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Intermediate to mafic volcanoclastic units in the peripheral Blake River Group, Abitibi Greenstone Belt, Quebec: origin and implications for volcanogenic massive sulphide exploration

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Abstract: Three regionally mappable, plagioclase-rich, intermediate to mafic volcanoclastic units from the peripheral parts of the Archean Blake River Group show intriguing similarities, including a lack of an intimate association with lava flows; and a bedded aspect, with thick, coarse beds displaying a typical sequence of internal features, suggesting deposition from high-density mass flows. The bounding facies and the great volume of variably amygdaloidal clasts and plagioclase crystals contained in the deposits supports major submarine explosive eruptions as the source of the bulk of the material. The physical resemblance between the different volcanoclastic units initially suggested a stratigraphic correlation, but preliminary geochemical data argues against this: the D'Alembert tuff consists of basaltic andesite and andesite of transitional to calc-alkaline affinity, whereas the Stadacona unit essentially comprises tholeiitic basalt, with very different profiles on multi-element plots. Any hypothesis involving a megacaldera and a huge underlying magma chamber to explain the origin of these volcanoclastic units would need to justify such chemical differences. The authors favour a simpler scenario in which the D'Alembert tuff and the Stadacona unit were derived from much smaller, geographically and chemically distinct magma chambers. The explosive eruptions could have taken place at different times and no stratigraphic correlation between the volcanoclastic units is necessary. Peripheral areas of the Blake River Group contain more fragmental material than the traditional Noranda camp, and therefore offer exploration potential for large volcanogenic massive sulphide deposits formed in part by subseafloor replacement, which are preferentially hosted in volcanoclastic rocks (e.g. Bouchard-Hébert, LaRonde Penna).

Résumé : On remarque dans la périphérie du Groupe de Blake River (Archéen) trois unités volcanoclastiques intermédiaires à mafiques, riches en plagioclase, que l'on peut cartographier à l'échelle régionale et qui présentent plusieurs similitudes, notamment l'absence d'une association étroite avec des coulées de lave et un aspect lité. La séquence typique des caractéristiques internes des lits épais et grossiers suggère que ces lits ont été déposés par des coulées de masse de haute densité. Les séquences encaissantes et le volume considérable de fragments vésiculaires et de cristaux de plagioclase dans les dépôts appuient l'hypothèse que des éruptions explosives sous-marines ont produit la plus grande partie du matériel contenu dans ces roches. La ressemblance physique entre les diverses unités volcanoclastiques pourrait suggérer qu'il existe une corrélation stratigraphique, mais les données géochimiques préliminaires militent contre cette possibilité. En effet, le tuf D'Alembert se compose d'andésites basaltiques et d'andésites d'affinité transitionnelle à calco-alkaline, alors que l'unité de Stadacona comprend essentiellement des basaltes tholéïtiques, avec des profils multi-éléments très distincts. Toute hypothèse impliquant une caldeira géante et une énorme chambre magmatique sous-jacente pour expliquer l'origine de ces roches volcanoclastiques devra tenir compte de ces différences dans la composition chimique. Nous présentons un scénario plus simple dans lequel le tuf D'Alembert et l'unité de Stadacona sont dérivés de chambres magmatiques distinctes beaucoup plus petites, chacune possédant ses propres caractéristiques chimiques. Les éruptions explosives peuvent avoir eu lieu à différents moments, et une corrélation stratigraphique entre les unités ne s'avère pas nécessaire. La périphérie du Groupe de Blake River contient davantage de roches volcaniques fragmentaires que le camp de Noranda classique et offre ainsi un bon potentiel d'exploration pour les gîtes de sulfures massifs volcanogènes importants; plusieurs de ces gîtes se sont formés en partie par remplacement sous le fond marin et sont encaissés préférentiellement dans des roches volcanoclastiques (p. ex. Bouchard-Hébert, LaRonde Penna).

INTRODUCTION

Archean volcanic rocks assigned to the Upper Blake River assemblage in Ontario (Ayer et al., 2005) and the Blake River Group in Quebec are known to host more than 200 Mt of base-metal ores and more than 25 million ounces of gold, including past production (e.g. Gibson and Watkinson, 1990; Barrett et al., 1991; Barrett and MacLean, 1994; Gibson et al., 2001; Dubé et al., 2004; Mercier-Langevin et al., 2004; Mercier-Langevin, 2005; Dubé et al., in press). This includes the giant, gold-rich, Horne and LaRonde Penna volcanogenic massive sulphide deposits (Fig. 1). Thus the Blake River Group clearly represents one of the most prolific Archean volcanic assemblages for base and precious metal exploration.

As part of phase 3 of the Geological Survey of Canada's Targeted Geoscience Initiative (TGI) program, a multidisciplinary, integrated study of the Blake River Group in Quebec and Ontario has been initiated, in collaboration with the two provinces, the private sector and several universities (Ayer et al., 2006). The Blake River subproject includes 1:20 000 mapping, volcanology, structure, geochronology, alteration and mineral-deposit studies, geochemistry, isotope geochemistry, as well as 2-D seismic studies and 3-D modelling. One aim of this subproject is to improve the understanding of the stratigraphy and volcanic architecture of the Blake River Group as a whole in order to help exploration for volcanogenic massive sulphide deposits.

This endeavour will involve a diverse group of workers over many years, but as a step toward that goal, the authors present here a preliminary survey of three of the major occurrences of intermediate to mafic volcanoclastic rocks, including pyroclastic rocks, in the Blake River Group. Some of the largest volcanogenic massive sulphide deposits in the Blake River Group (e.g. LaRonde Penna, Bouchard-Hébert) occur in volcanic sequences characterized by the presence of such rocks, among other facies. Therefore, understanding the distribution and origin of mafic to intermediate volcanoclastic units is important for both the reconstruction of the geological evolution of the region and mineral exploration purposes. Pearson (2005) and Daigneault and Pearson (2006) suggested that these units might be part of a semicontinuous belt in the peripheral part of the Blake River Group in Quebec and Ontario. In addition to the volcanoclastic rocks, Pearson (2005) used the distribution of inferred ring faults, carbonate alteration zones, and mafic to intermediate dykes to define a "megacaldera" he called the Misema caldera; but are all the peripheral volcanoclastic units correlatable, and do they really form a semicontinuous belt? Because there are persistent terminology problems involved in the description of volcanoclastic rocks (*see* White and Houghton (2006) for a recent discussion), what is especially needed as a base for discussions and interpretations is a consistent inventory of these deposits using a single rock-naming scheme (Appendix A).

During the summer of 2006, the authors examined three regionally mappable, plagioclase-rich, intermediate to mafic volcanoclastic units, in which the clastic rocks are bedded and not clearly genetically associated with lava flows: the D'Alembert tuff; the Stadacona unit; and the Jévis Sud tuff. The last was only visited briefly as it is being mapped in detail by Ph.D. candidate Claude Pilote at Université du Québec à Chicoutimi (Pilote et al., 2007). A fourth regionally mappable, plagioclase-rich, intermediate to mafic volcanoclastic unit — the Bousquet scoriaceous tuff in the easternmost Blake River Group (Fig. 1) — has some common traits with the three already mentioned and will be discussed elsewhere. The senior author also visited many areas of the 'volcanoclastic belt' away from the sites described here, to see if similar units indeed occurred; the results of these investigations will be presented elsewhere.

In this contribution, the authors focus on the three units listed above and try to answer several questions:

- What are their common characteristics and differences?
- Are stratigraphic correlations between these units plausible, based on their physical characteristics and geochemistry?
- What is their origin in terms of the modes of fragmentation, transport, and deposition?

Additionally, the authors report on attempts to date some of these rocks by the U-Pb method.

GEOLOGICAL SETTING

The Blake River Group is the youngest (ca. 2701–2696 Ma) dominantly volcanic package in the Abitibi Greenstone Belt (Mortensen, 1987, 1993; Corfu et al., 1989; Corfu, 1993; Ayer et al., 2002, 2005; Lafrance et al., 2005; David et al., 2006). It consists largely of submarine, basaltic to rhyolitic, tholeiitic to calc-alkaline volcanic rocks (Dimroth et al., 1982; Gélinais and Ludden, 1984; Grunsky, 1988; Laflèche et al., 1992; Lafrance and Dion, 2004; Péloquin and Piercey, 2005) that are intruded by several generations of plutons and mafic to intermediate dykes and sills (Paradis et al., 1988; Galley and van Breemen, 2002; Galley, 2003). Several schemes have been proposed to divide the volcanic rocks into subgroups or formations (e.g. Goodwin, 1977; Gélinais et al., 1984; Péloquin et al., 1990; Couture and Goutier, 1996; Goutier, 1997; Péloquin et al., 2001), but stratigraphic work is still in progress, so the present authors avoid using formational names. The only such names mentioned here are those of two stratigraphic units not clearly belonging to the Blake River Group in Quebec, i.e. the Hébécourt Formation and the Rivière Dufresnoy Formation.

The Hébécourt Formation is slightly older than the Blake River Group in Quebec (before 2701 Ma) and consists mainly of mafic tholeiitic lavas including variolitic horizons (Goutier, 1997). It lies north of the Blake River Group, as defined in

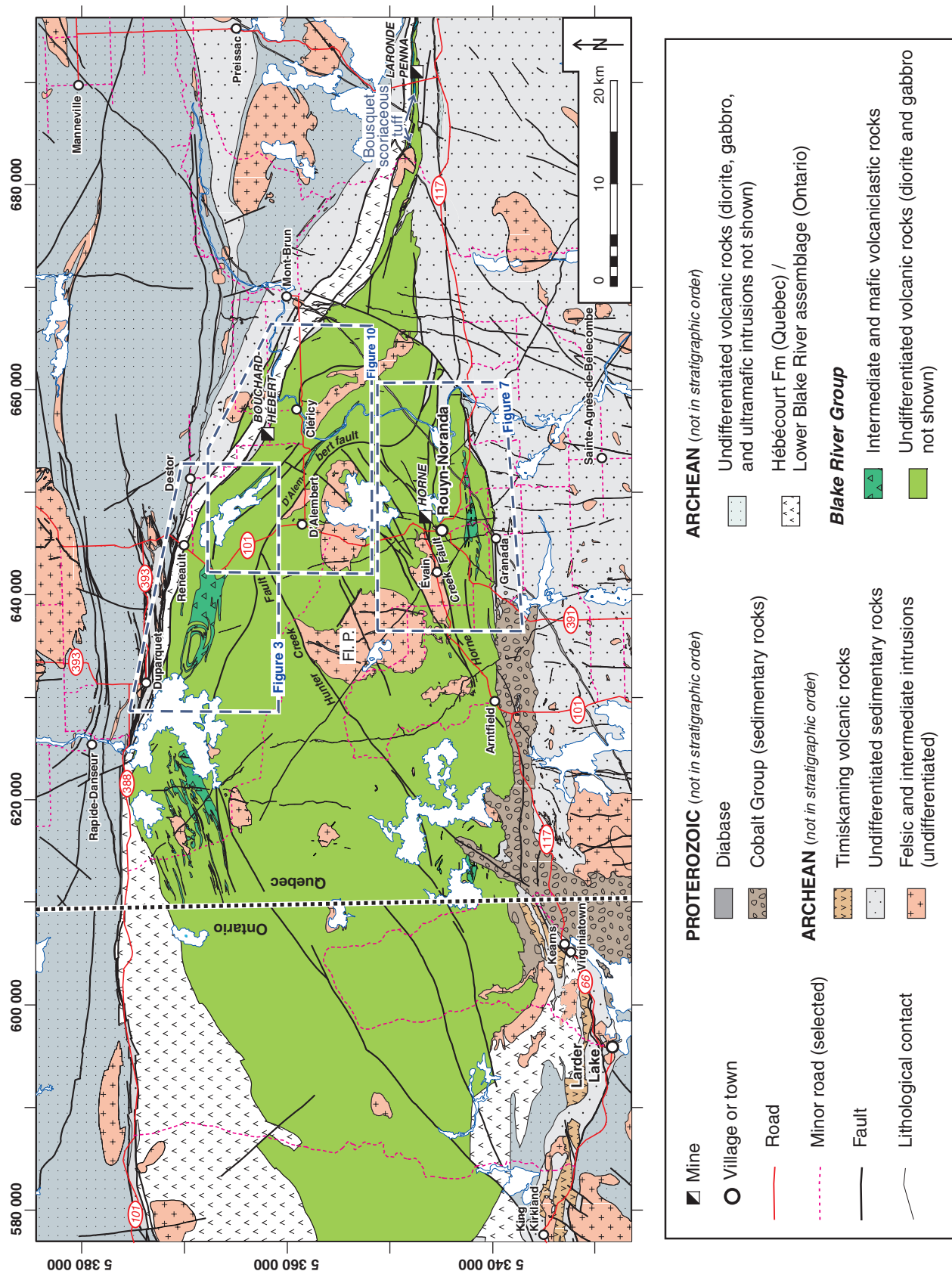


Figure 1. Simplified geological map of a portion of the southern Abitibi Greenstone Belt showing selected volcanogenic massive sulphide mines and the distribution of mafic to intermediate volcaniclastic rocks in the Blake River Group. Fi: P. = Flavrian Pluton.

Quebec, extending from the Ontario border to beyond the LaRonde Penna mine to the east (Fig. 1). The Hébécourt Formation corresponds to the Lower Blake River assemblage (formerly Kinojevis assemblage) in Ontario (Ayer et al., 2002, 2005).

The Rivière Dufresnoy Formation belongs to the Kewagama Group, a submarine sedimentary package younger than the Blake River Group and dominated by turbidite sequences (Goutier, 1997). The Kewagama Group is correlated to the Porcupine assemblage in Ontario (Ayer et al., 2005). The bulk of the Kewagama Group is located northeast of the Hébécourt Formation in the Mont-Brun area, whereas the Rivière Dufresnoy Formation is located in the Bouchard-Hébert mine area (Fig. 1).

The Blake River Group is famous not only for its extraordinary endowment of mineral deposits, but also for its well preserved volcanic textures and structures. In many (but not all) areas, metamorphic grade is low (greenschist and subgreenschist facies; e.g. Jolly (1978); Powell et al. (1995)), strong tectonic fabrics are absent, and hydrothermal alteration has not destroyed primary textures (Hannington et al., 2003). The combination of exceptional economic interest and good state of preservation has made the Blake River Group a favourite locale for volcanological studies of Archean sequences (e.g. classic work on pillow lavas: Dimroth et al., (1978)). Careful documentation and interpretation of the physical volcanology of the Blake River Group has the potential to improve the understanding of subaqueous volcanism.

Work by de Rosen-Spence (1976), Lichtblau and Dimroth (1980), Gibson (1989), and others, has allowed the identification of a subsidence structure known as the Noranda cauldron. The subsidence area is traditionally portrayed to be bounded in part by the very linear Horne Creek and Hunter Creek faults (Gibson and Watkinson (1990); Fig. 1), but recent work is starting to question this idea (H. Gibson, pers. comm., 2007). Other cauldron limits are even less clearly established, but possibly correspond to the general areas of the Flavrian Pluton to the west and the D'Alembert fault to the northeast. The east-tilted and dissected Noranda cauldron is thought to have formed in piece-meal fashion. The term 'caldera', although used in some publications, is rejected by Gibson and Watkinson (1990) because the Noranda subsidence structure lacks the classic circular or elliptic shape. In a recent review on calderas, Cole et al. (2005) further stressed that "...it is important to distinguish between well-defined calderas and older, eroded structures..." that they call cauldrons or ring structures depending on the level of erosion.

The giant Horne deposit lies just south of the inferred southern boundary of the cauldron, but most of the 'Noranda-type' Cu-Zn volcanogenic massive sulphide deposits in the Noranda camp occur within it. This illustrates the often-reported link between subsidence structures, including calderas, and volcanogenic massive sulphide deposits (e.g. Stix et al., 2003, and references therein). The recent suggestion by Pearson (2005) of a much larger

'megacaldera' in the Blake River Group has important implications for exploration and reconstruction of the volcanic architecture of the region. According to Daigneault and Pearson (2006), the Blake River Group comprises at least three imbricated and partly overlapping subsidence structures: the Misema 'megacaldera', the 'New Senator caldera' and the Noranda cauldron. As already mentioned, one of the arguments utilized by Pearson (2005) in support of the megacaldera model is the presence of a semicontinuous belt of intermediate to mafic volcanoclastic units in the peripheral part of the Blake River Group in Quebec and Ontario. The authors now present the recent observations on three of these units.

REGIONALLY MAPPABLE, PLAGIOCLASE-RICH UNITS

Among the intermediate to mafic volcanoclastic rocks found in the periphery of the Blake River Group, the three units described here (D'Alembert tuff, Jévis Sud tuff, Stadacona unit), and the Bousquet scoriaceous tuff display several common features (Table 1).

A final common characteristic for at least the D'Alembert tuff and the Jévis Sud tuff is that the coarse, poorly sorted beds (coarse lapilli tuff and tuff breccia) often display a consistent sequence of primary structures, illustrated in Figure 2. This suggests similar transport and deposition mechanisms, whereas the resemblance in the clast assemblages support similar eruption processes (more on this below). Specifically, the beds were likely deposited by submarine water-supported density currents such as those described by Fiske and Matsuda (1964) or McPhie and Allen (2003).

Previous workers (e.g. Dimroth and Demarcke, 1978; Stone, 1990) generally have called these rocks "pyroclastic", "pyroclastic flow", or "pumice flow" deposits because of the presence of "pumice" (scoriaceous intermediate to mafic clasts), their bedded aspect, and their structural characteristics reminiscent of subaqueous mass flows (e.g. Dimroth and Rocheleau, 1979, p. 116). It is clear that these volcanoclastic rocks are not pillow breccia, hyaloclastite, peperite, or autoclastic products and so if they are indeed primary, they can be called 'pyroclastic' (Differentiating between, on the one hand, a deposit in which the fragments were derived directly from a submarine explosive eruption, moved laterally in an eruption-fed density current (e.g. White, 2000), and were deposited to their final resting place without subsequent remobilization — a true submarine pyroclastic flow deposit — and, on the other hand, a deposit in which the fragments were similarly derived, transported, and deposited, but were later remobilized by, say, an earthquake-triggered subaqueous mass flow of loose debris on the slope of a volcano, is impossible at present. Because many submarine pyroclastic flows are probably water-supported (for possible exceptions *see* for example Kokelaar and Busby (1992)), the transport and deposition mechanisms for both primary and

Table 1. Common characteristics for some of the peripheral intermediate to mafic volcanoclastic units in the Blake River Group in Quebec (“Y” = yes).

	D’Alembert	Jévis Sud	Stadacona	Bousquet
Elongate map distribution, with lateral continuity of volcanoclastic rocks for several kilometres (albeit with lateral and vertical facies changes)	Y	Y	Y	Y
Overall stratified character, with individual beds having thicknesses between a few centimetres and several tens of metres	Y	Y	Y	Y
Scarcity (not necessarily absence) of interbedded coherent volcanic rocks such as massive or pillow lavas	Y	Y	Y	Y
Range of grain size from tuff to tuff breccia; coarse beds are poorly sorted	Y	Y	Y	Y
Common compositional characteristics, including:				
presence of free sand-grade plagioclase crystals	Y	Y	Y	Y
presence or dominance of plagioclase-phyric to plagioclase glomeroporphyritic clasts	Y	Y	Y	Y
locally, so-called ‘pumice’ (intermediate to mafic scoriaceous clasts) in various states of preservation	Y	Y	Y	Y
Clasts have shapes (subrounded to subangular) that suggest emplacement as brittle solids and/or reworking in a brittle state	Y	Y	Y	Y
Pillow lavas stratigraphically above and below volcanoclastic units, suggesting submarine emplacement	Y	Y	Y	Y
Fine-grained beds (tuff to fine lapilli-tuff) have the aspect of turbidite units, also suggesting subaqueous depositional environment	Y	Y	?	?

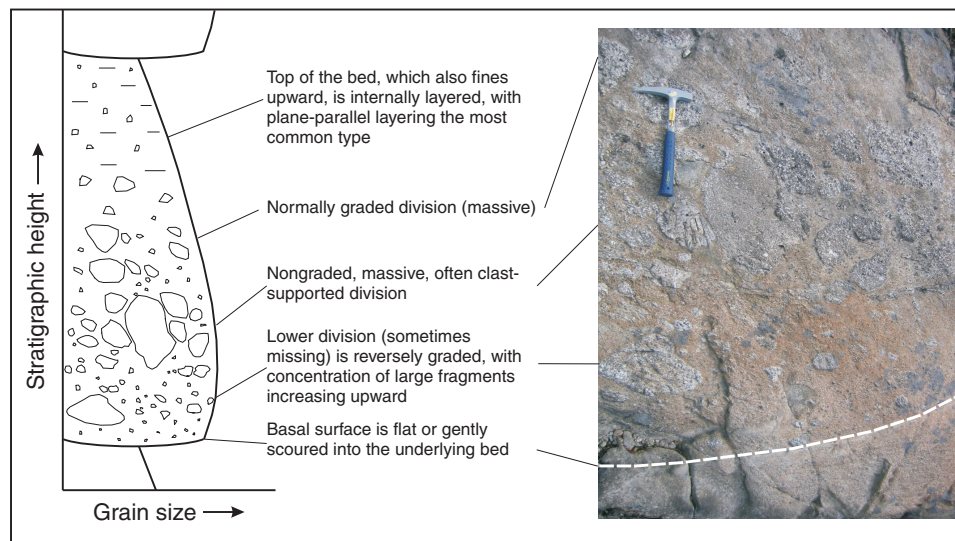


Figure 2. Internal divisions of a typical coarse bed in the D’Alembert tuff or the Jévis Sud tuff. Only coarse lapilli and blocks have been drawn, with the approximate shapes of the fragments, relative sizes, and orientations taken from a Jévis Sud tuff photograph (right; station 06-PSR-004, *see* Appendix B). Such beds are interpreted as submarine density current deposits (the high-concentration debris flows of Fisher (1984)), quite possibly, but not demonstrably, of the eruption-fed type.

secondary flows are the same. Furthermore, the original fragmentation mechanisms (largely controlling the nature, size distribution, and shape of the particles) can also be the same if one flow is the remobilized equivalent of the other.)

The authors now present details about each of the three volcanoclastic units.

D'Alembert tuff

Host volcanic sequence and economic geology

The D'Alembert tuff (informal name) belongs to a sequence of folded, mostly steeply dipping, Blake River Group volcanic rocks composed dominantly of intermediate to mafic lavas (Fig. 3). The sequence is limited to the north by the Hébécourt Formation and to the south by a fault segment linking the Baie Fabie fault (to the west) and the D'Alembert fault (to the southeast) (Fig. 1, 3). No volcanogenic massive sulphide deposits have been exploited in this area, but interestingly, a January 9, 2007 press release by Alexis Minerals Corporation mentions the occurrence of a "...base metal horizon...marked by a bedded cherty exhalite and intermediate tuffs containing stringers, bands and fragments of massive to semimassive sulphides" intercepted by diamond drilling in the area shown by a pink dot on Figure 3. Based on their geographic position only, volcanoclastic rocks in the Alexis/Xstrata drill holes appear to belong to the D'Alembert tuff; the authors will confirm this in the future. If such is the case, the D'Alembert tuff could represent a new target for base-metal exploration.

Lateral extent, thickness, and structural geology

Previous workers (Dimroth and Demarcke, 1978; Tassé et al., 1978) traced the D'Alembert tuff for over 15 km laterally from Lake Duparquet (D'Alembert Bay) to Lake Dufresnoy. Recent provincial geological maps — from which Figure 3 is adapted — show the tuff to extend to just east of Highway 101, making the strike length about 12.5 km. The volcanoclastic unit is about 300 m in maximum exposed stratigraphic thickness (Dimroth and Demarcke, 1978), but folding creates a wider belt. There exist two main outcrop areas containing thick, coarse volcanoclastic beds, suggesting a relative proximity to the source. For simplicity the present authors label these areas A2 (the "D'Alembert" site of previous workers: a hill north of the river of the same name) and A3 (the "Reneault" site of previous workers: a hill southwest of Reneault near Highway 101). Possible distal correlatives in D'Alembert Bay (area A1) and at "Destor beach" (area A4) were also examined briefly (Fig. 3).

The D'Alembert tuff lies at the core of a regional syncline. The volcanoclastic rocks around area A2 and westward are invaded by numerous dioritic to gabbroic intrusions, some of which are very coarse grained and layered on a decimetre

scale. Dimroth et al. (1973) described the intrusions as a composite laccolith ("several sill-like bodies separated by screens" of volcanoclastic rock). Goutier and Lacroix (1992) interpreted the eye-like structure on Figure 3 as a canoe fold (a syncline with a doubly plunging axis). Despite the folding of the sequence, penetrative deformation remains minor.

Proximal facies

There are no obvious interbedded sedimentary rocks or coherent (nonfragmental) lavas within the volcanoclastic strata in areas A2 and A3. Some interbedded lavas, including a felsic lens, are shown on Figure 3, south of A2. In both investigated areas, volcanoclastic rocks are clearly stratified. In area A3, the east-striking beds dip almost vertically and younging is to the south (Fig. 4a). In most of area A2, dips are 70–80° to the west or southwest, with younging in the same direction.

Tassé et al. (1978) classified the volcanoclastic beds into two types, according to their grain sizes, structures, and thicknesses. Beds of the first type are thicker (average of 2.75 m), coarser grained (mostly tuff breccia and rare breccia), and often do not display internal stratification (only 17% of beds include a stratified division). The bulk of these beds are therefore massive, with only normal or reverse grading observed (or both; Fig. 2). Beds of the second type are thinner (average thickness of 0.5 m), finer grained (lapilli tuffs and tuffs), and 67% include a stratified division above the massive division.

Coarse beds are up to 30 m in thickness (Tassé in Dimroth et al., 1974). Tassé et al. (1978) give median bed thicknesses of 0.25–0.5 m for their area A2 sections and 0.6–1.5 m for their area A3 sections. Overall, beds are also relatively coarse, with several clasts over 1 m reported (e.g. Tassé in Dimroth et al., 1974). The tuffaceous matrix of the coarse beds — and the finer beds as a whole — are very rich in plagioclase crystals (Fig. 4b). Amygdaloidal clasts are present and can reach several centimetres (Fig. 4c). Many volcanic clasts are plagioclase-phyric, but some are dense (nonvesicular) and aphyric (Fig. 4d), whereas others are aphyric, but amygdaloidal (Fig. 4e, middle).

Distal facies at area A1

Outcrops in D'Alembert Bay on Lake Duparquet (area A1, Fig. 3) contain layers of fine tuff to lapilli tuff, rich in feldspar crystals. Some of these crystals appear to be zoned on outcrop. Blocks up to 30 cm across are seen in the lapilli tuff. Fragments (blocks and lapilli) are feldspar-phyric to aphyric, mafic to felsic (visual estimate), and rounded to angular. The finer grained beds show channels and rare cross-bedding, and are interpreted as turbidite sequences (station 06-PSR-177). The authors conclude that area A1 is indeed a distal site of the D'Alembert tuff (*see also* 'Geochemistry' section below).

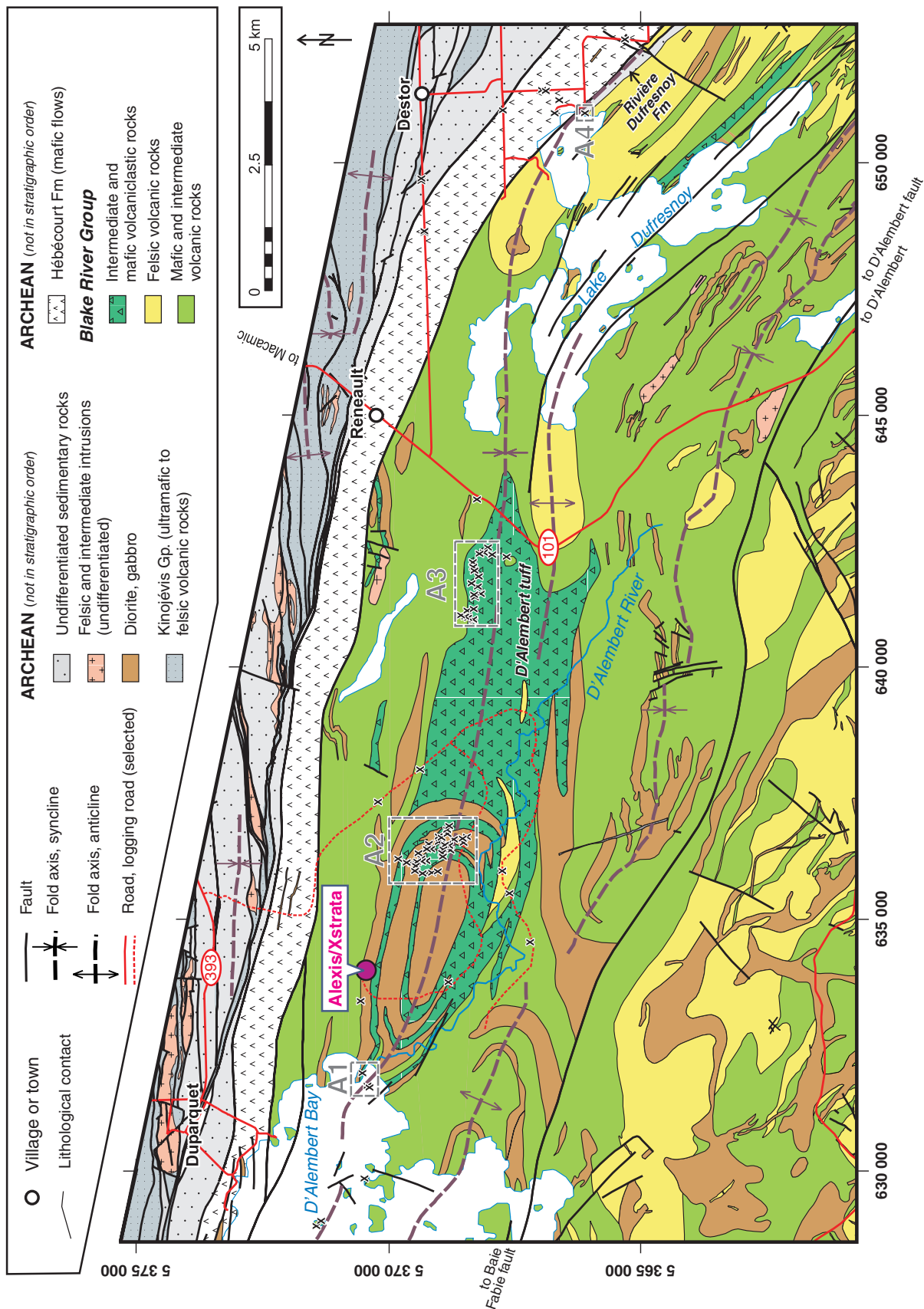


Figure 3. Simplified geology of the area between Lake Duparquet (including D'Alembert Bay) and Lake Dufresnoy, showing the distribution of the D'Alembert tuff and the senior author's 2006 field stations ("x"; only one station out of two shown in area A2). The pink dot represents the recent 'Baie D'Alembert' volcanogenic massive sulphide-style discovery. The rocks surrounding the tuff are dominantly intermediate to mafic volcanic rocks. Mafic to intermediate intrusions and felsic volcanic rocks have been omitted from the Kinojévis Group for clarity. Geology modified from 1:20 000 maps (NTS 32 D/06, 32 D/07, 32 D/11) by Ministère des Ressources naturelles et de la Faune (Québec). The UTM grid (NAD 83, zone 17) is superimposed.

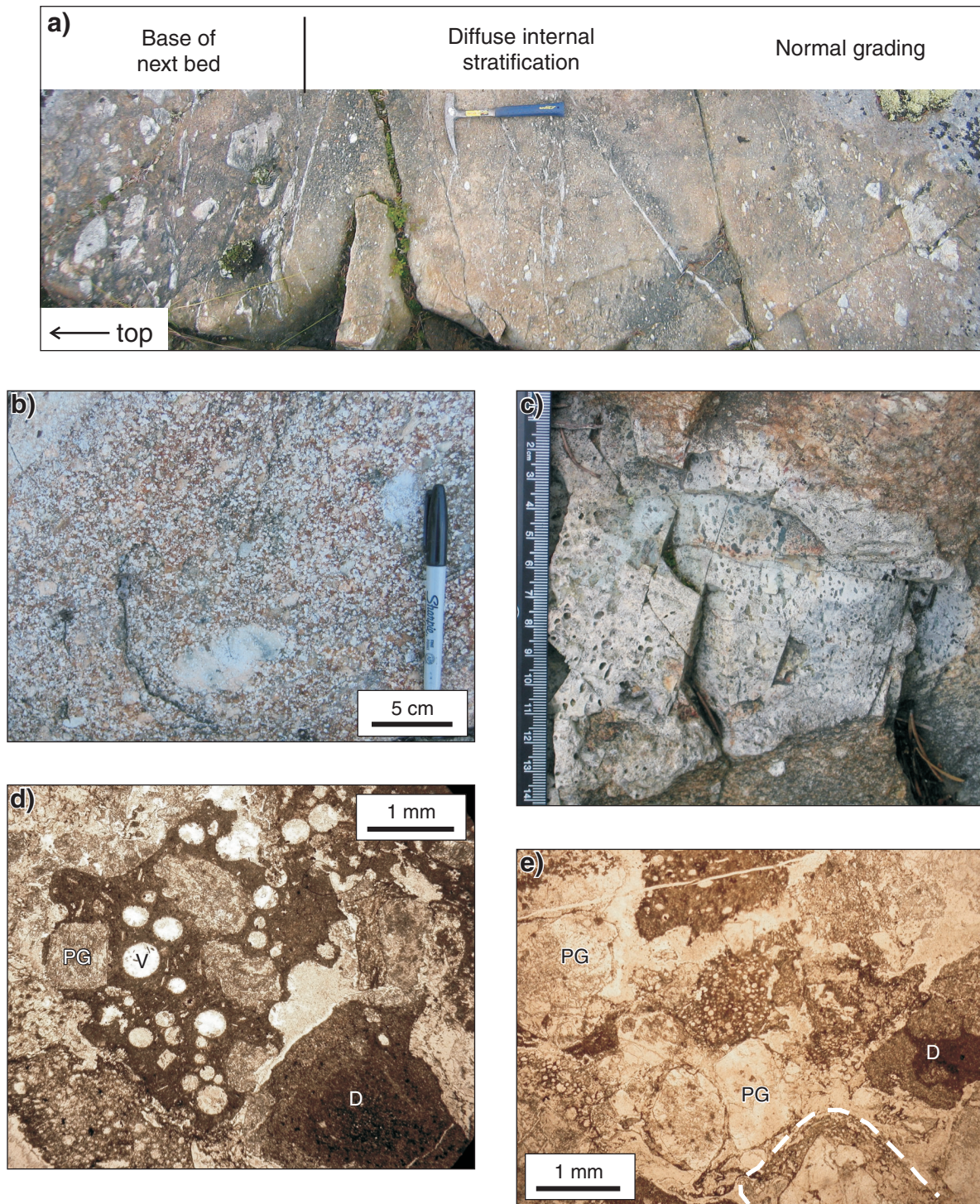


Figure 4. The D'Alembert tuff. **a)** Subhorizontal outcrop in area A3, showing the summit of a thick, normally graded bed and the base of another one. The east-striking strata dip subvertically; younging is to the south (station 06-PSR-162); hammer for scale is 32 cm long. **b)** Subhorizontal outcrop in area A2, illustrating the high plagioclase content in a fine lapilli tuff or coarse tuff (station 06-PSR-030). **c)** Close-up view of a block-sized, aphyric, moderately amygdaloidal clast at the same station as Figure 4a. There, most fragments are plagioclase-phyric, but this one is not. Ruler graduated in centimetres. **d), e)** Photomicrographs showing a coarse tuff from area A2 containing intermediate to mafic volcanic fragments ranging from dense (D) to formerly vesicular (V) (now amygdaloidal) and from aphyric to plagioclase-phyric (PG; porphyritic example outlined in Fig. 4e). Free-standing plagioclase crystals such as seen in Figure 4e are also an important component. Very few microlites are present in the intermediate to mafic fragments, the groundmass of which is inferred to consist of altered glass. Plane-polarized light (sample BR-020).

Possible distal facies at area A4

At Destor beach (site A4 on Fig. 3; stop III-6 from Dimroth and Rocheleau (1979)), one small outcrop exposes about 7 m of fine tuff (mudstone) to lapilli tuff (conglomeratic) beds (Fig. 5a). Beds are a few millimetres to 20 cm thick. Coarser beds display a few aphyric, possibly felsic volcanic clasts, mostly 1 cm or less across. Finer layers have plane-parallel lamination, but no obvious crosslamination. Rocks have been affected by synsedimentary and tectonic deformation including isoclinal folding. Tassé et al. (1978) suggested that petrographically, the Destor beach deposits are “similar to those of D’Alembert”; however, Goutier (1997) assigned them to his Rivière Dufresnoy Formation (Fig. 3).

For comparison, the typical outcrops of the Rivière Dufresnoy Formation are located a further 2 km to the south-east (Stop III-7 from Dimroth and Rocheleau (1979)). Station 94-JG-7219 shows 70% medium- to coarse-grained sandstone (normally graded to planar-laminated beds, 3–100 cm thick), and 30% mudstone (gray to black beds 1–13 cm thick; Fig. 5c). Nearby, station 94-JG-7221 displays 10% pebbly sandstone beds with channelized bases, 70% coarse- to very coarse-grained sandstone, and 20% siltstone.

Petrographic examination of a lapilli-bearing tuff or granule-bearing volcanogenic sandstone from Destor beach shows a variety of clasts ranging from microporphyritic and/or plagioclase-phyric mafic or intermediate rock to fine-grained, possibly felsic rock, coexisting with slightly altered 0.5–3 mm long plagioclase crystals and possibly traces of elongate mudstone fragments (Fig. 5b). The feldspar crystals and porphyritic clasts could have been derived from the same source as these components in the D’Alembert tuff, but some lava flows also contain plagioclase in the region so a source other than that of the D’Alembert tuff is also plausible. Because the Rivière Dufresnoy Formation contains a significant mudstone component, the occurrence of a possible mudstone intraclast in the Destor beach turbidite sequences argues against a correlation of this outcrop with the D’Alembert tuff.



Figure 5 (opposite). Site A4 and other sites previously thought to be D’Alembert tuff correlatives. **a)** Steeply dipping part of the Destor beach outcrop (station 06-PSR-156). The bed just to the right of the pen tip is isoclinally folded, yet synsedimentary deformation features such as load casts are still visible in other beds (arrow). North and younging are to the left. **b)** Station 94-JG-7219 in the Rivière Dufresnoy Formation, 2 km to the southeast, showing the succession of sandstone and mudstone beds. The scale bar is graduated in centimetres (see text for details). **c)** Photomicrograph of a sand-grade bed from Destor beach, containing altered plagioclase crystals (PG), plagioclase-phyric volcanic clasts (example outlined), and a tachylitic volcanic fragment (T) or mudstone intraclast (M).

Geochemistry

Newly collected samples were processed by Actlabs in Ancaster, Ontario; they analyzed major elements by fusion XRF and the trace elements discussed herein by fusion ICP-MS. From the D'Alembert tuff area the authors show eleven volcanoclastic samples (coarse tuff to tuff breccia), four lavas (pillowed to massive), and one gabbro crosscutting the tuffs in area A2. These rocks range in composition from basalt to andesite (Fig. 6a, b). All D'Alembert tuff samples plot as transitional or calc-alkaline on the La-Yb and Th-Yb diagrams, but two area A3 rocks plot as tholeiitic on the Zr-Y diagram (Fig. 6c, d, e). These two plot as transitional on the La-Yb and Th-Yb diagrams, and contain about twice as much TiO_2 (1.21–1.30%) than the other seven volcanoclastic samples (0.52–0.69%). The Ti contents are not obviously related to grain size. There could be several geochemical subunits in area A3, and more sampling will be done in this sector to better characterize the chemical variation within the D'Alembert tuff.

One volcanoclastic rock from area A1, consisting of a fine lapilli tuff from thin beds with very abundant feldspar crystals (sample BR-083), is distinctively more calc-alkaline on the Barrett and MacLean (1999) graphs (Fig. 6c, d, e). This sample also has the steepest slope on the multi-element plots (Fig. 6f). For the low-Ti volcanoclastic samples from areas A2 and A3, multi-element plots reveal slightly spiked patterns, moderate slopes, and a moderate Nb-Ta anomaly (Fig. 6f). The two high-Ti rocks from area A3 have somewhat gentler slopes, and less pronounced Nb-Ta anomalies. All D'Alembert tuff samples have small positive Zr-Hf anomalies and small negative Ti anomalies, resembling in those respects recent calc-alkaline arc andesite such as those from Redoubt Volcano in Alaska (Fig. 6g).

Stadacona unit

Host volcanic sequence

The Blake River Group volcanic rocks between the Larder Lake–Cadillac Fault and Lake Osisko (Fig. 7) constitute a package of moderately northward dipping, north-facing strata. The package includes, in its middle part, an intermediate to mafic volcanoclastic unit, historically known as the Stadacona “breccia” (Goodwin et al., 1972) or Stadacona tuff and agglomerate (Wilson and McQuarry, 1948). The use of ‘breccia’ is incorrect relative to the definition of Appendix A, since the rocks do not include more than 75% blocks or bombs, so the present authors simply call it the “Stadacona unit” (informal name) for simplicity. Pillow lavas are present above, below, and locally within the volcanoclastic unit (e.g. Goodwin et al. (1972); Dimroth and Rocheleau (1979); present authors’ observations), confirming a submarine depositional setting.

Lateral extent and thickness

The approximately east-striking Stadacona unit extends about 10 km laterally and nearly 1 km to the north. True stratigraphic thickness must be less, because Gilbert (1986) notes that dips in the Lake Pelletier area are as low as 20° locally. He estimated a 600 m true maximum thickness for a sequence including the volcanoclastic rocks (lapilli tuff, tuff breccia, tuffs) as well as intercalated lavas and some mafic intrusions.

Observations

Overall, the Stadacona unit is more deformed than the D'Alembert tuff, as reported by Dimroth and Rocheleau (1979, p. 147). A weak schistosity is commonly developed and the clasts are elongate (Fig. 8a). Plagioclase crystals (Fig. 8b, c, d) are ubiquitous in the tuff fraction, which is commonly very dark grey or bluish grey on fresh surfaces. Subangular to subrounded, plagioclase-phyric, variably amygdaloidal, intermediate to mafic clasts are commonly present, but the clast assemblage is polymict. For example, felsic fragments are readily apparent at the top of the Stadacona unit just east of the Granada road (Fig. 8b). Near the top of the unit in northeastern Lake Pelletier, a bed, 10 m thick or less consists of less than 50 cm angular fragments of aphanitic rhyolite. Pyrite is commonly present in trace amounts. Carbonate and chlorite occur both in amygdaloids and in the tuffaceous matrix. Epidote occurs locally in amygdaloids (Fig. 8e). Ash- to lapilli-sized intermediate to mafic volcanic fragments contain 0–40% amygdaloids and 0–40% plagioclase phenocrysts, commonly in a tachylitic groundmass. Free quartz crystals, derived from felsic clasts, occur in the matrix of many tuffs (Fig. 8f). Gilbert (1986) reported isolated clinopyroxene (augite) crystals.

Gilbert (1986) noted the heterogeneous character of the Stadacona unit in terms of grain size and clast compositions, with facies changes visible both laterally and in a north-south direction. Graded tuff breccia beds in the central portion of the unit are 5–20 m thick; tuff beds are very rare in the Lake Pelletier area and those present do not exceed 15 cm thick. Dimroth and Rocheleau (1979) suggested that many of the primary features of the unit have been obliterated by deformation and metamorphism, but that ‘pumice’ relicts can still be identified in the ‘matrix’. They also noted that the thicker beds have reverse grading near their bases, passing upward into a normally graded massive division, and finally a well stratified upper division. Thinner beds are normally graded. These bedding features are comparable to those of the D'Alembert tuff and the Jévis Sud tuff (Fig. 2).

Geochemistry

The authors have analyzed three volcanoclastic samples from the Stadacona unit. All three are basalt samples that mostly plot as tholeiitic, although one sample plots as

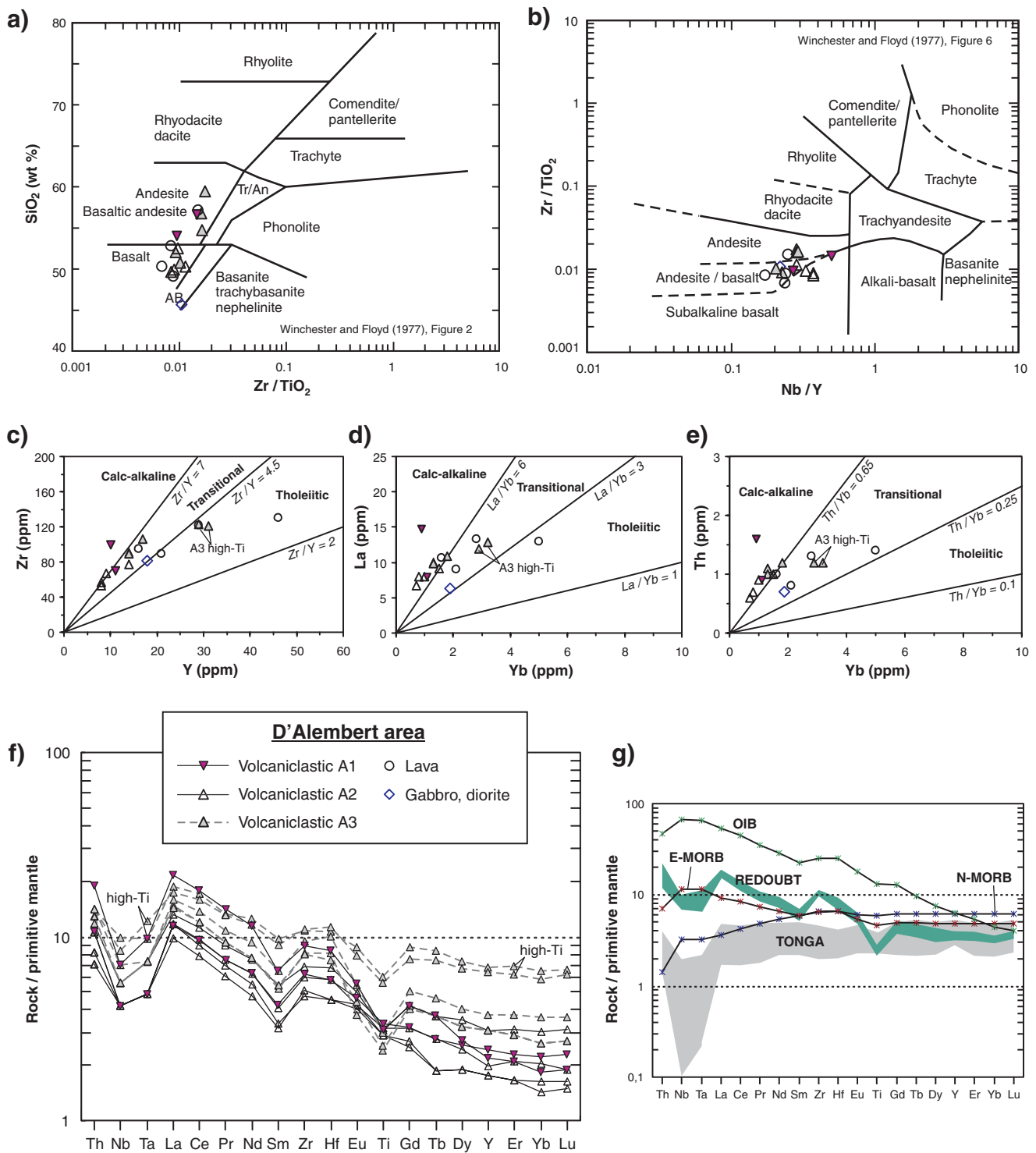


Figure 6. Geochemistry of the D'Alembert tuff and neighbouring lavas and intrusions. **a), b)** Classification diagrams from Winchester and Floyd (1977) show that all samples are andesite, basaltic andesite, or basalt. **c), d), e)** Affinity diagrams from Barrett and MacLean (1999). See text for discussion. **f)** Primitive mantle-normalized multi-element plots for volcaniclastic rocks only. The elements chosen, except Eu, are thought to be largely immobile under greenschist-facies metamorphic conditions (e.g. Jenner, 1996). **g)** Profiles for normal mid-ocean ridge basalt (N-MORB), enriched MORB (E-MORB), and ocean-island basalt (OIB), shown for comparison (the vertical axis spans three orders of magnitude whereas Figure 6f only displays two). Normalization values in Figures 6f and 6g and MORB/OIB profiles are from Sun and McDonough (1989). Also shown are the summarized spectra of modern tholeiitic island-arc lavas from Tonga (21 andesite and basaltic andesite from several sources) and that of calc-alkaline andesite from Redoubt Volcano on the Alaska Peninsula (31 samples of the 1989–1990 eruption products from Nye et al., 1994). Both types of arc lavas have Nb-Ta anomalies, but the Tonga (tholeiitic) patterns are much flatter. Tr/An = trachyandesites, AB = alkali basalt.

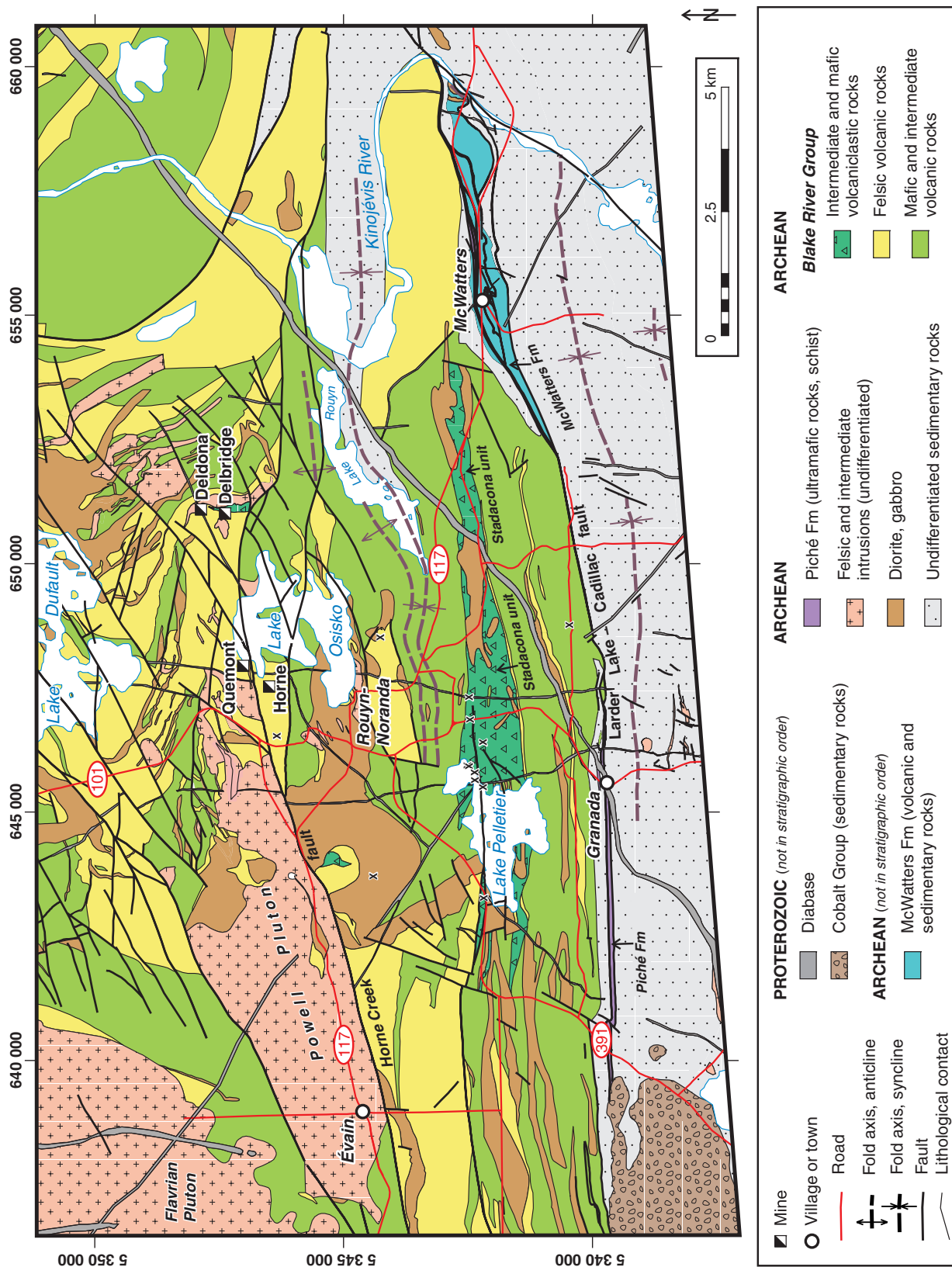


Figure 7. Simplified geology of the area between Évain and Kinojévis River, showing the distribution of the Stadacona unit (turquoise colour with triangles) and the senior author's 2006 field stations ("x"). Northward younging, mafic to intermediate volcanic rocks are dominant above and below the Stadacona unit. Geology modified from 1:20 000 maps (NTS 32 D/02, 32 D/03, 32 D/06, 32 D/07) by Ministère des Ressources naturelles et de la Faune (Québec). The UTM grid (NAD 83, zone 17) is superimposed.

transitional on the La-Yb graph (Fig. 9a–e). Despite the presence of xenocrystic quartz and felsic clasts, overall the Stadacona unit volcanoclastic rocks are clearly more mafic and more tholeiitic than the D’Alembert tuff, and plot in distinct domains on the graphs shown. Gilbert (1986) analyzed eleven Stadacona volcanoclastic samples, ranging in size from lapilli tuff to tuff breccia, for major elements and obtained ten basalt samples and one basaltic andesite based on the silica contents alone.

The multi-element profiles of the Stadacona samples in this study are flatter than those of D’Alembert tuff samples (Fig. 9f), as expected for tholeiitic rocks. The D’Alembert tuff samples display a Nb-Ta trough, that does not appear on the Stadacona profiles due to lower Th values. To summarize, preliminary data indicates that the Stadacona unit is very different geochemically from the D’Alembert tuff, even though they have many physical characteristics in common (Table 1). Implications for stratigraphic correlations and the volcanic architecture of the Blake River Group are outlined below.

Jévis Sud tuff

Host volcanic sequence and economic geology

In the area southeast of Lake Dufresnoy, but north and east of the D’Alembert fault, Blake River Group volcanic rocks are folded, faulted, and generally northwest striking and steeply dipping (Goutier (1997); Fig. 10). As with the D’Alembert tuff host sequence farther west, intermediate to mafic lavas dominate the package, but here they coexist with a significant amount of felsic volcanic rocks and the synvolcanic Cléricky Pluton (marked “tonalite” on Fig. 10). The Bouchard-Hébert volcanogenic massive sulphide mine (formerly Mobrun) demonstrates the mineral potential of the area. The mine exploited two distinct deposits: the Main lens (3.3 Mt; Barrett et al. (1992); Riopel et al. (1995)), and the 1100 lens (9.6 Mt; Doucet et al. (2006), p. 66). South of the D’Alembert fault, Blake River Group rocks belong to a different package that hosts the classic Noranda-type Cu-Zn volcanogenic massive sulphide deposits of the Central Noranda camp; these volcanic rocks are intruded by the postvolcanic Lac Dufault Pluton and numerous diorite and/or gabbro dykes.

The Bouchard-Hébert area contains at least two thin and elongate intermediate to mafic volcanoclastic units (Fig. 10), called the Jévis Nord tuff and the Jévis Sud tuff (informal names; Pilote et al., 2007). The latter unit, which parallels the Kinojévis River, was the first in the Blake River Group to be interpreted as a sequence of “pumice flows” (submarine pyroclastic flow deposits) by U.S. volcanologist Dick Fiske back in the 1970s (Goodwin et al., 1972) and has locally been called “fiskite de Cléricky” (Trudel, 1978).

Salient observations

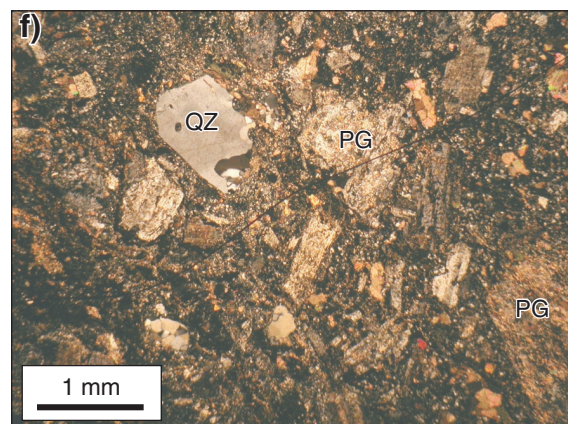
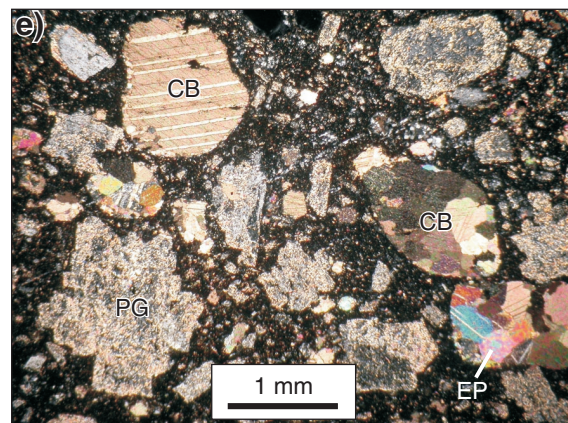
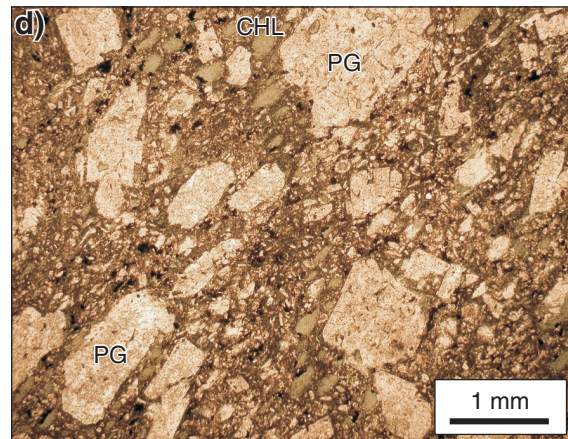
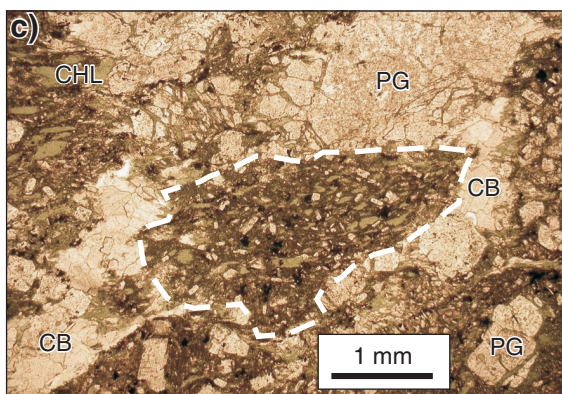
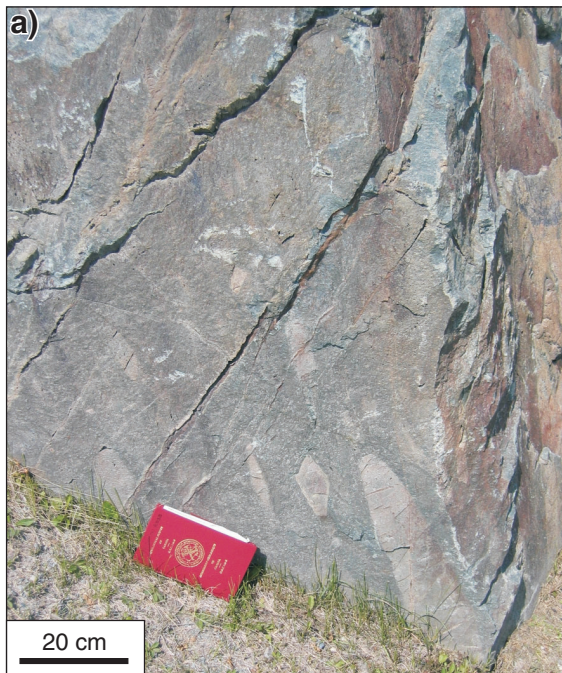
At Jévis Sud, pillow lavas are exposed stratigraphically above and below volcanoclastic rocks. The volcanoclastic sequence comprises tuff, lapilli tuff, and tuff breccia; dips steeply; and stratigraphic younging is to the north. One coarse depositional unit, several metres thick, has reverse grading at the base, then a massive tuff-breccia zone, followed by normal grading and finer grained, planar-bedded material (Fig. 2). This sequence is quite similar to that observed in many coarse beds from the D’Alembert tuff (*see above*). Normally graded, finer grained beds resembling turbidite sequences, with partial Bouma sequences, occur above the thick beds.

Most fragments in the coarse beds are plagioclase-phyric, and variably amygdaloidal. Trudel (1978) reported that lithic fragments are dominantly andesitic and display various petrographic textures (porphyritic, pilotaxitic, vitreous, tachylitic, etc.). Plagioclase crystals are a major constituent of the tuff fraction. Dense felsic clasts increase in abundance toward the base of the section. These felsic clasts are plausibly derived from a fragmental silicic lava (Fig. 11a) stratigraphically underlying the intermediate to mafic volcanoclastic rocks. In terms of the visual aspect (and possibly depositional processes), the Jévis Sud tuff outcrops appear equivalent to the proximal D’Alembert tuff (Table 1).

The Jévis Sud tuff volcanoclastic rocks are intruded by slightly discordant intermediate to mafic sills (some several metres thick) and minor, thinner amoeboid dykes. Some of these dykes are separated into globular masses with chilled margins, called “pillows” by Dimroth and Rocheleau (1979, p. 50) (Fig. 11b, c). The best interpretation of the “pillowed dykes” is that the volcanoclastic debris was unconsolidated and water saturated when the dykes were emplaced. This also demonstrates that the volcanoclastic deposits were not welded at the time of dyke emplacement (Trudel (1978) signalled that “pumice” clasts appeared “welded” in thin section).

GEOCHRONOLOGY

As the three major intermediate to mafic volcanoclastic units described here (D’Alembert tuff, Jévis Sud tuff, Stadacona unit) and the Bousquet scoriaceous tuff belong to different rock packages within the Blake River Group, the question of whether or not they have the same age naturally arises. High precision U-Pb dating, although very difficult given the rock compositions, would contribute significantly to resolving correlation questions. Therefore a serious attempt at dating the D’Alembert tuff, the Stadacona unit, and the Bousquet scoriaceous tuff was made. For each unit, two to three geochronological samples were collected in distinct sites to increase the odds of success. The volcanoclastic samples yielded very few zircon grains, and most zircon grains are considered to be inherited, rather than magmatic in origin.



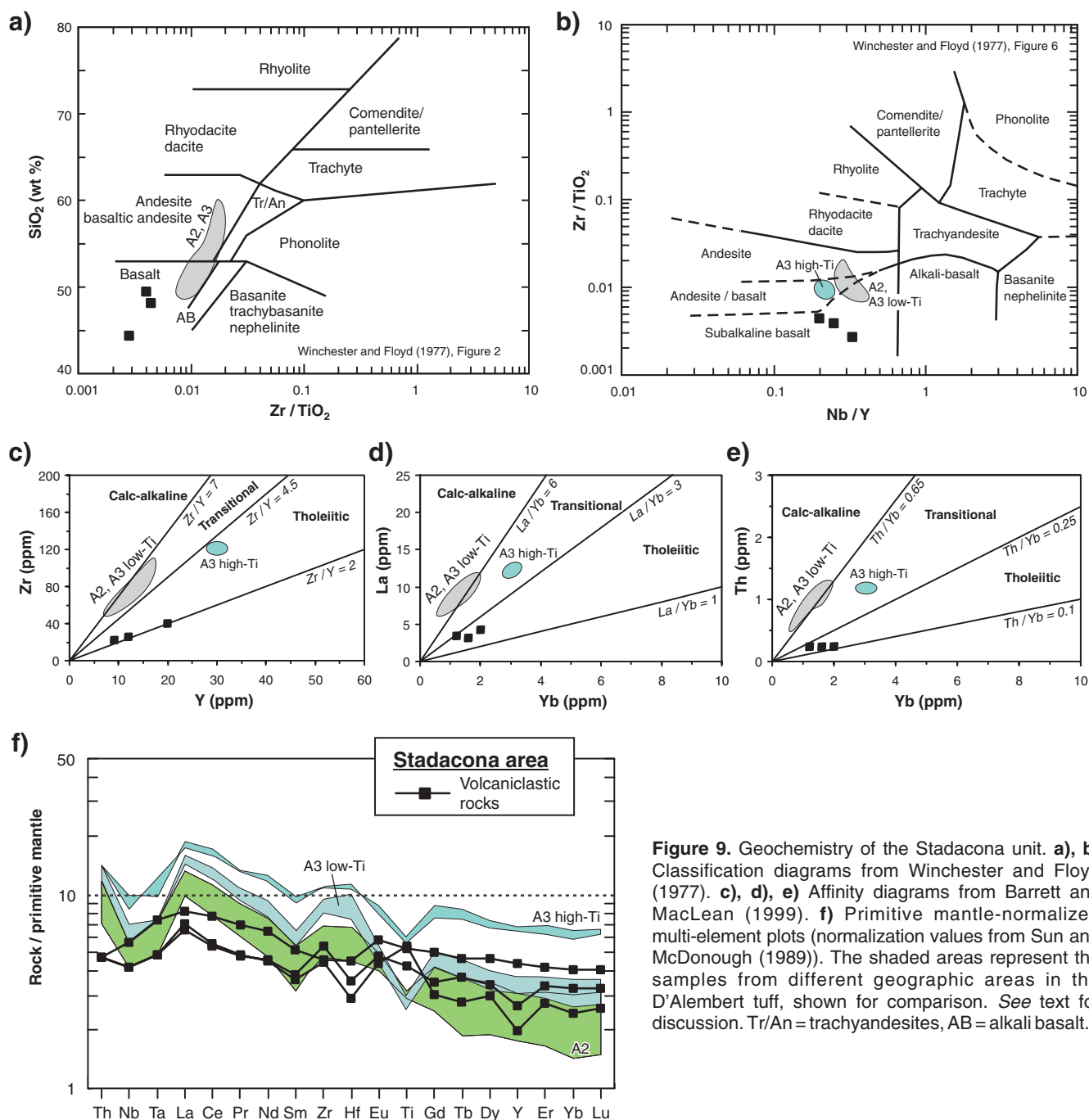


Figure 9. Geochemistry of the Stadacona unit. **a), b)** Classification diagrams from Winchester and Floyd (1977). **c), d), e)** Affinity diagrams from Barrett and MacLean (1999). **f)** Primitive mantle-normalized multi-element plots (normalization values from Sun and McDonough (1989)). The shaded areas represent the samples from different geographic areas in the D'Alembert tuff, shown for comparison. See text for discussion. Tr/An = trachyandesites, AB = alkali basalt.

Figure 8 (opposite). The Stadacona volcaniclastic unit. **a)** Near-vertical rock face on the Granada road (Fig. 7), showing subvertical elongation of aphyric clasts in a tuff breccia (station 06-PSR-182). **b)** Subhorizontal outcrop of a coarse lapilli tuff with small blocks east of the Granada road outcrop, showing a mixture of mafic to intermediate and felsic clasts, and the plagioclase-rich matrix (station 06-PSR-184). **c), d)** Photomicrographs (PPL) of a coarse tuff containing about 50% lightly to strongly sericite-altered whole or broken plagioclase crystals (PG), as well as intermediate to mafic volcanic clasts in various states of preservation (slightly plagioclase-phyric, amygdaloidal example outlined), in a finer grained, largely irresolvable matrix. Some of the unbroken plagioclase crystals likely belong to volcanic fragments which are difficult to separate from the matrix due to extensive alteration. Former vesicles in the volcanic clasts are now filled by chlorite (CHL). This mineral also fills cracks in the crystals and replaces some of the matrix, together with opaque minerals and local carbonate (CB) (sample BR-088). **e), f)** Photomicrographs (XPL) of sample BR-089, a lapilli tuff containing far fewer free plagioclase crystals, but rather a polymict assemblage of volcanic fragments including intermediate to mafic clasts (dominant) and rare felsic clasts. The rare felsic clasts contain some partly resorbed quartz phenocrysts (QZ), which also occur disseminated in trace amounts, e.g. in Figure 8f; they were presumably liberated from disaggregated felsic clasts. Figure 8e shows a single tachylitic clast which contains about 25% strongly sericite-altered plagioclase crystals and 25% undeformed amygdaloids containing carbonate and local epidote (EP). PPL = plane-polarized light; XPL = crossed-polarized light.

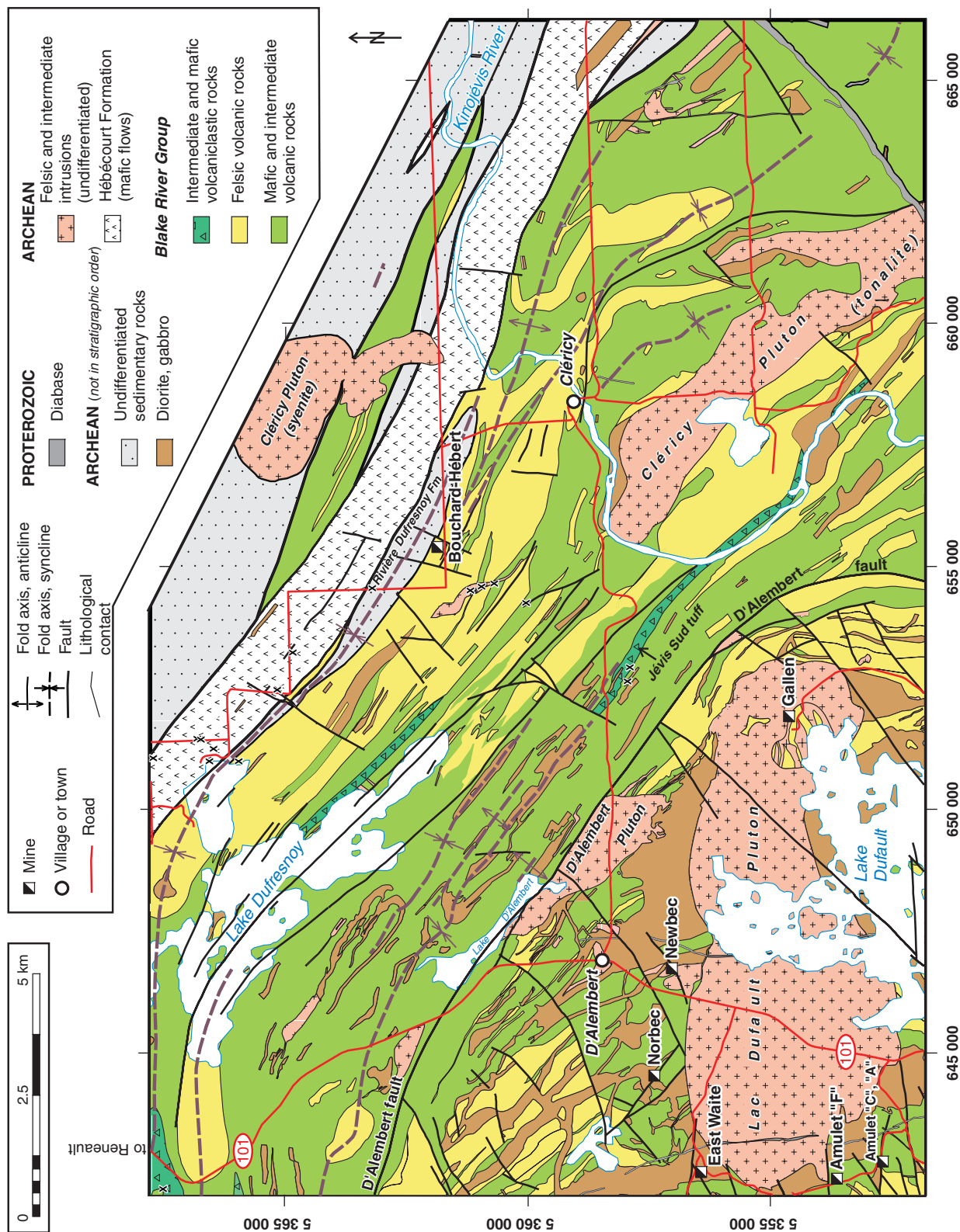


Figure 10. Simplified geology of the area between Lake Dufresnoy and Lake Dufault, showing two thin bands of intermediate to mafic volcanoclastic rocks, including the Jévis Sud tuff. The senior author's 2006 field stations appear as 'x's. The rocks surrounding the intermediate to mafic volcanoclastic units include a significant component of felsic volcanoclastic rocks, as opposed to those found around the D'Alembert tuff. Geology modified from 1:20 000 maps (NTS 32 D/06, 32 D/07) by Ministère des Ressources naturelles et de la Faune (Québec). The UTM grid (NAD 83, zone 17) is superimposed.

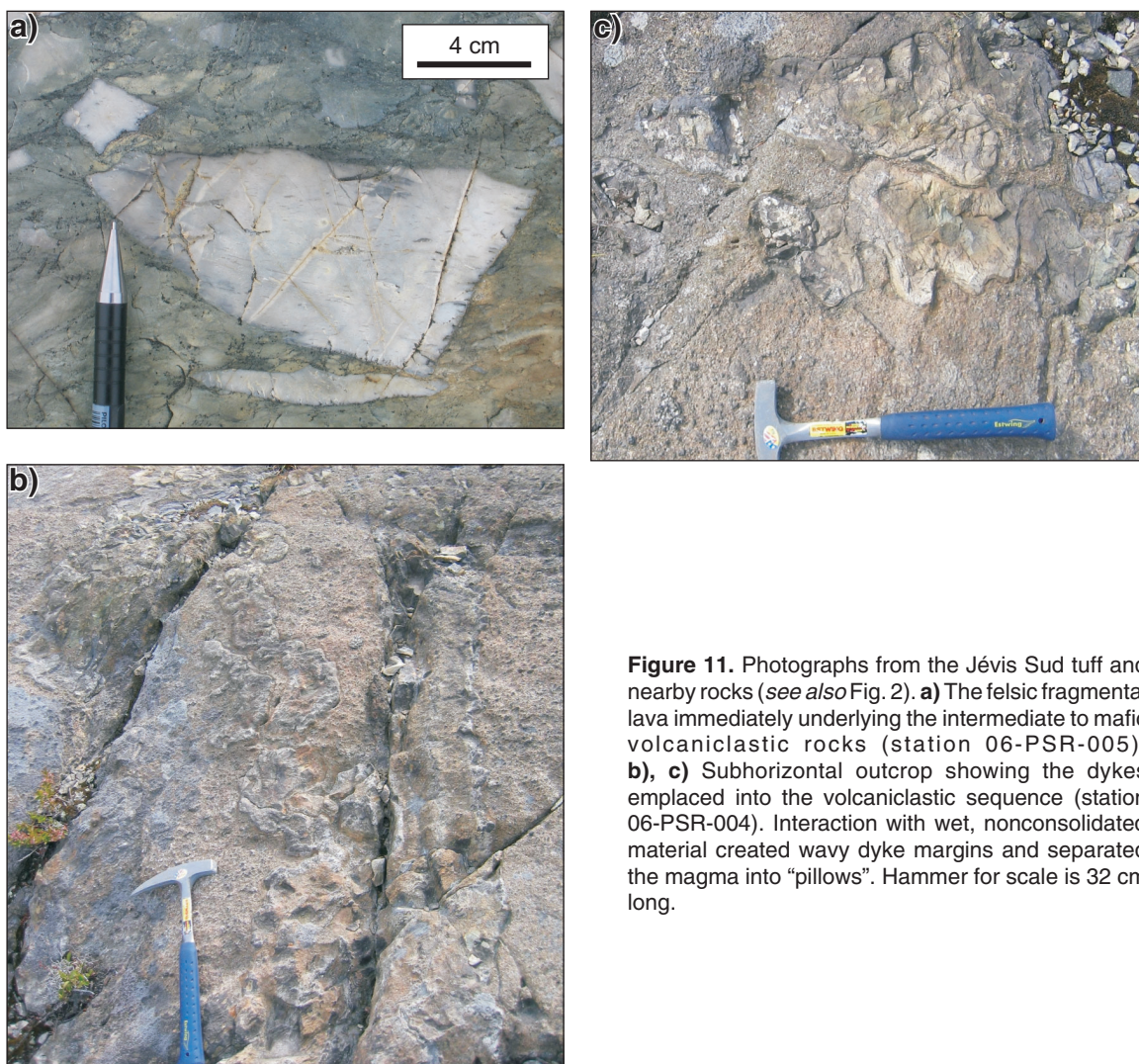


Figure 11. Photographs from the Jévis Sud tuff and nearby rocks (*see also* Fig. 2). **a)** The felsic fragmental lava immediately underlying the intermediate to mafic volcaniclastic rocks (station 06-PSR-005). **b), c)** Subhorizontal outcrop showing the dykes emplaced into the volcaniclastic sequence (station 06-PSR-004). Interaction with wet, nonconsolidated material created wavy dyke margins and separated the magma into “pillows”. Hammer for scale is 32 cm long.

It does not appear possible to obtain crystallization ages for the juvenile component in the intermediate to mafic volcaniclastic rocks themselves at present.

DISCUSSION

Several volcanological aspects warrant further discussion, including the depositional setting, transport processes, fragmentation mechanism of juvenile clasts, and eruptive setting of the Blake River Group intermediate to mafic volcaniclastic rocks described here. This discussion then leads to comments on the stratigraphic correlation (or lack of) between the different units and the implications for the volcanic architecture of the Blake River Group and the exploration for volcanogenic massive sulphide deposits.

Depositional setting

The presence of pillow lavas in the immediate host sequences of the investigated volcaniclastic units leads to the unequivocal interpretation of a subaqueous depositional environment. Turbidite sequences within the volcaniclastic units themselves further strengthen this idea. Given the lack of observed tractional reworking in the volcaniclastic deposits, the present authors can suppose that water depth was below storm wave base (≥ 200 m; e.g. Mueller et al. (1994)). It is not possible to further constrain the water depth for the Blake River Group units; the traditionally held view that magma vesiculation is suppressed at depths of several kilometres due to extreme hydrostatic pressures has been rendered invalid by the discoveries of vesicular juvenile fragments and vesicular coherent lavas in deep oceans during recent submersible missions (e.g. Clague et al., 2003, and references therein).

Transport processes and source of the fragments

From the poor sorting, structures, and internal organization of the coarse beds studied, the authors infer that they represent the deposits of water-supported, high-density mass flows, also referred to as submarine density currents or debris flows (Fisher, 1984). These currents were likely, but not demonstrably, of the eruption-fed type (White, 2000) i.e. submarine pyroclastic flows. Clast shapes and the lack of welding do not imply a high emplacement temperature and water must have been the interstitial fluid during transport, at least at the deposition sites.

Given the composition of the coarse beds, explosive eruptions of crystal-rich, gas-charged magmas are the most probable source of the bulk of the fragments. The viscosity of magma increases with the proportion of crystals; for example, adding 50% crystals to a liquid-only magma will increase its viscosity by a factor of two to five (Spera, 2000). Viscous magmas do not flow easily in volcanic conduits and do not permit escape of magmatic volatiles, increasing the internal gas pressure and thereby favouring explosive eruptions. Therefore, it is likely not a coincidence that all three units investigated contain abundant plagioclase crystals, and vesicular material.

The finer grained beds were clearly deposited by turbidity currents, as suggested by the presence of Bouma sequences. For the D'Alembert tuff, the fine-grained beds are mostly seen on Lake Duparquet (and perhaps at Destor beach), in the "distal ends" of the deposit. This suggests that the thin, fine-grained beds represent the distal equivalent of the thick, coarse beds: density currents deposit their coarsest fractions relatively near their sources. On the other hand, turbidite sequences are interbedded with coarse beds in the Jévis Sud tuff; this suggests a scenario in which the fine-grained material was produced by the same large-volume explosive eruptions that generated the fragments in the coarse-grained beds, but the fines took longer to sediment.

Generation of juvenile material

The exact fragmentation process ('magmatic' or phreatomagmatic) for the juvenile fraction (including the feldspar crystals) is difficult to ascertain. Magmatic explosive eruptions occur because the eruptions are inherently explosive (high magma viscosities, high gas contents, etc.), without the need for interaction between magma and the environment. Phreatomagmatic eruptions are explosive because of the violent interaction of magma with external fluids (most commonly groundwater, lake water, or seawater). The pyroclastic rocks produced by magmatic explosive eruptions tend to be more vesicular, on average, than those produced by phreatomagmatic eruptions (e.g. Houghton and Wilson, 1989), but this criteria alone is insufficient to convincingly distinguish between the two types. Phreatomagmatic products

normally involve more nonjuvenile material (lava fragments, basement rocks, etc.), but a submarine density current from a magmatic explosion can also entrain such debris along the way. The present authors are therefore unable to unambiguously establish the fragmentation process of juvenile clasts at this stage.

Eruptive setting

A submarine transport and depositional environment does not necessarily imply submarine eruptions, as pyroclastic flows can be generated on land and then enter the sea. When Dimroth and Demarcke (1978) and Tassé et al. (1978) studied the D'Alembert tuff they recognized it as the product of a series of submarine density currents, but they could not conceive that the vent site(s) had been subaqueous as well. They concluded that a subaerial volcano had been present nearby and was the source of the pyroclastic rocks (Dimroth and Demarcke, 1978; Tassé et al., 1978). At the time, hydrostatic pressure was widely thought to completely suppress explosivity beyond a certain ocean depth; it is now known that explosive eruptions are possible at water depths of several kilometres (e.g. Head and Wilson, 2003). Furthermore, since the depositional environment was likely submarine for the whole Blake River Group and older volcanic sequences in this part of the Abitibi Greenstone Belt, there are no plausible emergent sources for the pyroclastic rocks and the explosive eruptions therefore had to be submarine.

Stratigraphic correlations and volcanic architecture

It is intriguing to find so many common characteristics in the three volcanoclastic units described here; the Bousquet scoriaceous tuff in the Doyon-Bousquet-LaRonde mining camp also shares a number of common traits (Table 1). An informal correlation between at least the D'Alembert tuff, the Jévis Sud tuff, and the Stadacona unit seems possible based on their physical aspects. At the minimum, the outcrop, hand sample, and petrographic resemblances between these units have to be noted; however, a strict stratigraphic correlation would imply that all volcanoclastic units were derived at once from a common magma chamber, present in the upper crust beneath a large part of the Blake River Group. Such a giant shallow magma chamber would have produced a large regional-scale pluton, but such a feature is not currently recognized.

Mueller (2006) viewed the volcanoclastic units as "...andesitic ignimbrites and outflow sheets located along the double ring faults" of Pearson's (2005) megacaldera. This model implies that the three units discussed here were erupted at more or less the same time, in relation to the collapse of a giant caldera. One would expect that if this was the case, correlatable plagioclase-rich volcanoclastic rocks deposited by pyroclastic flows would indeed define a semicontinuous belt

in the periphery of the Blake River Group, something that cannot be confirmed thus far. One would also expect the volcanoclastic units to have been derived from the same magma, something that is contradicted by the present authors' preliminary geochemical data, which indicates that at least the D'Alembert tuff and Stadacona unit have very distinct signatures.

This distinct geochemical signature for two of the volcanoclastic units investigated argues against a common magmatic source — and therefore against the megacaldera model — except if the hypothesized magma chamber covering the entire area of the Blake River Group was strongly zoned. This zoning would somehow have been able to produce both tholeiitic basalt (e.g. the Stadacona unit) and calc-alkaline mafic to intermediate rocks (e.g. the D'Alembert tuff, and possibly the Jévis Sud tuff). Furthermore, to clarify this hypothetical 'giant zoned magma chamber' scenario, it would be necessary to explain why one magma type only seems preserved in volcanoclastic units from the northern part of the Blake River Group, whereas the other magma type seems limited to units exposed in the southern part.

It is much simpler to suppose that the Stadacona unit and the D'Alembert tuff were generated from two much smaller, geochemically distinct, magma chambers in different parts of the Blake River Group. In that scenario, the explosive eruptions could have taken place at different times and there is no necessary stratigraphic correlation between the volcanoclastic rocks. Their common physical characteristics could then be explained by similar processes affecting the respective magma chambers, i.e. crystal and gas enrichment leading to explosive eruptions, and then by similar submarine transport and deposition processes.

ECONOMIC IMPLICATIONS

The implications of this work for base-metal exploration in the Blake River Group are two-fold. The first relates to Pearson's (2005) megacaldera model, which has great appeal for explorationists, because calderas are major targets for volcanogenic massive sulphide deposits. One argument supporting the megacaldera hypothesis is the portrayal of a semicontinuous belt of presumably genetically related intermediate to mafic volcanoclastic rocks in the peripheral part of the Blake River Group. Both Daigneault and Pearson (2006) and Mueller (2006) proposed that megacaldera ring faults controlled the distribution of the volcanoclastic units, which were specifically referred to as "ignimbrites" erupted during caldera collapse. In such a scenario, correlatable volcanoclastic units representing submarine pyroclastic flow deposits should indeed define a semicontinuous belt in the periphery of the Blake River Group, something that cannot be confirmed at present. Preliminary geochemical data further

argues against the idea that the volcanoclastic units described here were derived from a common giant magma chamber. The present authors propose an alternative scenario in which the D'Alembert tuff and the Stadacona unit were derived from much smaller, geographically and chemically distinct magma chambers, without the need for a huge common chamber and a megacaldera.

The second economic implication of this work is that the volcanogenic massive sulphide potential of the peripheral areas of the Blake River Group, which contain the LaRonde Penna and Bouchard-Hébert mines, needs to be emphasized. Away from these two sectors, the Blake River Group periphery remains less well explored than the Central Noranda camp. One important difference between the peripheral areas and the central camp is the greater abundance of volcanoclastic rocks, as noted by Pearson (2005). LaRonde Penna and Bouchard-Hébert represent two of the largest volcanogenic massive sulphide deposits ever found in the Blake River Group, and they formed in part by seafloor replacement (Dubé et al., in press), a process which operates best on permeable, fragmental rocks. According to Doyle and Allen (2003), the majority of replacement-style volcanogenic massive sulphide deposits are in fact associated with volcanoclastic rocks, including both pumiceous and lithic-rich facies; they cite Kidd Creek, the Horne H lenses, Mattabi, Coniagas, and Ansil as Canadian examples. Doyle and Allen (2003) concluded that "pumiceous mass-flow deposits appear to be a particularly good host for the development of economic [VMS] deposits". The already mentioned press release by Alexis Minerals Corp. and Xstrata Copper about volcanogenic massive sulphide mineralization in the D'Alembert Bay area and the comment by Larocque and Hodgson (1993) that the immediate footwall of 1100 lens complex at Bouchard-Hébert consists of "an intermediate lapilli tuff" that contains altered pumiceous and lithic fragments suggest that the D'Alembert tuff, and similar volcanoclastic units in the Blake River Group, could potentially represent such "particularly good hosts".

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REFERENCES

- Ayer, J., Amelin, Y., Corfu, F., Kamo, S., Ketchum, J., Kwok, K., and Trowell, N.**
2002: Evaluation of the southern Abitibi greenstone belt based on U-Pb geochronology; autochthonous volcanic construction followed by plutonism, regional deformation and sedimentation; *Precambrian Research*, v. 115, p. 63–95.
- Ayer, J., Dubé, B., Goodfellow, W., Ross, P.-S., Bleeker, W., Taylor, B., Peter, J., Grunsky, E., Hillary, B., Thurston, P., Berger, B., Houlé, M., Beakhouse, G., Trowell, N., Snyder, D., McNicoll, V., Keating, P., Percival, J., Mercier-Langevin, P., Lauzière, K., Paradis, S., Goutier, J., Dion, C., Pilote, P., Legault, M., Monecke, T., Brouillette, P., Gosselin, P., and Van Breemen, O.**
2006: The Abitibi subprovince: an update on the goals and preliminary results of the PGS Program, TGI-3 Abitibi and Deep Search projects; in *Summary of Field Work and Other Activities 2006*, Ontario Geological Survey, Open File Report 6192, p. 4-1 to 4-19.
- Ayer, J.A., Thurston, P.C., Bateman, R., Dubé, B., Gibson, H.L., Hamilton, M.A., Hathway, B., Hocker, S.M., Houlé, M.G., Hudak, G., Ispolatov, V.O., Lafrance, B., Leshner, C.M., MacDonald, P.J., Péloquin, A.S., Piercey, S.J., Reed, L.E., and Thompson, P.H.**
2005: Overview of results from the Greenstone Architecture Project: Discover Abitibi Initiative; Ontario Geological Survey, Open File Report 6154, 146 p.
- Barrett, T.J. and MacLean, W.H.**
1994: Gisements de sulfures massifs de la région de Rouyn-Noranda; Ministère des Ressources naturelles (Québec), report ET 93-01, 127 p.
1999: Volcanic sequences, lithogeochemistry, and hydrothermal alteration in some bimodal volcanic-associated massive sulfide systems; in *Volcanic-associated Massive Sulfide Deposits: Processes and Examples in Modern and Ancient Settings*, (ed.) C.T. Barrie and M.D. Hannington; *Reviews in Economic Geology*, v. 8, p. 101–131.
- Barrett, T.J., Cattalani, S., Hoy, L., Riopel, J., and Lafleur, P.-J.**
1992: Massive sulfide deposits of the Noranda area, Quebec. IV. The Mobrun mine; *Canadian Journal of Earth Sciences*, v. 29, p. 1349–1374.
- Barrett, T.J., Cattalani, S., and MacLean, W.H.**
1991: Massive sulfide deposits of the Noranda area, Quebec. I. The Horne mine; *Canadian Journal of Earth Sciences*, v. 28, p. 465–488.
- Clague, D.A., Davis, A.S., and Dixon, J.E.**
2003: Submarine strombolian eruptions on the Gorda Mid-Ocean ridge; in *Explosive Subaqueous Volcanism*, (ed.) J.D.L. White, J.L. Smellie, and D.A. Clague; American Geophysical Union, *Geophysical Monograph*, v. 140, p. 111–128.
- Cole, J.W., Milner, D.M., and Spinks, K.D.**
2005: Calderas and caldera structures: a review; *Earth-Science Reviews*, v. 69, p. 1–26.
- Corfu, F.**
1993: The evolution of the southern Abitibi greenstone belt in light of precise U-Pb geochronology; *Economic Geology*, v. 88, p. 1307–1322.
- Corfu, F., Krogh, T.E., Kwok, Y.Y., and Jensen, L.S.**
1989: U-Pb geochronology in the southwestern Abitibi greenstone belt, Superior Province; *Canadian Journal of Earth Sciences*, v. 26, p. 1747–1763.
- Couture, J.-F. and Goutier, J.**
1996: Métallogénie et évolution tectonique de la région de Rouyn-Noranda; Ministère des Ressources naturelles (Québec), report MB 96-06, 110 p.
- Daigneault, R. and Pearson, V.**
2006: Physical volcanology of the Blake River caldera complex: a new interpretation of an old structure; in *The Komatiite-Komatiitic Basalt-Basalt Association in Oceanic Plateaus and Calderas: Physical Volcanology and Textures of Subaqueous Archean Flow Fields in the Abitibi Greenstone Belt*; Geological Association of Canada, Field Trip A3, p. 62–72.
- David, J., Dion, C., Goutier, J., Roy, P., Bandyayera, D., Legault, M., and Rhéaume, P.**
2006: Datations U-Pb effectuées dans la Sous-province de l'Abitibi à la suite des travaux de 2004-2005; Ministère des Ressources naturelles et de la Faune (Québec), report RP 2006-04, 22 p.
- de Rosen-Spence, A.F.**
1976: Stratigraphy, development, and petrogenesis of the central Noranda volcanic pile, Noranda, Quebec; Ph.D. thesis, University of Toronto, Toronto, Ontario, 166 p.
- Dimroth, E. and Demarcke, J.**
1978: Petrography and mechanism of eruption of the Archean Dalember tuff, Rouyn-Noranda, Quebec, Canada; *Canadian Journal of Earth Sciences*, v. 15, p. 1712–1723.
- Dimroth, E. and Rocheleau, M.**
1979: Volcanologie et sédimentologie dans la région de Rouyn-Noranda, Québec; Geological Association of Canada–Mineralogical Association of Canada Joint Meeting (Québec 1979), *Guidebook for Excursion A1*, 205 p.
- Dimroth, E., Boivin, P., Goulet, N., and Larouche, M.**
1973: Tectonic and volcanological studies in the Rouyn-Noranda area; Ministère des Richesses naturelles (Québec), report DP 138, 60 p.
- Dimroth, E., Côté, R., Provost, G., Rocheleau, M., Tassé, N., and Trudel, P.**
1974: Third progress report on the stratigraphy, volcanology, sedimentology and structure of Rouyn-Noranda area, counties of Rouyn-Noranda, Abitibi-west and Temiskamingue; Ministère des Richesses naturelles (Québec), report DP 300, 64 p.
- Dimroth, E., Cousineau, P., Leduc, M., and Sanschagrin, Y.**
1978: Structure and organisation of Archean subaqueous basalt flows, Rouyn-Noranda area, Quebec, Canada; *Canadian Journal of Earth Sciences*, v. 15, p. 902–918.
- Dimroth, E., Imreh, L., Rocheleau, M., and Goulet, N.**
1982: Evolution of the south-central part of the Archean Abitibi belt, Quebec. Part I: stratigraphy and paleogeographic model; *Canadian Journal of Earth Sciences*, v. 19, p. 1729–1758.
- Doucet, P., Moorhead, J., and Côté, S.**
2006: Report on mineral exploration activities in Québec 2005; Ministère des Ressources naturelles et de la Faune (Québec), report DV 2006-02, 88 p.

- Dubé, B., Mercier-Langevin, P., Hannington, M.D., Davis, D.W., and Lafrance, B.**
2004: Le gisement de sulfures massifs volcanogènes aurifères LaRonde, Abitibi, Québec: altération, minéralisation, genèse et implications pour l'exploration; Ministère des Ressources naturelles, de la Faune et des Parcs (Québec), report MB 2004-03, 112 p.
- Dubé, B., Mercier-Langevin, P., Hannington, M., Lafrance, B., Gosselin, G., and Gosselin, P.**
in press: The LaRonde Penna world-class Au-rich volcanogenic massive sulfide deposit, Abitibi, Québec: mineralogy and geochemistry of alteration and implications for genesis and exploration; *Economic Geology*.
- Fisher, R.V.**
1984: Submarine volcanoclastic rocks; in *Marginal Basin Geology*, (ed.) B.P. Kokelaar and M.F. Howells; Geological Society of London, Special Publication 16, p. 5–27.
- Fiske, R.S. and Matsuda, T.**
1964: Submarine equivalents of ash flows in the Tokiwa Formation, Japan; *American Journal of Science*, v. 262, p. 76–106.
- Galley, A.G.**
2003: Composite synvolcanic intrusions associated with Precambrian VMS-related hydrothermal systems; *Mineralium Deposita*, v. 38, p. 443–473.
- Galley, A.G. and van Breemen, O.**
2002: Timing of synvolcanic magmatism in relation to base-metal mineralization, Rouyn-Noranda, Abitibi volcanic belt, Quebec; Geological Survey of Canada, Current Research 2002-F8, 9 p.
- Gélinas, L. and Ludden, J.N.**
1984: Rhyolitic volcanism and the geochemical evolution of an Archean central ring complex: the Blake River Group volcanics of the southern Abitibi belt, Superior province; *Physics of The Earth and Planetary Interiors*, v. 35, p. 77–88.
- Gélinas, L., Trudel, P., and Hubert, C.**
1984: Chemostratigraphic division of the Blake River Group, Rouyn-Noranda area, Abitibi, Quebec; *Canadian Journal of Earth Sciences*, v. 21, p. 220–231.
- Gibson, H.L.**
1989: The Mine sequence of the Central Noranda Volcanic Complex: geology, alteration, massive sulfide deposits and volcanological reconstruction; Ph.D. thesis, Carleton University, Ottawa, Ontario, 800 p.
- Gibson, H.L. and Watkinson, D.H.**
1990: Volcanogenic massive sulphide deposits of the Noranda Cauldron and shield volcano, Quebec; in *The Northwestern Quebec Polymetallic Belt: a Summary of 60 Years of Mining Exploration*, (ed.) M. Rive, P. Verpaalst, Y. Gagnon, J.-M. Lulin, G. Riverin, and A. Simard; Canadian Institute of Mining, Metallurgy and Petroleum, Special Volume 43, p. 119–132.
- Gibson, H.L., Kerr, D.J., and Cattalani, S.**
2001: The Horne mine: geology, history, influence on genetic models, and a comparison to the Kidd Creek mine; *Exploration and Mining Geology*, v. 9, p. 91–111.
- Gilbert, M.**
1986: Géologie du groupe volcanique de Blake River dans la région du lac Pelletier, ceinture de l'Abitibi; M.Sc. thesis, Université de Montréal/Ecole Polytechnique de Montréal, Montreal, Quebec, 94 p.
- Goodwin, A.M.**
1977: Archean volcanism in Superior Province, Canadian Shield; in *Volcanic Regimes in Canada*, (ed.) W.R.A. Baragar, L.C. Coleman, and J.M. Hall; Geological Association of Canada, Special Paper 16, p. 205–241.
- Goodwin, A.M., Ridler, R.H., Annells, R.N., Briggs, D.N., Naldrett, A.J., Spence, A., and Spence, C.D.**
1972: Volcanisme précambrien des régions de Noranda-Kirkland Lake-Timmins-Michipocoten et Mamainse Point, provinces de Québec et d'Ontario; XXIVième Congrès géologique international, excursion A40-C40, Montréal, Québec.
- Goutier, J.**
1997: Géologie de la région de Destor (SNRC 32D/07); Ministère des Ressources naturelles (Québec), report RG 96-13, 37 p.
- Goutier, J. and Lacroix, S.**
1992: Géologie du secteur de la faille de Porcupine-Destor dans les cantons de Destor et Duparquet; Ministère de l'Énergie et des Ressources (Québec), report MB 92-06, 62 p.
- Grunsky, E.**
1988: Multivariate and spatial analysis of lithogeochemical data from metavolcanics with zones of alteration and mineralization in Ben Nevis township, Ontario; Ph.D. thesis, University of Ottawa, Ottawa, Ontario, 710 p.
- Hannington, M.D., Santaguida, F., Kjarsgaard, I.M., and Cathles, L.M.**
2003: Regional-scale hydrothermal alteration in the Central Blake River Group, western Abitibi subprovince, Canada: implications for VMS prospectivity; *Mineralium Deposita*, v. 38, p. 393–422.
- Head, J.W. and Wilson, L.**
2003: Deep submarine pyroclastic eruptions: theory and predicted landforms and deposits; *Journal of Volcanology and Geothermal Research*, v. 121, p. 155–193.
- Houghton, B. and Wilson, C.J.N.**
1989: A vesicularity index for pyroclastic deposits; *Bulletin of Volcanology*, v. 51, p. 451–462.
- Jenner, G.A.**
1996: Trace element geochemistry of igneous rocks: geochemical nomenclature and analytical geochemistry; in *Trace Element Geochemistry of Volcanic Rocks: Applications for Massive Sulphide Exploration*, (ed.) D.A. Wyman; Geological Association of Canada, Short Course Notes 12, p. 51–77.
- Jolly, W.T.**
1978: Metamorphic history of the Archean Abitibi belt; in *Metamorphism in the Canadian Shield*; Geological Survey of Canada, Paper 78-10, p. 63–78.
- Kokelaar, P. and Busby, C.**
1992: Subaqueous explosive eruption and welding of pyroclastic deposits; *Science*, v. 257, p. 196–201.
- Lafliche, M.R., Dupuy, C., and Dostal, J.**
1992: Tholeiitic volcanic rocks of the late Archean Blake River Group, southern Abitibi greenstone belt: origin and geodynamic implications; *Canadian Journal of Earth Sciences*, v. 29, p. 1448–1458.
- Lafrance, B. and Dion, C.**
2004: Synthèse de la partie est du Groupe de Blake River, phase 1: secteur à l'est de la faille du ruisseau Davidson (32D/07 SE); Ministère des Ressources naturelles, de la Faune et des Parcs (Québec), report RP 2004-04, 14 p.

- Lafrance, B., Davis, D.W., Goutier, J., Moorhead, J., Pilote, P., Mercier-Langevin, P., Dubé, B., Galley, A.G., and Mueller, W.U.**
2005: Nouvelles datations isotopiques dans la portion québécoise du Groupe De Blake River et des unités adjacentes; Ministère des Ressources naturelles et de la Faune (Québec), report RP 2005-01, 15 p.
- Lafrance, B., Moorhead, J., and Davis, D.W.**
2003: Cadre géologique du camp minier de Doyon-Bousquet-LaRonde; Ministère des Ressources naturelles, de la Faune et des Parcs (Québec), report ET 2002-07, 45 p.
- Larocque, A.C.L. and Hodgson, C.J.**
1993: Carbonate-rich footwall alteration at the Moberly mine, a possible Mattabi-type VMS deposit in the Noranda camp; *Exploration and Mining Geology*, v. 2, p. 165–169.
- Lichtblau, A.P. and Dimroth, E.**
1980: Stratigraphy and facies at the south margin of the Archean Noranda caldera, Québec; *in* Current Research, Part A; Geological Survey of Canada, Paper 80-1A, p. 69–76.
- McPhie, J. and Allen, R.L.**
2003: Submarine, silicic, syn-eruptive pyroclastic units in the Mount Read Volcanics, western Tasmania: influence of vent setting and proximity on lithofacies characteristics; *in* Explosive Subaqueous Volcanism, (ed.) J.D.L. White, J.L. Smellie, and D.A. Clague; American Geophysical Union, Geophysical Monograph 140, p. 245–258.
- Mercier-Langevin, P.**
2005: Géologie du gisement de sulfures massifs volcanogènes aurifères LaRonde, Abitibi, Québec; PhD thesis, Institut national de recherche scientifique, Québec, Québec, 698 p.
- Mercier-Langevin, P., Dubé, B., Hannington, M.D., Davis, D., and Lafrance, B.**
2004: Contexte géologique et structural des sulfures massifs volcanogènes aurifères du gisement LaRonde, Abitibi; Ministère des Ressources Naturelles de la Faune et des Parcs (Québec), report ET 2003-03, 60 p.
- Mortensen, J.K.**
1987: Preliminary U–Pb zircon ages for volcanic and plutonic rocks of the Noranda–Lac Abitibi area, Abitibi subprovince, Quebec; *in* Current Research, Part A; Geological Survey of Canada, Paper 87-1A, p. 581–590.
1993: U–Pb geochronology of the eastern Abitibi subprovince. Part 2 Noranda–Kirkland Lake area; *Canadian Journal of Earth Sciences*, v. 30, p. 29–41.
- Mueller, W.**
2006: A new interpretation of the Blake River Group, Abitibi greenstone belt: the importance of volcanological facies mapping and the discovery of a megacaldera; *Ashfall* (Newsletter of the Volcanology and Igneous Petrology Division, Geological Association of Canada), v. 62, p. 10–13.
- Mueller, W., Chown, E.H., and Potvin, R.**
1994: Substorm wave base felsic hydroclastic deposits in the Archean Lac des Vents volcanic complex, Abitibi belt, Canada; *Journal of Volcanology and Geothermal Research*, v. 60, p. 273–300.
- Nye, C.J., Swanson, S.E., Avery, V.F., and Miller, T.P.**
1994: Geochemistry of the 1989–1990 eruption of redoubt volcano: part I. Whole-rock major- and trace-element chemistry; *Journal of Volcanology and Geothermal Research*, v. 62, p. 429–452.
- Paradis, S., Ludden, J., and Gélinas, L.**
1988: Evidence for contrasting compositional spectra in comagmatic intrusive and extrusive rocks of the late Archean Blake River Group, Abitibi, Quebec; *Canadian Journal of Earth Sciences*, v. 25, p. 134–144.
- Pearson, V.**
2005: The Blake River Group: an imbricated caldera complex; *in* Québec Exploration 2005, Program and Abstracts, Québec, Québec, p. 105.
- Péloquin, A.S. and Piercey, S.J.**
2005: Geology and base metal mineralization in Ben Nevis, Clifford and Katrine Townships; Discover Abitibi Initiative; Ontario Geological Survey, Open File Report 6161, 86 p.
- Péloquin, A.S., Potvin, R., Paradis, S., Laflèche, M.R., Verpaest, P., and Gibson, H.L.**
1990: The Blake River Group, Rouyn-Noranda area, Quebec: a stratigraphic synthesis; *in* The Northwestern Quebec Polymetallic Belt: a Summary of 60 Years of Mining Exploration, (ed.) M. Rive, P. Verpaest, Y. Gagnon, J.-M. Lulin, G. Riverin, and A. Simard; Canadian Institute of Mining, Metallurgy, and Petroleum, Special Volume 43, p. 107–118.
- Péloquin, A.S., Verpaest, P., Ludden, J.N., Dejou, B., and Gaulin, R.**
2001: La Stratigraphie du Groupe du Blake River Ouest, Ceinture de l’Abitibi, Québec; Ministère des Ressources naturelles (Québec), report ET 98-03, 37 p.
- Pilote, C., Mueller, W., and Perron, M.**
2007: Les dépôts pyroclastiques sous-marins de la caldeira de Misema, Groupe de Blake River [abstract]; Abstract book (“Recueil des résumés”), Carrefour des sciences de la Terre, April 2007, Université du Québec à Chicoutimi (UQAC), p. 38.
- Powell, W.G., Carmichael, D.M., and Hodgson, C.J.**
1995: Condition and timing of metamorphism in the southern Abitibi greenstone belt, Quebec; *Canadian Journal of Earth Sciences*, v. 21, p. 787–805.
- Riopel, J., Hubert, C., Cattalani, S., Barrett, T.J., and Hoy, L.D.**
1995: Géologie, structure et géochimie du gisement de sulfures massifs Moberly (district de Rouyn-Noranda); Ministère des Ressources naturelles (Québec), ET 92-02, 142 p.
- Spera, F.J.**
2000: Physical properties of magma; *in* Encyclopedia of Volcanoes, (ed.) H. Sigurdsson, B. Houghton, S.R. McNutt, H. Rymer, and J. Stix; Academic Press, London, United Kingdom, p. 171–190.
- Stix, J., Kennedy, B., Hannington, M., Gibson, H., Fiske, R., Mueller, W., and Franklin, J.**
2003: Caldera-forming processes and the origin of submarine volcanogenic massive sulfide deposits; *Geology*, Boulder, Colorado, v. 31, p. 375–378.
- Stone, W.E.**
1990: Archean volcanism and sedimentation in the Bousquet gold district, Abitibi greenstone belt, Quebec; implications for stratigraphy and gold concentration; *Geological Society of America Bulletin*, v. 102, p. 147–158.

- Sun, S.-S. and McDonough, W.F.**
 1989: Chemical and isotopic systematics of oceanic basalts: implications for mantle composition and processes; *in* *Magmatism in the Ocean Basins*, (ed.) A.D. Saunders and M.J. Norry; Geological Society of London, Geological Society, Special Publication, v. 42, p. 313–345.
- Tassé, N., Lajoie, J., and Dimroth, E.**
 1978: The anatomy and interpretation of an Archean volcanoclastic sequence, Noranda region, Quebec; *Canadian Journal of Earth Sciences*, v. 15, p. 874–888.
- Trudel, P.**
 1978: Géologie de la région de Cléricky; Ministère des Richesses naturelles (Québec), report DP-598, 149 p.
- White, J.D.L.**
 2000: Subaqueous eruption-fed density currents and their deposits; *Precambrian Research*, v. 101, p. 87–109.
- White, J.D.L. and Houghton, B.F.**
 2006: Primary volcanoclastic rocks; *Geology*, v. 34, p. 677–680.
- Wilson, M.E. and McQuarry, W.R.**
 1948: Stadacona Mine; *in* *Structural Geology of Canadian Ore Deposits*, a Symposium Arranged by a Committee of the Geology Division; Canadian Institute of Mining and Metallurgy, Special Volume 1, p. 776–782.
- Winchester, J.A. and Floyd, P.A.**
 1977: Geochemical discrimination of different magma series and their differentiation products using immobile elements; *Chemical Geology*, v. 20, p. 325–343.

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APPENDIX A

Terminology

Because the terminology for clastic volcanic rocks is somewhat controversial and very often misused, it is essential to define the terms employed to avoid any confusion. All quotes in this appendix are from White and Houghton (2006). Primary volcanoclastic deposits are assemblages of clasts “that were mobilized directly by explosive or effusive volcanism and not stored at any time prior to arrival at the depositional site”. They include 1) pyroclastic deposits that form “from volcanic plumes and jets or pyroclastic density currents”, including pyroclastic flows and surges; 2) autoclastic deposits that form “during effusive volcanism when the exterior of a dome or lava flow cools and fragments in contact with air”; 3) hyaloclastite and pillow breccia that form “during effusive volcanism when extruding magma or flowing lava is chilled and fragmented from contact with water”; and 4) peperite (not discussed in this paper).

All primary volcanoclastic rocks, as well as the resedimented ones, can be described with nongenetic grain-size names such as tuff, lapilli tuff, tuff breccia, and breccia (the last comprises >75% blocks or bombs). Epiclastic rocks, by contrast, are “formed following weathering of volcanic (including volcanoclastic) rocks to produce new particles different in size and shape from those formed and distributed by an eruption”; these are not volcanoclastic and they receive sedimentary rock names such as ‘basaltic sandstone’.

Pyroclastic flows are high-concentration, pyroclastic density currents (as opposed to surges, which have a lower concentration of particles). The medium between the clasts can be gaseous or liquid during transport in a pyroclastic flow. The deposits do not need to show heat retention features; however, the clasts need to fit the criteria for pyroclastic deposits outlined above. Subaqueous eruption-fed density currents (e.g. White, 2000) are a type of pyroclastic flow.

APPENDIX B

Stations and samples mentioned in the text

Station	Sample	Easting*	Northing*
94-JG-7219	n/a	652 504	5 364 497
94-JG-7221	n/a	652 552	5 364 433
06-PSR-004	n/a	652 918	5 358 044
06-PSR-005	n/a	652 624	5 358 097
06-PSR-030	n/a	633 750	5 368 811
06-PSR-049	BR-020	636 369	5 368 766
06-PSR-156	n/a	650 990	5 366 103
06-PSR-162	n/a	641 442	5 368 301
06-PSR-176	BR-083	631 696	5 370 411
06-PSR-177	n/a	631 662	5 370 375
06-PSR-182	n/a	646 852	5 342 425
06-PSR-183	BR-088	646 382	5 342 166
06-PSR-184	BR-089	647 293	5 342 445
*UTM NAD 83, Zone 17 (measured by GPS) n/a = not applicable			