Magmatism, Alteration and Polymetallic Mineralization in Late Devonian to Early Carboniferous Felsic Volcanic and Plutonic Rocks of the Eastern Cobequid Highlands

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Introduction

During the late 1970s and early 1980s Gulf Minerals Exploration Limited conducted an extensive exploration program in search of uranium in Late Devonian to Early Carboniferous felsic volcanic and plutonic rocks of the eastern Cobequid Highlands (Fig. 1). This exploration program involved detailed geological mapping, soil geochemical surveys, geophysical surveys, lithogeochemical sampling of bedrock, and a significant reverse circulation and diamond-drill program (Downey, 1981). The most intense exploration and diamond drilling (>100 holes averaging ~125 m depth) was focused within the Debert Lake area along a zone (ca. 5 km x 1 km) where felsic volcanic and volcaniclastic rocks of the Byers Brook Formation (BBF) were intruded by high-level felsic plutonic rocks of the Hart Lake-Byers Lake (HLBL) granite (Donohoe and Wallace, 1982a, b). Due to the lack of significant uranium mineralization encountered in the drilling and the implementation of a moratorium on uranium mining and exploration by the Province of Nova Scotia in 1982, the parent company of the former Gulf Minerals Exploration Limited chose not to renew their mineral claims.

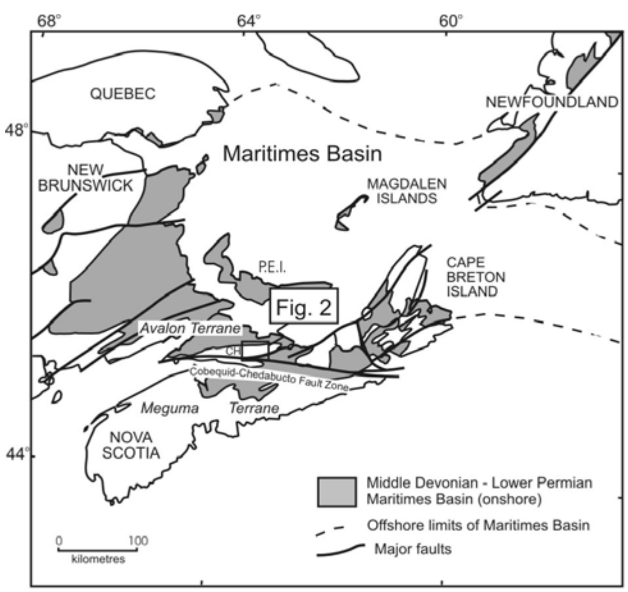

Figure 1. Regional map of Atlantic Canada depicting the distribution of the Maritimes Basin, major faults and location of the Cobequid Highlands in northern mainland Nova Scotia (CH). The region depicted in Figure 2 is indicated.

Until a recent geophysical and diamond-drilling program conducted by Capella Resources in 2007, the area has seen very limited exploration. Renewed interest in the area has been largely due to the presence of anomalous base metal and precious metal concentrations (e.g. Sn, W, Mo, Zn, Pb and Ag) and anomalously high field strength element concentrations (e.g. Th, Zr, Nb, Hf), in particular, highly anomalous concentrations of rare earth elements (up to 1.2 wt.% total REE; Gower, 1988). Although the polymetallic nature of mineralization within the area was recognized, little effort was targeted toward understanding its nature and origin. This study presents the preliminary results of an ongoing geological, geochemical and petrological study of volcanic and plutonic rocks of the Hart Lake-Byers Lake granite and Byers Brook Formation intended to develop a better understanding of their magmatic evolution, and the nature, origin and setting of mineralization and associated alteration in the Debert Lake area.

MacHattie, T. G. 2010: *in* Mineral Resources Branch, Report of Activities 2009; Nova Scotia Department of Natural Resources, Report ME 2010-1, p. 65-75.

General Geology of the Hart Lake-Byers Lake Granite and Byers Brook Formation

Late Devonian to Early Carboniferous mafic-felsic volcanic and plutonic rocks dominate the crust exposed in the eastern Cobequid Highlands between the Rockland Brook Fault and unconformably overlying Late Carboniferous sedimentary rocks of the Cumberland Basin (Fig. 2). The core of this volcano-plutonic complex includes the ca. 362 Ma Hart Lake-Byers Lake granite and ca. 358-355 Ma felsic volcanic and volcaniclastic rocks of the Byers Brook Formation (Donohoe and Wallace, 1982a, b; Dunning *et al*., 2004). The HLBL granite is dominated by medium- to coarse-grained, hornblende-biotite-magnetite-bearing alkali-feldspar granite (Pe-Piper, 1996). Pegmatitic and granophyric textures are ubiquitous (Fig. 3a) features, which attest to the overall shallow level of magma emplacement. Inclusions of variably consumed mafic magmatic material are common (Fig. 3b), and indicate that felsic and mafic magmatism were in part contemporaneous. The HLBL granite intruded the BBF, an up to ca. 7 km thick, felsic volcanic sequence dominated by volcanicalstic rocks with a pyroclastic or epiclastic origin (Fig. 3c, d), with lesser volumes of lava flows and co-genetic porphyritic intrusions (Fig. 3e, f), and rare to minor vesicular basalt and siliciclastic sedimentary rocks (Fig. 3g, h). Porphyritic diabase dykes and diorite pods intruded both the granite and the overlying volcanic rocks.

Chemistry of Devonian-Early Carboniferous Magmatism in the Eastern Cobequid Highlands

To better understand the felsic magmatic evolution of the HLBL granite and BBF volcanism, the nature and distribution of local and regional alteration patterns, and potential mineralization associated with both, a compilation of whole rock lithogeochemistry from Late Devonian-Early Carboniferous igneous rocks of the eastern Cobequid Highlands has been undertaken (Figs. 4-6; see captions for references). This includes samples from outcrops as well as an extensive dataset from drill core sampling in the Debert Lake area. A limited amount of new sampling has been conducted to augment the database and to infill areas that had not been sampled from either drill core or outcrop (Fig. 4).

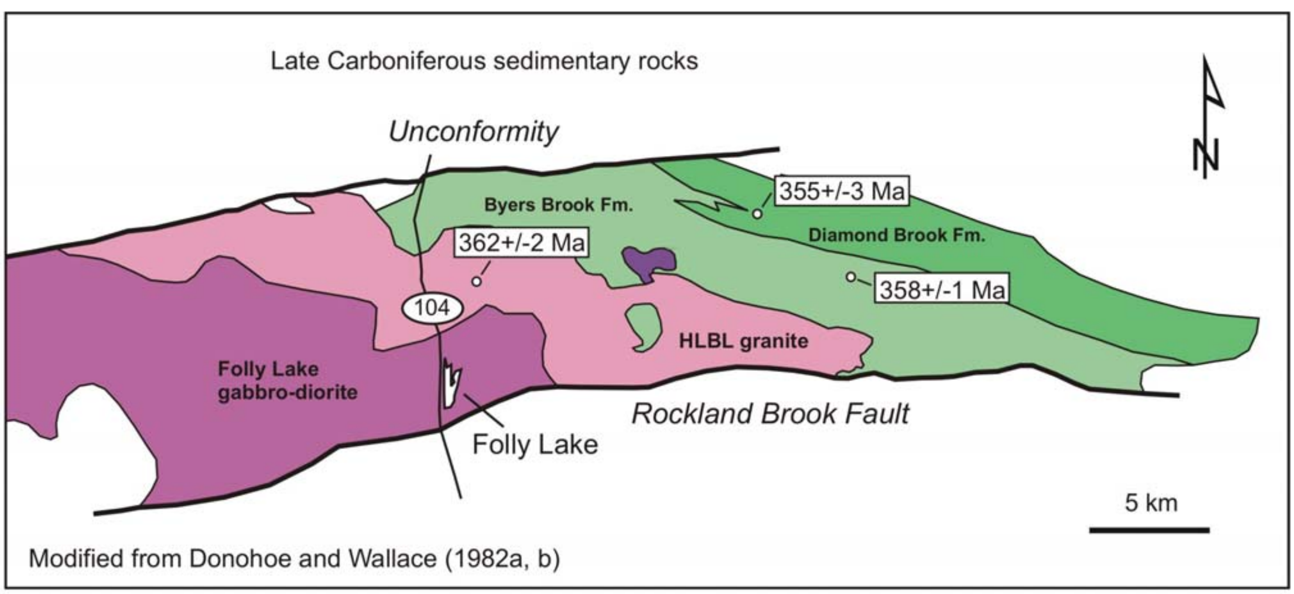

Figure 2. Geological map of the major Late Devonian-Early Carboniferous rock units of the eastern Cobequid Highlands in central mainland Nova Scotia. Ages shown are U-Pb zircon crystallization ages (Dunning *et al*., 2004).

Figure 3. (a) Hornblende-magnetite-bearing granite pegmatite of the Hart Lake-Byers Lake granite. (b) Mafic inclusion-rich medium- to fine-grained granite of the Hart Lake-Byers Lake granite. (c) Homogeneous crystal-lapilli tuff of the lower Byers Brook Formation. (d) Welded crystal-lapilli tuff. (e) Micofolding in flow banded rhyolite. (f) Autobrecciated rhyolite flow top. (g) Vesicular basalt. (h) Finely laminated red/grey siltstone.

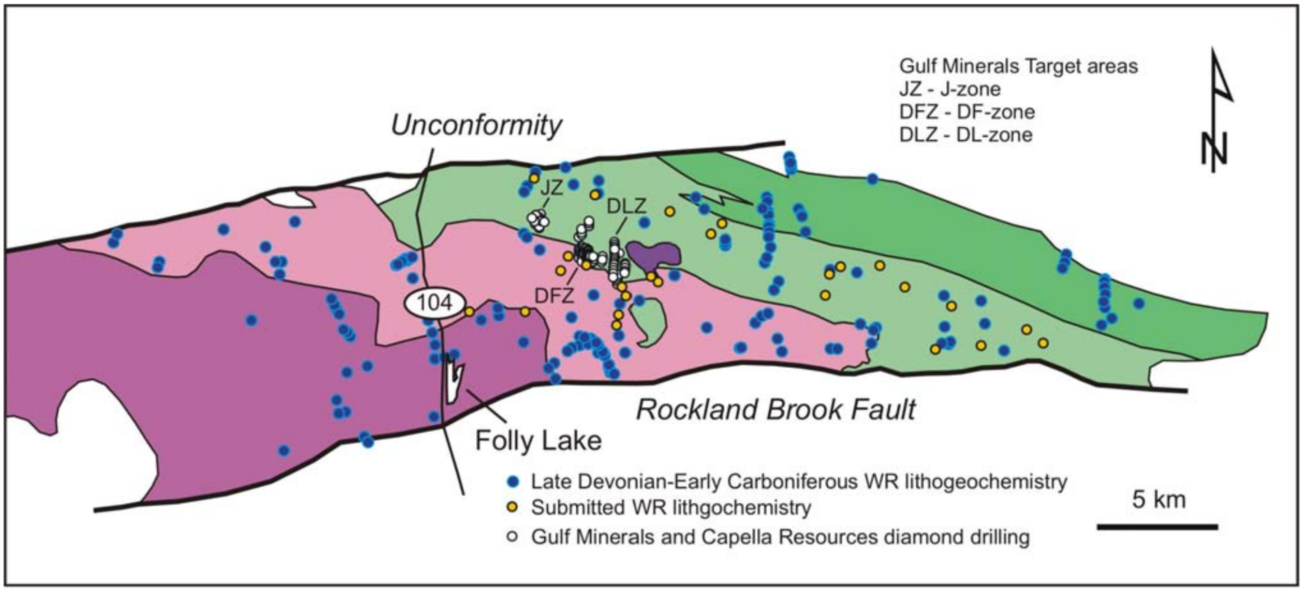

Figure 4. Map of the major Late Devonian-Early Carboniferous rock units of the eastern Cobequid Highlands in central mainland Nova Scotia showing the locations of whole rock (WR) lithogeochemical data from the Hart Lake-Byers Lake granite and Byers Brook Formation (Pe-Piper *et al*., 1989; Pe-Piper, 1996; Piper and Dessureau, 1999; Pe-Piper, unpublished data), new sampling conducted by the author, and the locations of diamond-drill holes (Gulf Minerals Exploration Limited and Capella Resources) in the Debert Lake area. Principal Gulf Minerals target zones are indicated.

Alkali Alteration in the Debert Lake Area

Regional sampling of unaltered Late Devonian-Early Carboniferous igneous rocks in the eastern Cobequid Highlands (Fig. 4) indicates that magmatism is distinctly bi-modal with respect to silica contents, and includes mafic magmas with SiO_2 contents from ~45-50 wt.% and felsic magmas with silica contents predominantly from ~70-80 wt.% (Fig. 5a). Samples from drill core in the Debert Lake area display a similar pattern (Fig. 5b), but, a significant number of samples possess silica contents between ~60-70 wt.%, a population that is present, but less pronounced, within the unaltered sample set (Fig. 5a). Plots of Na_2O and K_2O versus silica (Fig. 6a, b) indicate that the high proportion of samples possessing intermediate silica levels from the drill core sampling coincides with high Na_2O (>8 wt.%) and low K_2O (< to <<1 wt.%). This suggests that sodic alteration is accompanied by a decrease in SiO_2 and that unaltered rocks with intermediate silica contents are rare in the Debert Lake area. Conversely, the majority of the most felsic samples (~70-80 wt.%) collected from the drill core tend to possess similar, or lower, Na_2O contents than unaltered rocks, and overlapping to significantly elevated K_2O (Fig. 6b). This suggests that potassic alteration has little effect on silica, and based on the sampling conducted to date, that potassic alteration is more pervasive than sodic alteration. An inverse relationship between Na_2O and K_2O for drill core samples (Fig. 6c) suggests that chemically exclusive and distinctive sodic and potassic alteration zones occur in the Debert Lake area. Delineating their spatial distribution, relative timing, and relationship with respect to mineralization is currently in progress.

Chemical Zoning in the Hart Lake-Byers Lake Granite

In order to better understand the magmatic evolution of the HLBL granite and its role with respect to the mineralization and alteration recognized in the Debert Lake area, a GIS-based chemical and petrological study of its magmatic phases has been initiated. Chemical zoning at a regional scale within the granite for certain major and trace elements is clearly evident. With respect to CaO content, the central portion of the granite is notably higher than the very CaO depleted northwestern and eastern portions of granite (Fig. 7a). Because CaO decreases with increasing silica, on a regional scale, the core of the granite is less differentiated that its margins. With respect to Th concentration, the eastern portion of the granite is higher than any other portion of the granite (Fig. 7b), a potentially important observation with respect to rare earth mineralization (see below).

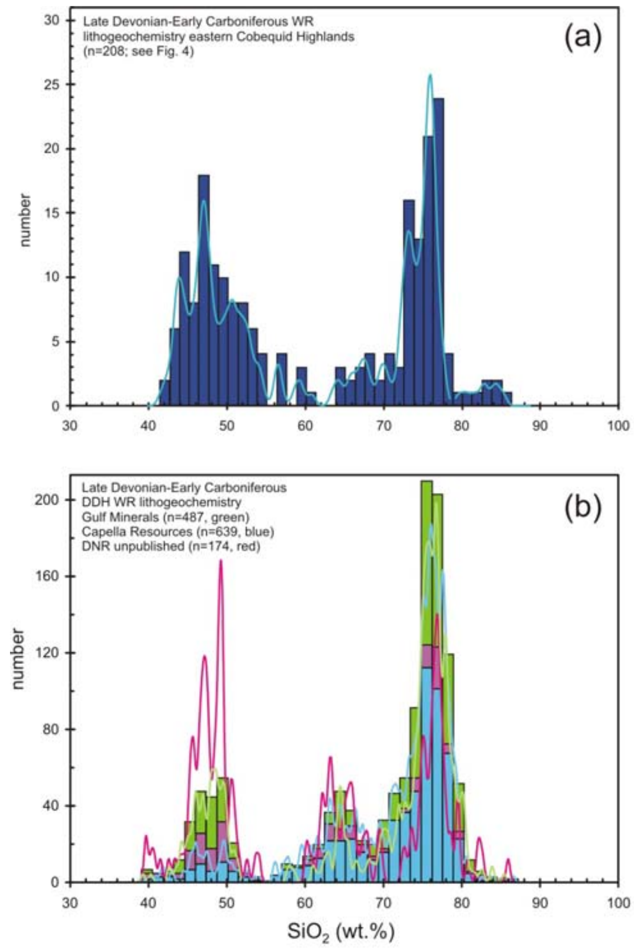

Figure 5. (a) Probability density histogram for whole rock lithogeochemical data (SiO_2 wt.%) available from Late Devonian-Early Carboniferous igneous rocks of the eastern Cobequid Highlands (see Fig. 4 for sample locations and caption for references). (b) Probability density histogram for whole rock lithogeochemical data (SiO_2 wt.%) from samples collected from Gulf Minerals Exploration Limited and Capella Resources diamond-drill core (Downey, 1978a; Gower, 1988; Cole *et al*., 2008; Nova Scotia Department of Natural Resources, unpublished data).

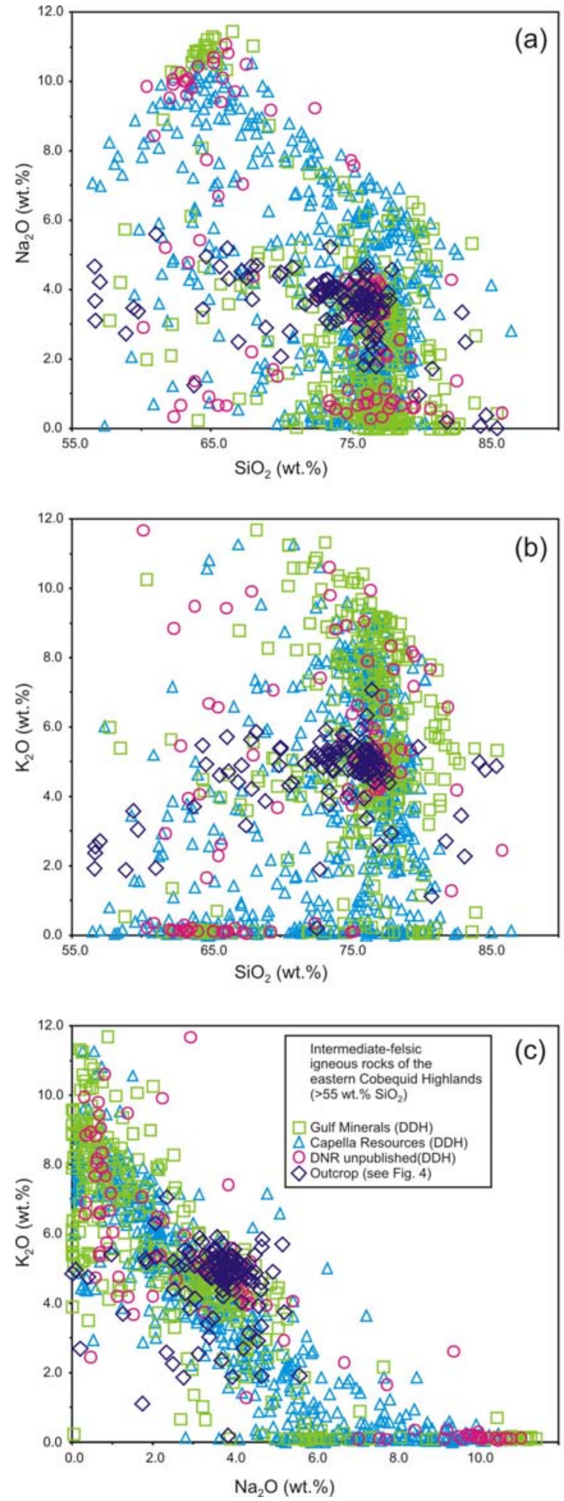

Figure 6. (a) SiO_2 (wt.%) versus Na_2O (wt.%); (b) SiO_2 (wt.%) versus K_2O (wt.%) and; (c) Na_2O (wt.%) versus K_2O (wt.%) variation diagrams for whole rock lithogeochemical data available from the eastern Cobequid Highlands (see Fig. 4 and caption for references) and whole rock lithogeochemical data available from sampling of diamond-drill core in the Debert Lake area (see Fig. 5 and caption for references).

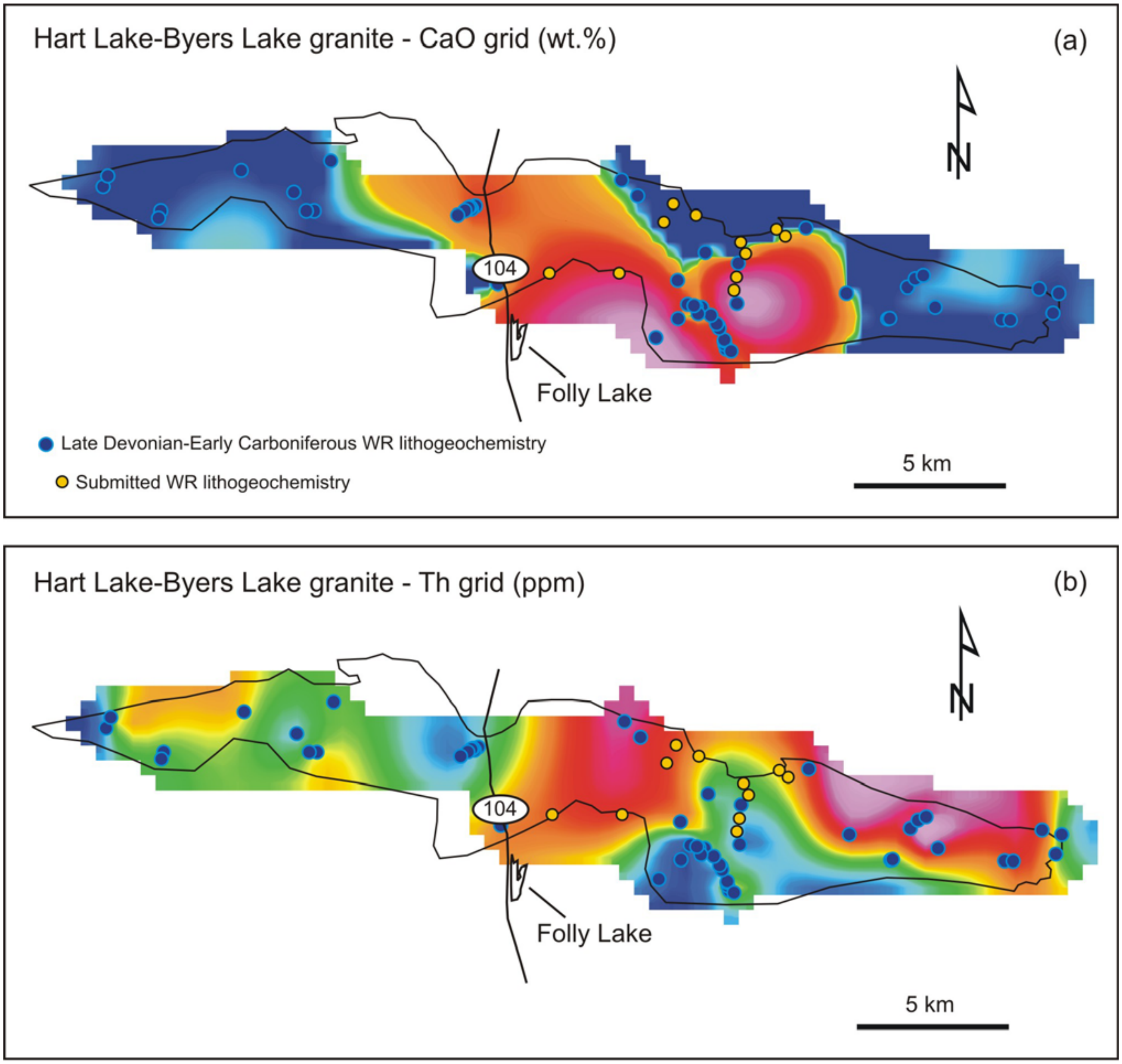

Figure 7. (a) CaO (wt.%) log-grid for 51 samples of the Hart Lake-Byers Lake granite (Pe-Piper *et al*., 1989; Pe-Piper, 1996; Pe-Piper, unpublished data). (b) Th (ppm) log-grid. Outline of Hart Lake-Byers Lake granite is shown. The locations of new samples collected from the granite are also shown. CaO maximum (red) is 5.1 wt.% and minimum (blue) is 0.1 wt.%. Th maximum (red) is 56 ppm and minimum (blue) is 11 ppm.

New sampling conducted from the granite in the Debert Lake area and areas farther south (see Fig. 7b), combined with data currently being compiled from Gulf Minerals Exploration Limited's assessment reports, is expected to significantly refine the resolution and accuracy of the gridding.

Mineralization in the Debert Lake Area

The diamond drilling conducted by Gulf Minerals Exploration Limited in the late 1970s and early 1980s, and more recently by Capella Resources in

2007, is focused within the Debert Lake area, on a ca. 5 km x 1 km zone that straddles the intrusive contact between the HLBL granite and Byers Brook Formation (Fig. 4). Gulf Minerals informally divided the area into three zones, the J-zone (JZ) in the west, a central DF zone, and the DL zone (DL) to the southwest (Fig. 4). Mineralization in the Debert Lake area is polymetallic in nature, however, because only a limited number of partial geochemical analyses from Gulf Minerals extensive drilling in the area are recorded in assessment reports, little is known about the nature, extent, type(s) and style(s) of mineralization present. Chatterjee (1984) suggested that the polymetallic nature and elemental associations of the mineralization in the Debert Lake area were consistent with an epithermal environment related to late-stage magmatic activity and subvolcanic intrusive rocks. Limited assay data, compiled from Gulf Minerals assessment reports, augmented by assays from the most recent drilling in the J-zone by Capella Resources in 2007 reveal the presence of variably anomalous concentrations of Sn (up to 578 ppm), W (up to 410 ppm), Mo (up to 0.37%), Zn (up to 0.37%), Pb (up to 0.26%), Ag (up to 93 g/t) and Bi (up to 265 ppm).

Gower (1988) reported highly anomalous REE concentrations (up to 1.2 wt.%) from four samples collected over a 1 m wide zone of brecciated, granophyric granite within Gulf Mineral's diamond-drill hole DL-16. This drillhole is located in the southern portion of the DL zone close to the contact between the HLBL granite and overlying felsic volcanic/volcaniclastic rocks of the Byers Brook Formation (Fig. 4). The REE are found within fluorite-calcite-zircon-sphene-allanite-albite veins and Gower (1988) suggested the bulk of the REE are hosted by allanite and unidentified Nb-Th-Y-REE-bearing minerals. The trace element analyses reported in Gower (1988) are listed in Table 1 and plotted on a primitive mantle-normalized extended element plot in Figure 8. All samples have similar REE patterns characterized by pronounced negative Eu anomalies and a fairly flat pattern for the remaining REE (e.g. $(La/Yb)_N$ ~0.6-1.3). Significant Th (160-600 ppm) and Hf (230-1000 ppm) concentrations also characterize this interval (Table 1, Fig. 8).

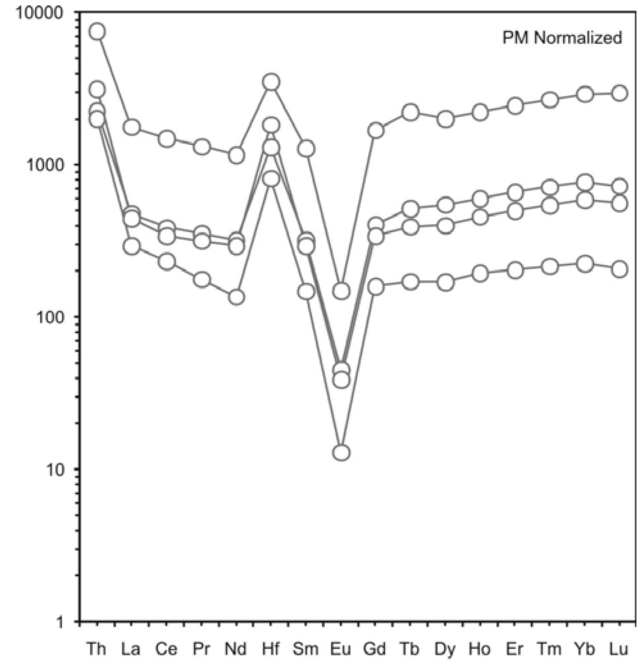

Figure 8. Primitive mantle normalized extended element plot for brecciated granophyre samples collected from Gulf Minerals DDH DL-16 (Gower, 1988).

A downhole gamma and lithological log for DL-16 reproduced from Downey (1978b) is shown in Figure 9. The ~1 m wide high Th and REE section sampled by Gower (1988) coincides with a significant zone of elevated gamma (>100 cps). Note that this zone is significantly wider than the interval sampled (e.g. ~8 m versus ~1 m), suggesting mineralization is significantly more widespread. However, due to the poorly preserved nature of the core through this interval (Fig. 10) because of earlier sample removal and original poor core recovery, precise identification of the brecciated and veined granophyre described by Gower (1988) has not been possible. Geochemical sampling within this interval and from other sections of the core, including brecciated granophyre identified at greater depth, has been conducted in an attempt to identify REE mineralization.

Conclusions and Future Work

The ca. 5 km x 1 km long intrusive contact zone between the Byers Brook Formation and the Hart Lake-Byers Lake granite in the Debert Lake area is

Table 1. Trace element analyses from DDH DL-16. Data from Gower (1988).

Sample No.	C6877	C6878	C6879	C6880
Depth (m)	66.1-66.4	66.4-66.6	66.6-66.8	66.8-67.0
Width (m)	0.3	0.2	0.2	0.2
Sc	13	2	18	4
Hf	370	1000	520	230
U	28	58	39	25
Th	180	600	250	160
La	310	1150	290	190
Ce	650	2500	570	390
Pr	88	330	79	44
Nd	400	1460	370	170
Sm	130	520	120	60
Eu	7	23	6	2
Gd	219	911	184	86
Tb	51	220	39	17
Dy	370	1350	270	115
Ho	90	330	68	29
Er	290	1079	220	90
Tm	50	188	38	15
Yb	340	1290	260	100
Lu	49	200	38	14
Total REE (ppm)	3045	11551	2553	1323
Total REE (wt.%)	0.30	1.16	0.26	0.13

Concentrations are in ppm except where indicated. Values in italics are extrapolated using the primitive mantle normalized values for bounding REE (see Fig. 8).

host to anomalous polymetallic (Sn, W, Mo, Zn, Pb, Ag, Bi, F, Th, Zr, Hf and REE) mineralization and pervasive potassic and sodic alteration. Although an epithermal model for mineralization related to late-stage intrusive felsic magmatism has been proposed (Chatterjee, 1984), little is known about the precise nature and extent of this mineralization and its relationship to alteration. To better understand the mineralization and alteration in the Debert Lake area, detailed geochemical and petrological sampling of the historic Gulf Minerals drillcore and bedrock is required. Assay data reported from the >100 holes drilled by Gulf Minerals (>13 000 m) are not sufficient at this time to assess the potential of the area to host significant base, precious or rare metal mineralization.

Within a regional context, detailed mapping and sampling along the extension of the contact zone between the Hart Lake-Byers Lake granite and Byers Brook Formation northwest and southeast of the Debert Lake area should be conducted, in conjunction with a compilation of the detailed geological mapping and reverse circulation drilling conducted by Gulf Minerals. The intrusive rhyolite domes found within the Byers Brook Formation should also be examined as potential hosts for high-level polymetallic mineralization.

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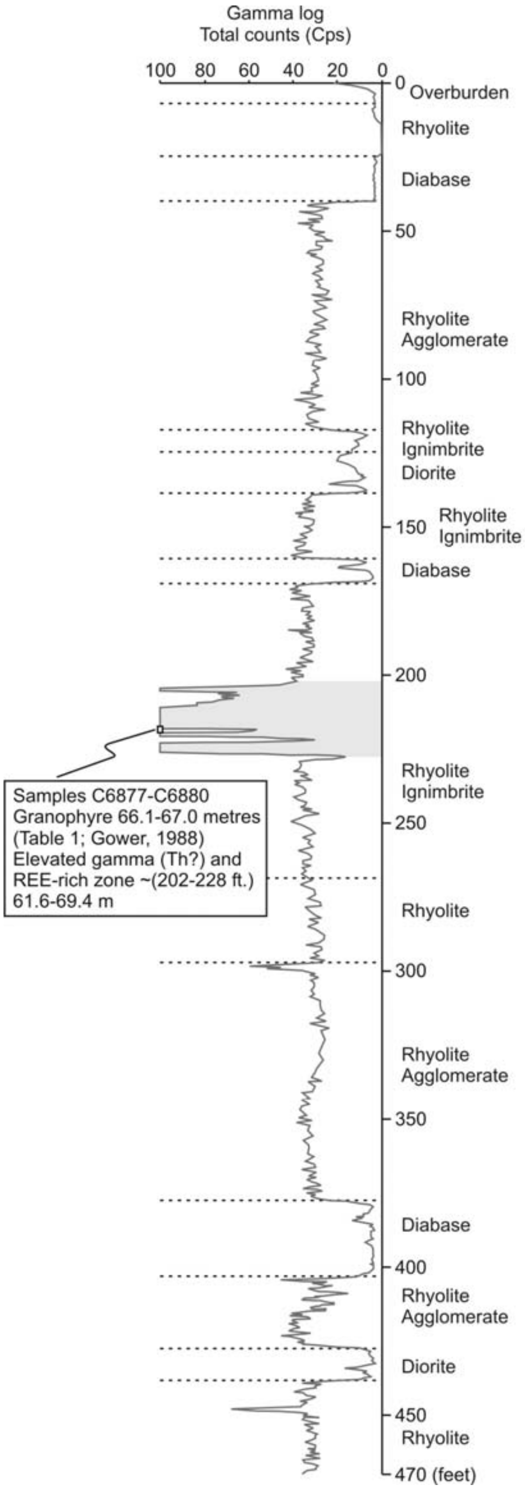

Figure 9. Down-hole gamma log (counts per second) for diamond-drill hole DL-16, reproduced from Downey (1978b). Samples collected for trace element analyses displaying elevated Th, Hf and REE (C6877-C6880) are indicated (see Table 1; Gower, 1988). Note the zone of elevated gamma is ~8 m wide (~61.5-69.5 m), significantly wider than the ~1 m wide interval (66.1-67.0 m) sampled by Gower (1988).

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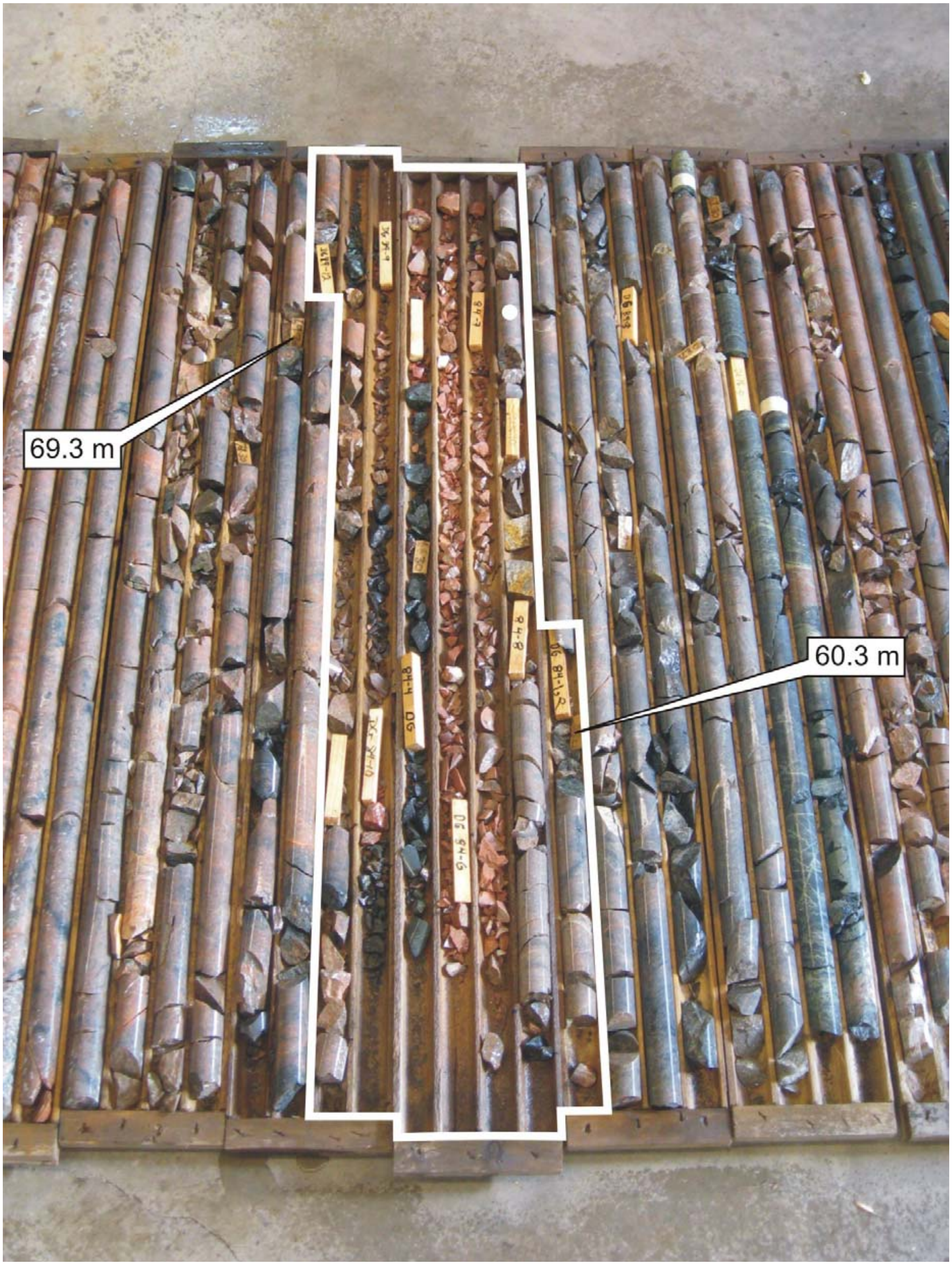

Figure 10. Image of drill core DL-16. Highlighted in white (~60-69 m) is the interval displaying elevated REE concentrations. The precise locations of elevated REE samples C6877-C6880 (Table 1) are uncertain. Core diameter is 4.76 cm.

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