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Spherulitic Aphyric Pillow-Lobe Metatholeiitic Dacite Lava of the Timmins Area, Ontario, Canada: A New Archean Facies Formed from Superheated Melts

E. DINEL, B. M. SAUMUR, AND A. D. FOWLER,[†]

Department of Earth Sciences, University of Ottawa, 140 Louis Pasteur, Ottawa, Canada K1N 6N5
and Ottawa Carleton Geoscience Centre

Abstract

Fragmental rocks of the V10 units of the Vipond Formation of the Tisdale assemblage previously have been identified as pillow basalts, but many samples are shown to be intermediate-to-felsic in character, likely tholeiitic dacite in composition. Specifically, the V10b unit is mapped as a pillow-lobe dacite. Aside from being more geochemically evolved in terms of their "immobile" trace elements, these rocks differ from typical pillow basalts in that they have more abundant primary breccia and hyaloclastite. The pillow lobes are contorted, having been folded in a plastic state and are zoned, typically having a spherulite-rich core. Moreover, the flows are aphyric, interpreted to mean that they were erupted in a superheated state. This along with their pillow-lobe nature demonstrates that they were erupted as relatively low-viscosity melts for such silicic compositions. Interaction with water quenched the outer pillow lobe and contributed to the formation of the abundant breccia. The fact that the melt was crystal and microlite free inhibited crystal growth, such that the bulk of the lobes were quenched to crystal-free glass. Nucleation occurred only in the cores, where cooling rates were lower in comparison to the medial and exterior areas of the pillow lobes, although in the cores crystal growth rates were high so that abundant spherulite formation took place. The flows are exposed over a strike length of more than 10 km and are interpreted to be continuous and to have resulted from fissure eruptions. The resulting porous, permeable, high Fe/Mg, high-surface area glassy rocks may have been ideal for channeling and reacting with gold-bearing hydrothermal solutions. Descriptions of most other Archean subaqueous felsic lobes document that the lavas were phyric and that spherulites formed near the external lobe margin. The distinctly different zoning of the V10b pillow lobes suggests that they constitute a new Archean facies formed from superheated melts.

Introduction

THE TIMMINS area of the Abitibi subprovince of Ontario has been a prolific gold producer and continues to be so. The bulk of the mineralization is contained within mafic metavolcanic rocks primarily within the Tisdale assemblage, an approximately 3-km-thick tholeiitic suite of 2710 to 2704 Ma rocks (Ayer et al., 2005) consisting predominantly of metabasalts with intercalated metakomatiites toward its base and intermediate and/or felsic rocks toward its top. There is an important structural control on the mineralization: much of the ore is situated in quartz-carbonate shear and extension veins in close proximity and structurally related to the Porcupine-Destor deformation zone and its second-order parallel shear zones.

Examination of the literature shows that there is also an intrinsic permeability control on the mineralization. Brisbin (1997) noted that most of the large, prolific veins at the McIntyre mine occur along flow contacts marked by carbonaceous argillite and/or hyalobreccia and, more generally there was an affinity of hydrothermal fluids for rocks with high permeability. Vein, replacement ores, and hydrothermal alteration are localized in areas of high permeability such as flow tops. Ferguson et al. (1968) reported that mineralization, at least in part, is related to flow contacts, and Dunbar (1948) observed that the ore favors the upper part of the Tisdale group (now Tisdale assemblage), which has a fragmental character. The bulk of the mineralization is stratigraphically located in the Hersey Lake, Central, and Vipond Formations. The Hollinger-McIntyre and Dome systems are located in volcanic rocks of the Vipond and Central Formations. In this paper we report on what we interpret to be a new Archean volcanological facies and speculate on its suitability as a host for gold mineralization.

The V10b unit is a distinctive marker horizon in the Timmins camp, (e.g., Ferguson, 1968) which locally was abundantly mineralized. The V10b is part of a series of similar units that was collectively termed the V10 "Member" by Brisbin (1997). The unit has been variously identified as a dacite or andesite flow (e.g., Ferguson, 1968), "chicken-feed" (e.g., Brisbin, 1997), and pillow basalt (Pyke, 1982). The term "chicken-feed," defined by Graton et al. (1933), is a local name applied to granulated glassy material filling spaces between the pillows and is more rarely found within the pillows themselves (i.e., hyaloclastite). Elsewhere the chicken-feed has been described as consisting of broken spherulites or varioles (Ferguson, 1968; Brisbin, 1997) and by Griffis (1962) as brecciated spherules and angular porcelainic fragments or shards.

The McIntyre mine geologists (Griffis, 1962) divided the V10 into the V10a, b, c, and d, whereas at the Dome mine (Ferguson, 1968) they are loosely correlated with what are termed the Andesite, Upper Andesite, and Dacite flows (V10b and V10c). Rocks of andesitic and dacitic composition were also reported at the Hollinger mine. Graton et al. (1933, p. 3) considered that the flows are mainly of intermediate composition, ranging from albite-dacite toward andesite. According to Graton et al. (1933), none of the flows on the Hollinger property were considered basic enough to be properly called basalt. Today, through the use of modern geochemical analyses, it is evident that most of the volcanic rocks of the region are mafic and likely followed in order of

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[†] Corresponding author: e-mail, afowler@uottawa.ca

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abundance by lavas of ultramafic and then intermediate to felsic compositions.

We have focused on the V10b unit because it held significant mineralization and it is well exposed on surface; access to the former underground workings at the Dome, McIntyre, Hollinger, and other nearby mines is no longer possible. We particularly focus on the freshest, best preserved outcrops of the V10b in order to document its volcanological features without the complications of strain and alteration associated with mineralization. We document the physical volcanology, petrography, and geochemistry of these rocks and demonstrate that they are similar in appearance to pillow basalts and how the two can be distinguished. We suggest that rocks of this type are largely restricted to the Archean and speculate on their suitability as hosts for hydrothermal gold mineralization.

Pillows versus lobes and varioles versus spherulites

For clarity, we briefly review a few terms important for the work. The distinction between subaqueously formed pillow lavas and lava lobes is not sharp. For instance, McPhie et al. (1993) commonly used the term "pillow lobes." Lava lobes (e.g., De Rosen-Spence et al., 1980; Ayres and Péloquin, 2000) are typically large-scale lenticular features with pointed terminations. De Rosen-Spence et al. (1980) described them as folded sheets, 1 to 10 m thick, and 10 to 500 m long. Lobes are often found associated with domes and typically crop out as isolated elements within abundant surrounding hyaloclastite. Lobes are closed structures, have a distinctive zoning (described below), and grade into hyaloclastite (McPhie et al., 1993) into which they are sometimes intrusive.

Compositionally, pillows are generally thought to be restricted to mafic systems, although they have been described from felsic rocks (e.g., Bevins and Roach, 1979). Others considered that the rhyolite lobes they mapped were essentially pillows formed at the flow front during advancement (Dimroth et al., 1979; De Rosen-Spence et al., 1980). Typically pillows (of basaltic systems) form clusters of meter-scale entities that are individually molded such that the convex geometry of one pillow's side is reflected as a concave side in its immediately adjacent neighbor. They are coherent, have a distinctive cooling margin, and may be zoned with respect to vesicle distributions (McPhie et al., 1993) or crystal habit (e.g., Fowler et al., 1986). In addition, their surfaces may have wrinkles, corrugations, contraction, or spreading cracks (McPhie et al., 1993) and more rarely they may have multiple rinds (Kawachi and Pringle, 1988). Typically, at least in ancient environments, they are associated with the distal portions of massive flows (e.g., Dimroth et al., 1978). Hyaloclastite is preserved but is far less abundant than in felsic systems. Pillows may be intrusive into unconsolidated sediment in which case they are associated with pepperite. The bulbous forms of the V10b unit that we describe contain elements of both lobes and pillows and accordingly we use the term pillow lobes.

The term variole should refer to a centimeter-sized leucocratic globule within a fine-grained mafic igneous rock (see Lofgren, 1974, or Fowler et al., 1986, for details). As such, it is a useful, general, descriptive, and nongenetic field term, particularly for altered rocks. Detailed work may show them to be amygdules, blotchy alteration, lapilli, spherulites, or phenocrysts. Spherulites are fibrous branching mineral growths that commonly, but not necessarily, have a spherical geometry. The crystallographic orientation of each fiber within the ensemble is different from that of its neighbors; hence the branching is termed "noncrystallographic." Within Archean basalts spherulites are typically composed of plagioclase and less commonly clinopyroxene (Fowler et al., 1986). Once a detailed textural determination has been made the field term variole should be discarded. Varioles of Archean basalts were thought to be quenched immiscible droplets (e.g., Gélinas et al., 1976). Although the term variolitic basalt is entrenched for Archean basalts that are clearly spherulitic, it makes no sense to apply the term spherulite to felsic rocks and a different term for the identical texture in mafic rocks. Therefore, we have retained the word variole in this text, chiefly when quoting or reporting on the work of others, although for the most part, the textures have been proven to be spherulitic.

Sampling and Analysis

The mapping and sampling of the Fire-tower outcrops at Timmins were completed during the summer of 2004, and additional samples from other V10b outcrops were collected during June 2005. They were processed at the University of Ottawa. The samples were crushed, to a size less than ~1 cm, using a steel plate Jaw Crusher, and pulverized to a very fine powder, using a porcelain shatter box. The powders were placed into platinum crucibles and fused into disks composed of 1 g of sample mixed with 4 g of flux, which consisted of 78.53 percent lithium tetraborate ($Li_2B_4O_7$) and 21.47 percent lithium metaborate fused.

The major oxides were analyzed by X-ray fluorescence at the University of Ottawa, using a Philips 2400 spectrometer controlled by the software XRF SuperQ. Ferrous iron was determined by the modified Wilson (1960) technique (Whipple 1974) at the Ontario Geoscience Laboratory in Sudbury. The trace elements were analyzed by means of an inductively coupled plasma mass spectrometer (ICP-MS) at the Ontario Geoscience Laboratories after the rocks had been digested for 14 d in a closed beaker, using hydrochloric, hydrofluoric, perchloric, and nitric acids. The samples collected in 2005 were analyzed at the SGS laboratory in Toronto also by ICP-MS. The relative error of the analyses is generally less than 1 percent for the major oxides and less than 5 percent for the trace elements including REE.

A geochemical database of the Vipond Formation was provided by the Porcupine Joint Venture (now Goldcorp Inc.). Their samples (55), collected in 2001 were analyzed for major oxides and traces elements by ALS Chemex laboratories. Details on the analytical techniques are contained in Saumur (2005) and Dinel (2007).

Geology of the Tisdale Assemblage

The Tisdale assemblage was subdivided into five formations by Ferguson (1968), Dunbar (1948), and Jones (1948). The majority of the gold deposits of the Timmins area are contained within it, particularly the Vipond Formation (Brisbin 1997). It is characterized by very distinctive high Fe tholeiitic spherulitic pillowed mafic volcanic flows and variolitic hyaloclastic mafic flows which are intercalated with massive mafic flows and carbonaceous argillite. Certain units within the

Vipond Formation, including the V8 and V10b units, serve as marker horizons within the Timmins camp. The V8 unit is variable in terms of its thickness (Ferguson, 1968) and overall it has a striking appearance characterized by large meter-sized elongated basalt pillows with thick zones (10–15 cm) of hyaloclastite. The pillows are spherulitic with spherulites typically being concentrated in a ~20-cm band just within the pillow margins.

Brisbin (1997) described the V10a unit (at McIntyre) as a fine-grained massive flow that is 12 to 35 m thick and is locally underlain and overlain by carbonaceous interflow sediments. At the Dome mine, the unit is termed the Andesite flow. Overlying this is the V10b unit (at McIntyre) described as a 20- to 40-m-thick unit with a distinctive chicken-feed texture, which at the Dome mine formed the upper portion of the Andesite flow. The V10c unit (at McIntyre) is a massive flow identical to the V10a unit, approximately 5 to 20 m thick, and correlative with the base of the Dacite flow at the Dome mine. The V10d unit has the same texture as the V10b unit and is known as the upper portion of the Dacite flow at the Dome mine, where, in addition to having chicken-feed texture, it has also been described as having a "ropey flow top." It appears that at the Dome mine the Dacite flow comprises two facies of the same unit and that the Andesite flow is composed of "several flows, which lens out along strike" (Holmes, 1968, *in* Ferguson, 1968; Brisbin, 1977). At Hollinger, the V10a and b units were apparent, but neither the V10c nor the V10d units were recognized (Jones, 1968, *in* Ferguson, 1968).

It is not possible to ascertain the details of the gold mineralization within the V10 units as there is no longer access to the underground workings, and detailed descriptions do not exist. However, Brisbin (1997) reviewed the distribution of ore in the various mines having rocks of the V10 Member. The V10a unit hosted the most important ore bodies at the Vipond mine, whereas portions of the 92, 93, and 44 veins at Hollinger were hosted in the V10a and V10b units. Furthermore, the Dacite ore at the Dome mine was hosted in all four of the V10 units. Typically, gold mineralization is found associated with quartz-ankerite fault-fill and extensional veins that are distributed along structures or flow contacts. Hurst (1935), Graton et al. (1933), Ferguson (1968), and Brisbin (1997) all described ore either being distributed at flow contacts or in veins parallel to flow contacts. In addition, Hurst (1935) described significant gold mineralization in pyritic orebodies within the mines of the camp. These orebodies have irregular geometry and disseminated mineralization associated with pyritization of the host rock. Hurst (1935) postulated that the chemical composition of the wall rock controlled the formation of pyrite and was an important factor in determining the locus of gold deposition.

Geology of the V10b Unit

We inspected and sampled numerous outcrops of the chicken-feed V10b unit in and around Timmins that appear on the map of Ferguson (1968) over a strike length of approximately 10 km (Fig. 1A). The Fire-tower outcrops, where the primary features of the V10b unit are best exposed and preserved, are situated within 300 m of the former Vipond mine shaft that was part of the Hollinger-McIntyre system. The area is composed of three hummocky exposures that afford three-dimensional observation of the flow morphology. Although the rocks are strained, their original textures are still well preserved. They were subjected to a penetrative deformation that produced a nearly vertical stretching lineation. The mineralogy is dominantly composed of chlorite, albite, and carbonate (calcite and ankerite) typical of greenschist facies metamorphism.

The Fire-tower outcrop is dominated by amoeboid pillow lobes with an abundance of intervening breccia (Figs. 1B, 2A). The pillow lobes are in general meter scale, ranging in size from 10 cm to 4 m, and weathered to a pale green (chloritic) to buff (ankeritic) or white (albitic) color. Many of the pillow lobes are characterized by a highly contorted and folded geometry and some have the appearance of having been necked. The folding pattern is not consistent over the outcrop and does not coincide with the regional pattern. The foliation observed is not axial planar to these folds but is related to later regional-scale deformation. The pillow-lobe geometry is therefore interpreted to be primary and formed as a result of plastic deformation during effusion.

V10b pillow lobes can be classified into three types depending upon their internal components and size. However, all pillow lobes are surrounded by massive 5-cm-thick dark green-colored margins composed of extremely fine grained-altered glass dominated by chlorite and carbonate (Fig. 2B). Margins are aphyric, and there is a lack of primary porosity. In addition they have a crumbled look suggestive of in situ primary brecciation related to shearing during flow. Like other pillow-lobe components, the margins have been complexly deformed while still plastic.

In the largest pillow lobes (≥1 m), the margin gives way to a breccia zone of variable thickness (10–50 cm) consisting of millimeter-scale, brecciated, homogeneous or flow-banded aphyric chloritized and ankeritized glass. The fragments are blocky and angular with sharp boundaries and rotated clasts. In some places jigsaw fit breccias (Fig. 2C) are observed. Perlitic fractures (Fig. 2D) are evident in some clasts. Pore spaces between the altered glass clasts are filled with quartz, albite, and carbonate minerals. Chloritized breccia appears massive on weathered surfaces, whereas ankeritized material shows a distinct mottled porous texture where clasts appear brownish white because of carbonate dissolution. The latter is the material that was named chicken-feed by Graton et al. (1933), Ferguson (1968), Griffis (1968), and Brisbin (1997). Flow banding defined by varioles (spherulites) is commonly observed in the brecciated zones. Ribbons of spherulites are folded, demonstrating a complex flow history and pillow-lobe rotation (Fig. 2E). Also, a wrinkled or ropey structure is evident on some of the thinner extremities of the more contorted pillow lobes (Fig. 2F).

The cores of these large pillow lobes are of variable size (50 cm to 4 m) and composed of altered aphyric glass containing abundant spherulites. The spherulites weather to a white color and form millimeter-scale positive relief mounds. In places, generally toward the center of a particular pillow, the spherulites have impinged upon one another and form centimeter- to decimeter-scale white weathering amoeboid patches of rock (Fig. 2B). The spherulites are composed of fine radiating fibers of plagioclase in a matrix of chloritized-altered glass. Rarely, they have nucleated on the margins of

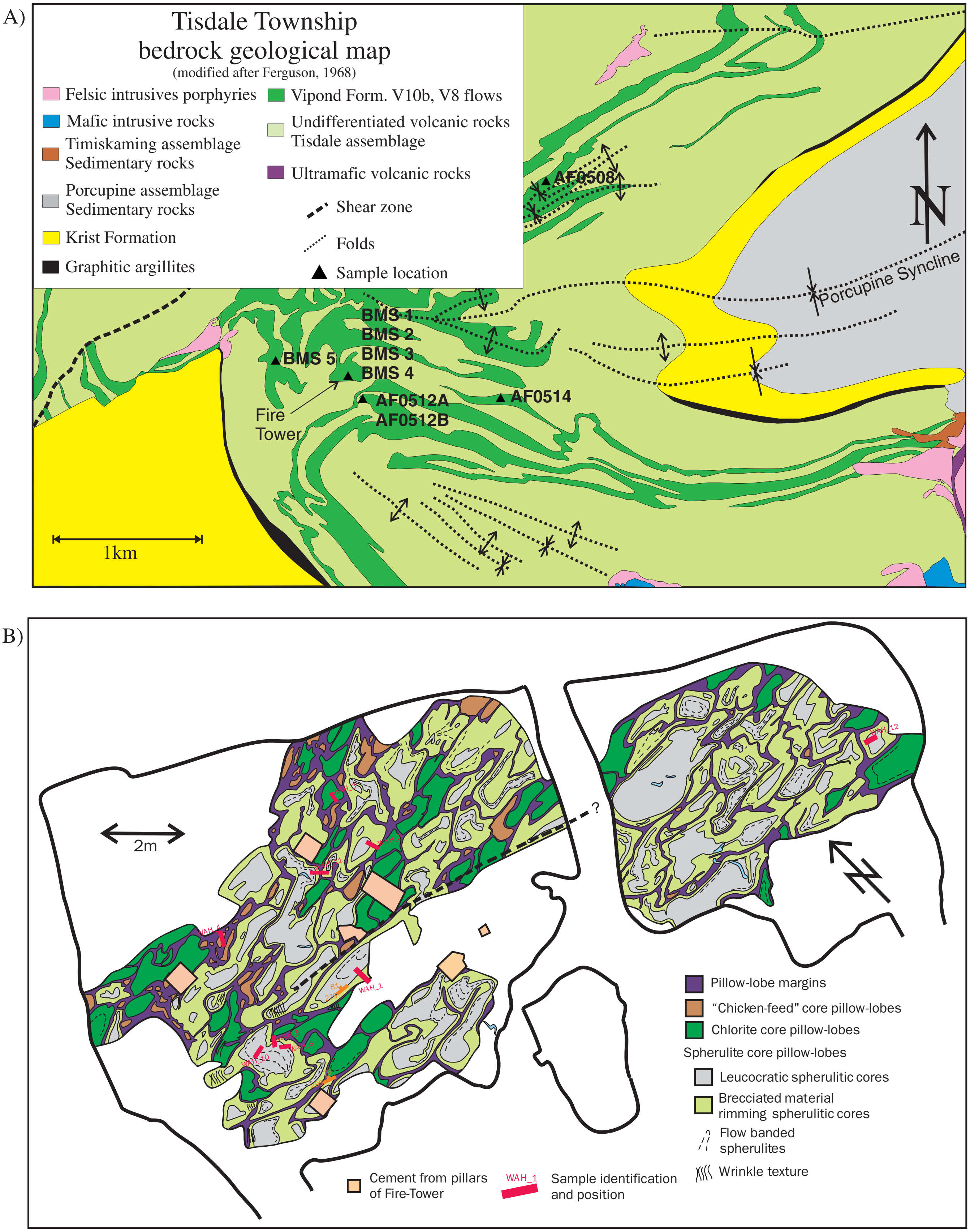

FIG. 1. A. Geology of a portion of Tisdale Township, Timmins area (after Ferguson, 1968), showing the distribution of the V10b and sample locations. B. Map of the Fire-tower outcrops (after Saumur, 2005).

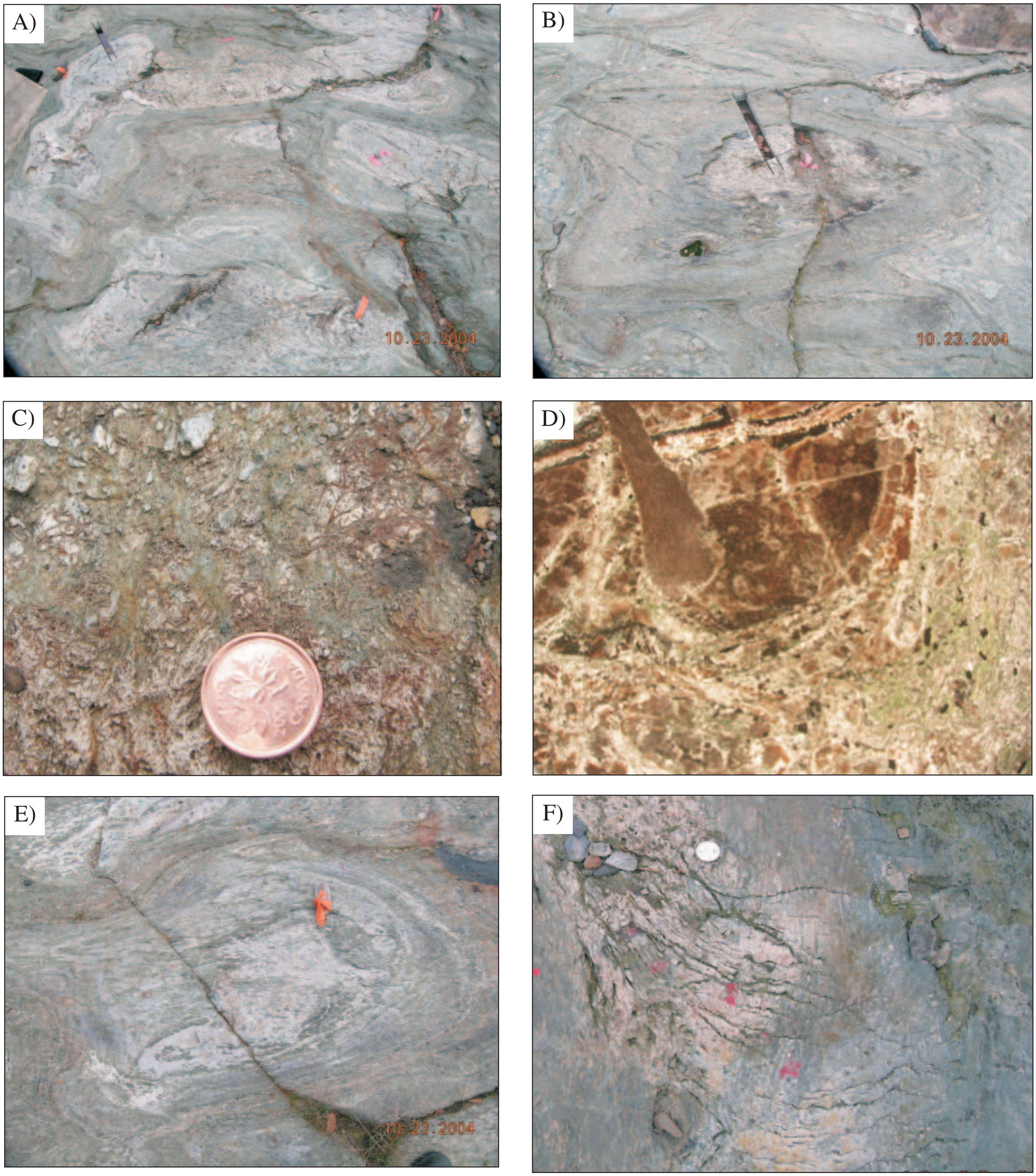

FIG. 2. A. Photo of a portion of the Fire-tower outcrops (field of view is ~3 m). B. Image of large pillow lobe (spherulite core), showing fine-grained margin and breccia zone (field of view is ~1 m). C. Image of jigsaw fit texture in chicken-feed from pillow breccia zone (coin is ~1 cm diam). D. Image of perlitic fracture (field of view is 5 mm). E. Flow banding in spherulite-rich pillow-lobe core (field of view is 1.5 m). F. Image of ropy wrinkles having a slight curvature associated with the pervasive foliation that is subaxial-planar to the curvature. The texture is primary, although deformed (coin is ~1 cm diam).

gas bubbles (Fig. 3A). The cores of the pillows are evidently less brecciated and altered and, therefore, were likely less permeable than their margins and breccia zones. Flow banding can commonly be traced within spherulitic cores. Figure 3B illustrates an idealized spherulitic core of a pillow lobe.

Smaller pillow lobes do not have the full range of features observed in the larger ones. Pillow lobes ranging from 40 cm to 1 m in size lack a spherulitic core and have chlorite breccia identical to that of the breccia zone of spherulitic pillow lobes. Typically there is a zone of ankerite rich chicken-feed surrounding these chloritic cores. The outer chicken-feed zone has more primary porosity than the chlorite breccia in the cores. Pillow lobes with chloritic cores commonly contain flow banding defined by spherulites. Hence a distinction is made between spherulites concentrated in pillow-lobe cores and spherulites defining flow banding. Only the largest of these smaller pillow lobes are contorted in a fashion similar to the larger pillow lobes.

The smallest pillow lobes are typically decimeter-scale brownish pods completely dominated by chicken-feed texture, and it is in these pillow lobes that this texture is best developed as millimeter- to centimeter-scale void spaces related to primary brecciation (Fig. 3C). The perimeter walls of the void spaces are quasiplanar, stand out in relief, and meet at well-defined corners. However, the carbonate within the voids is recessively weathered, forming conspicuous hemispherical pits, giving the allusion that the texture is composed of broken spherical fragments (i.e., spherulites).

Both of the smaller pillow-lobe types are similar in the sense that they are both almost entirely composed of breccia and are not as deformed as the larger spherulite-cored type. We interpret both pillow-lobe types as having had the same

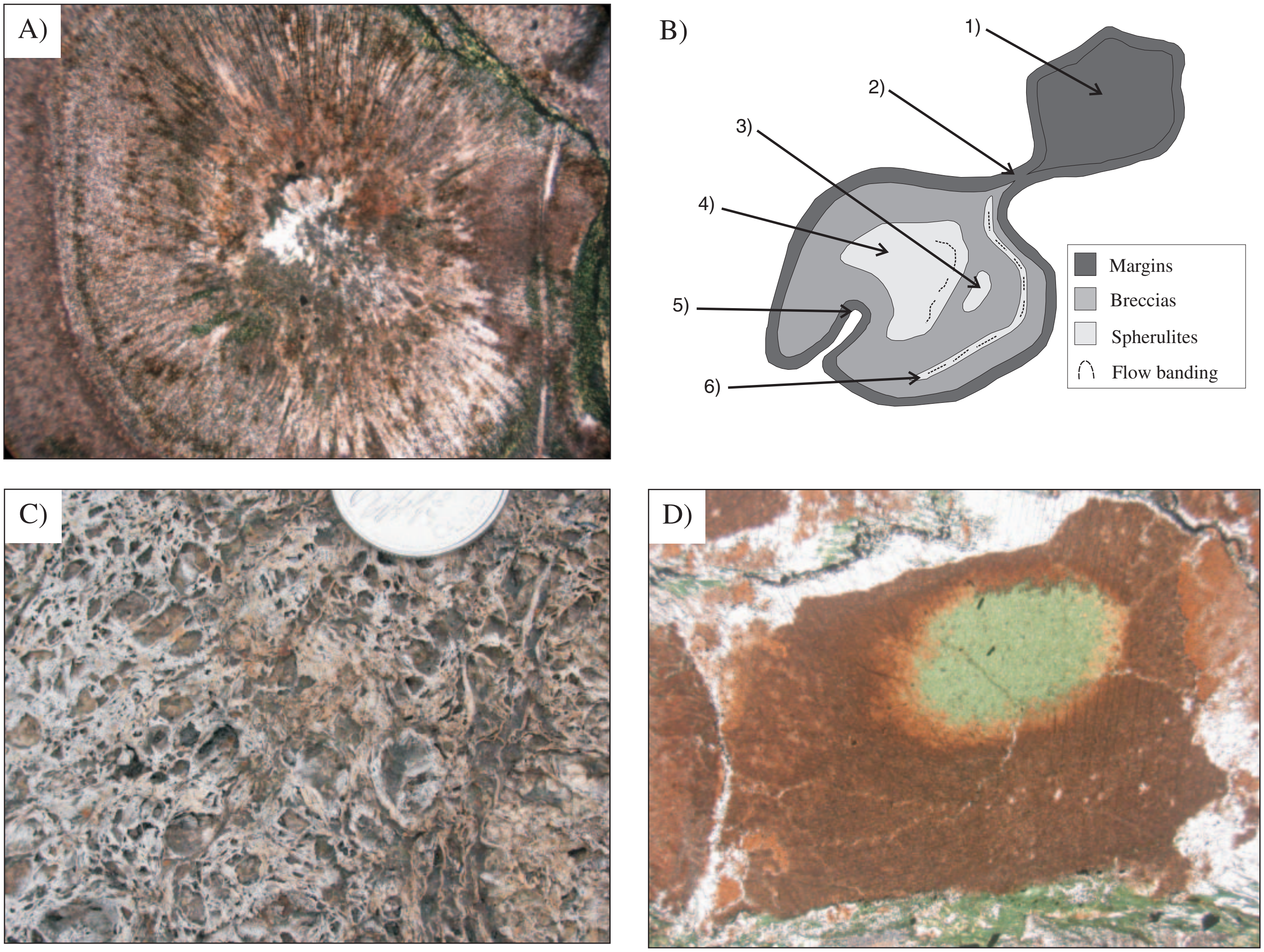

FIG. 3. A. Spherulite surrounding calcite interpreted to be an amygdule (field of view = 2 mm). B. Sketch of an idealized meter-scale pillow lobe. (1) Pillow lobe containing no spherulites; breccia may have a chicken-feed appearance. (2) Example of complex primary contortion and connection between two breccia zones as defined by margins (necking). (3) Observation of more than one spherulite-rich area in a pillow lobe is common. (4) The boundary between spherulitic cores and breccia is generally diffuse; the spherulites are discrete at the core's edge and coalesced at the core's interior. Spherulite—defined flow banding is common. (5) Margins are generally severely contorted and can be infolded. (6) Flow banding is common in the brecciated material and is defined by spherulites. C. Image of chicken-feed on weathered surface (coin is 2.5 cm diam). D. Chloritized chicken-feed clast partially replaced by ankerite (field of view = 4 mm).

primary volcanic origin but alteration played a major role in determining their appearance on weathered surfaces. Pervasive chloritization is associated with regional metamorphism (Thompson, 2005), whereas ankeritization overprints it (Fig. 3D). The ankeritization is related to subsequent hydrothermal alteration that was evidently dependent on permeability, as only the smallest of pillow lobes are completely ankeritized.

Geochemistry of the V10b Unit

Rocks of the Vipond Formation are tholeiitic in composition (Brisbin, 1997) and are characterized by flat chondrite-normalized REE patterns. Below we compare our samples of the V10b unit to those of the Vipond Formation geochemical database provided by the Porcupine Joint Venture in order to classify the rocks. Geochemical data, sample locations, and sample descriptions of the V10b specimens collected by us are given in Table 1.

Although slight LREE mobility in not uncommon, REE are generally considered reliable indicators of the protolith of volcanic rocks within the Abitibi subprovince (e.g., MacLean and Kranidiotis, 1987; MacLean, 1988; Kerrich and Xie, 2002; Ropchan et al., 2002; Polat and Kerrich, 2006; Wyman and Hollings, 2006; Dinel et al., 2008). Exceptions are rocks that have been subjected to amphibolite facies or higher metamorphism or those that have been altered by hydrothermal fluids having a high activity of Cl^- (e.g., McCuaig and Kerrich, 1998). REE abundances have been used to determine the protolith of moderately altered rocks within the Abitibi subprovince (e.g., VMS deposits: Gibson et al., 2000; gold deposits: Dinel et al., 2008, and Ropchan et al., 2002). MacLean (1990) and MacLean and Hoy (1991) have demonstrated that Ti Al, Zr, and Y are generally immobile in the volcanic rocks of VMS deposits of the area. However, Hynes (1980) has demonstrated their mobility in response to carbonatization of basalts. The majority of rocks in the Timmins area are lower greenschist facies (Thompson, 2005) and the fluids associated with Archean lode gold systems do not have a high activity of Cl^-; therefore we consider the REE and other immobile elements and oxides ($Ti\ O_2$, Al_2O_3, Zr, Y) to be reliable indicators of the primary lithogeochemistry. At the nearby Hoyle Pond mine, Dinel et al. (2008) demonstrated that REE, Al_2O_3, Zr, TiO_2, and Y were relatively immobile with respect to the sericite, albite, and carbonate alteration proximal and distal to veins and can be used to identify rock type, whereas, K_2O, Na_2O, Cr, Rb, CO_2, CaO, Eu, FeO, MgO, and to a minor extent the LREE, were mobile.

REE patterns of rocks of the tholeiitic suites of the Abitibi subprovince are typically flat, with basalts having REE concentrations approximately 10 to 30 times chondrite and rhyolites on the order of 100 to 400 times chondrite, with slight negative Eu anomalies in the more evolved rocks (Fowler and Jensen, 1989; Jackson et al., 1991; Hart, 2001; Hart et al., 2004). In contrast, rocks of the calc-alkaline suites typically have significant LREE enrichments and conspicuous negative Eu anomalies in their evolved rocks.

Data from the Porcupine Joint Venture database of the Vipond Formation show a wide range in REE concentrations from 6 to 90 times chondrite (Fig. 4A), with a gap between 35 and 45 times chondrite. The chondrite-normalized REE plots of the V10b rocks (Fig. 4B) are essentially flat with concentrations roughly 40 to 70 times chondrite and no conspicuous Eu anomalies. Most of our V10b samples plot above this gap (Fig. 4B) with the exception of two samples (sample AF0512A and B). These two samples were taken from an outcrop approximately 250 m south (down stratigraphy) of the Fire tower. Based on the flat REE pattern, we conclude that the V10b rocks are part of the tholeiitic suite and are intermediate to felsic in character. Because we are unaware of any specific classification scheme for the tholeiitic rocks of the area in terms of the REE, we use other elements to refine the classification.

Because one may argue that Archean volcanic rocks are not identical to their modern equivalents, we believe it makes most sense to compare our rocks to nearby Archean equivalents. Accordingly, we have used empirical diagrams designed by MacLean and Kranidiotis (1987), MacLean (1990), and Barrett et al. (1991) for similar rocks elsewhere in the Abitibi subprovince. These rocks represent a suite from basalt to rhyolite, the REE patterns of which are almost flat. Although the rocks are considered transitional by the authors they concluded that the relatively flat REE patterns indicate that the volcanic rocks are more closely related to tholeiitic than calc-alkaline magmas. The REE concentrations of rhyodacite and rhyolite from Noranda are approximately 60 to 100 times chondrite, essentially flat, and very similar to those of the V10b unit (see below). Unlike the V10b rocks, the rocks from Noranda have more pronounced negative Eu anomalies, possibly due to differences in igneous fractionation, although Eu unlike the other REE is fairly easily mobilized during alteration (e.g., Fowler and Doig, 1983). Thus we infer, based upon the comparison with the REE of the Noranda rocks, that the V10b rocks (except samples AF0512A and B) are evolved and possibly dacitic in composition.

We test this classification further by using other plots of immobile elements Al, Ti, and Zr as used by Barrett et al. (1991). A plot of the Porcupine Joint Venture data for the Vipond Formation volcanic rocks in Y versus Zr space (Fig. 4C) shows a trend consistent with the fractionation pattern defined by Barrett et al. (1991) for rocks from the Aldermac deposit in Noranda. In addition, data from the V10b rocks we sampled (except samples AF0512) plot as dacites. Figure 4D shows the TiO_2 versus Zr diagram of Barrett et al. (1991) and their modeled fractionation trend. Most of the samples of the Vipond Formation plot as andesites; however, the V10b samples plot closer to the dacite field, again with the exception of samples AF0512 A and B. In the Al_2O_3 versus Zr diagram (Fig. 4E), the Vipond Formation samples are concordant with the proposed fractionation trend of Barrett et al. (1991), and most of the V10b analyses plot in the dacite field, except samples AF0512 A and B. Although there is scatter in all of these diagrams, particularly in Figure 4C, with respect to the differentiation trend, the REE, Ti, Zr, Y, and Al_2O_3 data are consistent with the V10b rocks being part of the tholeiitic suite. The data are also consistent with the field observations of flow banding, contorted geometry, abundant breccia, and lobe zonation that suggest a composition approaching dacite. Using our data for REE (Fig. 4A) and the classification of our samples according to the fractionation trends of Barrett et al. (1991), we identify a range of REE concentrations for both

TABLE 1. Geochemical Data for Major Oxides (wt %) and Trace Elements (ppm) and Sample Description and Position in the Various Lobe Facies[1]

	BMS 1	BMS 2	BMS 3	BMS 4	BMS 5	AF0508	AF0512A	AF0512B	AF0514
	Firetower	Firetower	Firetower	Firetower	Vipond Rd.	Hwy. 101	Powerline	Powerline	Powerline
	5367897N	5367897N	5367897N	5367897N	5368037N	5369345N	5367700N	5367700N	5367665N
	0477565E	0477565E	0477565E	0477565E	0476983E	0479066E	0477820E	0477820E	0478630E
Sample description	Spherulitic core of lobe	Massive facies of lobe	Chill margin of lobe, hyaloclastite breccia	"Chicken feed" texture facies, highly ankeritized hyaloclastite breccia	Bulk sample	Highly strained lobe and breccia in contact with the variolitic basaltic flow	Lobe and breccia facies, showing margin to core transition	Lobe and breccia facies, showing margin to core transition	Highly strained lobe and breccia ("chiken feed") facies
Major element oxides (wt %)									
SiO_2	59.70	57.53	48.27	51.39	54.39	58.81	66.96	38.03	57.85
TiO_2	1.31	1.50	1.32	1.30	1.43	1.465	1.258	1.502	1.448
Al_2O_3	10.42	12.81	10.69	10.83	11.92	12.87	13.85	17.16	11.95
Fe_2O_3	1.76	1.77	3.11	2.23	2.97	11.787	7.463	21.46	13.173
FeO	4.67	10.81	17.91	12.46	13.00	-	-	-	-
MnO	0.22	0.17	0.31	0.32	0.26	0.174	0.069	0.242	0.198
MgO	1.15	2.31	3.67	2.51	3.14	2.08	2.4	6.56	1.76
CaO	6.84	3.42	5.07	7.46	3.93	3.96	0.71	4.46	3.81
Na_2O	3.81	3.89	0.19	2.11	2.41	4.4	2.69	0.31	4.85
K_2O	0.47	0.01	0.00	0.02	0.02	0.014	0.997	0.561	0.008
P_2O_5	0.46	0.51	0.47	0.46	0.51	0.52	0.11	0.14	0.52
S	0.01	0.10	0.02	0.03	0.05	-	-	-	-
CO_2	5.26	2.21	4.30	5.81	1.67	-	-	-	-
LOI	1.27	2.34	4.65	2.60	3.50	4.5	4.6	10.2	4.8
Total	97.35	99.38	99.97	99.52	99.18	100.58	101.107	100.625	100.367
Trace elements (ppm)									
Ba	158	22	24	39	89	29	464	368	25
Co	15	24	23	16	24	22	33	57	20
Cr	28	29	26	26	33	28	43	57	27
Cs	1.208	0.067	0.15	0.12	0.228	-	-	-	-
Ga	15	20	13	16	20	18	16	23	14
Hf	4.7	5.8	5	4.8	5.4	-	-	-	-
Nb	7.9	9.7	7.3	7.9	8.5	10	5	4	8
Ni	<1	<1	6	<1	<1	18	29	111	17
Pb	1	7	5	3	3	5	6	9	2
Rb	12.18	0.18	0.17	0.46	0.33	7	39	26	5
Sr	206.5	130.4	113.9	229.9	80.3	72	82	71	127
Ta	0.45	0.56	0.46	0.46	0.52	-	-	-	-
Th	0.78	1.14	0.78	0.76	0.88	8	7	9	8
U	0.228	0.467	0.232	0.223	0.257	2	3	4	2
V	31	41	45	34	41	38	278	391	42
Y	56.95	71.46	80.05	65.92	71.26	77.5	40.4	63.5	78.2
Zn	74	135	201	140	165.25	119	75	224	103
Zr	168.6	202.8	181.7	172.8	191.1	191	126	153	189
La	9.87	12.16	12.16	10.3	11.32	9.7	8.3	7.1	11.6
Ce	28.16	33.93	33.28	28.61	31.84	26.5	21.9	19.7	31.5
Pr	4.535	5.462	5.489	4.672	5.091	-	-	-	-
Nd	24.25	28.38	28.84	24.6	26.64	25.3	16.7	14.2	27.1
Sm	7.49	8.99	9.01	7.86	8.67	9.2	4.9	5	9.3
Eu	2.326	2.895	2.863	2.633	2.789	3.6	1.47	1.63	3.2
Gd	9.361	11.765	11.949	10.373	11.553	11.5	5.43	7.64	11.8
Tb	1.558	2.008	2.07	1.795	1.934	2.29	1.15	1.75	2.45
Dy	10.202	12.985	13.772	11.626	12.804	13.5	7.01	10.8	13.9
Ho	2.167	2.763	2.968	2.465	2.692	3.3	1.75	2.75	3.54
Er	6.525	8.312	8.93	7.367	8.004	9.39	5.01	7.86	9.6
Tm	0.942	1.208	1.306	1.084	1.197	1.44	0.77	1.19	1.54
Yb	6.19	7.99	8.7	7.23	7.88	8.4	4.6	7	8.8
Lu	0.932	1.194	1.328	1.102	1.199	1.46	0.82	1.2	1.58

[1] Sample location given with respect Universal Trans Mercator grid NAD 27

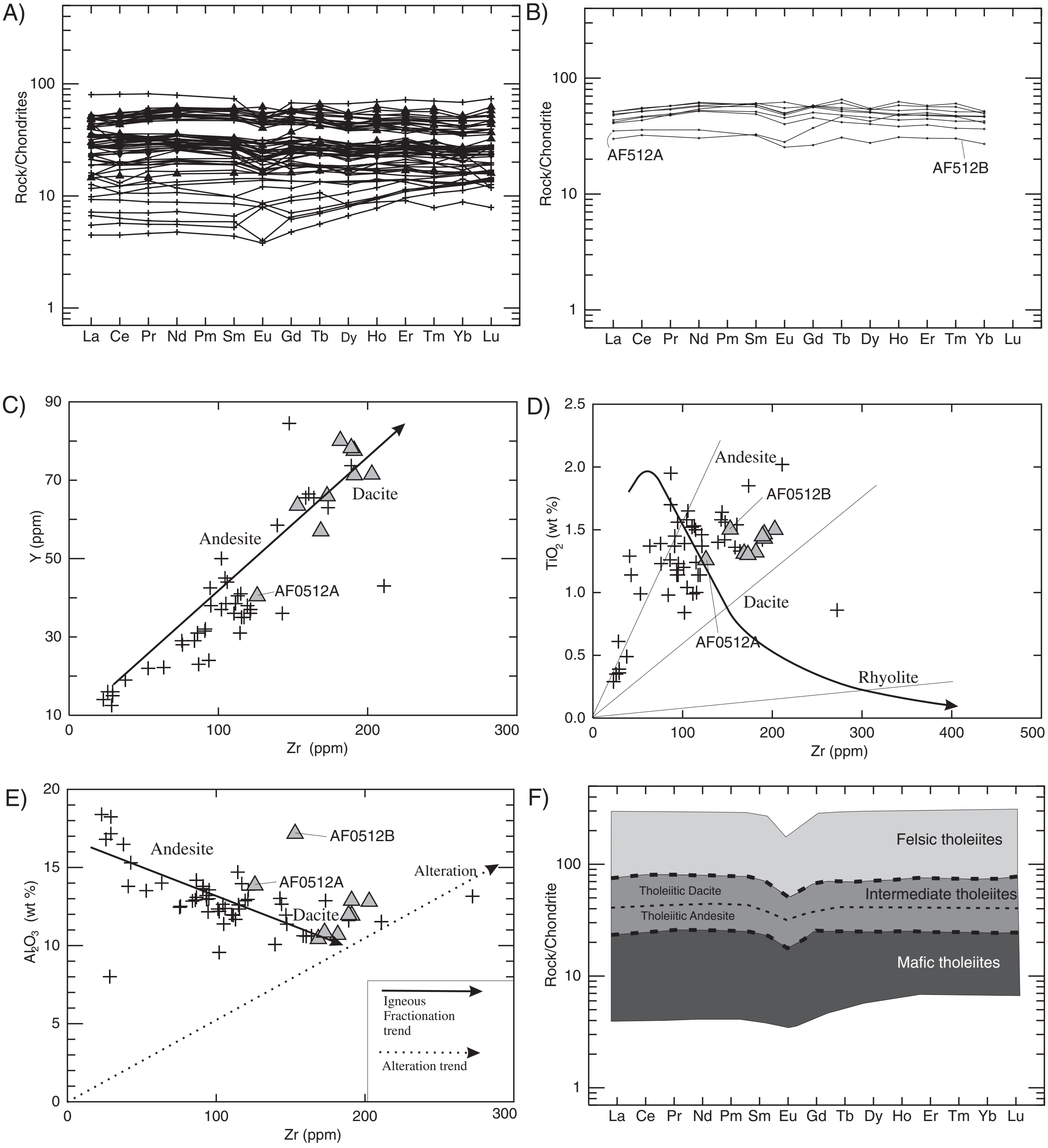

FIG. 4. A. REE plot of the Vipond Formation (data provided by the Porcupine Joint Venture). The data of Sun and McDonough (1989) were used to normalize (B) REE data from samples of the Fire-tower and other outcrops. C. Y vs. Zr plot based on Barrett et al. (1991). The samples identified with triangles represent the V10b samples. The crosses represent data from the Vipond Formation database. D. TiO$_2$ vs. Zr plot based on Barrett et al. (1991). The data identified with triangles represent the V10b samples. The crosses are from the Vipond Formation database. E) Al$_2$O$_3$ vs. Zr plot based on Barrett et al. (1991). The samples identified with triangles represent the V10b samples and the cross represents data from the Vipond Formation database. F. Proposed discrimination diagram for the tholeiitic suite of volcanic rocks of this study based on chondrite normalized REE.

mafic tholeiites and intermediate tholeiites of the Vipond Formation (Fig.4F).

Gibson et al. (1989) have documented silicification of andesite in the Amulet and Millenbach Formations near Rouyn Noranda, Québec. Their detailed mapping shows that the silicification of the rocks occurred during a short cessation of volcanism associated with hydrothermal alteration and sea-floor chert deposition. These rocks differ from those of the V10b rocks in that they show none of the complex zoning of the pillow lobes, they have both feldspar microlites and phenocrysts, and spherulites are only sparsely developed. Unlike the V10b rocks the silicified andesites at Noranda are variably bleached and have quartz-filled amygdules. The presence of explosion breccias and feeder dikes in the rocks of the Noranda camp demonstrates that they were emplaced in a phreatomagmatic environment compared to the more passive depositional environment of the V10b rocks. Geochemically the Amulet and Millenbach Formation rocks have slightly elevated LREE and a wider range of Eu/*Eu values in comparison to the V10b rocks (see Lesher et al., 1986, for data). Therefore, we conclude that the V10b rocks are not direct analogues of the silicified andesites of the Amulet and Millenbach Formations.

Figure 5A is a Jensen plot (Jensen, 1976) of data from whole-rock samples taken from the Fire-tower outcrop. The data span the range from high Fe tholeiite basalt through andesite to tholeiitic dacite. Significantly, however, the data correlate with location in the pillow lobes. The specimens with high iron content come from the ankerite-rich and porous peripheral areas of the pillows, whereas the core, which is characterized by minimal porosity, plots within the dacite field. The high Fe data points are an artifact of alteration (ankeritization). In Figure 5B, we show the correlation between Fe_2O_3 (total iron wt %) and TiO_2. Compared to the expected igneous fractionation trend of a tholeiitic suite, the V10b samples define a trend almost orthogonal to the igneous trend, which we interpret to be due to the mobility of Fe.

Samples BMS-3 and BMS-1 show significant departure from the expected igneous trend. Sample BMS-3 is enriched in Fe and was collected from the pillow-lobe margin where brecciation and alteration (ankerite and chlorite) is strongly developed in comparison to the pillow-lobe core where sample BMS-1 was taken. The sample pair AF0512 A and B is similarly from the core and rim of a pillow lobe.

Discussion

Subaqueous felsic flows have been documented by numerous authors (e.g., Cas, 1978; De Rosen-Spence et al., 1980; Yamagishi and Dimroth, 1985; Kano et al., 1991; Scutter et al., 1998; Waters and Binns, 1998; Ayers and Peloquin, 2000), some of whom described pillowlike pods. Bevins and Roach (1979) described pillowed rhyodacite lavas from the Ordovician of Wales. They attributed the pillow formation to the fluid nature of the melt. These lavas contained less than 1 vol percent phenocrysts and may have been erupted on a relatively steep slope in deep water where ambient pressure would have prevented exsolution of the gas phase, thereby reducing viscosity. Cas (1978) described regionally extensive vesicular and porphyritic dacite-andesite and rhyodacite units associated with flyschlike sedimentary rocks, suggesting a deep-water environment of deposition. He attributed the large-scale coherent nature of the felsic flows to suppression of volatile exsolution in the deep marine environment and the concomitant reduction in melt viscosity. Scutter et al. (1998) described large (~25 km²) submarine rhyolite flows from Ponza, Italy, that were emplaced over domes. They demonstrated that flow was favored where eruptive rates were high,

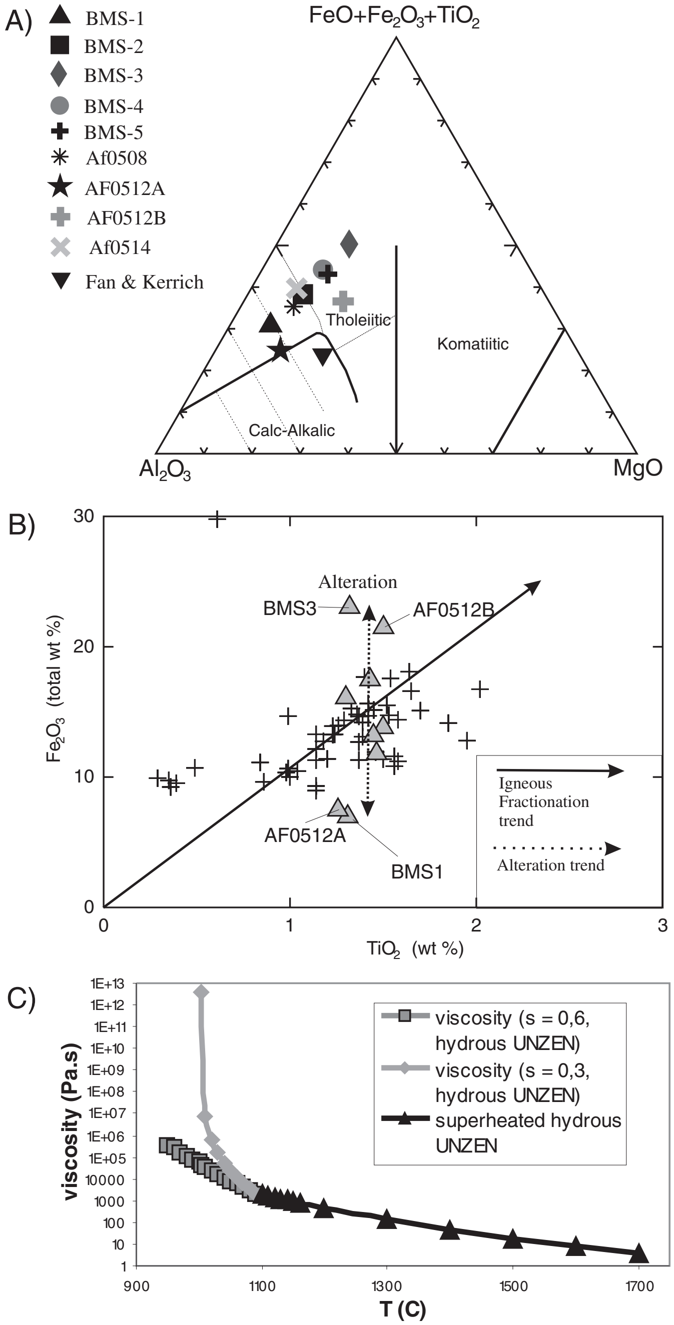

FIG. 5. A. Jensen plot (Jensen 1976) of the data from the Fire-tower outcrop and other outcrops. B. Fe_2O_3(total) (w%) vs. TiO_2 plot showing their relationship in the tholeiitic suite. The samples identified with triangles represent the V10b samples. The crosses are from the Vipond Formation database. Fe enrichment and depletion in some sample interpreted to represent alteration. C. Viscosity calculation for Mt. Unzen dacite melts as a function of temperature (triangles and squares), and melts plus crystals (diamonds).

topography steep, the cooling rate was slow, and that the magma had relatively low viscosity. Manley and Fink (1987) studied subaerial rhyolite flows from the southwestern United States and documented a variable internal stratigraphy consisting of seven zones in which the rhyolite flows typically have glassy margins and spherulitic cores. Kano et al. (1991) described porphyritic rhyolites that were erupted into a submarine environment. These are composed of large (1–15 m) flow-banded and folded lobes, blocks, and rhyolite breccias and are considered to be the equivalent of subaerial block lavas. We interpret the V10b lavas to have been erupted in a subaqueous environment as coherent flows, consistent with the mafic pillow lavas that are ubiquitous within the Tisdale assemblage (Pyke, 1982; Brisbin, 1997).

We are unaware of any previous detailed work on aphyric pillow-lobe dacitic lava facies in the Timmins area, and apparently little has been published on this volcanic facies elsewhere. De Rosen-Spence et al. (1980) described the various facies of rhyolite and dacite from the Quaternary of Iceland, and quartz and plagioclase phenocryst-bearing rhyolite and dacite flows from the Archean of the Rouyn-Noranda area, Québec. They described a core, rim, and border facies of meter-scale lava pods, lobes, and tongues characterized by increasing matrix crystallinity toward the core and breccia toward the margin, the overall architecture of the bodies being similar to young shallow endogenous cryptodomes (e.g., Goto and McPhie, 1998). Importantly the Archean rocks described by De Rosen-Spence et al. (1980) have quartz and plagioclase phenocrysts and the lobes are characterized by an internal stratigraphy different from that which we report here. They noted that in most flows a gradation from microlitic to felsitic to spherulitic textures can be observed from the center to the margin of the lava bodies; however, microlitic textures are present only in some of the larger lava pods and lobes. They also mentioned unusual spherulitic flows, but they did not study them in detail or report their location. Péloquin et al. (1996) used the spherulitic nature and chemical composition of rhyolites in the Rouyn-Noranda area of Québec as a correlation tool with potential for VMS exploration.

Rocks similar to those of the V10b rocks also have been described from the Héva Formation near Val d'Or (Scott and Mueller, 2001). The Héva Formation is a 25-km-long subaqueous spherulitic dacite lava flow consisting of a massive facies, a medial lobe-hyaloclastite facies, and an upper hyaloclastite facies. The flow is described as being aphanitic. It is interpreted to have formed in an extensional setting at elevated temperatures and discharge rates. Scott and Mueller (2001) considered that the melt was of low viscosity due to high confining pressures and reduced volatile solution.

Although superficially similar to pillow basalt, which is ubiquitous in the region (e.g., Pyke, 1982), we use the term "pillow lobe" for the V10b rocks because there are significant morphological differences. Although they are clustered meter-scale objects and have the typical molded appearance of pillows and other features such as wrinkles and well defined margins, they are like lobes in that they have an abundance of hyaloclastite, are internally brecciated, flow-banded, and zoned in a manner different from mafic pillows.

Emplacement

We have not found exposures of the bounding facies, however, previous work (described above) suggests that the four V10 units are a pair of couplets, each composed of a massive facies (V10a and c) and chicken-feed facies (i.e., pillow-lobe dacitic flow of this study, V10b and d). We interpret the pillow lobes to represent tubes and lobes formed during subaqueous flow, with some brecciation and flow banding having been caused by movement during emplacement. Further brecciation was caused by thermally driven granulation. The massive flows were likely deposited first and then a transition to the pillow-lobe morphology ensued in a manner typically interpreted for Archean submarine basalts (e.g., Dimroth et al., 1978), possibly due to a change in slope or effusion rate or both. Given the sinuous outcrop pattern of the V10b rocks, which was likely more nearly linear predeformation, and that they crop out over a strike length greater than 10 km, we postulate that the lavas most likely emanated from a fissure. Clearly we cannot trace the unit continuously, however it is known from previous underground work that the V10 units were continuous over distances of 100s of meters underground (e.g., Ferguson, 1968). One could argue that the facies represent domes and lobes, however the outcrop pattern is not correct: the pillow lobes are small, molded, and clustered, without the zonation described by De Rosen Spence et al. (1980) and the massive unit apparently lacks brecciation or the zonation of shallow submarine cryptodomes (e.g., Goto and McPhie, 1998; Stewart and McPhie, 2003). Moreover, we have neither observed pepperites nor pyroclastic deposits.

Development of pillow-lobe zonation and spherulite formation

Large pillow lobes are characterized by a thin margin that grades inward to a breccia zone and finally to a spherulitic core. We interpret the zones to be related to the thermal history of the melt in the pillow lobes. The contorted nature, banding, and tortuous outline of many of the pillow margins is evidence that the lava was viscous in comparison to basaltic melts and that it most likely flowed down a steep gradient once it was erupted. The lava cooled quickly below the glass transition, stiffened, and was brecciated both by physical and thermal stresses associated with cooling by seawater and movement.

Spherulites are most prevalent within the cores of large pillow lobes where they coalesced to form decimeter- to meter-scale patches. Spherulites form in silicate melts; they are commonly associated with glass and typically grow when diffusion is sluggish (i.e., high viscosity) and the cooling is rapid. Granasy et al. (2005) demonstrated that in strongly undercooled polymeric liquids dynamic heterogeneities exist. In essence, with undercooling, the rotational diffusivity of growth species in the melt diminishes much faster than their translational diffusivity. Thus growth species impinge upon and adhere to a growing ensemble due to growth front nucleation, but with a mismatched geometry, thus explaining the characteristic noncrystallographic branching.

In common with all crystals, spherulites require nuclei from which to grow. The aphyric lava contained no crystals (i.e., it was superheated) and likely contained no crystal nuclei because it was at a supraliquidus temperature). The lack of spherulites in the margin, and the paucity within the brecciated zone is different from the zonation of Archean spherulitic pillow basalts (Fowler et al., 1986) and is interpreted as evidence that the dacitic pillow-lobe exteriors cooled too quickly for crystal nucleation and crystal growth to occur. On the other hand the cores of the pillow lobes have abundant spherulites. Here, the cooling rate was relatively slow in comparison to the exterior because of the thermal insulation caused by the encapsulating material. Therefore, sufficient time existed during cooling of the pillow-lobe cores for nuclei to form, but the cooling rate was still sufficiently fast that spherulites arose rather than more compact and closer-to-equilibrium habits such as dendrites. Also, at large undercoolings the melt can be in a state where nucleation is slow relative to crystal growth, favoring the formation of few large spherulites rather than many small better faceted crystals (e.g., Fowler et al., 2002).

Although not explicitly stated, it appears that De Rosen-Spence et al. (1980) interpreted the spherulites they observed to have formed through devitrification. Because diffusion is so sluggish below the glass transition, spherulite growth at ambient temperature is unlikely (Ryan and Sammis, 1981; Manley, 1992). Indeed, experimental work by Lofgren (1971) demonstrated that devitrification of felsic glasses proceeds at elevated temperature and in the presence of an alkali solution. We interpret the spherulites within the cores of the pillow-lobe dacites to be primary because their distribution is related to position in the pillow lobe, that is, the former thermal gradient. Moreover, the spherulites within the cores are not related to fractures. Spherulites associated with flow banding were most likely formed above the glass transition as shown for rhyolites by Manley (1992).

Varolitic pillow basalts are ubiquitous in the region. The varioles are most prevalent as plagioclase spherulites in the Fe-rich basalts of tholeiitic suites and to a lesser extent as clinopyroxene spherulites in Mg-rich basalts. Typically the pillows are zoned with respect to their spherulite distribution. In general the spherulites are most conspicuous as centimeter-sized spheres within the outer 10 to 20 cm of the pillow margins.

The breccias within the V10b rocks are in part blocky, platy, and angular, consistent with autoclastic processes (i.e., they have a significant amount of hyaloclastite). In addition some are jig-saw fit breccias interpreted to be the result of thermal contraction granulation. The presence of sharp clast boundaries with overprinted alteration and rotated clasts precludes the textures being pseudobreccias produced by alteration (e.g., De Rosen-Spence, 1980). The convoluted banding of the pillow lobes is indicative of plastic deformation during flow and is related to the zonation of individual pillow lobes. Because the core material of the large pillow lobes remained above the glass transition during the time that the lobes were in motion, the lobes were still being deformed after the main plastic deformation and brecciation at the margins had occurred. Small pillow lobes are far less folded and are thoroughly brecciated most likely because they quenched quickly to a glass.

Temporal distribution of aphyric dacites

The aphyric pillow-lobe facies described here may be largely restricted to the Archean because the lavas were erupted in a superheated state, requiring the higher geothermal gradient of the Archean. The dacites, in common with komatiites and the widespread spherulitic basalts of the Archean, were developed as a result of this high geothermal gradient. The aphyric pillow-lobe dacite lavas we describe differ from the Archean subaqueous quartz phenocryst-bearing felsic flows first described by De Rosen-Spence et al. (1980) that form lava lobes, pods, and tongues. Some of these flows are true rhyolites, but most are probably siliceous iron-rich dacites and a few flows are silicified andesites.

In contrast to the pillow-lobe dacites, they contain phenocrysts, and the large lobes have microlitic and felsitic textures in their cores and spherulites are apparent at the margins, not the cores.

Aphyric pillow-lobe dacite may have been erupted elsewhere in the Abitibi subprovince (e.g., Scott and Mueller, 2001) and the unusual spherulitic flows mentioned by De Rosen-Spence et al. (1980) in the Rouyn Noranda area may be the same. Although aphyric dacites and dacitic pillows have been reported elsewhere, aphyric pillow lobes with spherulitic cores have not been described before, and in Archean rocks of the Timmins area, at least, they have sometimes been misidentified as basalts.

Recently, aphyric dacites have been reported from the Powder River basin, Wyoming, United States. These were subaerially erupted and formed laterally extensive and voluminous (~4 km) flows of aphyric andesite and dacite that overlie Miocene olivine basalt (McConnell et al., 2002). Waters and Binns (1998) described neovolcanic submarine porphyritic and aphyric dacite lavas with contrasting morphologies from the Manus basin, Papua New Guinea. Whereas the porphyritic dacitic lavas form prominent steep-sided conical peaks, the aphyric dacite lavas form a 15-km-long, 500-m-high linear ridge dominantly composed of chaotic autoclastically fragmented flows, plus sheet and lobate flows. The lobes are up to 5 m in diameter and have ropey wrinkles and fractures. Unfortunately there are no petrographic details given, presumably because sampling of intact lobes was not possible. Rarely, smooth to ropy sheet flows were observed near the ridge crest. Waters and Binns (1998) interpreted the linear ridge, parallel to the extension direction of the basin, to have formed from fault-controlled fissure eruptions in which low-viscosity dacite melts were erupted at, or above, their liquidus temperatures. Calculations we have done show that the viscosity of a superheated dacite melt is approximately an order of magnitude less than a crystal bearing subliquidus dacite melt (Fig. 5C).

Recognition of Archean pillow basalts versus pillow-lobe dacites

The chief distinguishing features of pillow-lobe dacites are the spherulite-rich cores, abundant breccia, plastic deformation, flow banding, necking, and in situ shearing within the margins of the dacites. Generally within variolitic Archean pillow basalts the spherulites are concentrated in a centimeter-scale zone near and concentric with the pillow rim, whereas in the aphyric dacite pillow lobes the spherulites are concentrated in the cores. In addition the dacites have a much more convoluted geometry, and thus far we have yet to observe any dacite pillow lobes with the classic bulb and tail geometry visible in some pillow basalt outcrops. As demonstrated immobile elements such as the REE, Al, Ti, Y, and Zr also serve to classify the rocks.

Possible implications for gold mineralization

The V10 units were mineralized, although details were not recorded, and we speculate that the pillow-lobe dacite, because of its high porosity and permeability, would have been an ideal channelway for mineralizing fluids. Furthermore, the competency contrast between massive and fragmental flows would also yield greater permeability as a result of deformation.

Gold-bearing veins of the area commonly occupy the contacts between flows (e.g., Hurst, 1935). At the Hoyle Pond mine this relationship holds true (Dinel et al., 2008), but the alteration and deformation is very intense. We have been unable to determine if the effect is a result of primary permeability (e.g., flow-top breccias) or secondary permeability caused by the mechanical response of flows of differing competency, or both.

The pillow-lobe dacitic rocks are part of the tholeiitic suite and are therefore, by definition, Fe enriched and are characterized by a high Fe/Mg ratio. As demonstrated by Bolke (1988), an elevated Fe/Mg ratio in the host rocks favors the formation of pyrite from Au thio complexes and the scavenging of gold from solution. Finally, we note that gold mineralization is prevalent in volcanic rocks in other areas (e.g., Red Lake, Ontario). Here, too, brecciated rocks (presumably autobreccia) are described as chicken-feed, leading to the possibility that pillow-lobe dacites may be widespread hosts of Archean lode gold mineralization.

Conclusions

We propose that tholeiitic aphyric pillow-lobe spherulitic dacites of the Tisdale assemblage V10b unit represent a facies that may be largely restricted to Archean rocks. The lavas were erupted in a superheated state and formed coherent flows rather than domes or pyroclastic flows. Together with massive underlying facies they were likely erupted from fissures. Pillow-lobe zoning consists of a thin rim-breccia zone and spherulite-rich core. The pillow lobes are distinguished from pillows of mafic rocks by their zoning, abundant associated hyaloclastite, flow banding, contorted outlines, necking and their felsic compositions, indicated by REE and other immobile element geochemistry. The V10 fragmental rocks were mineralized in the former mines. Their high initial permeability, competency, and high Fe/Mg ratios may have made these rocks ideal hosts for lode gold mineralization.

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