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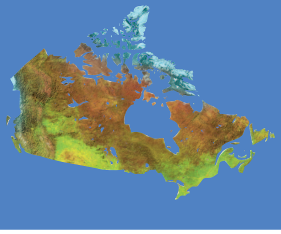

The Baie D'Alembert showing, an example of base-metal mineralization in mafic to intermediate volcanic rocks of the Blake River Group, Abitibi Greenstone Belt, Quebec

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Abstract: The Archean Blake River Group contains numerous volcanogenic massive sulphide (VMS) deposits, many of which are spatially associated with rhyolite domes and related volcaniclastic rocks. Therefore, most base-metal exploration in the Blake River Group has historically focused on rhyolite-rich areas. Yet the rhyolite-poor sectors may have VMS potential as well, and to illustrate this point, a recently discovered Cu-Zn showing, found in mafic to intermediate volcanic rocks, is described. Mineralization in the Baie D'Alembert showing occurs at, and stratigraphically below, the contact between aphyric lavas (transitional basalts and basaltic andesites) and a plagioclase-rich volcaniclastic unit known as the D'Alembert tuff (calc-alkaline basaltic andesites and andesites). The sulphide minerals are found within a marker horizon at this contact, and as stringers and impregnations below it. Mineralization formed in part by sub-seafloor replacement; several mafic to intermediate volcaniclastic units from the periphery of the Blake River Group could represent good hosts for replacement-style VMS mineralization.

Résumé : Le Groupe de Blake River, d'âge archéen, renferme de nombreux gisements de sulfures massifs volcanogènes, dont plusieurs sont associés spatialement à des dômes de rhyolite et à des roches volcanoclastiques apparentées. Par conséquent, dans le passé, la majeure partie de l'exploration ciblant les métaux communs dans le Groupe de Blake River a porté sur les zones riches en rhyolite. Toutefois, les secteurs contenant une faible proportion de rhyolite peuvent également présenter un potentiel en minéralisations de sulfures massifs volcanogènes. À titre d'exemple, nous décrivons un indice de Cu-Zn récemment découvert dans des roches volcaniques de composition mafique à intermédiaire. Dans l'indice de Baie D'Alembert, la minéralisation est présente au contact, et stratigraphiquement sous le contact, entre des laves aphyriques (basaltes et andésites basaltiques transitionnels) et une unité volcanoclastique riche en plagioclase appelée le tuf de D'Alembert (andésites et andésites basaltiques calco-alcalines). Au contact, les sulfures se trouvent dans un horizon repère, tandis qu'ils se présentent sous forme de filonnets et d'imprégnations sous le contact. La minéralisation résulte, en partie, d'un remplacement sous le fond marin. Plusieurs unités volcanoclastiques de composition mafique à intermédiaire situées en périphérie du Groupe de Blake River seraient susceptibles de renfermer des minéralisations de sulfures massifs volcanogènes de type remplacement.

INTRODUCTION

Archean volcanogenic massive sulphide (VMS) deposits containing copper, zinc, gold, and silver are often spatially associated with rhyolite domes and related volcaniclastic rocks in the Noranda mining camp (e.g. Knuckey et al., 1982; Gibson and Galley, 2007; Monecke et al., 2008) and elsewhere in the Blake River Group (e.g. Dubé et al., 2007; Mercier-Langevin et al., 2007) of the Abitibi Greenstone Belt. The broad spatial association between rhyolite domes and VMS deposits in the Noranda camp can be explained in the following manner: rhyolite domes are emplaced directly above volcanic conduits, which can exploit synvolcanic faults; hydrothermal fluids responsible for the generation of VMS deposits tend to follow the same synvolcanic faults during their ascension toward the seafloor (e.g. Gibson et al., 1999). This model has led to a situation where rhyolite-poor areas of the Blake River Group are under-explored relative to rhyolite-rich areas.

Yet, worldwide, there are numerous examples of VMS deposits not associated with felsic volcanic rocks, including in Archean successions (e.g. Franklin et al., 2005; Galley et al., 2007), suggesting that the VMS potential of the rhyolite-poor areas of the Blake River Group may be underestimated. Some of these areas have been examined by the author during an activity of the TGI-3 Abitibi project which was focused on mafic to intermediate volcaniclastic rocks and nearby lavas in the Blake River Group (Ross et al., 2007, 2008a, 2008b, 2009; Mercier-Langevin et al., 2008). In this report, the author describes the Baie D'Alembert showing, an example of Cu-Zn mineralization in mafic to intermediate lavas and volcaniclastic rocks of the Blake River Group. The depositional setting and transport processes for the volcaniclastic rocks in this area are also discussed.

REGIONAL GEOLOGICAL SETTING AND TERMINOLOGY

The Blake River Group is one of the most prospective Archean assemblages for VMS exploration, especially for gold-rich VMS (e.g. Dubé et al., 2007; Gibson and Galley, 2007; Mercier-Langevin et al., 2007; and references therein). The Blake River Group is the youngest (~2704–2695 Ma) volcanic-dominated assemblage in the Abitibi Greenstone Belt (McNicoll et al., 2008, 2009; Goutier et al., 2009). It consists largely of submarine, basaltic to rhyolitic, tholeiitic to calc-alkaline volcanic rocks, that are intruded by several generations of plutons as well as by mafic to intermediate dykes and sills (Fig. 1). Readers are referred to Ross et al. (2007, and references therein) for an overview of the geology of the whole Blake River Group, and a discussion of the terminology used to describe fragmental volcanic rocks.

For Archean rocks that have experienced metamorphism and in many cases severe hydrothermal alteration, magmatic affinities cannot be consistently determined using major elements. Therefore, ratios of immobile trace elements such as Zr/Y, La/Yb or Th/Yb are used to assign magmatic affinities (Ross and Bédard, 2009). 'Transitional' is employed to describe rocks which plot between tholeiitic and calc-alkaline fields.

LOCAL GEOLOGICAL SETTING

Base-metal mineralization occurs in at least two areas along the northern contact of the D'Alembert tuff with the surrounding intermediate to mafic volcaniclastic rocks (Fig. 2). The western occurrence is known as the Baie D'Alembert showing and is described in this report. The strata young southward in this area and the lavas stratigraphically underlying the D'Alembert tuff consist mostly of massive to pillowed basalts which are generally aphyric near the contact. The D'Alembert tuff is a major, bedded, plagioclase-rich, mafic to intermediate volcaniclastic unit that is interpreted as having been deposited by numerous subaqueous eruption-fed density currents (Ross et al., 2007, 2008b). Based on the average thickness of beds and average clast sizes, area A3 is considered more proximal to the vent(s) than areas A1 and A2 in the D'Alembert tuff (Fig. 2). Therefore, the Baie D'Alembert showing occurs in a relatively distal area, at least with regards to D'Alembert tuff volcanism. The vent area(s) for the lavas north of the D'Alembert tuff are not known. All of the rocks described in this report belong to the Reneault-Dufresnoy Formation of Goutier et al. (2007).

BAIE D'ALEMBERT SHOWING

The Baie D'Alembert showing was delineated by a series of relatively short Cu and Zn intercepts in several diamond drill holes located about 1.7 km east of D'Alembert Bay (Fig. 2). Both conductive sulphide minerals and graphite were intersected in holes drilled between 2003 and 2007 initially targeted at a MEGATEM anomaly by Noranda, now Xstrata Copper Canada, in a joint venture with Alexis Minerals Corporation (Masson, 2004; Guimont, 2006; Lemieux, 2007).

Mineralization occurs at, and stratigraphically below, the contact between the D'Alembert tuff and the underlying lavas (Fig. 3). This now-vertical contact marks the abrupt transition from effusive eruptions of aphyric transitional basalt to submarine explosive eruptions of plagioclase-phyric calc-alkaline basaltic andesite and andesite. The abrupt change in magma composition at the contact is interesting for two reasons: 1) it marks a pause in the volcanism, especially given the presence of 'exhalites' at the contact, a favourable criterion for VMS exploration; 2) it

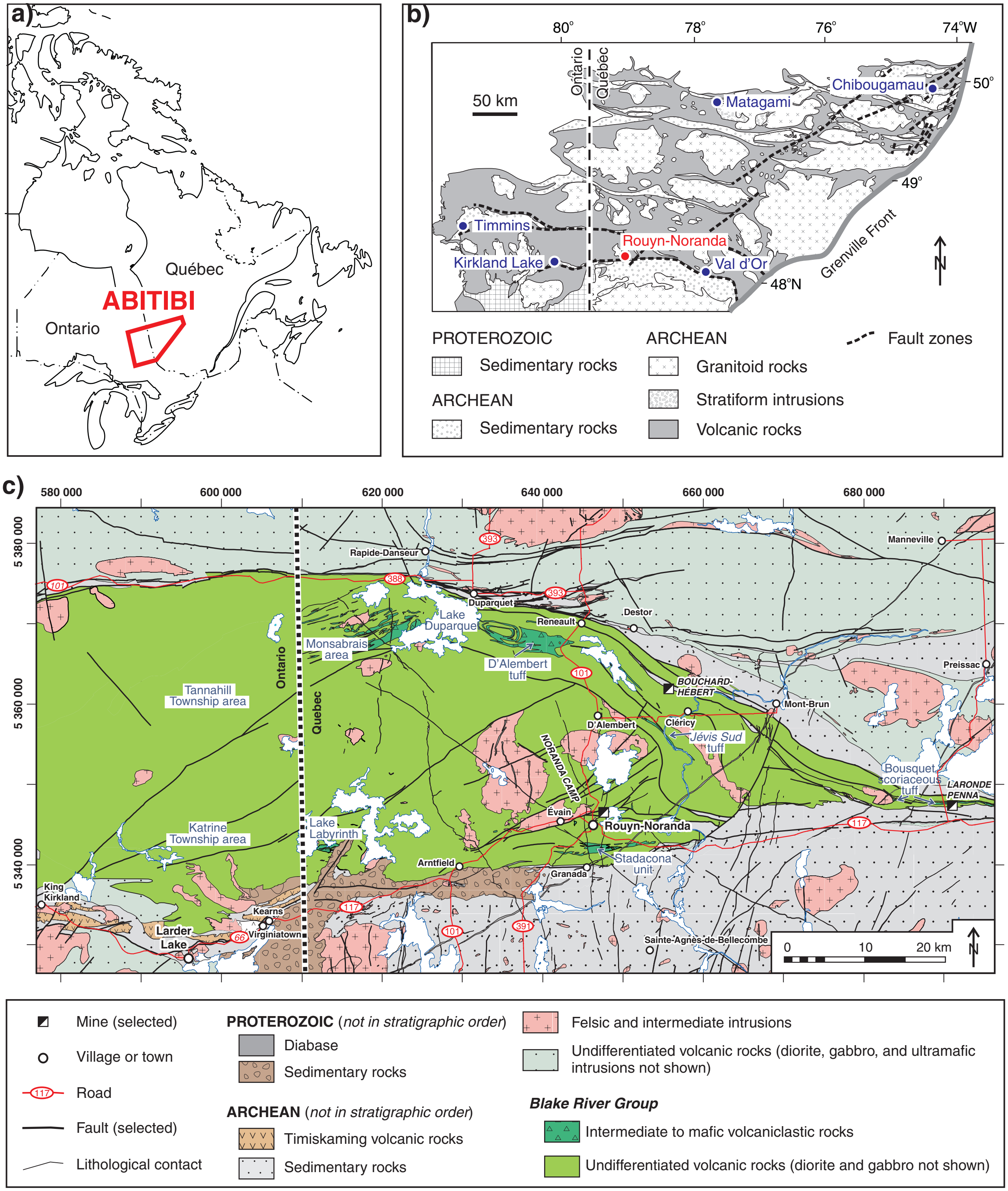


Figure 1. **a**) Map of eastern Canada showing the location of the Abitibi Greenstone Belt. **b**) Simplified geological map of the Abitibi and Pontiac subprovinces, after Legault et al. (2005). **c**) Simplified geological map of the Rouyn-Noranda area showing selected VMS mines and the distribution of mafic to intermediate volcaniclastic rocks in the Blake River Group (Quebec side only, since the information has not been compiled in Ontario). Grid on all maps is UTM NAD 83, zone 17.

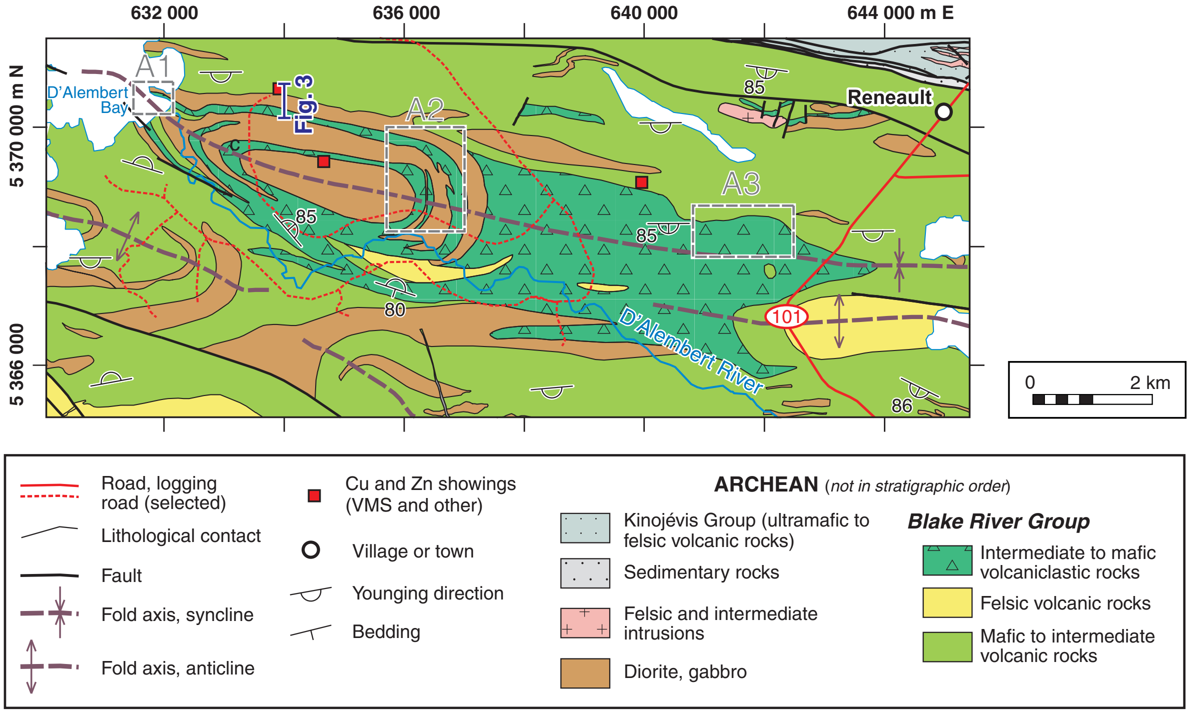


Figure 2. Geologic map of the Blake River Group in the area containing the D'Alembert tuff and the Baie D'Alembert showing. Rectangles for field areas A1 to A3 are superimposed (*see* Ross et al., 2007, 2008b for information about these areas).

shows that the accumulation of plagioclase crystals in the magma chamber possibly had a role in triggering the explosive submarine eruptions that generated the D'Alembert tuff. From oldest to youngest (north to south), the stratigraphy examined at the Baie D'Alembert showing consists of the following succession.

High-Zr basalts and basaltic andesites

First come approximately 100 m of massive, weakly amygdaloidal, high-Zr, transitional basalts and basaltic andesites (Fig. 4a-4e), with relatively smooth patterns and small negative Ti anomalies on extended trace element diagrams. Hydrothermal alteration is weak in this unit.

Low-Zr basalts

The second unit comprises ~115 m of low-Zr transitional basalts (Fig. 4a-4d) with a higher TiO_2/Zr or Ti/Zr ratio (Fig. 4e, 5), lower trace-element abundances and more spiked patterns on extended trace-element diagrams, relative to the underlying high-Zr lavas (Fig. 4f). The extended trace-element diagrams also feature low Th and weak positive Eu and Ti anomalies. This lava unit is brecciated to massive (Fig. 6a), with the brecciation being of volcanic and/or hydrothermal origin.

It can be seen from diamond-drill core from hole DUT-06–05 that the lower part of the low-Zr unit has suffered variable silicification, sericitization (K_2O up to 4.0%) and carbonate alteration (CO_2 up to 6.9%), giving the rock a bleached aspect (Fig. 7a). The upper part of the unit is not strongly bleached, but has some chlorite alteration leading up to a weakly mineralized sulphide stringer zone (Fig. 3, 6a, 6b). In hole DUT-07–09W, the upper part of the breccia has variable sulphide minerals in the matrix, including some sphalerite (Fig. 3). Where the rock is brecciated, a hard mineral (black in hand specimen; not optically resolvable in thin section) is often present in the matrix (Fig. 7b) and tends to define stylolite-like patterns in some cases. In hole DUT-06–07, a number of thin argillite and exhalite horizons are intercalated with this lava unit.

Marker horizon

Just at the contact between the lavas and the D'Alembert tuff, a few metres of argillite, including some sulphide-rich laminae, are found (Fig. 6c), often overlain by a few metres of a variably laminated, weakly mineralized sedimentary-exhalative material referred to as exhalite (Fig. 6d). The aspect and composition of this exhalite varies, with different amounts of fine-grained sediment, chert, graphite, and sulphides, indicating that it was probably formed on the seafloor at a time when hydrothermal fluids were venting. Hydrothermal brecciation and alteration of the underlying low-Zr transitional basalts, and formation of sulphide stringers / matrix impregnation, likely occurred below the seafloor at this stage as well.

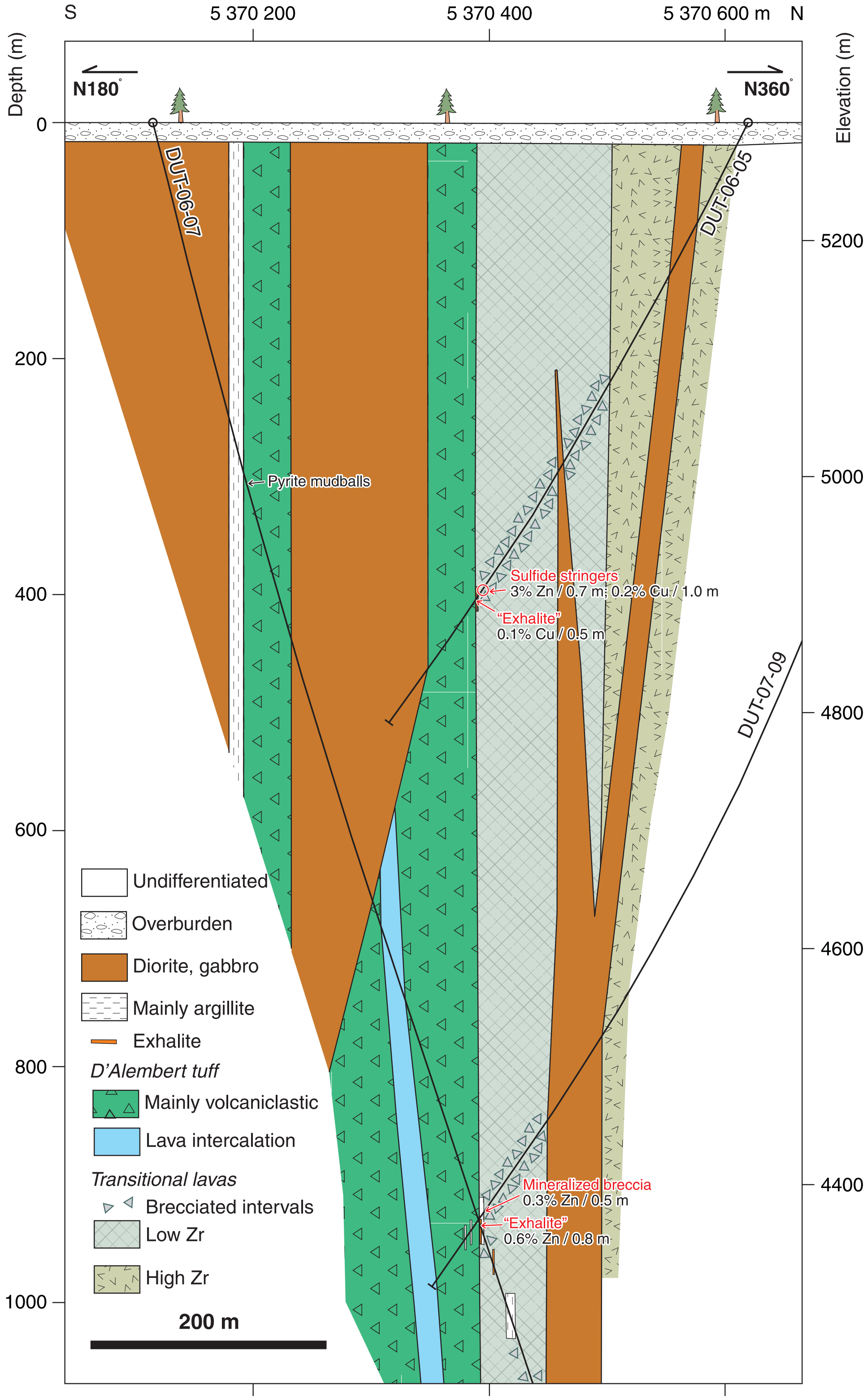


Figure 3. Vertical north-south section at 634 000 m E in the Baie D'Alembert showing area. The stratigraphic top is to the south and all the rocks illustrated belong to Reneault-Dufresnoy Formation of Goutier et al. (2007). Some minor intrusions of diorite and gabbro have been omitted. The upper part of drill hole DUT-07–09 has not been compiled (the lower part of this hole is known as DUT-07–09W). The co-ordinates at the top of the section are UTM northings. *See* text for discussion and Figure 2 for section location.

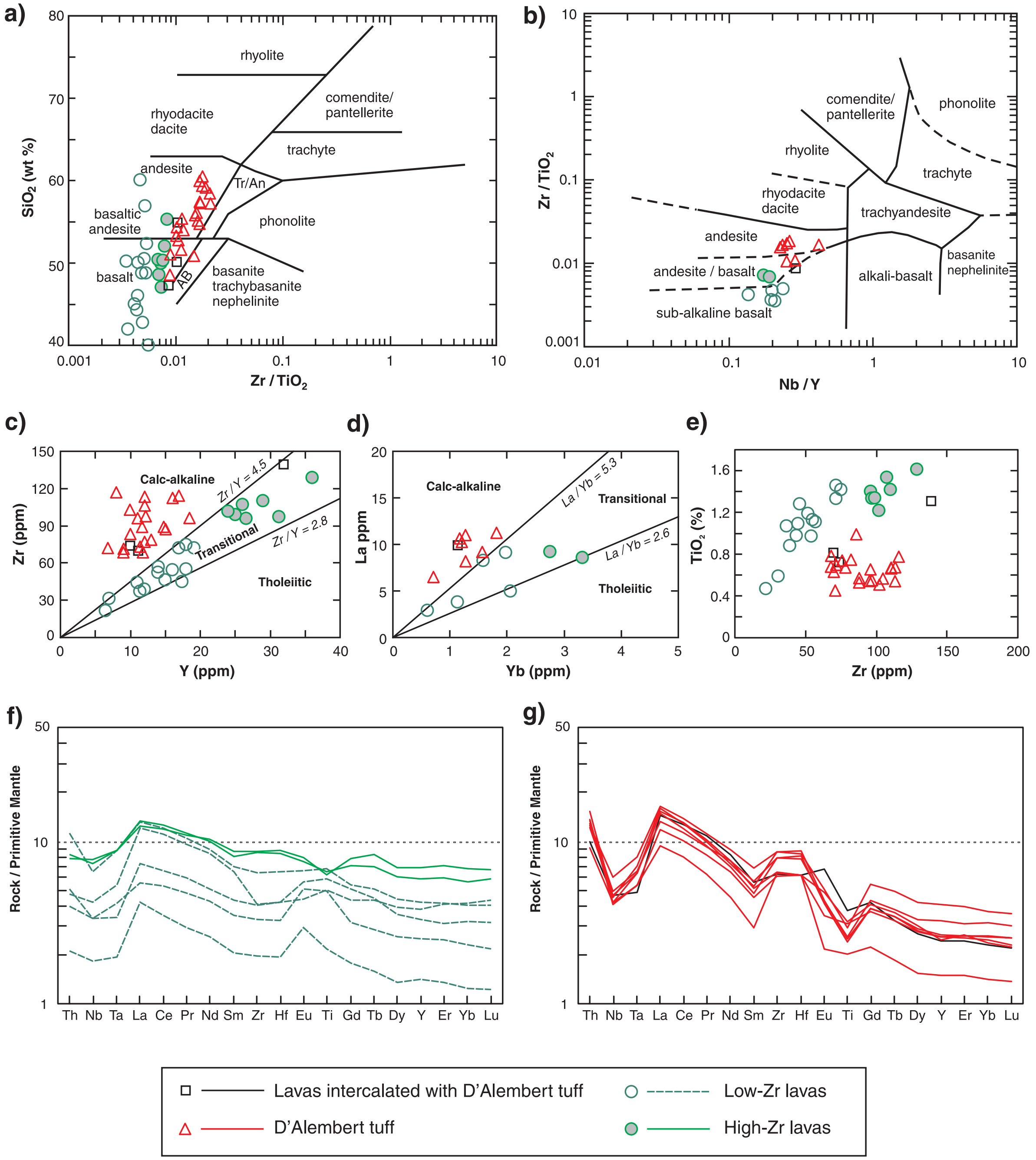


Figure 4. Geochemical data for lavas and volcaniclastic rocks from two representative re-logged diamond-drill holes (DUT-06–05, DUT-06–07) from the Baie D'Alembert showing. **a**), **b**) Classification diagrams of Winchester and Floyd (1977). Some of the SiO$_2$ variation in a) is due to hydrothermal alteration, especially for the lavas that define vertical arrays. **c**), **d**) Magmatic affinity diagrams of Ross and Bédard (2009). **e**) Binary diagram of TiO$_2$ vs. Zr. **f**), **g**) Extended trace-element diagrams, with normalization values from Sun and McDonough (1989). Data sources: Guimont (2006) and Lemieux (2007) (all elements by XRF at ALS Chemex; shown in a), c, and e only); author's unpublished Activation Laboratories data (major elements by XRF, trace elements by fusion ICP-MS; shown in all figures).

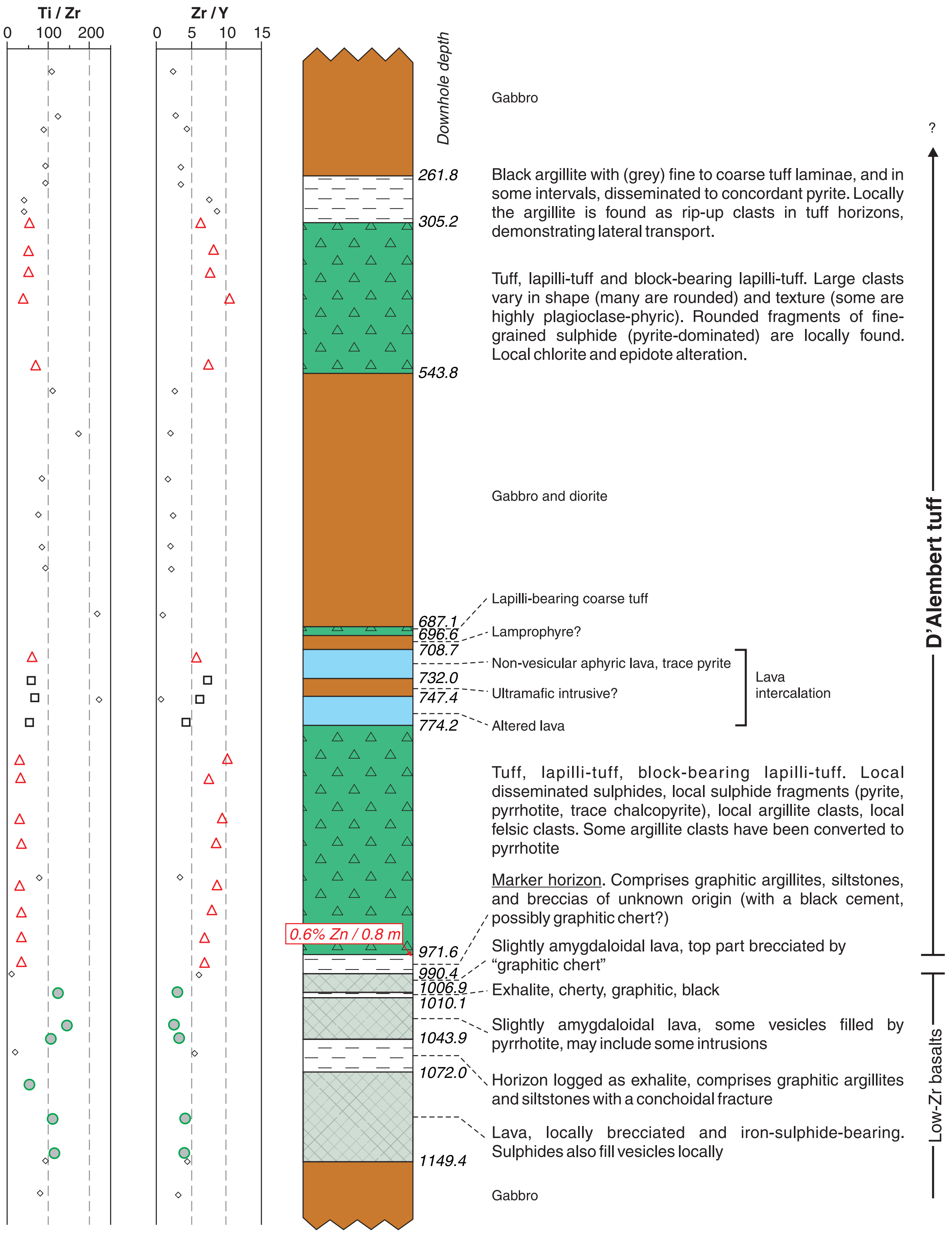
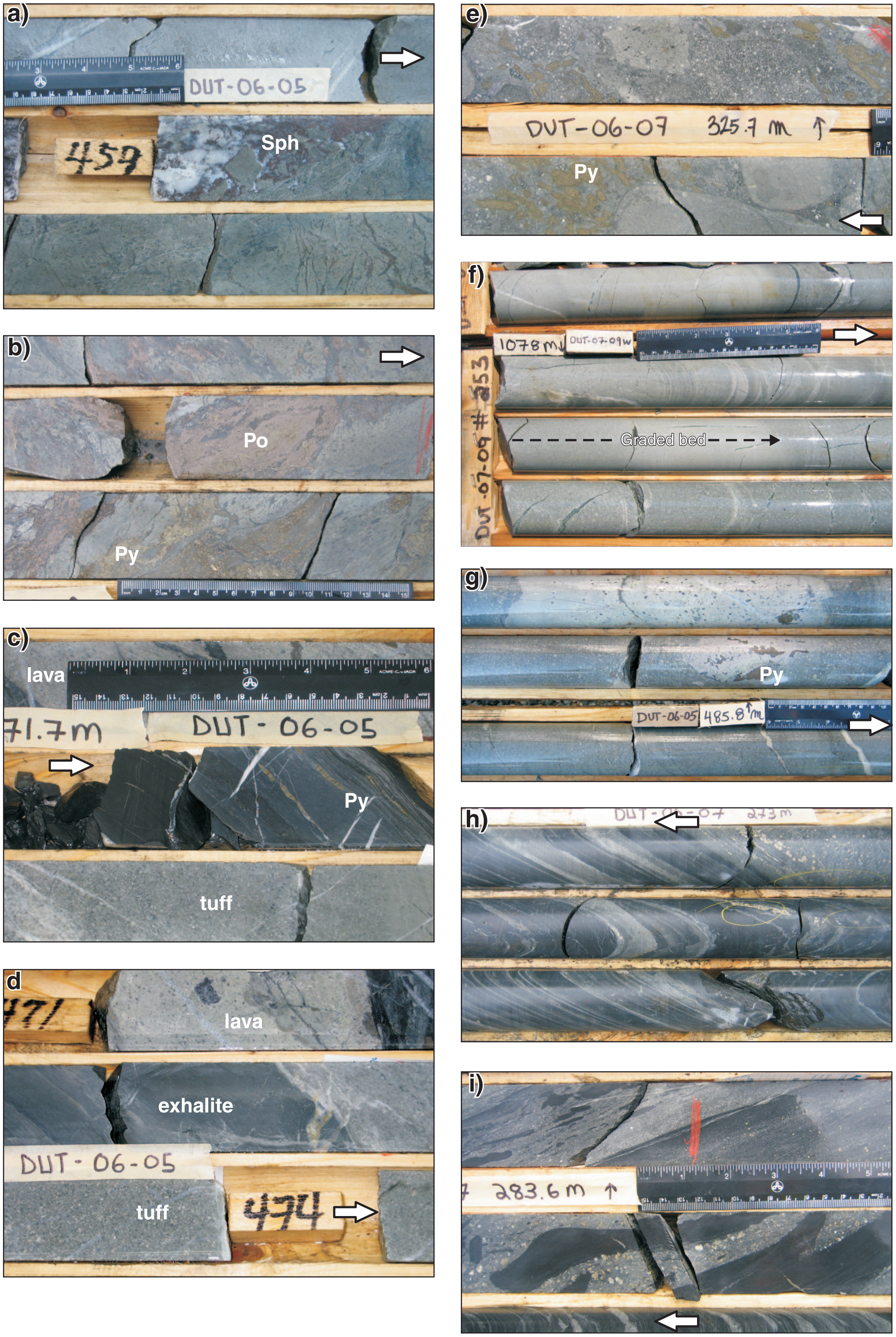


Figure 5. Summary log of diamond drill hole DUT-06–07, with the uppermost and lowermost gabbros truncated, and corresponding Ti/Zr and Zr/Y ratios. *See* Figure 3 for location and legend of geological patterns in the column. *See* Figure 4 for sources of geochemical data and legend of symbols (small diamonds: other geological units not illustrated in Figure 4).


a)
DUT-06-05
457
Sph
b)
Po
Py
c)
lava
71.7m
DUT-06-05
Py
tuff
d
471
lava
exhalite
DUT-06-05
tuff
474
e)
DUT-06-07 325.7 m
Py
f)
1078m
DUT-07-09w
DUT-07-09 #253
Graded bed
g)
Py
DUT-06-05 485.8 m
h)
DUT-06-07 273 m
i)
283.6 m

D'Alembert tuff

Overlying the marker horizon are approximately 170 m of well bedded volcaniclastic rocks from the D'Alembert tuff, ranging in grain size from fine tuff to block-bearing lapilli-tuff (Fig. 6e, 6f, 6g). These plagioclase-rich rocks have a calc-alkaline affinity, a basaltic andesite to andesite composition (Fig. 4a-4d), and a distinctively lower TiO_2 or Ti/Zr ratio than the underlying lavas (Fig. 4e, 5). Extended trace-element diagrams for the D'Alembert tuff show steep slopes, high Th, a good Nb-Ta through, a raised Zr-Hf plateau, small negative Eu anomalies, and moderate negative Ti anomalies (Fig. 4g). Altered plagioclase occurs both as free crystals and as phenocrysts within volcanic fragments (Fig. 7c). These fragments tend to be non-vesicular to slightly vesicular for the most part, although a few scoriaceous clasts were observed.

In upper part of this interval, sub-rounded fragments of very fine-grained pyrite ('pyrite mudballs,' M. Hannington, pers. commun., 2007) are incorporated in coarse beds of the D'Alembert tuff (Fig. 6e) in DUT-06–07. Presumably, pyrite clasts were derived from a seafloor sulphide accumulation (layer or mound) potentially located within a few kilometres of their final deposition site. Because the pyritic fragments are found at a stratigraphic level more than 100 m above the highest known exhalite, it is conceivable that the sulphide accumulation from which they were derived was not the lateral equivalent of the exhalites under the D'Alembert tuff, but rather was formed by a younger exhalative event. Therefore, exhalative activity seems to have occurred not only toward the end of the lava deposition and slightly afterwards, but also later on during breaks in the explosive volcanism that created the fragments now preserved in the D'Alembert tuff.

The D'Alembert tuff includes an approximately 15 m thick intercalation of lava that displays the same geochemical characteristics as the volcaniclastic rocks (Fig. 4a-4e), except for a positive Eu anomaly (Fig. 4g). Above the volcaniclastic-dominated interval, about 10 m of interbedded argillite and tuff occur (Fig. 6h, 6i, 7d). Finally, the whole succession is dilated by diorite and gabbro (Fig. 3, 5).

Figure 6. Photos of mineralization at the Baie D'Alembert showing, and of the host volcanic sequence including the D'Alembert tuff. In all pictures, the superimposed white arrow points toward the stratigraphic top, and the down-hole direction is to the right. **a**) The best zinc values are associated with sphalerite (Sph) stringers in lavas. Diamond-drill hole DUT-06–05, 459.1 m (centre of picture). 2010-048. **b**) Low copper values can be associated with pyrrhotite (Po) and pyrite (Py) stringers. Same hole, 464 m (centre of picture). 2010-039. **c**) Argillite at 471.7 m (centre of picture) in the same hole. Note the thin pyrite layers and a proportion of siltstone or fine tuff laminae. Under the ruler are altered lavas (stratigraphically below the argillite), whereas the bottom core in the photo consists of a plagioclase crystal-bearing tuff (stratigraphically above the argillite). 2010-047. **d**) An exhalite that lacks concordant pyrite but grades 0.11% Cu over 0.5 m (same hole, 472.7 m at centre of picture). 2010-040. **e**) Sub-rounded pyritic clasts in the D'Alembert tuff. Hole DUT-06–07, 325.7 m (above the black arrow). Note the great diversity of volcanic fragments in this coarse lapilli-tuff bed, suggesting that some of the volcanic clasts are not juvenile. 2010-044. **f**) Several coarse to fine tuff beds in the D'Alembert tuff, from DUT-07–09W at 1078.0 m (below black arrow on tape). 2010-041. **g**) Two block-sized volcanic fragments in the D'Alembert tuff. The fragments have been partly replaced, or vesicles have been filled, by sulphides. Note the abundance of plagioclase crystals in the tuffaceous fraction. DUT-06–05, 485.8 m (above black arrow on tape). 2010-046. **h**) Interbedded argillite (black bands) and fine to coarse tuff or siltstone/sandstone (grey bands) within the D'Alembert tuff. DUT-06–07, 273 m (below the number on the tape). 2010-051. **i**) Rip-up clasts of argillite within a plagioclase-rich tuff layer. Same hole, 283.6 m (above black arrow). 2010-050

SETTING AND TRANSPORT PROCESSES FOR THE D'ALEMBERT TUFF

The depositional environment for the D'Alembert tuff in the area of the Baie D'Alembert showing can be constrained from the examined drill cores. By thickness, volcaniclastic rocks from this area are dominated by lapilli-tuffs (e.g. Figure 6e) and tuffs (e.g. Figure 6f). Block-size (≥64 mm) fragments occur only sporadically (e.g. Figure 6g). So the lateral facies change from thick graded beds ranging in grain size up to tuff-breccia in area A3, to thinner, finer-grained beds (on average) in area A2, continues westward in the sector of the Baie D'Alembert showing. This suggests an increasing distance from the volcanic vent(s). The approximately 10 m thick section dominated by black argillite, with interbedded paler fine tuff (or siltstone/fine sandstone) at the stratigraphic top of the drilled part of the sequence (Fig. 6h), was likely deposited by turbidity currents (note the channel-like feature in Figure 7d). The presence of argillite, which had not been seen elsewhere in the D'Alembert tuff, and the overall scarcity of block-sized clasts in the volcaniclastic deposits, together suggest that the rocks studied are located relatively distally from the volcanic vent(s), at least compared to areas A2 and A3 (Fig. 2).

On the other hand, in a thicker and coarser (sand-grade), plagioclase-bearing tuff interbed in the argillite-dominated deposit, rip-up clasts of argillite up to 15 cm long are found (Fig. 6i), showing that the current that produced this layer had some erosive power. The currents (pyroclastic and/or turbiditic) that deposited the D'Alembert tuff also picked up pyrite fragments from the seafloor as already mentioned. In addition, a few blocks several decimetres across, some possibly deposited hot (not illustrated here), exist in the coarsest volcaniclastic layers, suggesting a relatively energetic setting at times. So it appears equally plausible that the argillites correspond to periods of volcanic quiescence. Indeed, argillite and other sediments are also intercalated with the lavas lower down in the sequence at multiple levels

(Fig. 3, 4), indicating several episodes of volcanic repose. This would mean that the D'Alembert tuff is the product of several explosive eruptions with significant time intervals between the explosive events.

SUBSEAFLOOR REPLACEMENT-TYPE VMS DEPOSITS IN MAFIC TO INTERMEDIATE VOLCANICLASTIC HOSTS

The Baie D'Alembert mineralization was formed by venting of hydrothermal fluids in the seawater column, but also by replacement of mafic to intermediate fragmental rocks below the seafloor. In the Baie D'Alembert showing, the fragmental rocks that have been replaced and invaded are brecciated lavas, but there exists in the Blake River Group a number of mafic to intermediate volcaniclastic units of variable origins (Fig. 1) which may represent good hosts for replacement-type VMS deposits.

Although accumulation of sulphides on the seafloor due to hydrothermal venting and precipitation is an important mechanism in the generation of many VMS deposits, it is a very inefficient way to trap Cu and Zn in sulphide lenses since most metals are lost to the seawater (Rona, 1984). A likely more efficient process to trap metals is subseafloor replacement of (most typically) volcaniclastic deposits (Gibson et al., 1999; Franklin et al., 2005). If coherent lava flows and volcaniclastic deposits are intercalated in a volcanic succession, hydrothermal fluids will rise along steep synvolcanic faults in the coherent lavas but they will be more likely to be dispersed laterally in the volcaniclastic deposits, especially at shallow depths below the seafloor, where the clastic deposits tend to

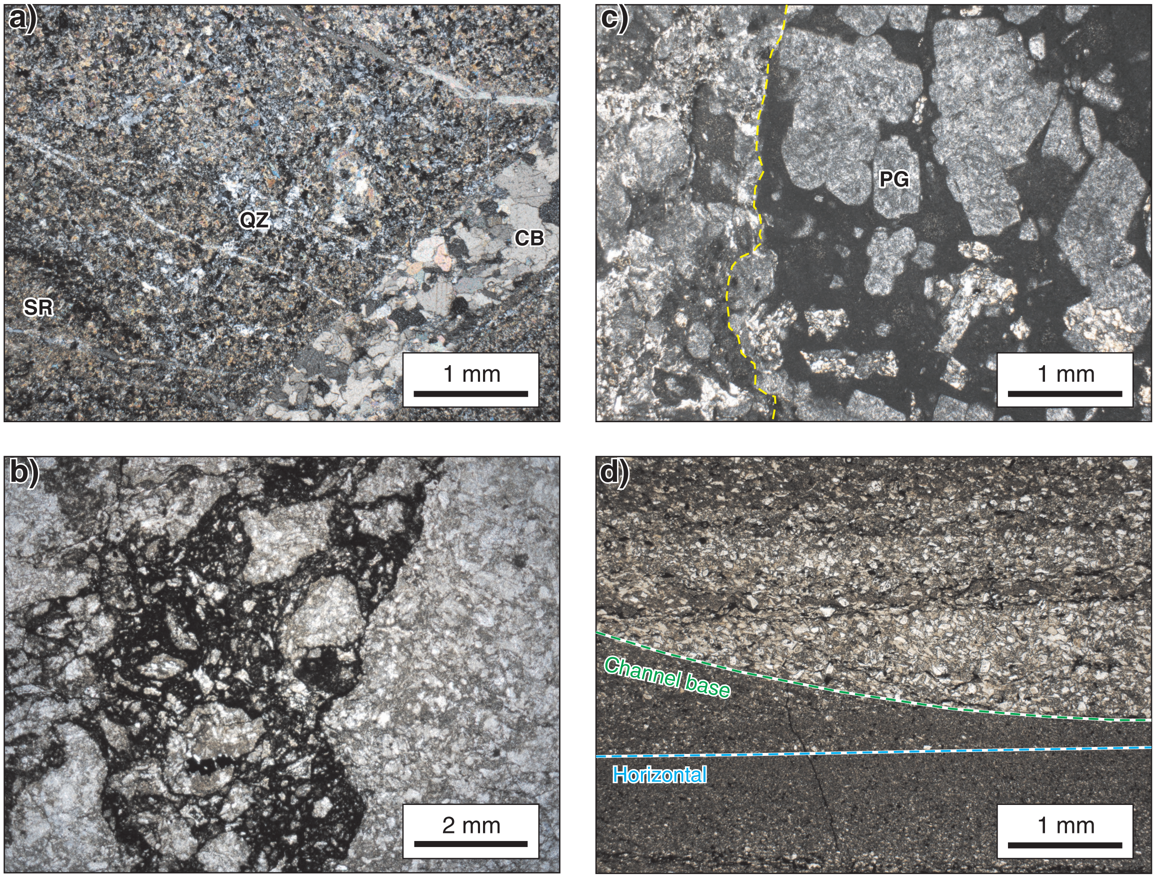


Figure 7. Photomicrographs from rocks in the Baie D'Alembert showing area. **a**) A sample from the lower part of low-Zr lavas, having suffered alteration to quartz (QZ), sericite (SR) and carbonate (CB) in DUT-06–05 at 273.4 m (sample BR-172). 2010-045. **b**) The upper part of the low-Zr lavas in DUT-06–05 at 359.65 m (sample BR-174). The rock is brecciated, with the matrix occupied by a mineral that is hard and black in hand specimen. 2010-043. **c**) Coarse tuff with 10 to 15% lapilli in the D'Alembert tuff from DUT-06–07 at 802.9 m (sample BR-189). Volcanic fragments can be plagioclase (PG)-phyric as in the example to the right of the dashed outline. Free plagioclase crystals are also part of the tuffaceous fraction, left of the outline. 2010-049. **d**) Laminated sedimentary to volcaniclastic rock (tuff to argillite) from DUT-06–07 at 275.85 m (sample BR-208). Most laminations are plane-parallel but some of the coarser laminations have erosive bases, demonstrating deposition from laterally moving currents. 2010-042. All photos in plane-polarized light, except a) in cross-polarized light.

be more porous and permeable (Doyle and Allen, 2003). In the Blake River Group, VMS deposits hosted by volcaniclastic-dominated successions tend to be larger than VMS deposits hosted by successions dominated by coherent lavas (e.g. Mercier-Langevin et al., 2009).

A review of the literature by Doyle and Allen (2003) indicates that most volcaniclastic rocks directly hosting replacement-type VMS deposits are felsic in composition (e.g. Mattabi: Morton and Franklin, 1987; LaRonde Penna: Dubé et al., 2007; Mercier-Langevin et al., 2007). However, a few mafic to intermediate examples are known in the Abitibi Greenstone Belt (Corbet: Gibson et al., 1993; Potter: Préfontaine et al., 2008) and elsewhere (Renström East: Doyle and Allen, 2003; Turner-Albright: Zierenberg et al., 1988). Another example of a massive sulphide lens apparently formed in part by replacement of intermediate to felsic volcaniclastic deposits in the Blake River Group is the 1100 lens at Bouchard-Hébert, formerly known as Mobrun (Larocque and Hodgson, 1993). One can therefore envisage that the Blake River Group mafic to intermediate volcaniclastic rocks could have been good potential hosts for replacement-style VMS mineralization.

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Geological Survey of Canada Project X91