS deposits requires substantial volumes of hydrothermal fluid to be mobilized through several hundred cubic kilometers of rock. At Noranda, regional syn-volcanic alteration in the Mine Sequence rocks indicates that hydrothermal fluid flow occurred on a scale similar to that of some of the largest active geothermal systems on land (e.g., Krafla, Salton Sea, Valles Caldera). Regional-scale alteration mapping provides a means of estimating the volumes of hydrothermal fluid involved and, therefore, the likelihood of forming large deposits. Alteration mapping that targets large-tonnage VMS deposits should encompass an area that greatly exceeds that normally associated with discordant alteration pipes. In the absence of a suitably large volume of altered rocks, the size of the exploration target should be scaled back accordingly. For example, there may be little value in pursuing a narrow alteration pipe, in the hope that it will lead to a large deposit, if the surrounding volcanic rocks give no indication of having interacted with a large volume of high-temperature hydrothermal fluid. This was clearly illustrated at Ben Nevis.

Examples where this type of mapping have been successful in defining significant alteration volumes at the regional scale include the Mt. Read volcanics in Tasmania (Eastoe et al. 1987) and the Strelley Volcanics in the Panorama district of Western Australia (Brauhart et al. 1998). Similar alteration is well documented in other large and productive volcanic complexes, including in the Matagami district of Quebec, at Snow Lake in Manitoba, in central Sweden, and in the Green Tuff Belt of Japan (MacGeehan and MacLean 1980; Skirrow and Franklin 1994; Baker 1985; Shikazono et al. 1995). However, alteration mapping in most VMS districts is not conducted at a scale that is large enough to encompass the limits of the hydrothermal system(s). In modern geothermal systems, the main aquifer zones associated with high-temperature fluid flow are located at depths of 1–2 km, well below any near-surface discharge, and may be related to hydrothermal venting as much as 10 km along strike. This geometry should be taken into consideration when designing a regional-scale alteration mapping program and when incorporating this alteration in an exploration model. Whole-rock X-ray diffraction offers a simple and relatively inexpensive means of quantifying the mineralogy in the large numbers of samples required for regional-scale alteration mapping and is particularly useful for fine-grained alteration that is difficult to characterize in the field. Similar approaches are now being tested with field-portable infrared spectrometers such as PIMA (Huston et al. 1998, 1999; Thompson et al. 1999).

In ancient volcanic terranes, where the interpretation of alteration mineral assemblages is complicated by regional metamorphism, detailed isotopic and mineral–chemical studies may be required to identify alteration associated with large-scale, syn-volcanic hydrothermal fluid flow. At Noranda, the regional subgreenschist to greenschist transition, which was previously interpreted to reflect burial metamorphism, has been shown to be at least partly a product of large-scale hydrothermal alteration coincident with the extrusion of the Mine Sequence volcanic rocks. Analogous situations may exist in other large volcanic complexes that have been metamorphosed to greenschist facies or higher. For example, in the Flin Flon belt of Manitoba a prehnite–pumpellyite to epidote–actinolite transition has been mapped within 8 km of the giant Flin Flon–Callinan deposit (ca. 80 Mt). This zonation has been attributed to burial metamorphism (Digel and Gordon 1995), but it may reflect a regional-scale thermal anomaly associated with the formation of the host volcanic complex, as at Noranda. Minerals such as chlorite, epidote, and actinolite can be used effectively to identify the products of hydrothermal alteration in these rocks because they are already stable at greenschist temperatures and are unlikely to have re-equilibrated during metamorphism, thereby retaining their chemical and isotopic characteristics.

Acknowledgements This study was funded by the Canadian Mining Industry Research Organization (CAMIRO Project 94E07 on Use of Regional-Scale Alteration Zones and Subvolcanic Intrusions in the Exploration for Volcanic-Associated Massive Sulphide Deposits). A suite of more than 500 samples from the Noranda camp was provided for this study from the original Cathles (1993) project. We also thank the Ontario Geological Survey for providing an extensive sample suite from the Clifford–Ben Nevis area, together with whole-rock analytical data from L. Jensen and E.C. Grunsky. Kendra Shaw and Julie Blonde assisted with whole-rock XRD. Microprobe analyses were conducted in the laboratories of the Geological Survey of Canada with the help of John Stirling. An earlier version of this paper was substantially improved by helpful comments from R.A. Koski, J.C. Alt, and R.J. Goldfarb. This is GSC Contribution no. 2000218.

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