

The Ben Nevis Volcanic Complex, Ontario, Canada: Part of the Late Volcanic Phase of the Blake River Group, Abitibi Subprovince *

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Abstract

The Ben Nevis volcanic complex occurs in the Misema–Duprat–Montbray formation of the Ontario portion of the Blake River Group. The Misema–Duprat–Montbray formation is considered contemporaneous with the Noranda formation of the Blake River Group although they display varying volcanic styles. The Noranda formation displays bimodal flow-dominated rhyolite-andesite volcanism, pyroclastic rocks being rare; the eastern part of the Misema–Duprat–Montbray is similar but becomes dominantly andesitic with subordinate rhyolites to the west. In both the Noranda and Misema–Duprat–Montbray formations, the andesites are of two end-member affinities (tholeiitic and calc-alkalic) with a third transitional andesite type. The Ben Nevis volcanic complex differs somewhat from the two formations in that it is not bimodal. It exhibits a continuous spectrum of lithologic units from basaltic-andesite to rhyolite; the andesites occur as either flows or as pyroclastic deposits, and the dacites-rhyolites are dominantly pyroclastic. Geochemically, the andesites are of a single, calc-alkalic affinity. The Misema–Duprat–Montbray formation has a published U-Pb age date of 2701 ± 2 Ma from a rhyolite in Pontiac Township in Ontario. A rhyolite in the Ben Nevis volcanic complex yields a new precise age of 2696.6 ± 1.3 Ma, making it younger than the main volcanic phases of the Misema–Duprat–Montbray. The Ben Nevis age overlaps published ages for the youngest formations of the Blake River Group in Québec, the Reneault-Dufresnoy (2696 ± 1.1 Ma) and Bousquet (2698 ± 1 Ma) formations. A new U-Pb age for a second, porphyritic Ben Nevis rhyolite of 2699.8 ± 3.6 Ma, although less precise, is also nominally younger than the earliest phase of the Misema–Duprat–Montbray volcanism.

The Ben Nevis volcanic complex shares other similarities, in addition to age, to the Reneault-Dufresnoy and Bousquet formations. Similar to the Bousquet formation, the Ben Nevis volcanic complex is not bimodal. Pyroclastic rhyolites are also common in the Ben Nevis volcanic complex, as in the Reneault-Dufresnoy and Bousquet formations. The rhyolites of all three late-phase volcanic formations exhibit greater LREE enrichment and larger negative Nb anomalies than the Noranda or Misema–Duprat–Montbray formation rhyolites. The syn-volcanic mineral deposits in the Reneault-Dufresnoy and Bousquet formations are polymetallic (gold, silver, and base metal sulfides), and similar but much smaller showings occur in the Ben Nevis volcanic complex. The similarity in age, lithological and geochemical character, and style of mineralization are consistent with the Ben Nevis volcanic complex having been emplaced during the late Blake River Group volcanism that formed the Reneault-Dufresnoy and Bousquet formations.

Introduction

THE ARCHEAN Blake River Group of the Abitibi subprovince of the Superior province of Canada (Fig. 1) has been one of the most prolific base metal- and gold-producing areas in the Abitibi greenstone belt. Since the 1920s the Noranda Camp produced significant quantities of Cu, Zn, Au, and Ag from deposits hosted within the Noranda cauldron of the Blake River Group (Spence and de Rosen-Spence, 1975; de Rosen-Spence, 1976; Gibson, 1989). The bulk of the ore mined included 2.6 million metric tons (Mt) of Cu and Zn from Cu-Zn (Noranda-type) volcanogenic massive sulfides (VMS) in 17 past-producing deposits from within the cauldron (Fig. 2; Gibson and Watkinson, 1990; Racicot, 1990). In addition,

significant quantities of Au were mined from deposits outside the cauldron, including the giant Au-rich Horne VMS deposit, immediately south of the cauldron boundary (Kerr and Mason, 1990), as well as the outlying Bouchard-Hébert mine in the Cléricy area (Riopel et al., 1995; Doucet et al., 2006), and the Bousquet and LaRonde mines in the Bousquet area to the east (Lafrance et al., 2003; Mercier-Langevin et al., 2004, 2007a, b; Fig. 2).

In contrast to the Blake River Group in Québec, in Ontario the group has received relatively minor exploration attention or geologic research. Felsic volcanic complexes are comparatively rare in the Blake River Group of Ontario, the Ben Nevis volcanic complex being one of the most significant (Fig. 2). This complex has been of interest to mineral exploration companies due to the presence of felsic volcanic rocks in a dominantly andesitic regime and mineralized showings (e.g., the Canagau mine and the Croxall Breccia, also known as the Interprovincial North and Brett-Tretheway showings, respectively) with exploration primarily aimed at Noranda-style

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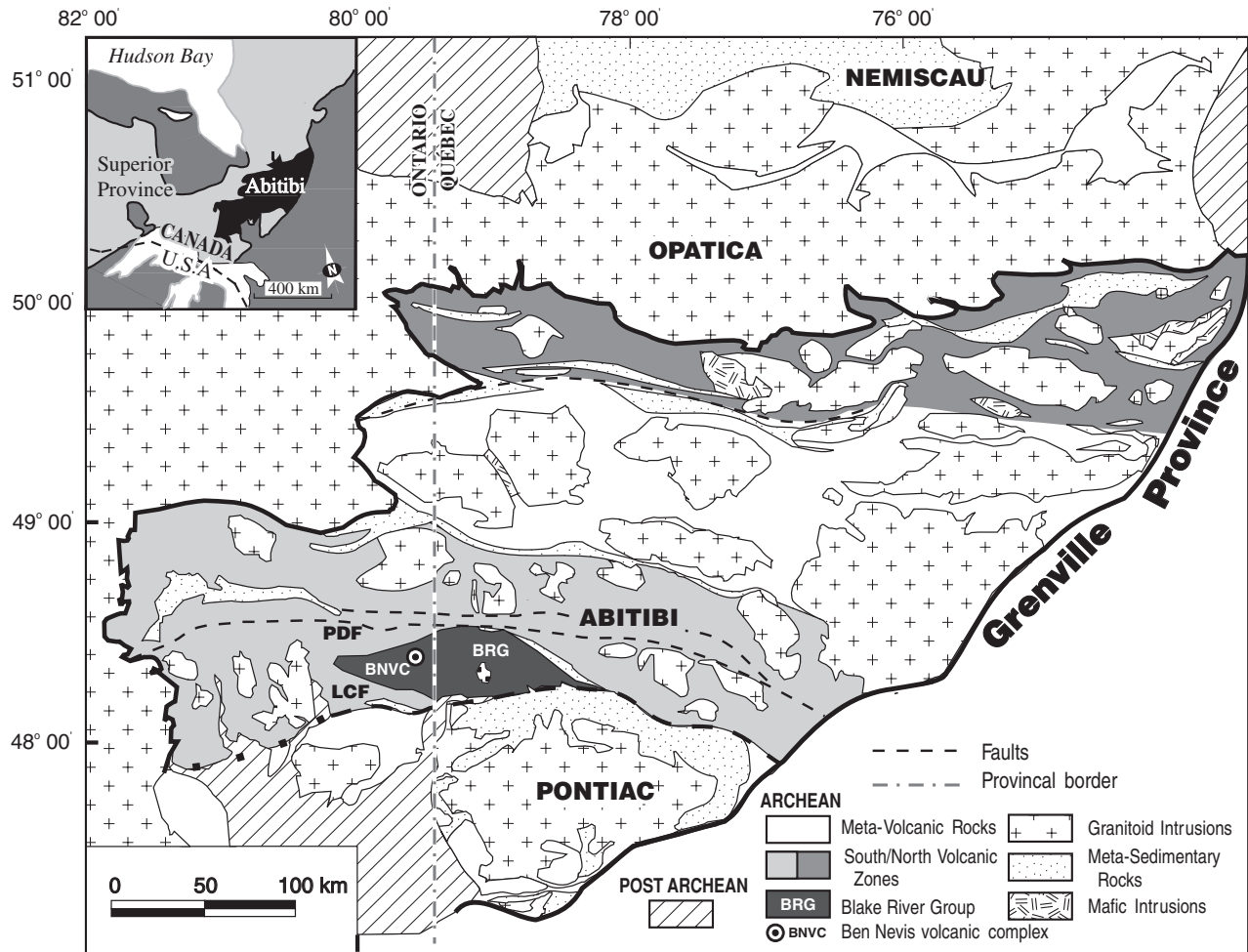


FIG. 1. Geology of the Abitibi subprovince of the Superior province of Canada modified after Goodwin and Ridler (1970) and Ludden and Hubert (1986).

VMS mineralization. Since the systematic mapping of Ben Nevis and Clifford Townships by Jensen (1975), thematic studies have centered around the Ben Nevis volcanic complex, including the metallogenic study by Wolfe (1977), a litho-geochemical study by Grunsky (1986, 1988), and regional hydrothermal alteration studies including mineral chemical studies (Hannington et al., 2003) and stable isotope studies (B.E. Taylor and A. Timbal, unpub. report for the Canadian Mineral Industry Research Organization, Project 94E07, 1998 p.123–130). This paper summarizes the results of a re-examination of the volcanic and intrusive rocks in the Ben Nevis-Clifford area in order to better define their character, their timing, and relationships to mineralization and the overall Blake River Group stratigraphy (MacDonald et al., 2005; Péloquin and Piercey, 2005; Piercey et al., 2008). We look at the position of the Ben Nevis volcanic complex within the gross stratigraphy of the Blake River Group in Ontario and Québec and compare it lithologically, geochemically, and geochronologically to the main phases of volcanism (formations) recognized in the Group and specifically to formations within the Group that are of the same age as the Ben Nevis volcanic complex. Given that the Noranda and Bousquet formations host world-class ore systems (e.g., Horne and

LaRonde mines), a more complete understanding of the stratigraphic and volcanologic setting of the Blake River Group in Ontario may provide clues to the potential for VMS mineralization within this relatively poorly understood part of the Blake River Group.

The Stratigraphy of the Blake River Group

The Blake River Group stratigraphy used here is compiled from the recent work of the Ministère des Ressources Naturelles Faunes et Parc du Québec and the Ontario Geological Survey (Fig. 2). The Blake River Group is comprised of the Lower Blake River assemblage in Ontario (Ayer et al., 2005; referred to as the Garrison subgroup by Goodwin, 1977), the Misema–Duprat–Montbray formation in Ontario and Québec (modified from Goodwin, 1977, using the interpretation by Dion and Rheaume, 2007), and the Hébécourt, Rouyn-Pelletier, Noranda, Renault-Dufresnoy, and Bousquet formations in Québec (Goutier and Lacroix, 1992; Goutier, 1997; Lafrance et al., 2003). The Lower Blake River assemblage (Garrison formation), and the Hébécourt and Rouyn-Pelletier formations appear to be laterally continuous on the map and have similar lithological and geochemical characteristics (Goodwin 1977; Goutier and Lacroix, 1992;

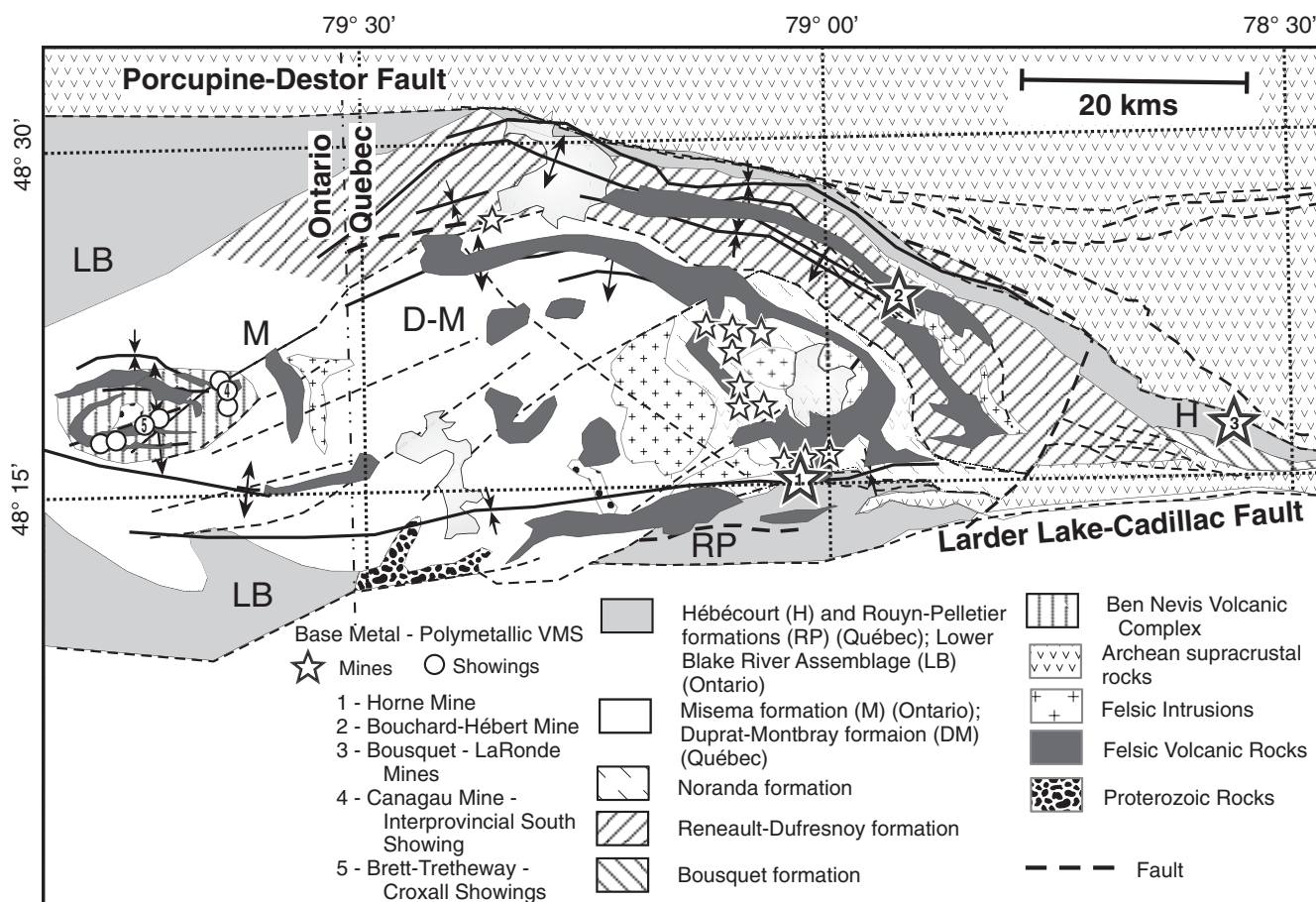


FIG. 2. Geology of the Blake River Group modified after Goodwin (1977), Goutier (1997), Lafrance et al. (2003), and Goutier et al. (2006). Locations of mines and mineral showings are indicated.

Ayer et al., 2005; J. Goutier, 2007, pers. commun.); they are dominated by Fe tholeiitic basalts with rare andesites. In the Misema–Duprat–Montbray formation, rhyolites form an important proportion of the eastern part of the formation but decrease in abundance to the west such that in Ontario the formation is dominantly andesitic with rare rhyolites. The Ben Nevis volcanic complex within the Misema–Duprat–Montbray formation has lithologic units, geochemistry, and an age similar to the Renault–Dufresnoy and Bousquet formations, suggesting that it is an outlier of these formations. The Renault–Dufresnoy and Bousquet formations contain andesites and rhyolites, as do the Noranda and Misema–Duprat–Montbray formations, but they have a greater abundance of pyroclastic rocks than the Noranda and Misema–Duprat–Montbray formations.

Historically, it was proposed that the Blake River Group represented an eastward progression of volcanism (Spence and de Rosen–Spence, 1975; Goodwin, 1977), such that the Lower Blake River assemblage and the Rouyn–Pelletier and Hébécourt formations were the least geochemically evolved and the oldest. The Misema–Duprat–Montbray formation was younger and overlay these formations, and the Noranda, Renault–Dufresnoy, and Bousquet formations were the most evolved and the youngest. Pélouquin et al. (1996, 2001) suggested that the formations of the Blake River Group were in

fact contemporaneous, and that the variations in magmatism represented lateral variations with an oceanic basin. Although the hypothesis of contemporaneous volcanism within a basin is supported in part by the similarity in many of the radiometric ages obtained for the various formations (Table 1, Fig. 3), the contact between the Hébécourt and Duprat–Montbray formations in Québec is conformable with the Duprat–Montbray formation overlying the Hébécourt formation (Goutier and Lacroix, 1992). Recently, it has been proposed that the Blake River basin is a “megacaldera” and that the Noranda formation is an intracaldera “cauldron” (Mueller et al., 2007), and new radiometric ages within the basin give a wider range for the time of formation (Lafrance et al., 2005; David et al., 2006, 2007).

The Noranda formation and the eastern part of the Misema–Duprat–Montbray formation are the best known and most studied area of the Blake River Group (Baragar, 1968; Spence and de Rosen–Spence, 1975; Goodwin, 1977; Dimroth and Rocheleau, 1979; Gélinais et al., 1984; Verpaelst, 1985; Ujike and Goodwin, 1987; Gibson and Watkinson, 1990; Laflèche et al., 1992a, b; Mortensen, 1993; Verpaelst et al., 1995; Goutier, 1997; Pélouquin, 2000; Hannington et al., 2003; Lafrance et al., 2005). The western part of the Misema–Duprat–Montbray formation has received comparatively little attention until recently (Jensen, 1975; Goodwin, 1977;

TABLE 1. Radiometric U-Pb Ages for the Blake River Group

Formation	Details	Radiometric ages (Ma)	Reference	Location in Figure 3
Noranda formation	Lake Turcotte dacite-rhyodacite	2698.5 ± 2.0	David et al. (2006)	3
Reneault-Dufresnoy formation		2697.9 ^{+1.3} _{-0.7} 2696.0 ± 1.1	Mortensen (1993) Lafrance et al. (2003) Lafrance et al. (2005)	4, 5, 6
Bousquet formation		2698.6 ± 1.5 2698.0 ± 1.0 2694.0 ± 2.0 2698.3 ± 0.8 2697.8 ± 1.0	Lafrance et al. (2003) Lafrance et al. (2003) Lafrance et al. (2003) Mercier-Langevin et al. (2004) Mercier-Langevin et al. (2004) Lafrance et al., 2005)	7
Misema-Duprat-Montbray formation	Four corners rhyolite Pontiac Township rhyolite Duprat-Monbray Ben Nevis Township rhyolite (Canagau rhyolite) Ben Nevis Township cryptodome	2701 ± 1 2701 ± 2 2696.6 ± 3.4 2696.6 ± 1.3 2699.8 ± 3.6	Mortensen (1993) Corfu et al. (1989) David et al. (2006) This study This study	1 8 2 9 10
Rouyn-Pelletier formation	Fish-roe rhyolite	2700.6 ± 1.6	Lafrance et al. (2005)	12
Lower Blake River assemblage	Harker Township rhyolite	2701 ± 3	Corfu and Noble (1992)	11

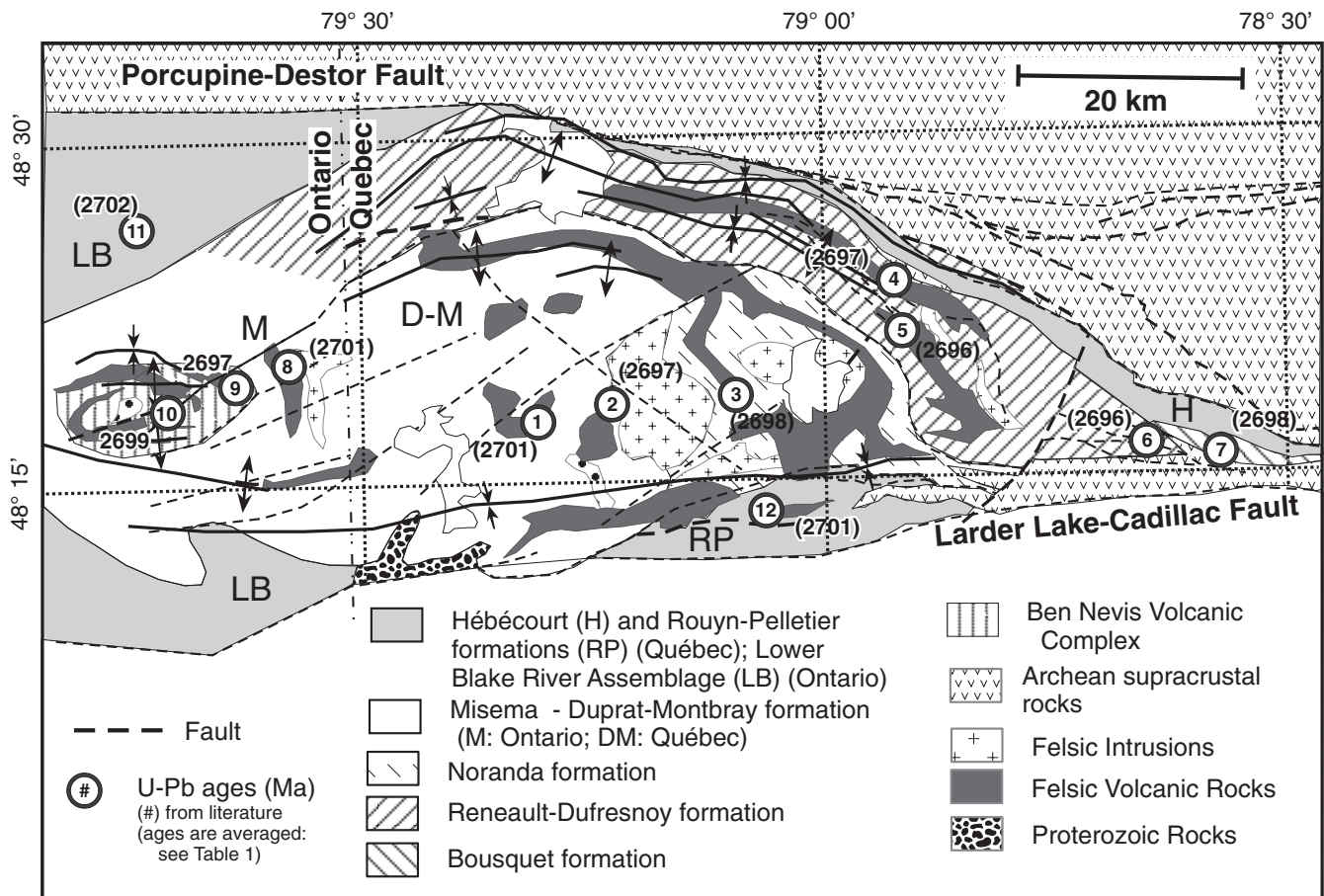


FIG. 3. Locations of U-Pb geochronology samples listed in Table 1. Broad ages indicated in the map locally represent averages. New U-Pb results from this study are shown (locs. 9 and 10).

Gélinas et al., 1984; Grunsky, 1986, 1988; Péloquin et al., 1989a, b, 2001; Péloquin, 2000; Péloquin and Piercey, 2005; Dion and Rhéaume, 2007). The Renault-Dufresnoy and Bousquet formations have been more recently defined. The Renault-Dufresnoy formation defined by Goutier (1997) incorporates the Renault and Dufresnoy chemostratigraphic divisions of Gélinas et al. (1977). The Bousquet formation defined by Lafrance et al. (2003) extends the Blake River Group east of the Davidson Creek fault (Fig. 2). Lafrance et al. (2003) and Lafrance and Dion (2004) proposed that the Bousquet formation is the stratigraphic equivalent to the Renault-Dufresnoy formation based on the similarity in ages.

The radiometric ages determined for the Renault-Dufresnoy and Bousquet formations (Table 1: Lafrance et al., 2005) are slightly younger than the central phase of the Blake River Group and overlap with the new radiometric age obtained for the Ben Nevis volcanic complex (Table 1). The Ben Nevis volcanic complex, therefore, was emplaced during the late phase (post-Noranda cauldron) volcanism of the Blake River Group. Below we characterize the Ben Nevis volcanic complex and compare it to the Renault-Dufresnoy and Bousquet formations as well as to the main phase volcanism of the Misema-Duprat-Montbray and Noranda formations.

Geology of the Ben Nevis Volcanic Complex

The Ben Nevis volcanic complex contains a spectrum of prehnite-pumpellyite facies volcanic rocks ranging from basaltic-andesite through andesite to rhyolite (Jensen, 1975; Hannington et al., 2003). The range in rock types distinguishes it from the surrounding Misema-Duprat-Montbray formation, which is dominantly basaltic-andesitic in Ontario. The Ben Nevis volcanic complex is intruded by the Late Archean Clifford stock (2686.9 ± 1.2 Ma: MacDonald et al. 2005; Piercey et al., 2008), which produces a domal anticlinal effect of outward-facing stratigraphy in Clifford Township and the western part of Ben Nevis Township (Fig. 4; Jensen 1975; Péloquin and Piercey, 2005). The Clifford domal-anticline folds the volcanic and early intrusive rocks of the Ben Nevis volcanic complex around its east-west-trending axis (Fig. 4). The anticline dies out to the east in Ben Nevis Township (Fig. 4). A synclinal fold occurs north of the Clifford stock and terminates at the Murdoch Creek-Kennedy Lake fault (Fig. 4).

The Ben Nevis volcanic complex is cut by two major faults and one subordinate fault. The northeast-trending Clifford and Murdoch Creek-Kennedy Lake faults converge east of the Clifford stock, and the smaller northwest fault (J. Riopel,

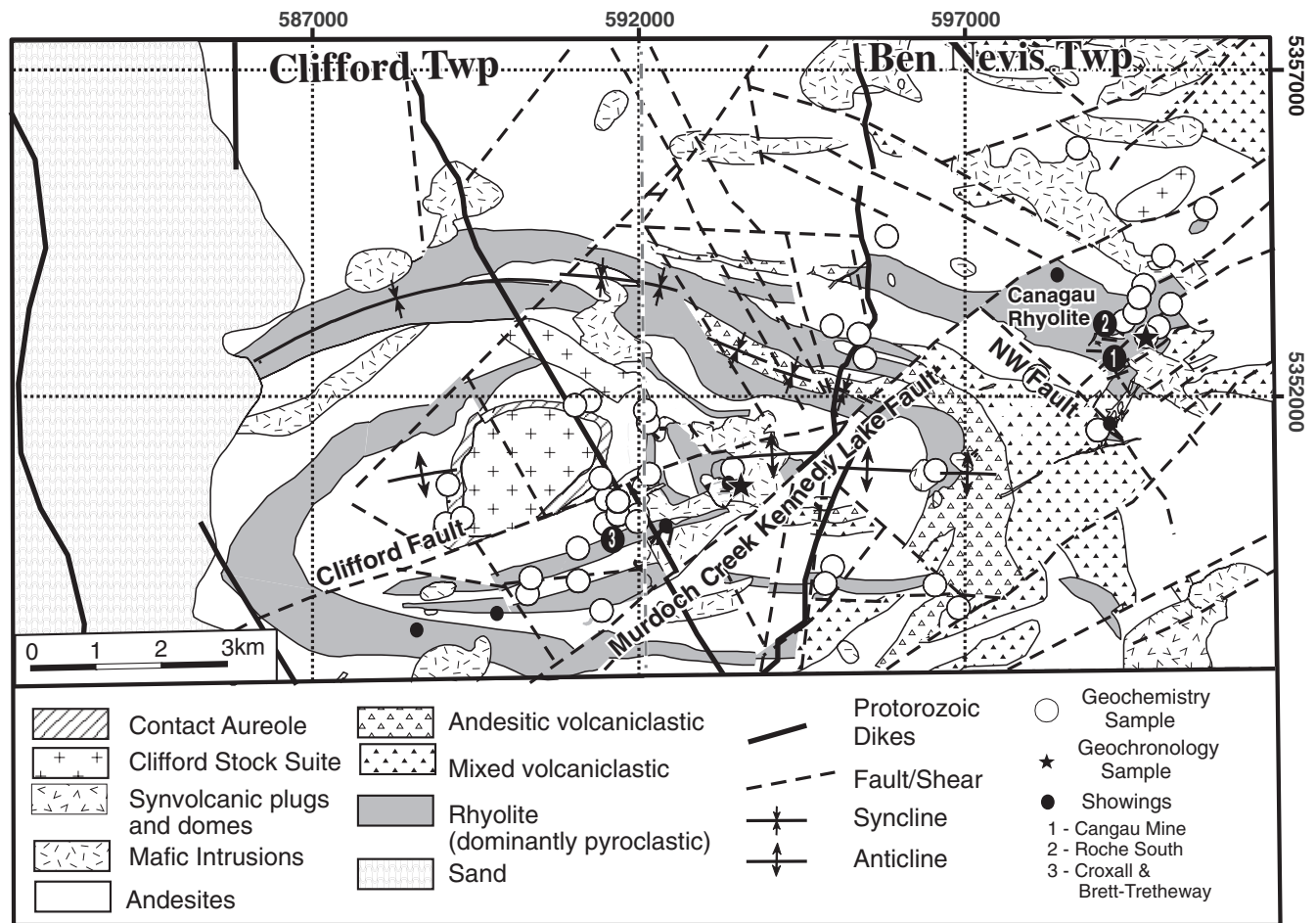


FIG. 4. Geology of the Ben Nevis volcanic complex, Ben Nevis and Clifford Townships (from Péloquin and Piercey, 2005, and MacDonald et al., 2005, after Jensen, 1975).

unpub. report for Mines et Exploration Noranda Inc., 1998, 25 p.) abuts the Murdoch Creek–Kennedy Lake fault at a high angle (Fig. 4). There is an apparent sinistral movement along the Murdoch Creek–Kennedy Lake fault, whereas the Clifford fault exhibits little displacement, and the stratigraphy is considered to be continuous across it. The northwest fault appears to be a structural boundary; the area east of the northwest fault is structurally complex and is cut by numerous small faults and deformation zones. The Clifford domal anticline dies out east of this fault. The Canagau mine showing (vein/replacement Zn–Pb–Au–Cu) and the Roche North and South showings (volcanic associated Zn ± Pb ± Ag ± Au) occur in the area south of the Murdoch Creek–Kennedy Lake fault and east of the northwest fault (Mineral Deposit Inventory Version 2, MDI2, 2004, Ontario Geological Survey Digital Data Set, http://www.mndm.gov.on.ca/mndm/mines/ermes/databases/mdi_sum_e.asp; Fig. 4).

Along the southern axis of the domal anticline centered around the Clifford stock, the lowest unit of the stratigraphy consists of pillowed to massive amygdaloidal basaltic andesite to andesite flows, some of which are plagioclase phyric. These flows are overlain by volcanoclastic andesites (tuffs, lapilli tuffs, and tuff breccias). Overlying the andesitic tuffs is a felsic volcanoclastic unit consisting of a matrix-supported polyolithic felsic tuff breccia (nomenclature from Fisher, 1966). Overlying the polyolithic tuff is another unit of amygdaloidal and variably plagioclase porphyritic basaltic-andesite to andesitic tuff. The uppermost stratigraphic unit, south of the Clifford stock, consists of a tuff breccia to lapilli tuff, very similar to the underlying tuff breccia and consisting of a matrix-supported breccia with angular clasts of predominantly dacite to rhyolite. There appears to be a southward younging of the tuff breccia into a lapilli tuff on a regional scale, suggesting normal grading outward from the Clifford stock (Jensen 1975). Felsic flows are rare in the stratigraphy south of the Clifford stock and, where observed, are associated with the primarily felsic-polyolithic volcanoclastic units.

Along the eastern axis of the domal anticline centered around the Clifford stock, the lowest unit is, again, basaltic andesite to andesite, with both flows and volcanoclastic rocks being represented. The first felsic unit encountered along the anticlinal axis, south of the Clifford fault and north of the Murdoch Creek–Kennedy Lake fault, consists of flow-banded rhyolitic volcanoclastic rocks spatially associated with synvolcanic rhyolitic to dioritic dikes, which are interpreted to be part of a cryptodome. The rhyolitic-volcanoclastic rocks are clast supported, monolithologic, and consist of polygonally jointed rhyolite fragments that have flow banding (Fig. 5A). The quartz-plagioclase porphyritic massive rhyolite of the cryptodome is fine grained, indicating shallow depth of emplacement, and it has irregular contacts with the hosting volcanoclastic rocks, suggesting that the latter were unconsolidated during the emplacement of the massive rhyolite.

South of the Murdoch Creek–Kennedy Lake fault and west of the northwest fault, the stratigraphy in Ben Nevis youngs outward from and along the Clifford domal anticline axis and nose. The oldest unit in the sequence consists of aphyric pillowed, massive, and brecciated andesite flows. Upstratigraphy, along the anticlinal axis, there is a small plagioclase micropphyric massive rhyolite dome with polygonally jointed

breccia phases. This dome appears to have been emplaced at the base of a rhyolite tuff and tuff breccia unit, which extends to the north around the anticlinal axis and terminates just south of the dome. Along strike to the south, and overlying the rhyolite pyroclastic unit, is a unit of mixed pyroclastic rocks, consisting of interlayered andesite tuffs, lapilli tuffs and tuff breccias, rhyolite tuffs and tuff breccias, and heterolithic pyroclastic breccias. Above the mixed pyroclastic unit is an andesitic unit dominated by tuffs and tuff breccias but with interlayered pillowed flows and flow breccias. This unit is intruded by synvolcanic felsic dikes. The andesitic pyroclastic unit is overlain by amygdaloidal andesitic flows exhibiting pillowed, massive, and breccia facies. Synvolcanic intermediate to felsic dikes intrude this unit (Fig. 5B, C).

The northwest fault cuts the amygdaloidal andesite unit and the mixed pyroclastic unit (J. Riopel unpub. report for Mines et Exploration Noranda Inc., 1998, 25 p.; Fig. 4), with the amygdaloidal andesite unit occurring east of the fault. The facing directions west of the northwest fault vary from northeast on the north flank of the anticline to southwest on the south flank, whereas, east of the northwest fault the majority of facing directions are south to southwest. West-northwest-facing directions were observed locally in the Canagau area.

The rhyolite located east of the northwest fault is called the Canagau rhyolite (V. Pearson, unpub. report for Minnova Inc., 1992, 39 p.; J. Riopel, unpub. report for Mines et Exploration Noranda Inc., 1998, 25 p.; Fig. 4) and is host to the Roche North, Roche South, and Interprovincial North showings (Canagau mine). The Canagau rhyolite package consists predominantly of pyroclastic tuffs and tuff breccias (Fig. 5D), with local massive polygonally jointed domes and lobe and breccia flows. The tuffs of the Canagau rhyolite contain pumaceous fragments, and locally sag structures are observed beneath small bombs. However, the area is highly deformed, which commonly masks the original textures and morphologies of the rhyolites (Fig. 5E). The deformation commonly coincides spatially with Fe carbonate alteration and/or sericite alteration. Chlorite alteration also occurs but is not restricted to the deformation zones. The rhyolites are commonly cut by andesitic synvolcanic dikes. The Canagau rhyolite terminates to the southeast (Fig. 4). A thick diorite dike cuts the andesite flows and pyroclastic rocks southeast of the Canagau rhyolite, and a rhyolite dike cuts the diorite, indicating the synvolcanic nature of the diorite. A number of parallel northeast-trending faults of unknown displacement cut both the stratigraphy and the diorite intrusion southeast of the Canagau rhyolite. The andesite flows northeast of the Canagau rhyolite (Fig. 4) strike east-west to east-southeast and face to the south; thus, they are interpreted to underlie the Canagau rhyolite. These flows are locally interlayered with andesitic pyroclastic rocks.

The area north of the Murdoch Creek–Kennedy Lake fault is folded around a synclinal axis that terminates at the Murdoch Creek–Kennedy Lake fault (Fig. 4; Jensen 1975). On the north limb of the fold the oldest units are andesite flows exhibiting pillowed, massive, and breccia facies, with rare pyroclastic facies. The andesites are variably plagioclase porphyritic and/or amygdaloidal. Some pillowed flows exhibit extreme epidote-quartz alteration of the pillow centers and

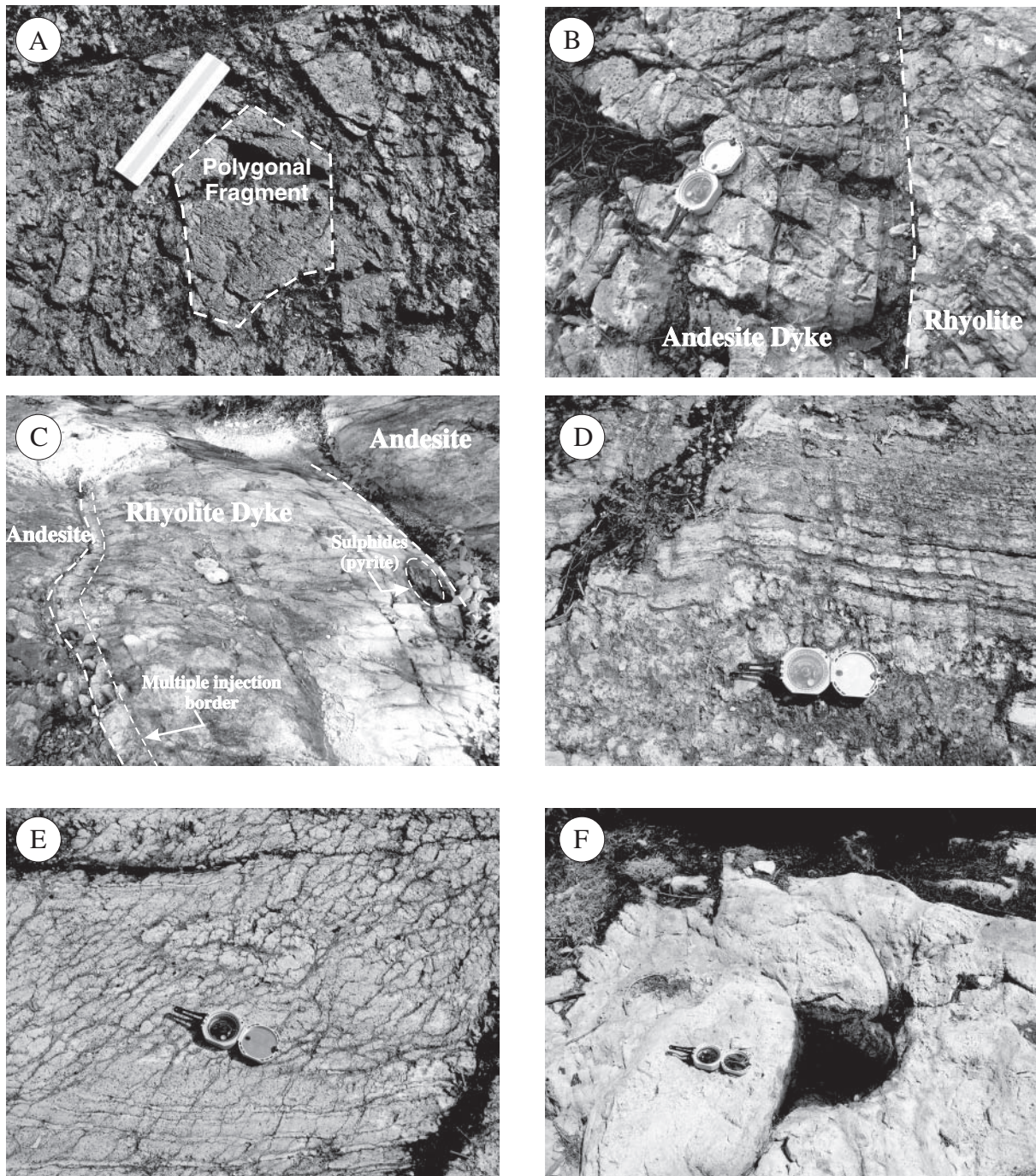


FIG. 5. Ben Nevis volcanic complex extrusive and synvolcanic intrusive rocks. A. Polygonally jointed, flow-banded rhyolite clasts from cryptodome. B. Multiple injection borders in andesite dike intruded into rhyolite. C. Rhyolite dike intruded into andesite. D. Lapilli and bedded tuff. E. Tectonic overprinting of pyroclastic rocks producing pseudobreccia. F. Epidotized and silicified (light gray) andesite pillows.

rims (Fig. 5F). Rhyolite pyroclastic rocks, tuffs, and tuff breccias occur above the andesites and alternate with andesite flow units. The pyroclastic rhyolites are heterolithologic lapilli and tuff breccias with accidental andesite fragments and variably textured (cherty, laminated, massive, fragmental) aphyric and porphyritic rhyolite fragments and laminated tuffs. Small polygonally jointed massive rhyolites are present in very minor abundance in this area.

In the Ben Nevis volcanic complex, MacDonald et al. (2005) recognized VMS-style alteration as one of the three alteration types occurring in the area of the Clifford stock. In that area and to the east in Ben Nevis Township, the VMS-style alteration most commonly observed is chlorite-quartz-epidote-pyrite assemblages filling amygdules in varying proportions. These mineral assemblages are also present in some rocks, commonly the more mafic members of the Blake River

Group, as patches, typically near permeable zones in the rocks (i.e., near hyaloclastite or in volcanic breccias and in pillowed facies concentrated in either the pillow center or rim). Silicification and chlorite alteration are present in some drill holes in Clifford Township and at surface in Ben Nevis Township. In both Clifford and Ben Nevis Townships the mineralization is observed in the hyaloclastite along pillow margins,

where chalcopyrite, pyrite, and quartz are interstitial to angular hyaloclastite (Fig. 6A, B). In Ben Nevis Township, sulfides are also observed along fractures, in the multiple injection borders of both rhyolitic and andesitic high-level synvolcanic dikes (Fig. 5C), and in the matrix of brecciated rhyolite (Fig. 6C). Network silicification is common in the andesites that have been intruded by rhyolitic synvolcanic dikes in the

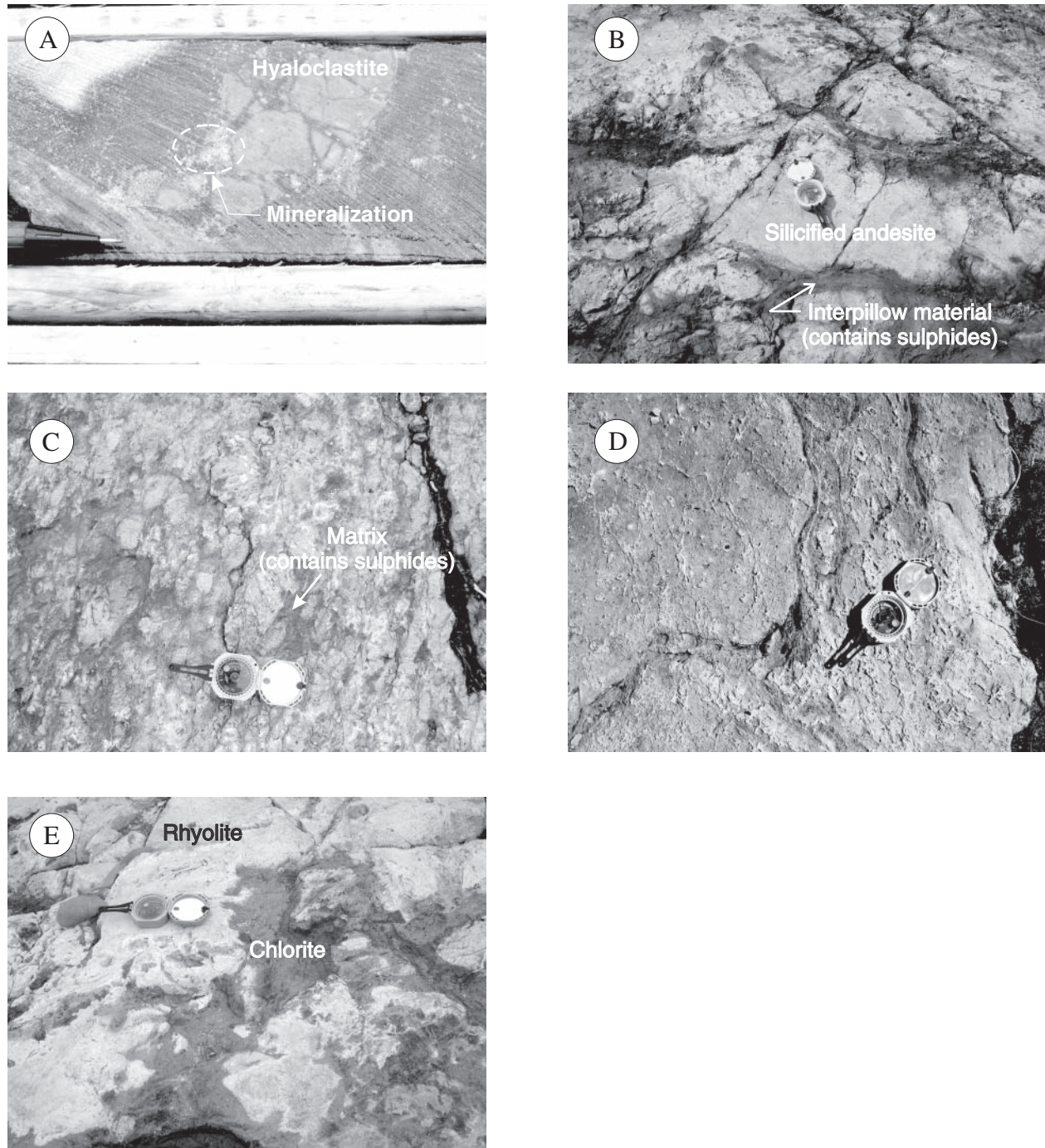


FIG. 6. A. Pillow lava with chlorite alteration at the edge of the pillow, silicification of the hyaloclastite (white fragments), and a sulfide assemblage of pyrite-chalcopyrite. B. Highly silicified andesite pillows, with pyrite in the interpillow hyaloclastite. C. Rhyolite breccia with pyrite in the breccia matrix. D. Network silicification of andesites near synvolcanic rhyolite dikes. E. Highly chloritized rhyolite.

Interprovincial South showing area (Fig. 6D). Sericite alteration is common in the felsic volcanic rocks, and intense chlorite alteration with associated sulfide mineralization is observed at one locality (Fig. 6E). This same outcrop is cut by a deformation zone spatially associated with the Fe carbonate alteration. Strong epidote alteration of pillow rims and/or pillow cores is observed in some andesite flows of the Ben Nevis volcanic complex (Fig. 5F). This epidotization may be an indication of regional epidote alteration similar to that associated with VMS deposits (Galley, 1993; Hannington et al., 2003).

The mineralization at the borders of the high-level synvolcanic dikes suggests that they acted as conduits for the hydrothermal fluids. Thus the present exposure of the Ben Nevis volcanic complex is interpreted to have been below the sea floor during the hydrothermal event and not at the rock-seawater interface. Also the polymetallic nature of the mineralization at the Canagau mine (V. Pearson, unpub. report for Minnova Inc., 1992, 39 p.) suggests that the Ben Nevis volcanic complex was deposited at shallower water depths than the Noranda cauldron (Gagnon et al., 1995; Mercier-Langevin et al., 2004).

Geochemistry

Geochemical samples of ~1 kg each were collected from surface exposures. Weathered surfaces from surface samples

were either removed in the field or with a diamond saw. Samples were analyzed at the Ontario Geoscience Laboratories in Sudbury, Ontario, in 2003, and at Activation Laboratories in Ancaster, Ontario, and the Ontario Geoscience Laboratories in 2004. Details of the analytical methods and the data set for this study are included in a digital supplement that accompanies this paper (<http://www.segweb.org>).

For the purposes of this study, altered rocks were avoided, and the data for altered rocks were removed from the database using common alteration indicators and indices (analyses with LOI greater than 4 wt %, analyses with $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ greater than 10; analyses with Na_2O greater than 5 wt % were retained if their $\text{Al}_2\text{O}_3/\text{Na}_2\text{O}$ ratios were less than 10). Analyses falling outside the dominant trend of the Hashiguchi alteration index (Hashiguchi et al., 1983: $[\text{MgO} + \text{K}_2\text{O}]/[\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO} + \text{MgO}]$) versus SiO_2 , MgO , and TiO_2 (Fig. 7A-C) also were discarded. The analyses retained in this study fall along the diagenetic-hydrothermal divide in the alteration box plot of Large et al. (2001; Fig. 7D). The extensions of the trends outside the designated fields of this diagram are considered to be due to primary rock chemistry and not alteration. Thus the Ben Nevis volcanic complex samples used in this study are considered to be minimally altered.

The rocks of the Ben Nevis volcanic complex range from basaltic-andesite to rhyolite (Fig. 8A, B) and are not bimodal, exhibiting no silica gap (Fig. 9A). They generally fall within

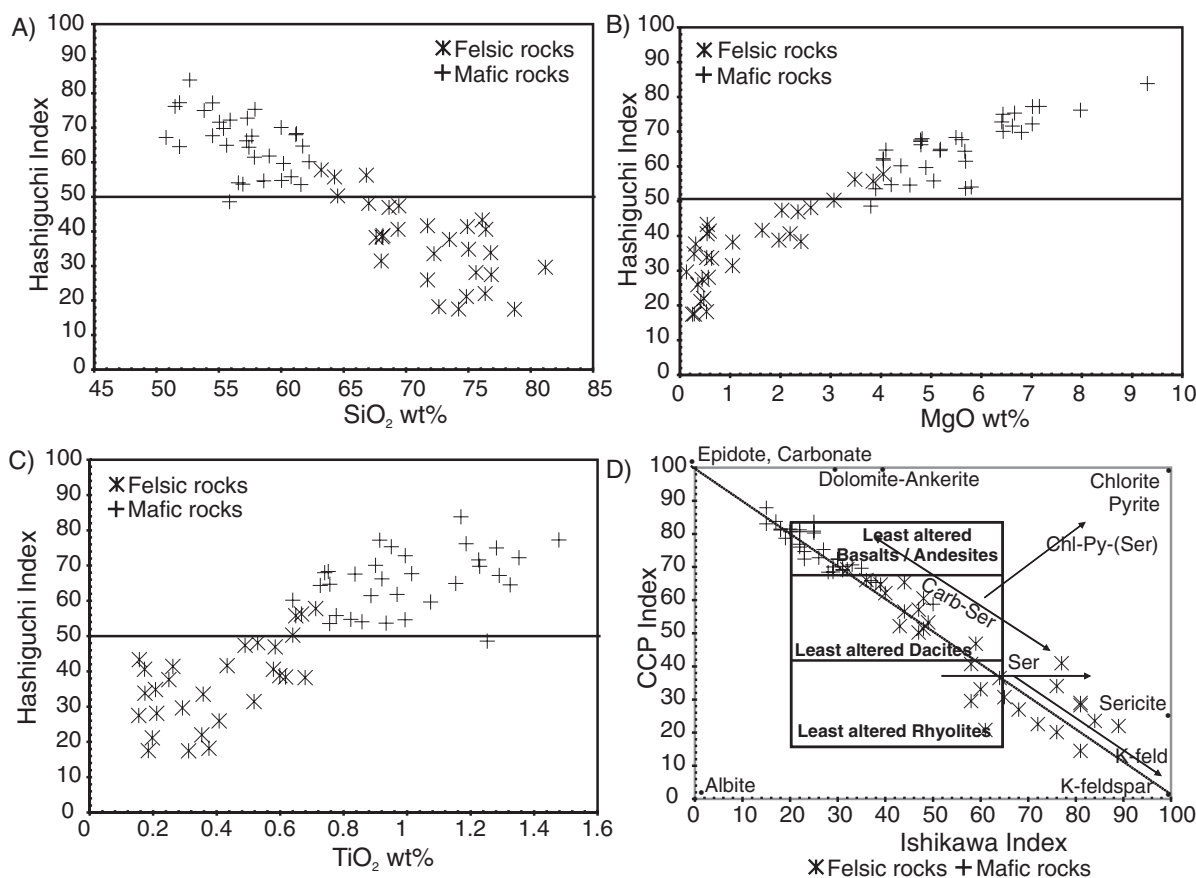


FIG. 7. Alteration diagrams. Hashiguchi Index (Hashiguchi et al. 1983: $[\text{MgO} + \text{K}_2\text{O}]/[\text{Na}_2\text{O} + \text{K}_2\text{O} + \text{CaO} + \text{MgO}]$) vs. (A) SiO_2 , (B) MgO , and (C) TiO_2 . D. Alteration box plot (Large et al., 2001). Oxides are recalculated to anhydrous values.

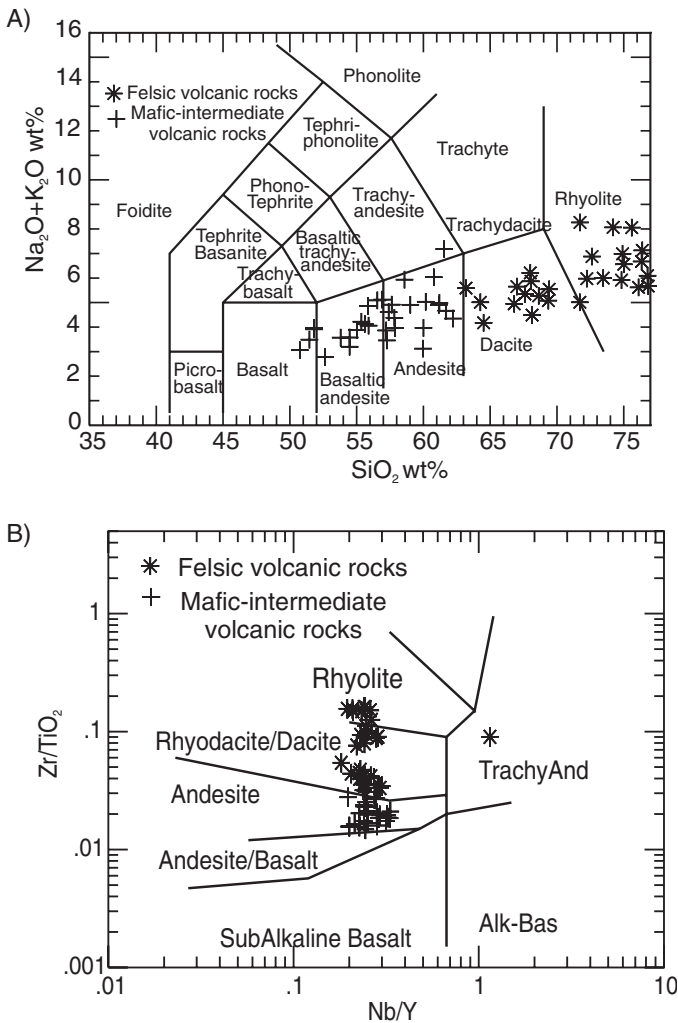


FIG. 8. (A) LeBas et al. (1986) and (B) Winchester and Floyd (1977) rock-type classifications of the Ben Nevis volcanic complex.

the calc-alkalic field of the Jensen (1976) AFM diagram (Fig. 10A). The mafic rocks exhibit no iron enrichment on an MgO wt percent versus $\text{FeO}_{(\text{total})}$ wt percent diagram (Fig. 11A), and trace element data support the hypothesis of a single geochemical affinity (Figs. 12A, 13A). The felsic volcanic rocks in Ben Nevis and Clifford Townships range from dacites to rhyolites (Fig. 8A, B). Two populations are defined based on the Y ppm versus Zr/Y diagram (Fig. 12A). The first population has Zr/Y ratios >5 , with the ratios remaining approximately constant to increasing with increasing Y; the second has Zr/Y ratios <5 with the ratios decreasing with increasing Y. Although it is possible that the samples with Y <32 ppm and Zr/Y >5 may be related to either evolutionary trend, their $(\text{La}/\text{Yb})_{\text{CN}}$ ratios and trace element patterns in multielement normalized diagrams resemble those of the population with Zr/Y >5 implying a common ancestry (Figs. 12A, 13A, 14A, B). In an La_{CN} versus Yb_{CN} diagram (Fig. 15), both populations exhibit increasing La_{CN} with increasing Yb_{CN} , but the samples with Zr/Y >5 generally have higher La_{CN} values for the same Yb_{CN} values as the Zr/Y <5 samples. The populations overlap at approximately $(\text{La}/\text{Yb})_{\text{CN}} = 3.55$, and the

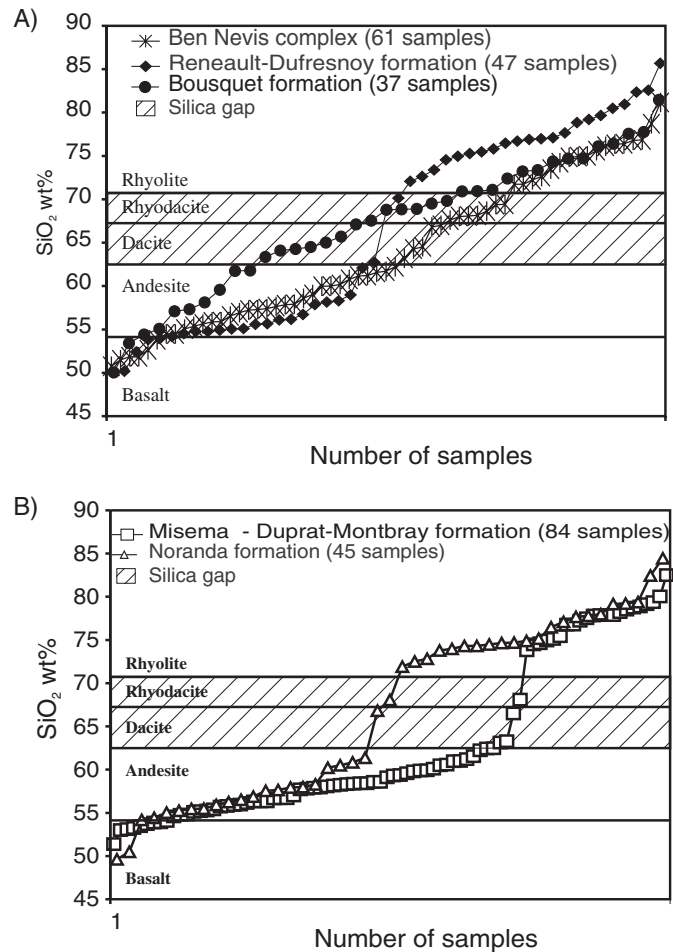


FIG. 9. SiO_2 wt percent line graph showing the silica gap defining bimodality for (A) the Ben Nevis volcanic complex (data from Pélouquin and Piercey, 2005) and the Reneault-Dufresnoy and Bousquet formations (data from Lafleche et al., 1992a, b; Riopel et al., 1995; and Lafrance et al., 2003; Mercier-Langevin et al., 2004, respectively) and (B) the Noranda and Misema-Duprat-Montbray formations (data from Camiré, 1989; Gibson, 1989; Paradis, 1990; Pélouquin, 2000; Pélouquin and Piercey, 2005; Pélouquin et al., 2001).

samples with Zr/Y >5 and Y <32 ppm generally have $(\text{La}/\text{Yb})_{\text{CN}} \geq 3.55$. The populations are not easily distinguishable in the $(\text{La}/\text{Yb})_{\text{CN}}$ versus La_{CN} diagram (Fig. 13A) due to the overlap in ratios; however, the samples with Zr/Y >5 generally have higher La/Yb ratios.

In multielement normalized diagrams (Fig. 14A, B), the HREE of the felsic rocks with Zr/Y <5 overlap and extend to higher values than the HREE of the felsic rocks with Zr/Y >5 and have similar to slightly lower LREE. The felsic samples, in both populations, have negative Nb and Eu anomalies and positive Zr and Hf anomalies. The rhyolites with Zr/Y <5 occur throughout Ben Nevis and Clifford Townships, whereas the rhyolites with Zr/Y >5 occur only in the Canagau rhyolite area and immediately south of the Clifford fault (Pélouquin and Piercey, 2005).

U-Pb Geochronology

Uranium-lead geochronological samples for this project were collected during fieldwork in 2003 and 2004 and

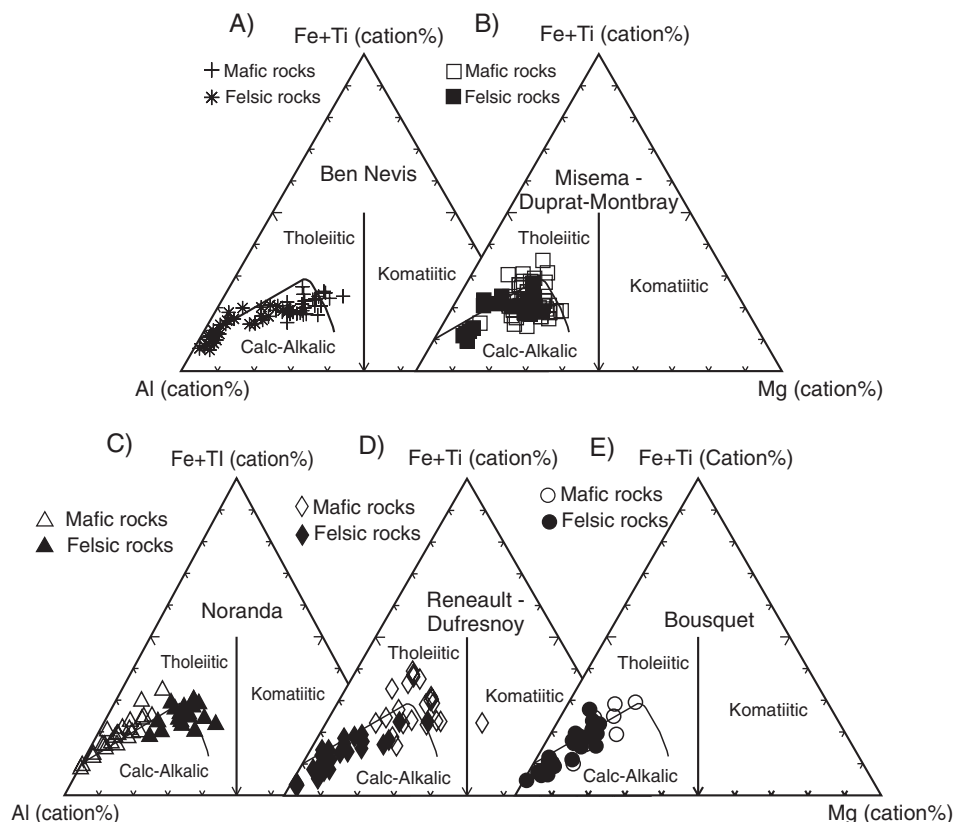


FIG. 10. Jensen (1976) AFM diagram for (A) the Ben Nevis volcanic complex, (B) the Misema–Duprat–Montbray formation, (C) the Noranda formation, (D) the Renault–Dufresnoy formation, and (E) the Bousquet formation. Geochemical data from references listed in Figure 8.

analyzed at the Jack Satterly Geochronology Laboratory at the University of Toronto. All samples had weathered surfaces removed in the field using a hammer and chisel, and each piece was subsequently washed and dried in the laboratory before further processing. Zircons were separated using standard Wilfley table, heavy liquid, and magnetic separation methods. The best quality, least magnetic fractions of zircon were handpicked on the basis of clarity, and the absence of cores, cracks, alteration, and (Pb-bearing) inclusions. All zircon fractions were subjected to an air abrasion treatment (Krogh, 1982) in order to remove exterior portions of grains that may have experienced postcrystallization Pb loss.

Analysis of Blake River Group zircons broadly followed the methods described by Ayer et al. (2002, 2005), using a mixed ^{205}Pb – ^{233}U isotope tracer solution (Krogh, 1973) and small (0.7–2.4 μg) multi- or single grain fractions without ion exchange separations of Pb and U. Isotopic compositions of Pb and U were determined on a VG354 mass spectrometer using a Daly detector equipped with a digital ion counting system. System dead-time corrections during the analytical period were 19.5 ns for both Pb and U. Corrections for Daly mass discrimination were 0.05 percent/a.m.u., whereas those for thermal mass discrimination were estimated at 0.1 percent/a.m.u. Laboratory procedural blanks at the Jack Satterly Geochronology Laboratory are routinely at the 0.5- and 0.1-pg level or less for Pb and U, respectively. In most cases, the

measured total common Pb in the Blake River Group samples was small and was assigned the isotopic composition of the lab blank. The decay constants used for the U–Pb system are those of Jaffey et al. (1971). Age errors in the text, tables, and figures are all presented at the 95 percent confidence level. Error ellipses in the concordia diagrams are shown at the 2σ level. Discordia lines and concordia intercept ages were determined by the regression methods outlined in Davis (1982), using the inhouse program ROMAGE. In most cases, the calculated ages and errors using either the Davis (1982) or IsoPlot/Ex (Ludwig, 2001) algorithms are equivalent. U–Pb concordia diagrams were generated using the IsoPlot/Ex program of Ludwig (2001).

Two samples were collected for U–Pb dating (Figs. 3, 4): one from a polygonally jointed massive flow of the Canagau rhyolite, and the other from the composite diorite-quartz-feldspar porphyritic cryptodome in the western part of Ben Nevis Township. The polygonally jointed rhyolite flow from the Canagau mine area (sample 03ASP-0179-1) contained a moderately abundant population of small, pale yellow, sharply faceted doubly terminated subequant zircon prisms. Three small multigrain fractions yield a colinear array ranging from being concordant to almost 5 percent discordant (Fig. 16A, Table 2). Regression of all three analyses defines an upper intercept age of 2696.6 ± 1.3 Ma (50% probability of fit; MSWD = 0.45) with an essentially zero-age lower intercept (90 ± 120 Ma). The 2696.6 Ma age is interpreted to represent

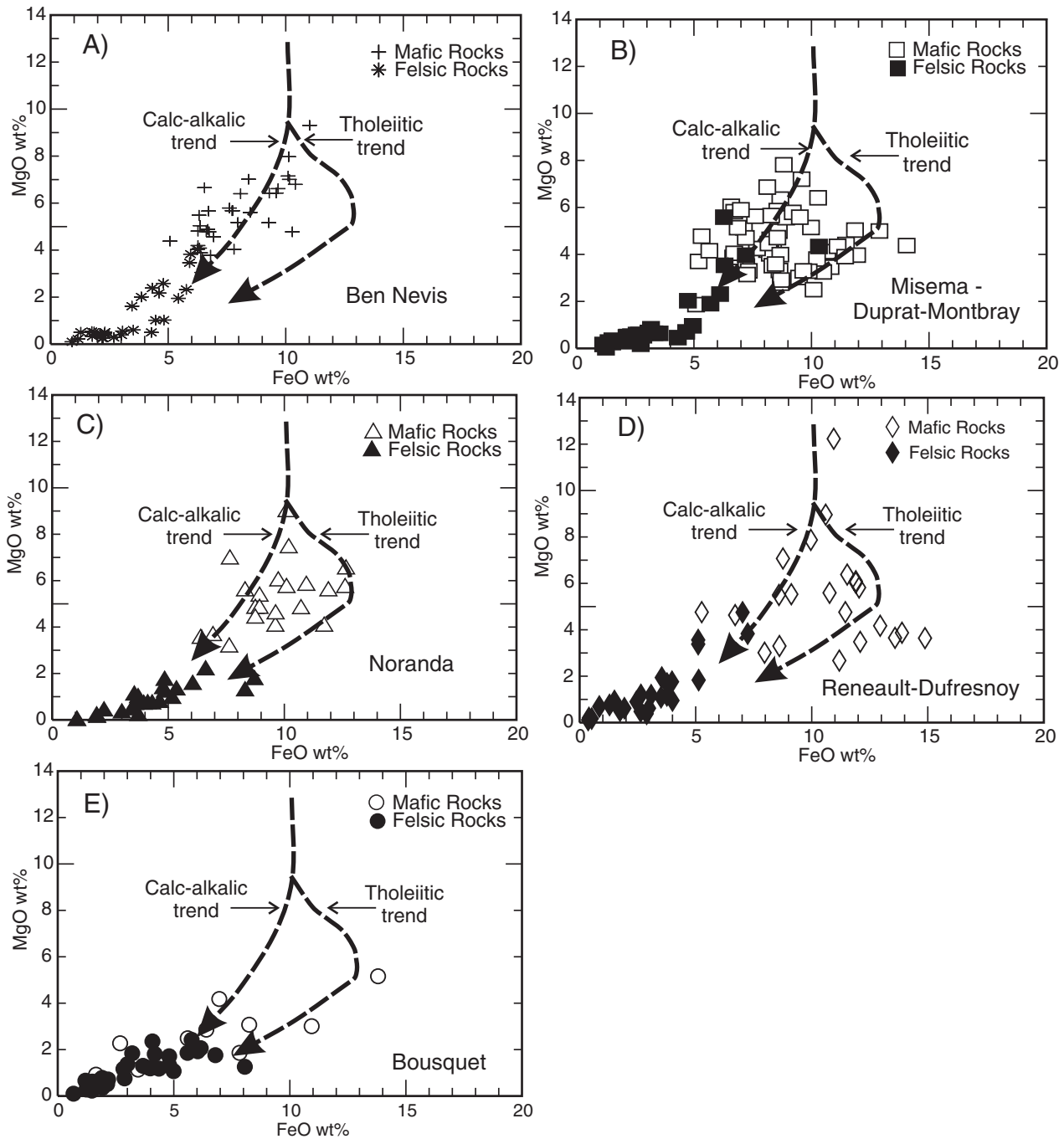


FIG. 11. $\text{FeO}_{\text{total}}$ wt % versus MgO wt % for (A) the Ben Nevis volcanic complex, (B) the Misema–Duprat–Montbray formation, (C) the Noranda formation, (D) the Renault–Dufresnoy formation, and (E) the Bousquet formation. The two evolutionary trends exhibited by andesites (Fe enrichment and no Fe enrichment) are shown. Geochemical data from references listed in Figure 9.

the primary age of crystallization of the rhyolite. This age is equivalent to that of the youngest volcanic members of the Blake River Group recognized elsewhere (2701–2697 Ma: Mortensen, 1993; Ayer et al., 2002; Lafrance et al., 2005; David et al., 2006). In detail, the Ben Nevis Township rhyolite appears to be younger than the principal phases of volcanism identified in the Misema–Duprat–Montbray and Noranda formations of the Blake River Group (Table 1; see below).

The quartz- and feldspar-porphyrific intrusive rhyolite (sample 03ASP-0130-1), interpreted to be a synvolcanic cryptodome within the Blake River Group, was sampled east of the Clifford stock on the axis of the Clifford antiform. This sample contained two principal zircon populations (clear and colorless, short, small, square prisms; larger, slightly more elongate, pale brown equivalents). Three analyses of the best quality, air-abraded prismatic grains from the smaller size

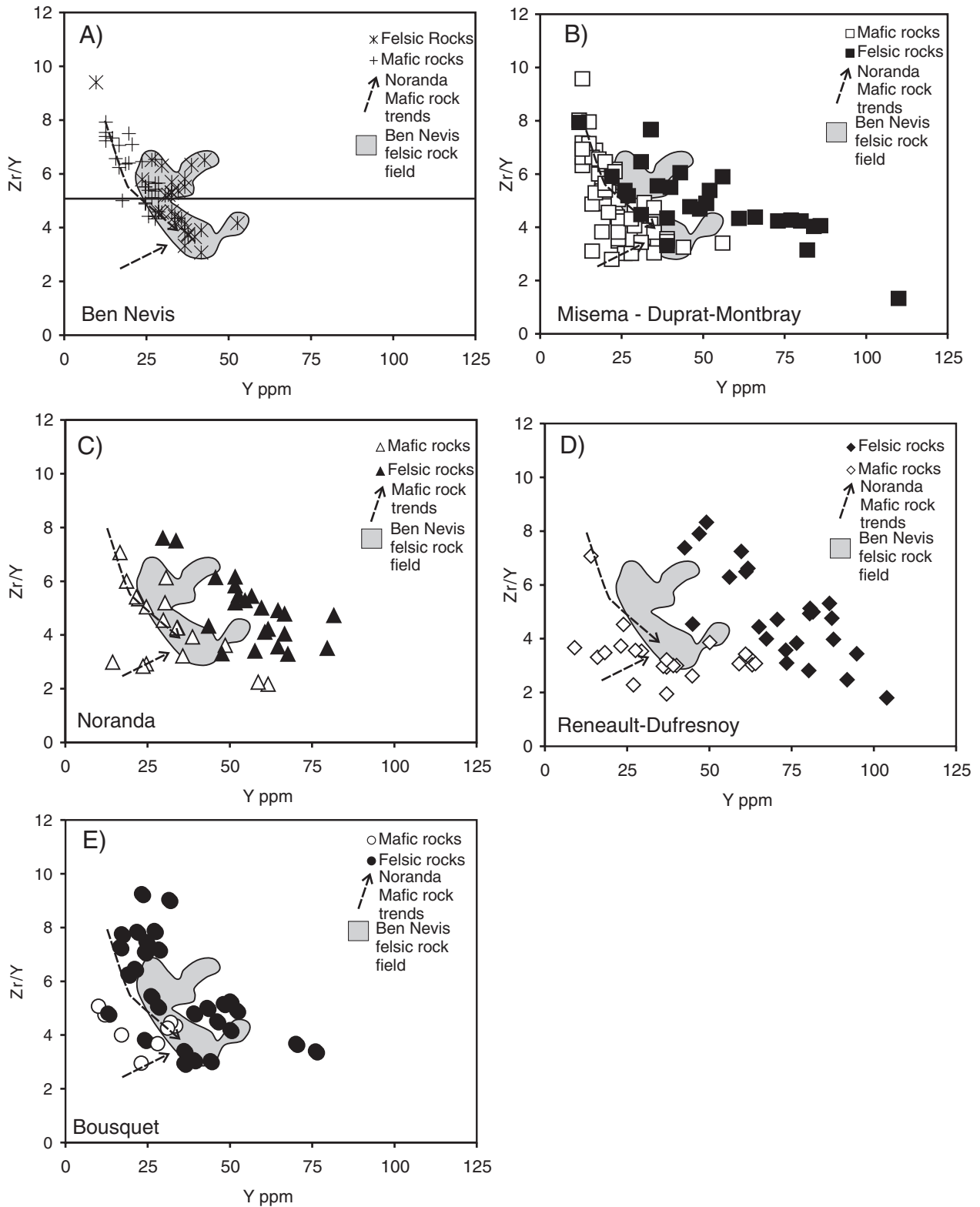


FIG. 12. Zr ppm vs. Zr/Y for (A) the Ben Nevis volcanic complex, (B) the Misema–Duprat–Montbray formation, (C) the Noranda formation, (D) the Renault–Dufresnoy formation, and (E) the Bousquet formation. The two evolutionary trends exhibited by the andesites are shown. Geochemical data from references listed in Figure 9.

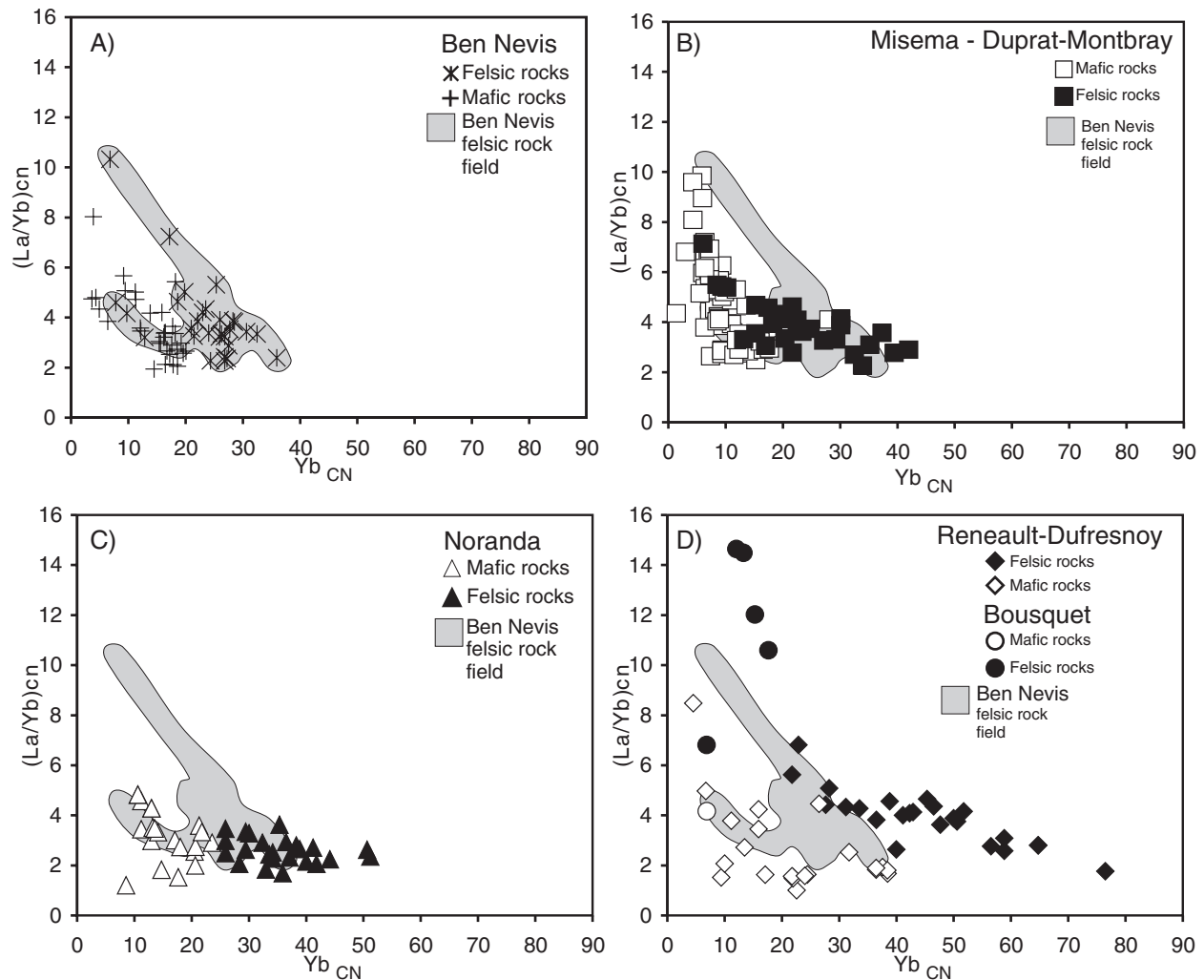


FIG. 13. Yb vs. La/Yb (chondrite-normalized) for (A) the Ben Nevis volcanic complex, (B) the Misema–Duprat–Montbray formation, (C) the Noranda formation, (D) the Renault–Dufresnoy formation, and (E) the Bousquet formation. Chondrite normalization are values from McDonough and Sun (1995). Geochemical data from references listed in Figure 9.

fraction (two single grains and one fraction comprising three smaller zircons) yield a narrow range of $^{207}\text{Pb}/^{206}\text{Pb}$ ages (2694.9–2696.6 Ma) that are only slightly discordant (0.1–0.3%). A fourth single grain analysis (fraction A2a) is just over 1 percent discordant (Fig. 16B, Table 2). Regression of all four analyses suggests an upper intercept age of 2699.8 ± 3.6 Ma with a lower intercept of approximately $1639 (\pm 240)$ Ma (probability of fit = 75%; MSWD = 0.28). A simple weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age calculation for the three most concordant analyses yields an age of 2696.4 ± 1.2 Ma (probability of fit = 68%; MSWD = 0.38). However, all fractions appear to demonstrate a small degree of discordance and the more conservative age of 2699.8 ± 3.6 Ma is thus regarded as the more robust estimate for the timing of crystallization for the rhyolite porphyry. This age falls within the principal range of ages published for the Blake River Group (2697–2701 Ma: Ayer et al., 2002, compilation by Goutier et al., 1994; Lafrance et al. 2005) and supports the synvolcanic nature of this felsic cryptodome intrusion.

Comparison of the Ben Nevis Volcanic Complex to the formations of the Blake River Group

The general characteristics of the Ben Nevis volcanic complex, the Noranda, Misema–Duprat–Montbray, Renault–Dufresnoy, and Bousquet formations are listed in Table 3. Lithologically the Ben Nevis volcanic complex and the Bousquet formation are not bimodal; a continuous spectrum of lithologic units from basalt to rhyolite occurs (i.e., there is no silica gap: Fig. 9A; Jensen, 1975; Lafrance et al., 2003; Péloquin and Piercey, 2005). The Noranda formation (cf. de Rosen Spence, 1976; Goodwin, 1977; Gélinais et al., 1984) and the Renault–Dufresnoy formation (cf. Trudel, 1979; Gélinais et al., 1984; Laflèche et al., 1992a, b; Goutier, 1997) are bimodal: a silica gap exists between 62 and 71 percent SiO_2 and dacites are rare (Fig. 9A, B). The eastern portion of the Misema–Duprat–Montbray formation exhibits bimodality similar to that of the Noranda formation. However, rhyolites become increasingly rare to the west, such that bimodality is

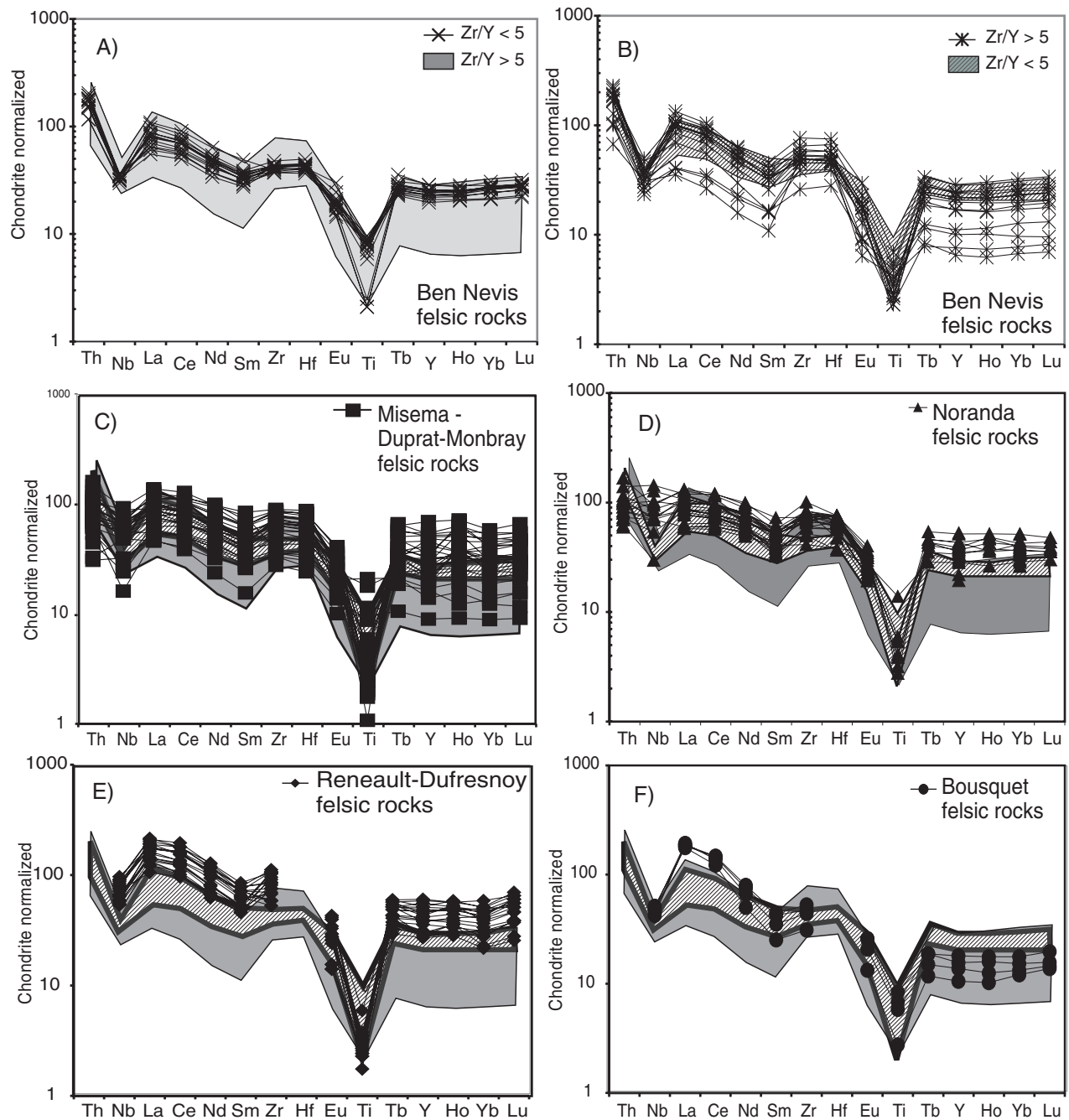


FIG. 14. Chondrite-normalized spider diagrams for the Blake River Group felsic rocks. (A). The Ben Nevis volcanic complex with Zr/Y ratios <5. (B). The Ben Nevis volcanic complex with Zr/Y ratios >5. (C). The Misema–Duprat–Montbray formation. (D). The Noranda formation. (E). The Renault–Dufresnoy formation. (F). The Bousquet formation. Chondrite normalization values are from McDonough and Sun (1995). Geochemical data from references listed in Figure 9.

not apparent (cf. Jensen, 1975; Goodwin, 1977; Péroquin et al., 2001; Péroquin and Piercey, 2005).

All of the Blake River formations examined here are subaqueous and have been metamorphosed to prehnite-pumpellyite and lower greenschist facies (Powell et al., 1995; Jensen, 1975; Hannington et al., 2003). In the younger volcanic packages (the Renault–Dufresnoy and Bousquet formations, and the Ben Nevis volcanic complex) pyroclastic deposits are more abundant than in the central phase Noranda

and Misema–Duprat–Montbray formations (Jensen, 1975; Trudel, 1979; Goutier, 1997; Lafrance et al., 2003; Mercier–Langevin et al., 2004; Péroquin and Piercey, 2005), which are dominantly subaqueous flows. The pyroclastic rocks of the late Blake River Group volcanism are both mafic-intermediate and felsic. In the Ben Nevis volcanic complex the majority of the felsic rocks are pyroclastic, whereas in the Renault–Dufresnoy and Bousquet formations the felsic rocks occur as both pyroclastic deposits and felsic flows. High-level

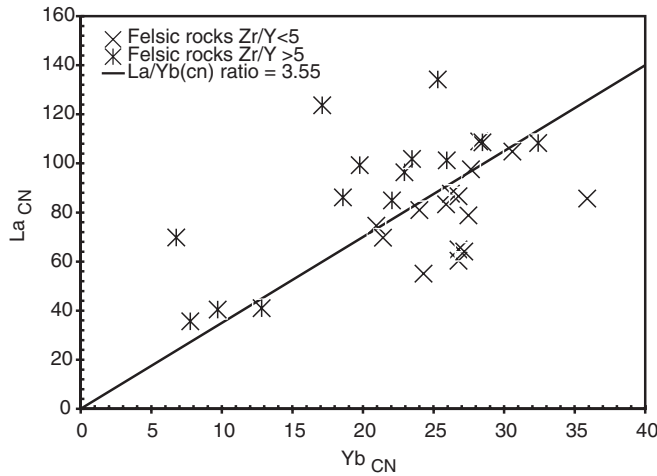


FIG. 15. Yb vs. La (chondrite-normalized) for the felsic rocks of the Ben Nevis volcanic complex. Chondrite normalization values are from McDonough and Sun (1995).

synvolcanic dikes are considered important in both the Ben Nevis volcanic complex and the Bousquet formation (Lafrance et al., 2003; Mercier-Langevin et al., 2004). Such dikes have been described in the Noranda cauldron (Gibson, 1989) but do not appear to be major features in the Misema–Duprat–Montbray or Reneault-Dufresnoy formations.

The Ben Nevis volcanic complex is entirely calc-alkalic in affinity (Figs. 10A, 11A), whereas two end-member affinities (tholeiitic and LREE-enriched tholeiites, here called “calc-alkalic” for simplicity) and an affinity transitional between the two have been defined in the mafic-intermediate rocks of the Noranda and Misema–Duprat–Montbray formations (Gélinas et al., 1984; Laflèche et al., 1992a, b; Péloquin et al., 2001). These affinities were originally defined on the basis of major element oxides (Gélinas et al., 1984) and are evident in a Jensen (1976) AFM diagram (Fig. 10B, C) and in an $\text{FeO}_{(\text{total})}$ versus MgO diagram (Fig. 11B, C). The andesites of the

Reneault-Dufresnoy (Gélinas et al., 1984; Goutier, 1997; Laflèche et al., 1992a, b; Riopel et al., 1995) and the Bousquet (Lafrance et al., 2003; Mercier-Langevin et al., 2004) formations have similar affinities (Figs. 10D, E, 11D, E). However, there are few analyses available in the literature for the Bousquet formation, and these are concentrated in the areas studied by Lafrance et al. (2003) and Mercier-Langevin et al. (2004). The Ben Nevis volcanic complex thus differs from most of the Blake River Group in that it exhibits a single affinity (Figs. 10A, 11A).

The trace elements confirm a single affinity for the Ben Nevi volcanic complex and multiple affinities for the rest of the Blake River Group. The calc-alkalic end-member andesites of the Noranda and Misema–Duprat–Montbray formations exhibit decreasing Zr/Y ratios with increasing Y ppm, whereas the tholeiitic end members show increasing Zr/Y ratios with increasing Y ppm (Fig. 12B, C). Although these trends are poorly defined for the intermediate rocks of the Reneault-Dufresnoy and Bousquet formations (Fig. 12D), the Reneault-Dufresnoy formation appears to have the same spectrum of andesites, and the few intermediate samples from the Bousquet formation are transitional as defined in Figure 12E. The intermediate rocks of the Ben Nevis volcanic complex again only exhibit the calc-alkalic trend (Fig. 12A).

The Zr/Y ratios of the felsic rocks of the Blake River Group overlap (Table 3, Fig. 12). The Ben Nevis volcanic complex has a restricted range of Zr/Y ratios (3.07–6.52) similar to those of the Noranda formation (3.28–7.6; Table 3). However, a single sample from the complex has a very high ratio (Zr/Y = 9.4), similar to those of the Bousquet formation (Zr/Y_{max} = 9.04; Table 3, Fig. 12). The range of Y contents of the Ben Nevis volcanic complex is, however, lower than any of the other Blake River Group members (Fig. 12). The (La/Yb)_{CN} ratios of the Ben Nevis felsic rocks most closely resemble those of the Reneault-Dufresnoy formation (Table 3) but at lower Y_{CN} contents (Fig. 13). Again, a single sample falls in the field of high (La/Yb)_{CN} ratio typical of the Bousquet formation felsic rocks (Table 3, Fig. 13).

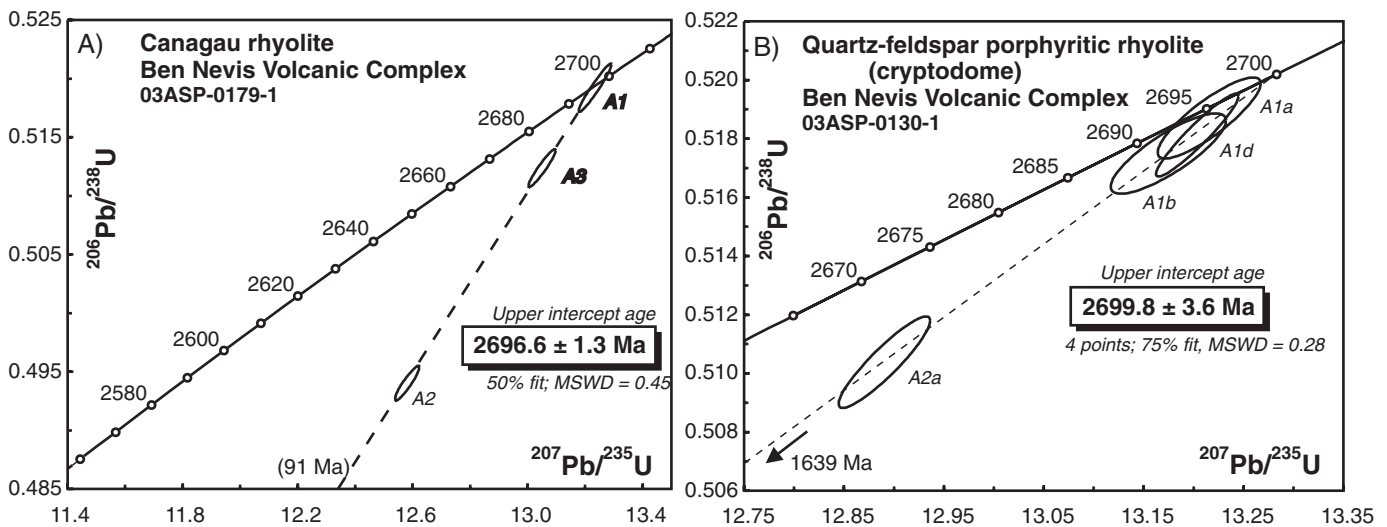


FIG. 16. Concordia diagrams showing U-Pb isotope data for zircons from the Ben Nevis volcanic complex. (A). Canagau rhyolite. (B). Porphyritic rhyolite cryptodome.

TABLE 2. U-Pb Isotope Data for Zircon from Samples of the Ben Nevis Volcanic Complex

Sample Fraction no.	Analysis	Description	Weight (mg)	U (ppm)	Th/U ¹	Pb [*] (pg)	Pb _c ² (pg)	²⁰⁶ Pb/ ²⁰⁴ Pb	Isotopic ratios ³				²⁰⁷ Pb/ ²⁰⁶ Pb Age (Ma)	Disc. ⁴ (%)	Corr. Coeff. ⁵			
									²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²⁰⁶ Pb	²⁰⁷ Pb/ ²⁰⁶ Pb ± 2σ						
03ASP-0179-1		Canagau rhyolite, Ben Nevis Twp. (NAD83, Zone 17, UTM 599636E, 5352799N)																
A1	MAH4053b	Three small, pale yellow, sharp subequant prisms	0.0007	102	0.46	39.9	0.4	6519	0.51917	0.00168	13.2323	0.0464	0.18485	0.00019	2696.9	1.7	0.1	0.9588
A2	MAH4054	Six very small, pale yellow, sharp subequant prisms	0.0007	298	0.58	119.0	1.1	6132	0.49406	0.00121	12.5774	0.0349	0.18464	0.00020	2694.9	1.8	4.8	0.9216
A3	MAH4055c	Seven very small, pale yellow, sharp subequant prisms	0.0007	126	0.55	52.0	0.6	4734	0.51234	0.00130	13.0484	0.0385	0.18471	0.00019	2695.7	1.7	1.3	0.9394
03ASP-0130-1		Quartz- and feldspar-porphyrific rhyolite cryptodome, Ben Nevis Twp. (NAD83, Zone 17, UTM 593407E, 5350603N)																
A1a	MAH4022	One clear, pale brown, short, stubby euhedral prism	0.0016	244	0.49	225.9	7.3	1756	0.51867	0.00112	13.2145	0.0422	0.18478	0.00033	2696.3	2.9	0.1	0.8515
A1b	MAH4023c	One clear, pale brown, short, stubby euhedral prism	0.0010	239	0.45	146.1	6.3	1348	0.51746	0.00111	13.1732	0.0472	0.18463	0.00040	2694.9	3.6	0.3	0.8231
A1d	MAH4058	Three clear, pale brown, short, stubby euhedral prisms	0.0024	124	0.53	177.5	0.4	27790	0.51810	0.00115	13.2031	0.0338	0.18482	0.00016	2696.6	1.5	0.2	0.9407
A2a	MAH4024	One clear, pale brown, short, stubby euhedral prism	0.0012	252	0.56	177.8	2.6	3901	0.51036	0.00127	12.8882	0.0374	0.18315	0.00022	2681.6	2.0	1.1	0.9103

Notes: All fractions represent least magnetic, air-abraded single zircon grains, free of inclusions, cores or cracks, unless noted; Pb^{*} = total radiogenic Pb (in pg); uranium decay constants are from Jaffey et al. (1971)

¹ Th/U is model value calculated from radiogenic ²⁰⁶Pb/²⁰⁶Pb ratio and ²⁰⁷Pb/²⁰⁶Pb age assuming concordance

² Pb_c is total measured common Pb (in pg) assuming the isotopic composition of laboratory blank: 206/204 = 15.612; 208/204 = 39.360 (errors of 2%)

³ Pb/U isotope ratios are corrected for spike, fractionation, blank, and, where necessary, initial common Pb; ²⁰⁶Pb/²³⁸U is corrected for spike and fractionation

⁴ Disc. (%) - percent discordance for the given ²⁰⁷Pb/²⁰⁶Pb age

⁵ Correlation coefficient

TABLE 3. Characteristics of the Noranda and Misema formations, the Ben Nevis Volcanic Complex, and the Reneault-Dufresnoy and Bousquet formations of the Blake River Group

	Noranda	Misema– Duprat–Montbray	Ben Nevis	Reneault-Dufresnoy	Bousquet
Lithologic units	Andesites and rhyolites (basalts and dacites are rare)	Andesites dominant, minor rhyolites (basalts and dacites are rare)	Basaltic andesite, andesite, dacite and rhyolite	Basalt, andesite and rhyolite (dacites are rare)	Basalt, andesite, dacite and rhyolite
Morphologies	Subaqueous flow facies	Subaqueous flow facies	Subaqueous flow facies and pyroclastic deposits; rhyolites dominantly pyroclastic	Subaqueous flow facies and pyroclastic deposits	Subaqueous flow facies, volcanoclastic and pyroclastic deposits
Geochemical affinities	Tholeiitic, transitional and calc-alkalic	Tholeiitic, transitional and calc-alkalic	Calc-alkalic	Tholeiitic, transitional and calc-alkalic	Tholeiitic, transitional and calc-alkalic
Bimodality	Bimodal	May be bimodal, but paucity of rhyolites makes determination inconclusive	Not bimodal	Bimodal	Not bimodal
Zr/Y ratio (felsic rocks)	3.28–7.6	1.36–7.92	3.07–6.52 (one sample: 9.4)	1.8–8.33	4.81–9.04
(La/Yb) _{CN} ratio (felsic rocks)	1.65–3.49	1.68–5.32	2.26–7.23 (one sample: 10.32)	1.77–6.81	6.81–14.64
Negative Nb anomaly (felsic rocks)	Weak	Weak	Strong	Strong	Inferred to be strong (no Th data)
VMS deposits	Noranda-type base metal VMS	VMS showings, no known deposits	Gold-rich VMS showing, no known deposits	Gold-rich VMS	Gold-rich VMS
Notable characteristics	Laterally extensive rhyolite flows	Restricted rhyolite flows or domes	Synvolcanic dikes with mineralized borders	Sedimentary rocks overlie formation	Synvolcanic dikes, rhyolite domes
Age	≈2698 Ma	≈2701 Ma	≈2698 Ma	≈2697 Ma	≈2697 Ma

In chondrite-normalized spider diagrams (Fig. 14A-C), the slopes of the Ben Nevis felsic rocks with Zr/Y >5 resemble the felsic rocks of the Misema–Duprat–Montbray formation and the felsic rocks of the Reneault-Dufresnoy formation with the lower Yb_{CN} values. Compared to the Misema–Duprat–Montbray, however, the Ben Nevis felsic rocks have larger negative Nb anomalies. The felsic rocks of the Reneault-Dufresnoy formation have higher overall REE and trace element concentrations and overlap the fields for the Ben Nevis felsic rocks only at the highest Yb_{CN} values. The amplitude of the negative Nb_{CN} anomalies is similar for both the Reneault-Dufresnoy formation and Ben Nevis volcanic complex. The Noranda formation generally has flatter chondrite-normalized REE and trace element patterns and smaller negative Nb anomalies compared to the Ben Nevis felsic rocks. The felsic rocks of the Bousquet formation have steeper chondrite-normalized REE-trace element patterns than those from Ben Nevis, but a strong negative Nb anomaly is inferred for the Bousquet formation rhyolites despite the lack of thorium data.

Graphical representations of the ranges and averages of Zr/Y and (La/Yb)_{CN} ratios (Fig. 17) are used to compare the units examined here to the rhyolite types defined by Lesher et al. (1986) and reexamined by Hart et al. (2004) (Table 4). In the Zr/Y diagram (Fig. 17A), the range of rhyolite types for the Ben Nevis complex is grossly similar to that of the Reneault-Dufresnoy formation, placing them in the FII

category (Fig. 17A), as they extend to lower and higher values than the FIIIa rhyolites. However, the population with Zr/Y <5 may be FIIIa rhyolites.

Gold-rich VMS showings occur in the Ben Nevis volcanic complex (e.g. Canagau showing: Canadian Intergovernmental Working Group on the Mineral Industry, 2003; Mineral Deposit Inventory Version 2, MDI2, 2004, Ontario Geological Survey Digital Data Set, http://www.mndm.gov.on.ca/mndm/mines/ermes/databases/mdi_sum_e.asp). The deposits of the younger volcanic formations (Reneault-Dufresnoy and Bousquet) are also notably gold rich (Bouchard-Hébert mine in the Reneault-Dufresnoy formation: Barrett et al., 1992; Ripopel et al., 1995; and the Bousquet 2, Dumagami and LaRonde mines in the Bousquet formation: Lafrance et al., 2003; Dubé et al., 2004; Mercier-Langevin et al., 2007a, b). However, within the Noranda formation the VMS deposits are typically Cu-Zn deposits (Franklin et al., 2005). The gold-rich Horne mine is outside the Noranda cauldron (Kerr and Gibson, 1993). Small showings occur in the bimodal portion of the Misema–Duprat–Montbray formation but no known VMS showings occur in its andesite dominant phase.

Discussion

Radiometric U-Pb ages for rhyolite from the Misema–Duprat–Montbray formation place deposition between approximately 2697 and 2701 Ma (2696.6 ± 3.4 Ma; David et al., 2006;

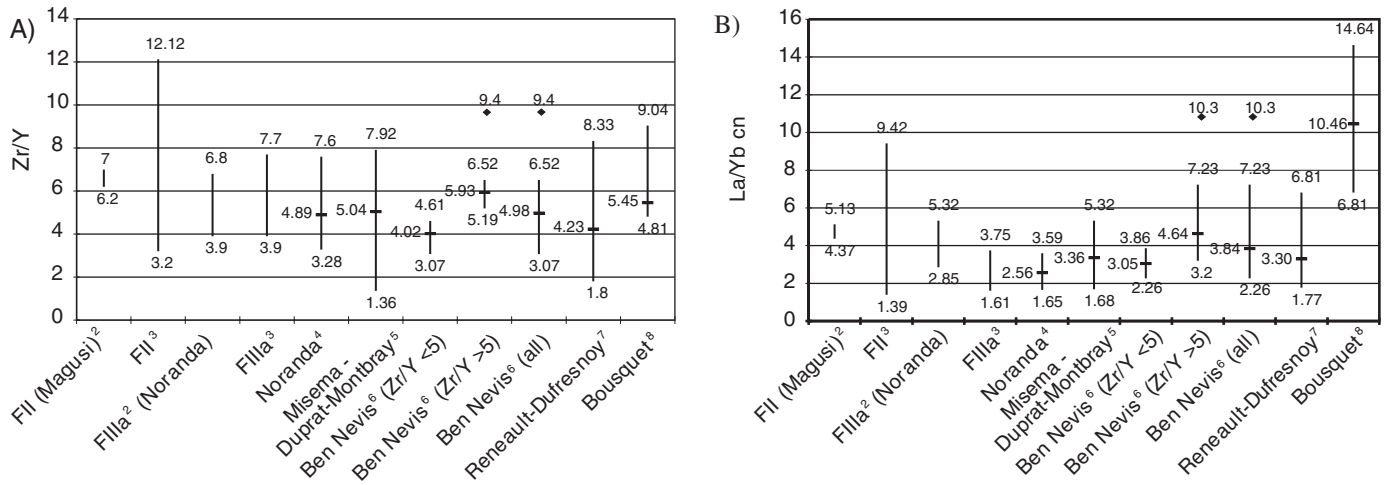


FIG. 17. Range and averages of (A) Zr/Y ratios, and (B) (La/Yb)_{CN} ratios for the Lesher et al. (1986) classification of Archean rhyolites (see also Hart et al., 2004) and the Blake River Group felsic volcanic units examined here. Chondrite normalization values are from McDonough and Sun (1995). Superscripts refer to references listed in Table 4.

2701 ± 2 Ma: Corfu et al., 1989; and 2701 ± 1 Ma: Mortensen, 1993; Fig. 3, Table 1). The Ben Nevis volcanic complex has U–Pb zircon ages of 2696.6 ± 1.3 and 2699.8 ± 3.6 Ma (Figs. 3, 4, 16; Tables 1, 2). These ages place the Ben Nevis volcanic complex in the younger part of the Misema–Duprat–Montbray formation and are similar to those determined for the Reneault–Dufresnoy (2697.9 ± 1.3/–0.7 Ma: Mortensen, 1993; 2696.0 ±

1.1 Ma: Lafrance et al., 2003) and Bousquet formations (2698.6 ± 1.5, 2698.0 ± 1.0, 2694.0 ± 2.0 Ma: Lafrance et al., 2003; 2698.3 ± 0.8, 2697.8 ± 1.0 Ma: Mercier–Langevin et al., 2004). This suggests that the Ben Nevis rhyolitic complex is a part of this younger post-Noranda cauldron volcanic event.

There are also similarities in styles of volcanism between the Ben Nevis volcanic complex and the Reneault–Dufresnoy

TABLE 4. Trace Element Geochemical Criteria for the Classification of Rhyolites into F Types (Lesher et al., 1986; Hart et al., 2004)¹

Rhyolite type	Y (ppm)	Yb (ppm)	Sc (ppm)	(La/Yb) _{CN} ⁹	(La/Yb) _{CN} ¹⁰	(La/Yb) _{CN} ¹¹	Zr/Y
FII (Magusi) ²	38–48	3.9–5.8	7.8–12	2.3–2.7	—	4.37–5.13	6.2–7.0
FII ³	11–73	1.3–7.9	—	—	1.3–8.8	1.39–9.42	3.2–12.12
FIIa ² (Noranda)	25–70	3.4–9.3	7.0–20	1.5–2.8	—	2.85–5.32	3.9–6.8
FIIa ³	25–96	3.4–9.3	—	—	1.5–3.5	1.61–3.75	3.9–7.7
Noranda ⁴ (n=24)	30–82	4.4–8.7	7.3–23	—	—	1.65–3.59	3.33–7.65
Misema–Duprat–Montbray ⁵ (n=18)	12–110	1.52–10	5–78	—	—	1.68–5.32	1.36–7.92
Ben Nevis ⁶ (Zr/Y <5: n=15)	29–56	3.56–6.7	3–11.9	2.07–3.54	2.10–3.32	2.26–3.86	3.07–4.61
Ben Nevis ⁶ (Zr/Y >5: n=14)	10–43	1.15–5.51	2–10.1	2.94–6.64 (one sample: 9.47)	2.98–6.74 (one sample: 9.62)	3.2–7.23 (one sample: 10.32)	5.19–6.52 (one sample: 9.4)
Reneault–42–104 Dufresnoy ⁷ (n=24)	3.7–13	—	—	—	1.77–6.81	1.8–8.33	—
Bousquet ⁸ (n=29; REE n=5)	13–76	1.2–3	—	—	—	6.81–14.64	4.81–9.04

¹ The data, using the original chondrite factors of Lesher et al. (1986), Leedy chondrite/1.20, and Hart et al. (2004), average of 10 chondrites from Nakamura (1974), are included in the table for ease of comparison

² Lesher et al. (1986)

³ Hart et al. (2004)

⁴ Data from Péloquin (2000), Paradis (1990), F. Santaguida, H.L. Gibson, M.D. Hanningon and D.H. Watkinson (unpub. report for the Canadian Mineral Industry Research Organization, 1998, p.181–241)

⁵ Data from Péloquin (2000)

⁶ Data from Péloquin and Piercey (2005)

⁷ Data from Goutier (1997), Riopel et al. (1995)

⁸ Data from Lafrance et al. (2003), Mercier–Langevin et al. (2004)

⁹ Leedy chondrite/1.20 (Lesher et al., 1986)

¹⁰ Average of 10 chondrites, from Nakamura (1974)

¹¹ C1 chondrite from McDonough and Sun (1995)

and Bousquet formations and important differences between the Ben Nevis volcanic complex and the Misema–Duprat–Montbray formation. Deposition throughout the Blake River Group was subaqueous, as indicated by the presence of pillowed lavas and lobe and breccia rhyolite and dacite flows. However, compared to the main phase of volcanism of the Noranda and Misema–Duprat–Montbray formations, which are dominated by flow facies rocks (de Rosen-Spence, 1976; Gibson, 1989; Gibson and Watkinson, 1990), pyroclastic rocks are more common in the Renault-Dufresnoy and Bousquet formations and in the Ben Nevis volcanic complex. Lafrance et al. (2003) interpreted the Bousquet formation as forming from volatile-rich magmas, and Mercier-Langevin et al. (2004) suggested that boiling could explain the precious metal enrichment of the ores at LaRonde. Whereas the increase in abundance of pyroclastic rocks may be explained by an increase in volatile content (Busby, 2005), boiling implies deposition at shallower water depths than the flow-dominated formations of the Blake River Group.

The Renault-Dufresnoy and Bousquet formations and the Ben Nevis volcanic complex represent a late phase of volcanism within the Blake River Group at approximately 2697 Ma (average of U-Pb ages from Table 1; Fig. 18). These sequences are characterized by an increased abundance of felsic and intermediate volcanoclastic (pyroclastic and autoclastic) rocks intercalated with flows, indicating a change in magmatic regime relative to that of the Noranda cauldron. The increase in LREE enrichment in the felsic rocks in all three sequences, with higher chondrite-normalized La/Yb ratios and stronger negative Nb anomalies than the earlier formed rhyolites of the Noranda formation supports a fundamental change in magmatism. Lower Yb contents and higher $(La/Yb)_{CN}$ ratios may indicate greater depths of magma genesis (Ellam, 1992), which may be related to increasing crustal thickness due to the buildup of volcanic stratigraphy over

time and the construction of volcanic edifices on the basin floor. The increased crustal thickness, in turn, may have led to greater magma-crustal interaction, increasing the La and Th concentrations in the melts and producing the strong negative Nb anomalies seen in the late phases of the Blake River Group. This geochemical interpretation is consistent with the interpretation that the eruptive depth became shallower with time due to increased buildup of volcanic edifices.

The interpretation of a shallower environment of deposition for the late-phase volcanism compared to the main phase of volcanism of the Blake River Group may be supported by the presence of Au-rich massive sulfide deposits (e.g., Bousquet-LaRonde). Hannington et al. (1999) considered there to be two main factors resulting in the formation of gold-rich VMS deposits: contributions of magmatic volatiles as a source of gold and boiling in shallow marine settings. Lafrance et al. (2003) interpreted the Bousquet formation as having been produced by volatile-rich magma and suggest that Archean calc-alkalic volcanic sequences are therefore favorable for gold-rich VMS deposits. Mercier-Langevin et al. (2007a and b) also suggested that the gold-rich character of the Bousquet-LaRonde deposits may be due in part to repeated boiling of the ore-forming fluid. Similar factors may account for the occurrence of Au-rich polymetallic sulfide occurrences in the Ben Nevis complex (e.g., Canagau showing).

Conclusions

The Blake River Group in Ontario in Ben Nevis and Clifford Townships consists of a continuous spectrum of volcanic and high-level subvolcanic rocks that comprise the Ben Nevis volcanic complex within the Misema–Duprat–Montbray formation. The Ben Nevis volcanic complex consists of subaqueous rocks ranging from basaltic-andesite to rhyolite with both flow and pyroclastic origins; pyroclastic rocks constitute a significant proportion of the stratigraphy. The volcanic rocks

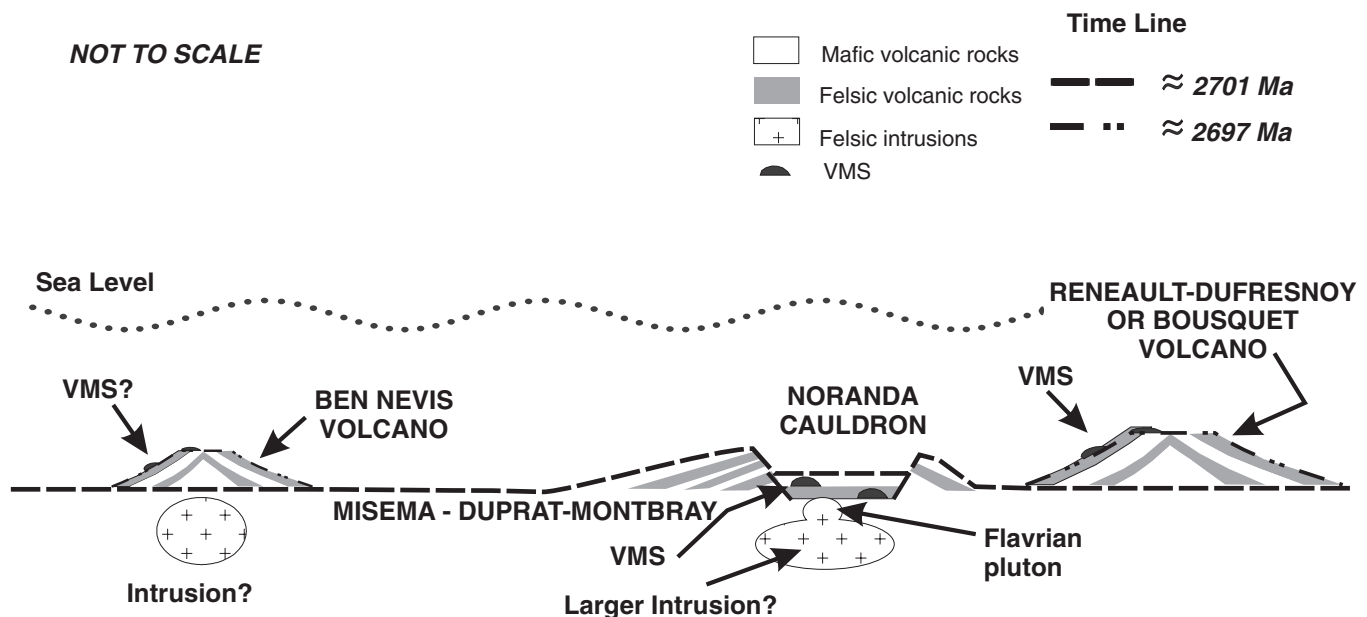


FIG. 18. Schematic diagram of the Blake River Group Basin at the time of the late phase volcanic event at approximately 2697Ma.

have calc-alkalic affinities as deduced from major, trace, and REE geochemical signatures of the rocks.

Within the greater stratigraphy of the Blake River Group, the Ben Nevis volcanic complex comprises part of a younger magmatic event. The main phase of volcanism, the Noranda and Misema–Duprpat–Montbray formations, is characterized by bimodal, subaqueous, tholeiitic to calc-alkalic assemblages that, in the case of the Noranda formation, host the base metal-rich deposits within the Noranda cauldron. In contrast, the Ben Nevis volcanic complex is younger and shares with the age-equivalent Reneault–Dufesnoy and Bousquet formations a continuous spectrum of volcanic rocks of both subaqueous flow and pyroclastic origins and the occurrence of Au-rich VMS mineralization. However, the Ben Nevis is entirely calc-alkalic, whereas the Bousquet and Reneault–Dufesnoy range from tholeiitic to calc-alkalic.

All three of the volcanic sequences attributed to the late phase of the Blake River Group have greater abundances of pyroclastic rocks (both felsic and mafic to intermediate), higher $(La/Yb)_{CN}$ ratios, and larger negative Nb anomalies (inferred in the case of the Bousquet formation) than the earlier phases of volcanism of the Blake River Group. The increase in abundance of pyroclastic rocks coupled with the presence of Au-rich VMS suggests that the late-phase volcanism occurred at shallower ocean depths, possibly due to the construction of stratovolcanoes on the Blake River basin floor. The lower Yb contents and higher $(La/Yb)_{CN}$ ratios and larger negative Nb anomalies suggest deeper magma genesis and a higher degree of magma-crust interaction for the late phases of Blake River volcanism, possibly due to the thicker volcanic piles.

Acknowledgments

The Discover Abitibi Initiative was funded by the Timmins Economic Development Corporation, which in turn received financial backing from FedNor, Northern Ontario Heritage Corporation, and private sector investors. We thank the Discover Abitibi Research Group in its entirety, and particularly John Ayer and Phil Thurston, for the conception of this project and their logistic, scientific, and moral support. The project was administered by the Mineral Exploration Research Centre at Laurentian University, and we thank Natalie Lafleur-Roy for handling all things administrative. Doug Hunter and the Wallbridge Mining Ltd. geological and technical staff are thanked for their assistance and support throughout this project. They have supplied property access, materials (specifically digitalized maps, air and satellite photos, and access to drill core), and scientific discussion and inspiration. ASP and STP are also supported by a Discovery Grant from the Natural Sciences and Engineering Research Council. We also wish to thank Tom Hart and Jean Goutier for their reviews of the manuscript. Their comments and critiques were greatly appreciated. We thank Mark Hannington for his editing and comments on the final version of this paper.

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