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THE LONG LAKE GROUP: PRELIMINARY U–Pb GEOCHRONOLOGY AND LITHOGEOCHEMISTRY, AND IMPLICATIONS FOR TECTONOSTRATIGRAPHIC ARCHITECTURE AND VMS MINERALIZATION

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ABSTRACT

The Long Lake group forms part of the Victoria Lake supergroup of central Newfoundland and hosts one defined VMS deposit and several other occurrences. The group is dominated by felsic volcanic rocks, and lesser amounts of mafic volcanic rocks and intercalated volcano-sedimentary rocks. The rocks formed, in volcano-sedimentary basins, within active volcanic arcs on the peri-Gondwanan margin of the Iapetus Ocean.

The southwestern portion of the Long Lake group is host to the Long Lake main VMS deposit, as well as several other VMS alteration systems and VMS occurrences. Structural overprinting, in the form of folding and faulting, has affected the group and its VMS deposits and occurrences, resulting in strongly attenuated alteration zones and massive sulphide horizons. In conjunction with extremely poor outcrop density, and accessibility challenges, this makes stratigraphic mapping and interpretations difficult. Structural repetition may be important in the case of the Long Lake main deposit.

The felsic volcanic rocks of the Long Lake group were originally associated with the rocks of the Tulks Volcanic group to the west; but more recent work assigned all of the felsic volcanic rocks in the group to a single formation; the ca. *506 Ma Costigan Lake formation, which is approximately 11 Ma older than the Tulks Volcanic group rocks.*

Results of this study suggest that the felsic rocks in the group are more appropriately divided into two main packages: 1) a lower stratigraphic package of ca. *511 Ma fine-grained to aphyric rhyolite and felsic tuff having high concentrations of high-field strength and rare-earth elements, and 2) an upper stratigraphic package of* ca. *506 Ma blue quartz-phyric felsic to intermediate tuff having significantly lower concentrations of high-field strength and rare-earth elements. There may also be contrasts in Nd isotopic signatures between the two sequences. Both packages of rocks are now in fault contact but appear to be prospective for volcanogenic massive sulphide accumulations, although their response to typical exploration techniques may be variable.*

INTRODUCTION

The Cambrian Long Lake group is situated within the Victoria Lake supergroup (VLSG) of central Newfoundland (Figure 1). It is composed of felsic and mafic volcanic and volcaniclastic rocks, and lesser sedimentary rocks; all of which formed in association with volcanic arcs and volcano-sedimentary basins on the peri-Gondwanan margin of the Iapetus Ocean. The group is known to host one volcanogenic massive sulphide (VMS) deposit (the Long Lake main deposit), as well as several VMS-style prospects and showings.

Field work conducted in the summer of 2012 had two main objectives: 1) to further understanding of the tectonostratigraphic architecture of the Long Lake group to assist with future exploration activity in the area, and 2) to document the volcanogenic massive sulphide mineralization at the Long Lake main VMS deposit. The study emphasized examination of archived diamond-drill core due to generally poor exposure. This report focuses mostly on the felsic volcanic rocks and associated mineralization.

EXPLORATION HISTORY

The following represents a brief review of previous exploration work conducted in the Long Lake group. More detailed accounts are in reports by Noranda (1998), Hussey (2006), Sparkes (2008), and Keller and Bernier (2012).

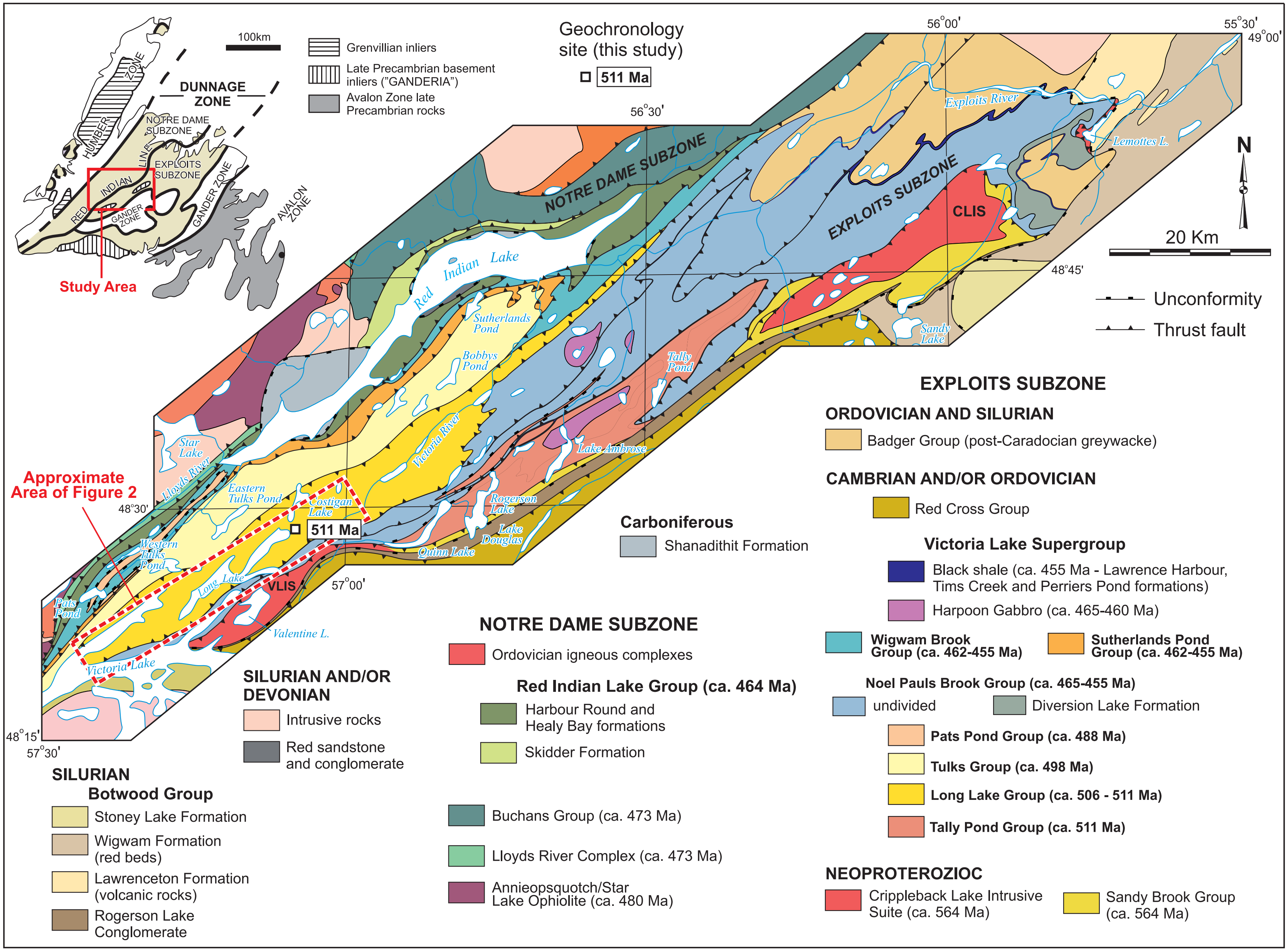


Figure 1. *Location and generalized geology of the area surrounding Red Indian Lake, including rocks of the Victoria Lake supergroup. CLIS–Crippleback Lake intrusive suite; VLIS–Valentine Lake intrusive suite. Geochronological results from this study are indicated, but others are omitted for the sake of clarity; geological map from a compilation by N. Rogers (Geological Survey of Canada) based, in part, on GSC mapping.*

The first recorded exploration work in the Long Lake group area was by ASARCO (American Smelting and Refining Company) in 1947, when they drilled two back-pack drillholes in a prominent rusty gossanous zone in felsic volcanic rocks at the tip of the Long Lake Peninsula (*see* Figure 2A for general location). No massive sulphide was intersected, but results were favourable and included 2.9% Cu over 0.3 m. In the early 1960s, the first systematic exploration effort by ASARCO included a reconnaissance soil- and stream-geochemistry program throughout the group, resulting in the definition of a strong copper and zinc anomaly approximately 1 km east of the eastern tip of Long Lake (termed the Long Lake soil anomaly), and a strong copper anomaly in the vicinity of the Long Lake Peninsula. Although five short drillholes in the Long Lake soil anomaly area in the late 1960s were unsuccessful in finding massive sulphide, they did encounter minor base metals and altered volcanic rocks. Interestingly, it is now known that the Long Lake soil anomaly is within 500 m from the surface projection of the currently defined Long Lake main VMS deposit.

Exploration resumed in the late 1970s by Abitibi-Price, whose initial focus was following up on AEM conductors underlying the lake itself, which extended to the southwest from the prominent rusty and gossanous felsic volcanic rocks on the tip of the Long Lake Peninsula. Electromagnetic (EM) anomalies were drill-tested in 1980, but most of the anomalies were explained by graphitic shale having variable contents of pyrite and pyrrhotite. In 1985, Abitibi-Price sold all of its mineral rights to British Petroleum Resources Canada Limited (BP).

During the period from 1985-1991, BP conducted reconnaissance soil geochemical surveys over parts of the eastern portion of the Long Lake group, and also flew the eastern portion of the group with an EM geophysical survey. The soil geochemical survey reproduced the original Long Lake soil anomaly, and identified a VLF conductor in the area. Subsequent trenching uncovered altered felsic rocks having disseminated pyrite and minor base-metal mineralization, but deep overburden prevented trenching at the VLF conductor.

In the early 1990s, Noranda focused exploration efforts on the same area examined by BP, and defined an alteration zone and drill targets. The first diamond-drill hole in 1994 intersected a narrow, high-grade barite-rich massive sulphide horizon having grades of 2.7% Cu, 1.1% Pb, 23.7% Zn, 45 gm of silver and 0.7 gm of gold over 2.2 m, located approximately 45 m below surface. This initial intersection was defined as the Long Lake main deposit (with drill testing through to 1997). Additional zones of mineralization representing extensions of the main mineralized zone (*e.g.*, South and East zones, West and North extensions) were also identified through soil and geochemical sampling programs followed by diamond drilling. Further, Noranda discovered a number of other areas having anomalous soil and whole-rock geochemistry readings, including the Isthmus grid , the Henry Waters and Swamp grid areas, and the Reid Lot 227 area (herein termed the Long Lake Grid–Paragon) (*see* Figure 2A for locations).

Noranda ceased all exploration in Newfoundland in 1997, after which they divided their central Newfoundland land package into six components for option. The Long Lake group was eventually optioned by Atlantic Zinc, after which the property went through several holders, finally being acquired by Messina Minerals Incorporated in 2004. Follow up work in the area around the Long Lake main deposit by Island Arc Exploration Incorporated consisted of prospecting, mapping and limited diamond drilling. This led to the discovery of the Lucky Gnome zone to the southwest of the Long Lake main zone; potentially representing a folded equivalent of the Long Lake deposit mineralized horizon. Between 2004 and 2011 Messina Minerals Incorporated focused their efforts on defining the Long Lake main deposit through additional diamond-drilling programs.

In 2003, Island Arc (subsequently Messina Minerals) reduced its claims in the Long Lake group, continuing to hold the claims in the northern portion of the group in good standing. Lapsed claims were staked by Crosshair Exploration Limited (work conducted by Paragon Minerals) and Cornerstone Resources. These companies conducted further work on the Swamp, Henry Waters, and the Long Lake Grid (Paragon), and the Long Lake Grid (Cornerstone), respectively. Work predominantly consisted of prospecting and diamond-drill programs, which followed up on, and built upon exploration activities by Noranda.

Much of the group is still held by various companies and individual prospectors with claims in good standing, although current exploration in the area is minimal.

REGIONAL GEOLOGICAL STRATIGRAPHY AND TECTONIC SETTING OF THE LONG LAKE GROUP

The Dunnage Zone of the Newfoundland Appalachians (Figure 1) represents the vestiges of Cambro-Ordovician continental and intra-oceanic arcs, back-arc basins, and ophiolites that formed in the Iapetus Ocean (Kean *et al.*, 1981; Swinden, 1990; Williams, 1995). The zone is bisected by an extensive fault system (the Red Indian Line) into a western peri-Laurentian segment (Notre Dame and Dashwoods subzones), and an eastern peri-Gondwanan segment (Exploits Subzone). The two main subzones of the Dunnage

Zone are differentiated based on stratigraphic, structural, faunal, and isotopic characteristics (Williams *et al.*, 1988). In the study area, the Red Indian Line separates the Buchans Group, which formed on the Laurentian side of the Iapetus Ocean, from the VLSG, which formed on the Gondwanan side of Iapetus. The deformation associated with final closure of the Iapetus Ocean culminated during the Silurian (Zagorevski *et al.*, 2007a), at which time, thrusting and folding juxtaposed these initially geographically distinct volcanic belts.

The VLSG was traditionally divided into two main volcanic sequences, termed the Tulks Hill and the Tally Pond volcanic rocks (Kean and Jayasinghe, 1980); both of which are stratigraphically overlain by Late Ordovician to Silurian cover sequences. Mapping in the 1970s and 1980s, by the Geological Survey of Newfoundland and Labrador (GSNL) at a scale of 1:50 000 included rocks in the Long Lake area with the Victoria Lake Group (Kean, 1977, 1982) and associated them with the Tulks Hill volcanic rocks (Kean and Jayasinghe, 1980). Early geochronological work in the Tulks Hill volcanic rocks recognized younger volcanic rocks in the west (*ca.* 462 Ma, Dunning *et al.*, 1987) compared to central portions (*ca.* 496 Ma, re-interpretation of age published by Evans *et al.*, 1990; G. Dunning, personal communication, 2008). Subsequent mapping programs by the Geological Survey of Canada (GSC) in the early 2000s (*e.g.*, Rogers *et al.*, 2005; van Staal *et al.*, 2005; Zagorevski *et al.*, 2010) and field programs by the GSNL (*e.g.*, Hinchey 2007, 2008; Hinchey and McNicoll, 2009) indicated the need for additional subdivisions. Results suggest a series of generally westward-younging tectonostratigraphic units including the Long Lake group represented by felsic volcanic rocks on the southeast shore of Long Lake (*ca.* 506 Ma; Zagorevski *et al.*, 2010), the Tulks group (*ca.* 496 Ma; G. Dunning, personal communication, 2008), the Pats Pond group (*ca.* 491–488 Ma; Zagorevski *et al.*, 2008; Hinchey and McNicoll, 2009), the Sutherlands Pond group (*ca.* 462–457 Ma, Zagorevski *et al.*, 2008; Dunning *et al.*, 1987) and the Wigwam Brook group (*ca.* 453; van Staal *et al.*, 2005; Zagorevski *et al.,* 2007b) (Figure 1). The Long Lake group rocks temporally overlap, at least partially, with the rocks of the Tally Pond group (*ca.* 513–509 Ma; Rogers *et al.*, 2005; McNicoll *et al.*, 2010) to the east. It should be noted that although the groups generally young to the west, this current geographical relationship does not necessarily preclude that they were all deposited one on top of the other from east to west; they may alternatively represent originally geographically separate volcanic groups. As discussed later in this paper, the Long Lake group may include more than one grouping of volcanic rocks.

In addition to the Cambro-Ordovician volcanic and volcaniclastic rocks of the VLSG, there are also large late Precambrian (565-563 Ma) intrusions (Evans *et al.*, 1990), which are interpreted to represent inliers of old basement, most likely of the crustal block Ganderia (*e.g.*, van Staal *et al.*, 1998). Previous lithogeochemical studies, based largely on subordinate mafic volcanic rocks, indicate that the VLSG is composed of distinct chemical groupings representing different tectonic environments (*e.g.*, active-arc, arc-rift, back-arc, and mature-arc, *see* Swinden *et al.*, 1989; Evans and Kean, 2002).

The Long Lake group is separated from the Tulks volcanic group to the west and northwest by a regionally extensive aeromagnetic vertical gradient anomaly that is recognizable on the regional aeromagnetic map of the Island, and is portrayed as a southeast-dipping thrust fault (Figure 1). The group is separated from the Tally Pond group to the east by a regionally extensive unit of Arenig–Caradoc-aged black shale, sandstone and siltstone belonging to the Noel Pauls Brook group (Rogers *et al*., 2005; van Staal *et al*., 2005).

LOCAL GEOLOGY – LONG LAKE GROUP

GENERAL INFORMATION

The Long Lake group volcanic rocks are bimodal, but felsic compositions predominate over mafic compositions. Felsic volcanic rocks are herein divided into two packages. Light-grey to white, quartz ± feldspar phyric felsic to intermediate, and medium- to coarse-grained pyroclastic rocks occur in the southeastern portion of the group (*e.g.*, upper stratigraphy of Figure 2A). White to grey to pink, aphyric to quartz±feldspar porphyritic, magnetite-bearing, massive rhyolite, and local fine-grained, magnetite-bearing, felsic tuff occur in the northern part of the group (*e.g.*, lower stratigraphy, Figure 2A, Plate 1A–D). Both packages of felsic rocks locally contain fine-grained felsic ash tuff and volcanogenic siltstone and graphitic shale, and both locally contain zones of hydrothermal alteration associated with disseminated to massive volcanogenic sulphides (Plate 2A–D). Iron formation is also commonly associated with the massive sulphide at the Long Lake main deposit (Plate 2E). Diamond-drill core from the area of the Long Lake main deposit (diamond-drill holes LL-94-18, LL-94-02, LL-00-02 and LL-94-07; lower stratigraphy) suggests that the rocks young to the southeast, and this is consistent with observed polarity of hydrothermal alteration zones, whereby VMS-style footwall alteration zones overlie massive sulphide. Collectively, these patterns suggest that the predominantly northeast-dipping felsic rocks in the lower part of the group are locally overturned. The stratigraphic succession in the vicinity of the Isthmus grid also appears to be overturned. In the vicinity of the Long Lake Grid of Paragon (upper stratigraphy), the Henry Waters Grid (lower stratigraphy), and the

Swamp Grid (lower stratigraphy), all in the southern part of the Long Lake group (Figure 2A), the stratigraphy appears to be right-way-up (*i.e.*, younging to the northwest). This variation is indicative of folding and/or thrusting in the group, which is illustrated in the conceptual sketch in Figure 3D. As suggested in Figure 3D, the overturned stratigraphy, when combined with the regional structural and geophysical relationships illustrated in Figure 3A, B, are inconsistent with all felsic and mafic rocks being ascribed to single respective groups.

Mafic volcanic rocks in the Long Lake group are dominated by mafic tuff, pillow basalt (Plate 2F), and breccia. Mafic rocks outcrop along the northwestern margin of the group (Figure 2A, B), and as a linear package from the southern tip of Long Lake northeastward toward the Long Lake Peninsula (Figure 2A). The latter is associated with a prominent magnetic high striking across the Long Lake Peninsula on the regional airborne magnetic intensity survey (Figure 2D). However, the presence of interleaved felsic volcanic rocks from the lower stratigraphy, with ubiquitous magnetite disseminations and stringers (Plate 3A), coupled with the poor outcrop control (Plate 4), makes it difficult to discriminate mafic rocks using aeromagnetic datasets. Although the mafic volcanic rocks have not been formally subdivided for the purposes of this study, those in the Long Lake Peninsula area may provide a structurally defined marker unit between the two packages of felsic rocks described above (Figure 2A).

In common with other parts of the VLSG, the Long Lake group contains a strongly developed penetrative fabric defined by a northeast-striking foliation. Foliation dip directions vary from being steeply northwest where the stratigraphy is right-way-up, to steeply to the southeast where it is overturned, and coincide with variable stratigraphic-facing directions in similar stratigraphies. This is an expected pattern based on the folding observed throughout the group (Plate 3A–D, Figure 3A–D). Detailed structural interpretations in the group are hindered by the poor outcrop, but local observations suggest polyphase deformation; conceptually illustrated as a series of fold-thrust belts in Figure 3D. The rocks are lower–middle greenschist-facies metamorphosed.

VARIATIONS IN MAP PATTERNS AND DIVISIONS OF FELSIC ROCK TYPES

The possible subdivision of the felsic volcanic rocks was recognized by Kean (1977, 1982) who divided felsic volcanic rocks into three packages: 1) grey, green and pink, fine-grained, bedded silicic tuff and breccia with some flows (representing the lower stratigraphy described above), 2) intermediate to silicic, white and green quartz-feldspar crystal tuffs and unseparated breccia (representing the upper stratigraphy described above), and 3) pink, buff and green aphanitic silicic vitric tuff and quartz-vitric tuff in the vicinity of the Long Lake deposit (included here with the lower stratigraphy, Figure 2B). Noranda determined that the felsic volcanic rocks could also be subdivided into two groups based upon zirconium concentrations. The regional aeromagnetic data suggest a contrast between the magnetite-bearing felsic volcanic rocks of the lower stratigraphy in the northwest from the magnetite-poor felsic tuffaceous rocks of the upper stratigraphy in the southeast (Figure 2D). This subdivision of the felsic volcanic rocks is consistent with the results of the current study and is substantiated by field mapping in addition to lithogeochemistry and geochronological studies (*see* below).

Recent mapping as part of the GSC TGI 3 program (van Staal *et al.*, 2005; Zagorevski *et al.*, 2010), further simplified the stratigraphy of the Long Lake group. They informally defined two formations: the Harmsworth Steady formation, and the Costigan Lake formation, of mafic and felsic composition, respectively (Figure 2A). However, the geochemical data of Zagorevski *et al.* (2010), suggest that the felsic volcanic rocks corresponding to the upper stratigraphy have lower concentrations of trace elements and less-pronounced Eu, Zr, and Ti anomalies than the remainder of the felsic volcanic rocks. In this report, the preliminary geochronological and geochemical data are used to support the idea of discrete sequences.

VOLCANOGENIC MASSIVE SULPHIDE (VMS) PROSPECTS AND OCCURRENCES

The Long Lake group hosts one known significant VMS deposit, known as the Long Lake main deposit, along with several VMS occurrences (Figure 2A). The Long Lake main deposit will be described first, followed by a brief description of other occurrences in the lower and upper felsic stratigraphy, respectively.

LONG LAKE MAIN DEPOSIT

The Long Lake main deposit is hosted by an intercalated sequence of felsic (Plate 1B) and mafic volcanic rocks with minor cherty, iron-rich exhalative sediments. The deposit consists of narrow intervals of barite-rich high-grade massive sulphide dominated by sphalerite, chalcopyrite, galena and pyrite (Plate 2D). The felsic volcanic rocks in the stratigraphic footwall are dominated by fine-grained felsic tuff and aphyric to quartz-phyric rhyolite that are intensely altered to assemblages with variable amounts of sericite, pyrite, chlorite, carbonate and silica. The impact of recrystallization is shown by polycrystalline silica, and in the sulphide horizons by coarse-grained crystalline sulphide, with

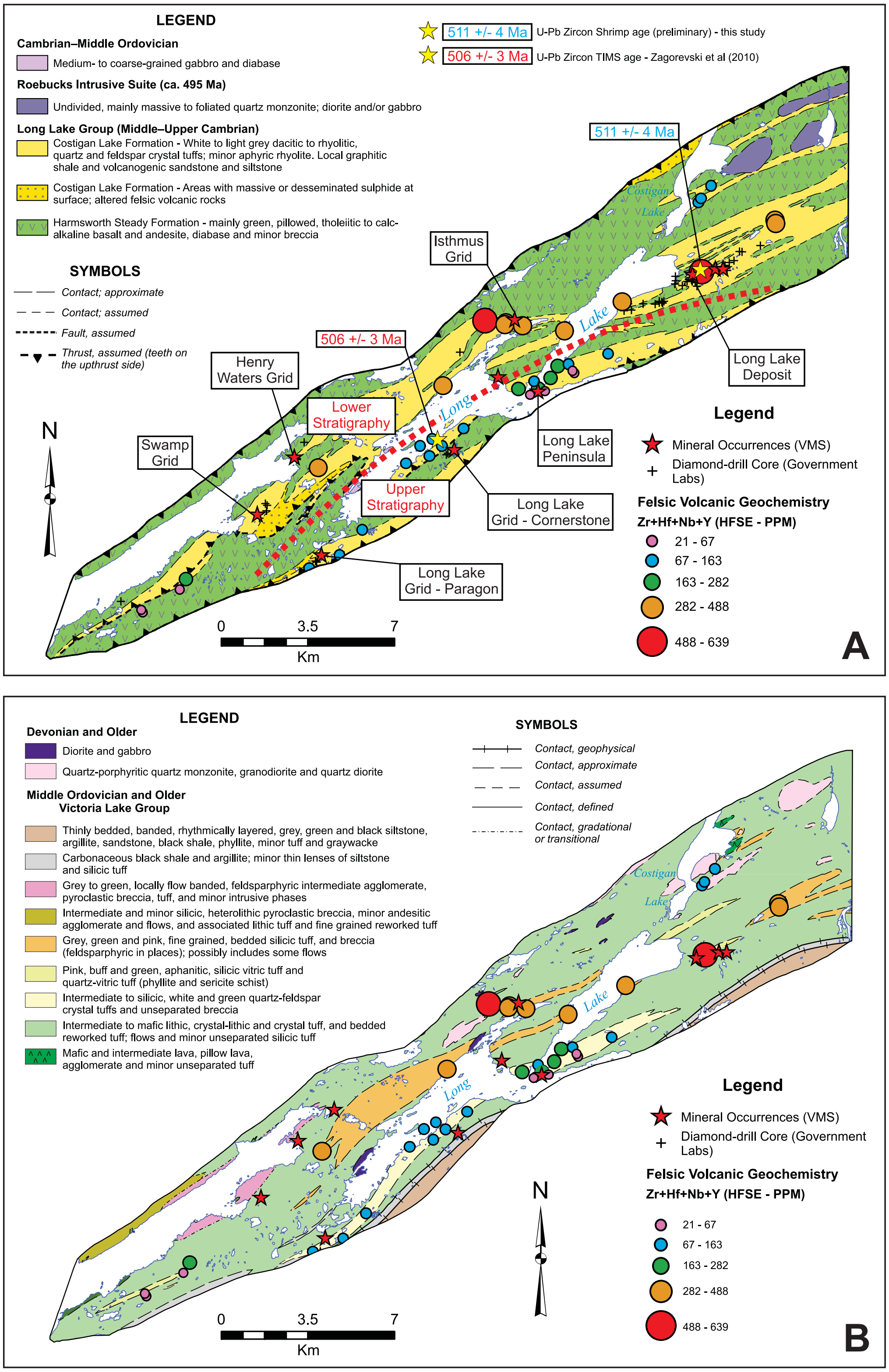
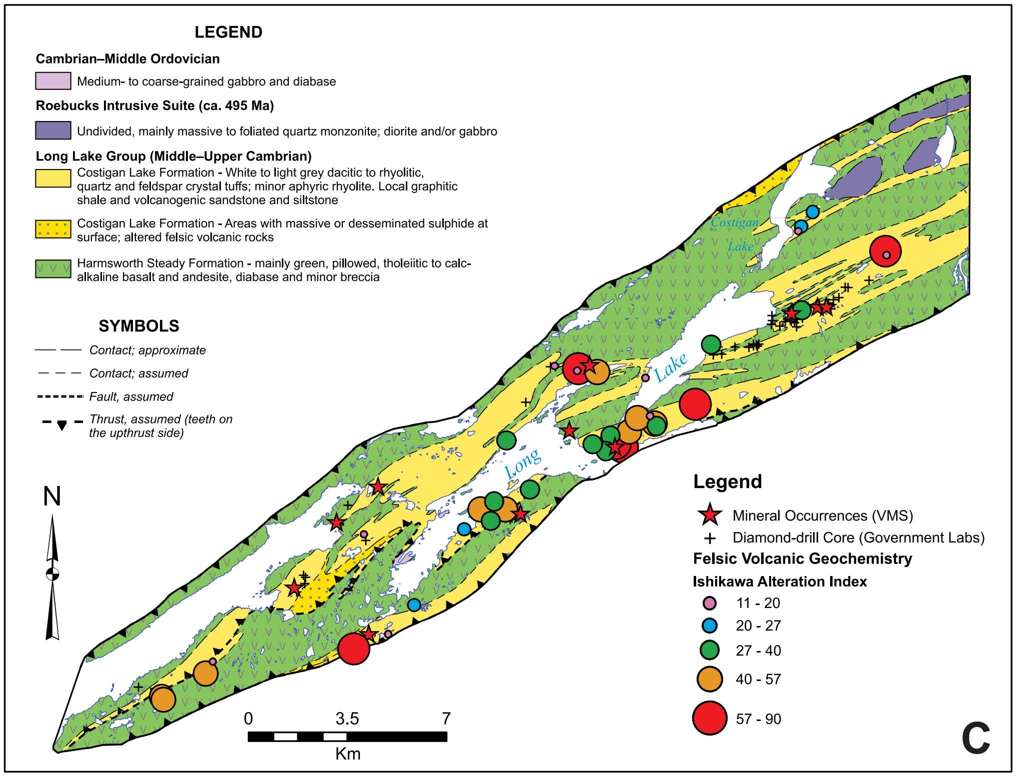
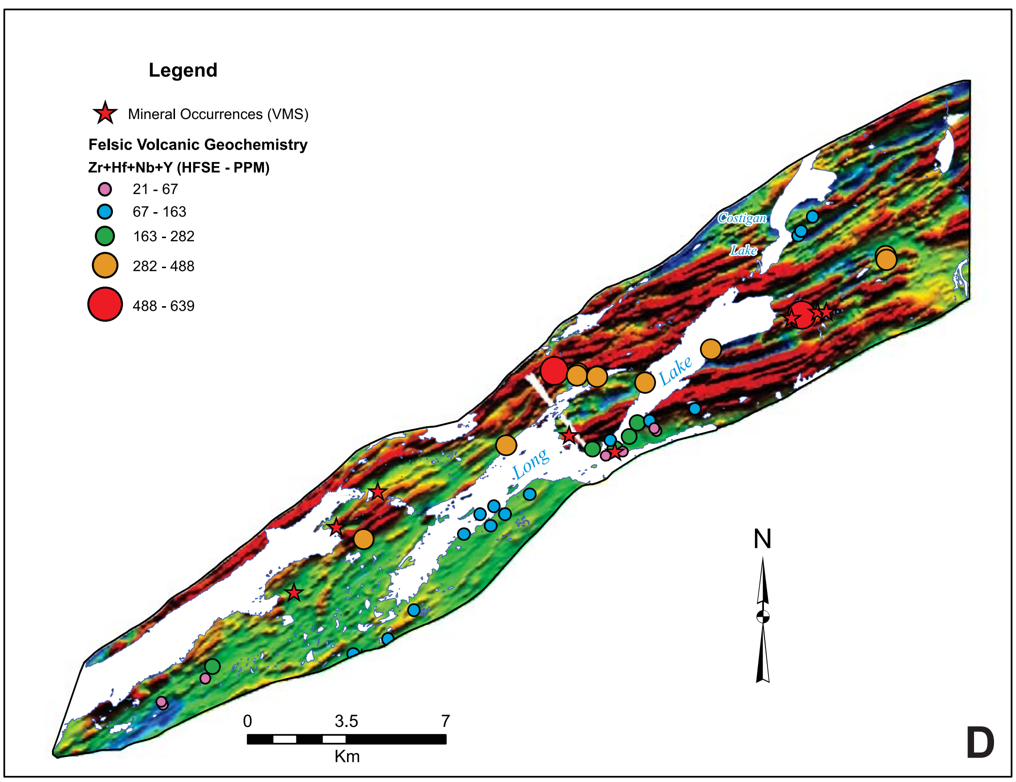


Figure 2. *A) General geology of the southwestern portion of the Long Lake group as mapped by van Staal* et al. *(2005) and Lissenberg* et al. *(2005). Also shown are the locations of the Long Lake main deposit and other areas of exploration focus and the location of the dated samples from the group. Dot plots represent the various concentrations of high-field strength elements (Zr+Hf+Nb+Y) for outcrop samples collected during the current study; breaks determined as Jenks natural breaks. The red dashed line trending from southwest to northeast is for descriptive purposes only and represents the approximate location*





proposed for the division of the upper and lower stratigraphy as discussed in the text; B) As in A, with the geology as mapped by Kean (1977, 1982); C) As in A, with dot plots representing Ishikawa alteration index values for outcrop samples collected during the current study; D) Total-field regional airborne magnetic intensity map for the area with dot plots representing the various concentrations of high-field strength elements (Zr+Hf+Nb+Y) for outcrop samples collected during the current study.

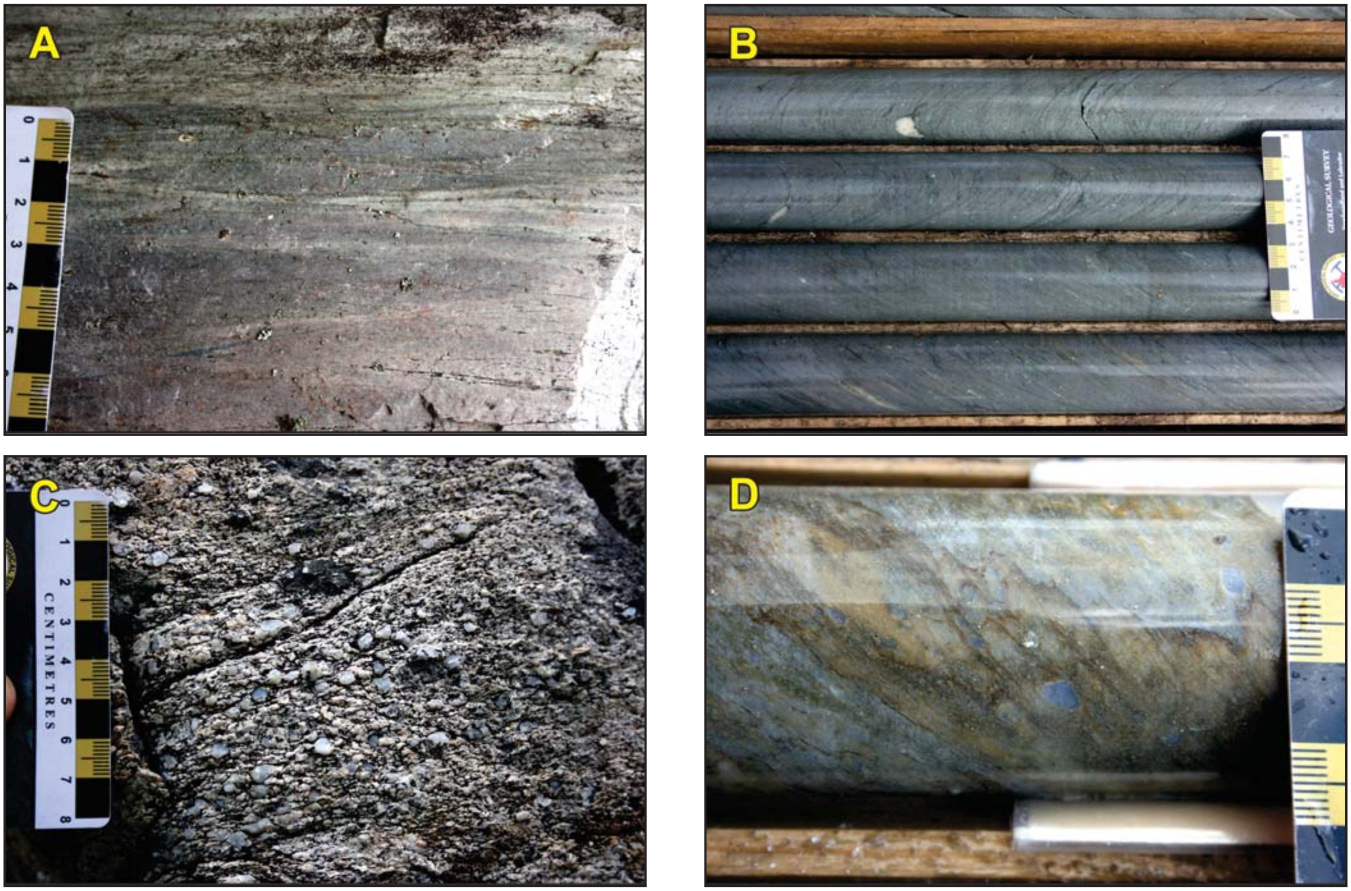


Plate 1. *A) Very fine-grained to aphyric pink flow-banded rhyolite–lower stratigraphy; B) Fine-grained, massive and homogenous feldspar phyric felsic volcanic–lower stratigraphy (DDH LL-94-18 @ approximately 490 m depth); C) Medium- to coarse-grained blue quartz-phyric felsic tuff–upper stratigraphy; D) Blue quartz-phyric felsic tuff–upper stratigraphy (DDH LL-06-01 @ approximately 170 m depth).*

pyrite commonly overprinting other sulphide minerals (Plate 2D).

The deposit and the concordant metamorphic foliation is interpreted to have been isoclinally folded in D_2 (F_2), with mineralization occurring on both the North and South limbs of a synform. This model is supported by the geophysical magnetic intensity patterns (Figure 3B) as well as observed variations in foliation dip directions (Figure 3A). The observed patterns in the vicinity of the Long Lake main deposit are suggestive of a series of tight, locally southeasterly overturned, asymmetrical folds occurring between the southern tip of Costigan Lake and the southeastern margin of the Long Lake group (Figure 3A–D). Folding was also seen in magnetite seams in a rhyolite occurring near the surface projection of the deposit (Plate 3A). This strong structural control of the deposit explains the attenuated and recrystallized nature of the sulphides and possibly the shape of some of the basalt lenticles. The interpretation is also favoured by the repetition and observed polarity of alteration lithogeochemical signatures in diamond-drill core (Figure 4). Additional mineralized zones have been discovered to the northeast and east-southeast of the main deposit; and these potentially also represent fold repetitions of the main mineralized zone (Noranda, 1998).

The currently defined resource for the Long Lake main deposit is 407 000 tonnes of indicated reserves with grades of 7.82% Zn, 1.58% Pb, 0.97% Cu, 49 g/t Ag, and 0.57 g/t Au; and an additional 78 000 tonnes of similar grade inferred resources (Keller and Bernier, 2012).

OTHER OCCURRENCES IN THE LOWER STRATIGRAPHY

Other mineralized occurrences in the lower stratigraphy include: 1) the Isthmus Grid, 2) the Henry Waters Grid, and 3) the Swamp Grid (Figure 2A). All three areas were visited in the field and examined in diamond-drill core.

The Isthmus Grid is located approximately 7 km to the southeast of the Long Lake main deposit (Figure 2A). Rock

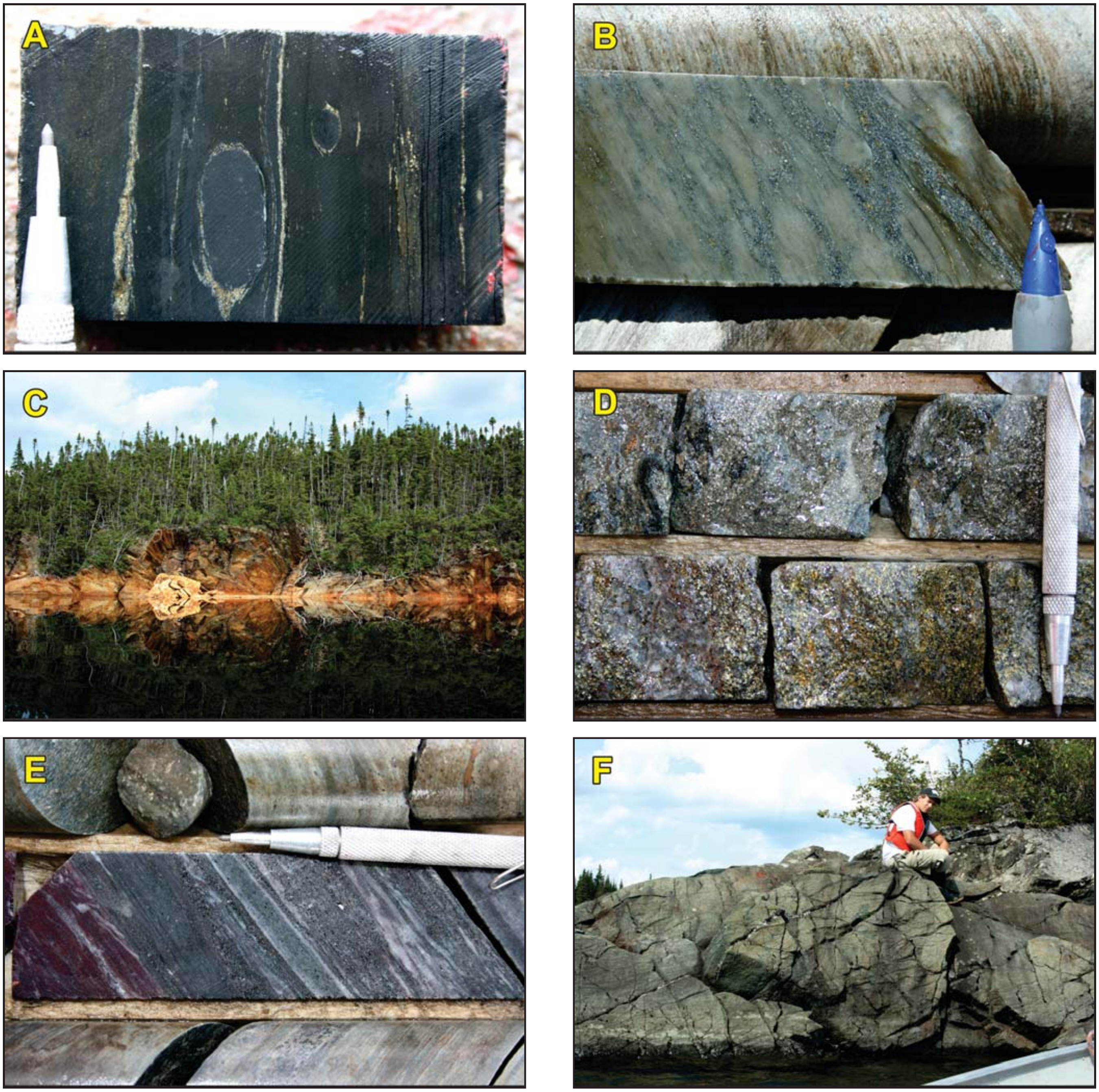


Plate 2. *A) Black graphitic shale with augen-shaped cherty fragments; Henry Waters Grid–lower stratigraphy; B) Base-metal-rich stringer sulphide mineralization hosted by silicified rhyolite–lower stratigraphy (DDH LLW-97-05 @ approximately 127 m depth); C) Prominent sericite-pyrite-altered quartz-phyric felsic tuff at the Long Lake Peninsula–upper stratigraphy, D) Recrystallized base-metal-rich massive sulphide with barite; Long Lake main deposit–lower stratigraphy (DDH LL-94-02 @ approximately 70 m depth); E) Iron formation associated with the base-metal-rich massive sulphide–lower stratigraphy (DDH LL-94-02 @ approximately 44 m depth); F) Pillow basalt from the southwestern area of Long Lake–lower stratigraphy.* See *Figure 2A for locations mentioned in the caption.*

types are dominated by quartz and feldspar-phyric, fine-grained and foliated rhyolite, and lesser amounts of feldspar and quartz-phyric felsic tuff and amygdaloidal basalt. The area has well-defined alteration zones that were drill tested in the 1970s by Asarco and by Noranda in the 1990s. Diamond-drill hole IS-95-01 was re-logged for this study, and is dominated by quartz and feldspar-phyric, light-grey, foliated rhyolite with variable intensities of sericite, pyrite, chlo-

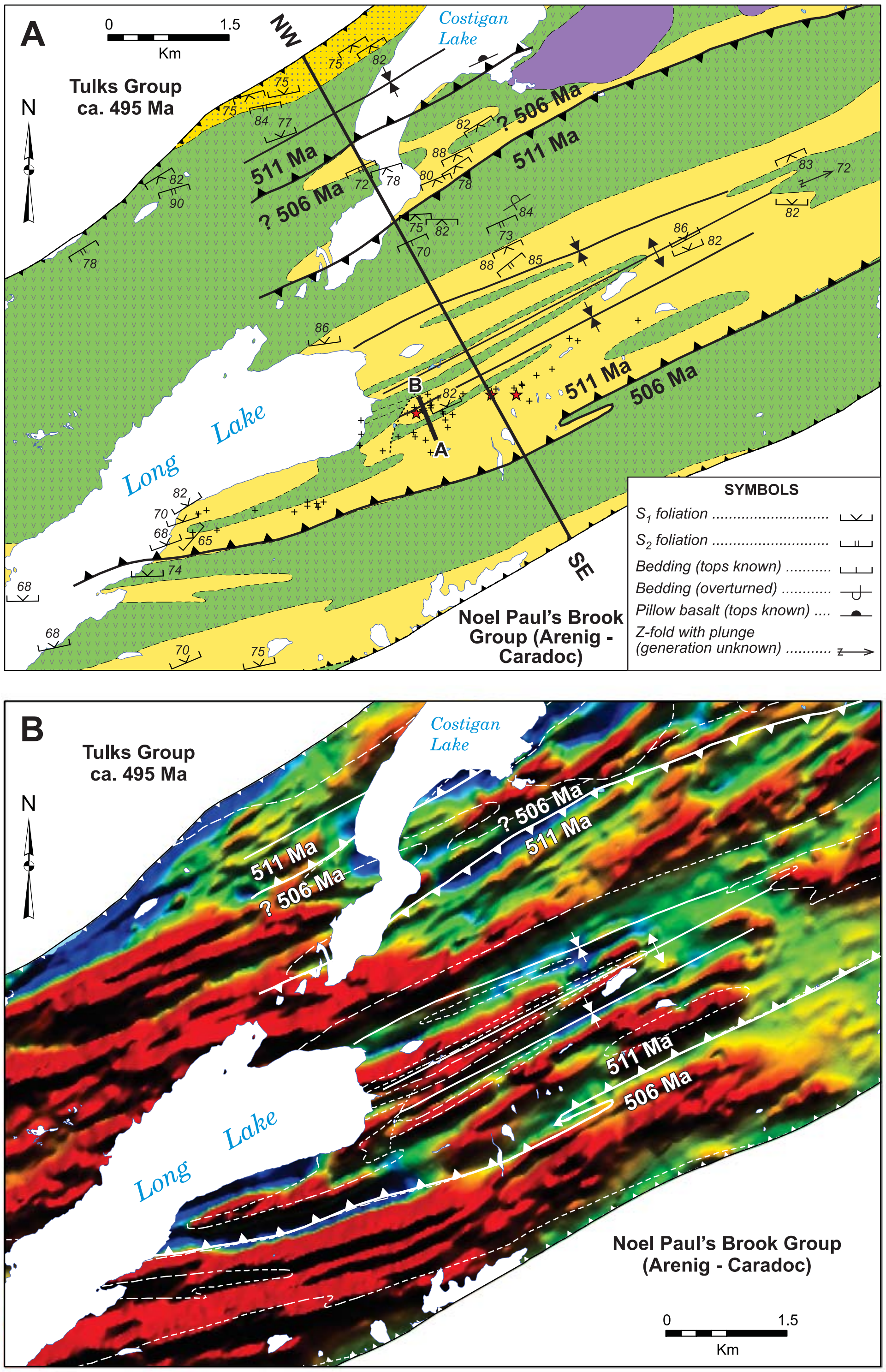
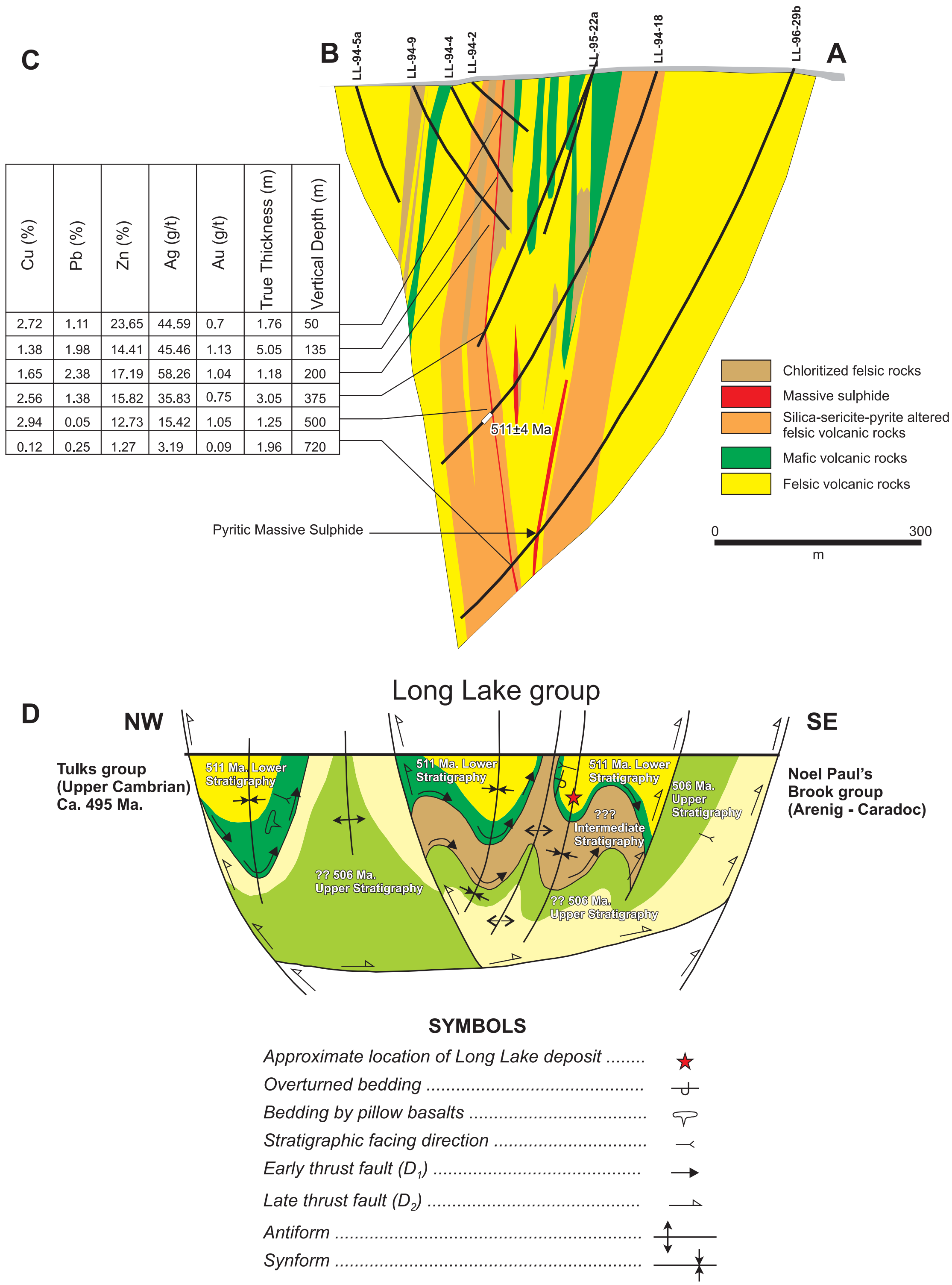


Figure 3. *A) Rock types and structural interpretations in the vicinity of the Long Lake main deposit area. Note the opposite dip polarity of foliation measurements to the northwest and southeast of the deposit area. Geology after van Staal* et al. *(2005). Structural measurements are from this study and compilations from Lissenberg et al. (2005), van Staal* et al. *(2005), and Kean (1977, 1982). The conceptual locations of overlying folds and thrusts, and the inferred location of upper and lower stratigraphic boundaries are superimposed on the map and are implied from the current study. Lithological legend as in Figure 2A; B) Regional aeromagnetic data for the area in A with the conceptual location of folds, thrusts, and stratigraphic units superimposed; C) Cross-section interpretation from the Long Lake main deposit along section line A–B shown in Figure 3A. Sec-*



Cu (%)	Pb (%)	Zn (%)	Ag (g/t)	Au (g/t)	True Thickness (m)	Vertical Depth (m)
2.72	1.11	23.65	44.59	0.7	1.76	50
1.38	1.98	14.41	45.46	1.13	5.05	135
1.65	2.38	17.19	58.26	1.04	1.18	200
2.56	1.38	15.82	35.83	0.75	3.05	375
2.94	0.05	12.73	15.42	1.05	1.25	500
0.12	0.25	1.27	3.19	0.09	1.96	720

tion reproduced from Noranda (1998). Note that the mineralized horizon is interpreted to be repeated via *synformal folding. Section is looking toward 70°; D) Conceptual northwest-southeast schematic cross-section through the Long Lake group in the vicinity of the Long Lake deposit* (see *Figure 3A for section line location). Note the regionally imbricated fold and thrust belt relationships inferred from the structural data and geophysical patterns observed in Figure 3A and B, with additional inferences based on lithogeochemical and isotopic data discussed in the text. The schematic representation of the upper (506 Ma) stratigraphy in the vicinity of Costigan Lake is based primarily on geochemical and Nd isotopic characteristics.*

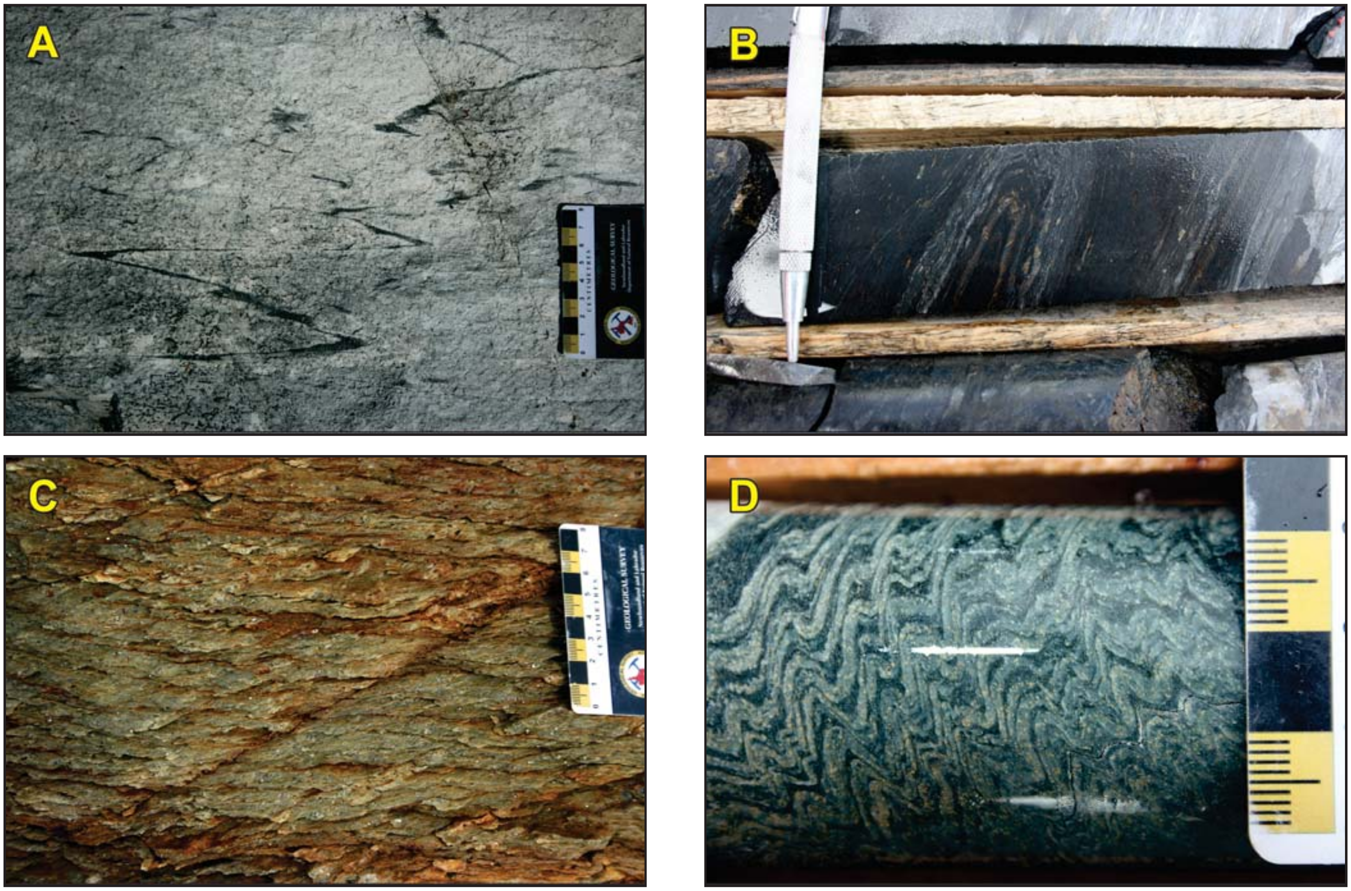


Plate 3. *A) Tight isoclinal folding of a magnetite seam within rhyolite located in the area of the surface projection of the Long Lake main deposit–lower stratigraphy. Note that Z, M and S folds are observed in the outcrop; B) Isoclinal folding within a fine-grained felsic ash tuff and graphitic shale sequence at the Long Lake Paragon grid location–upper stratigraphy (DDH LL-06-03 @ approximately 182 m depth); C) Well-developed C-S fabrics in the vicinity of the Long Lake Peninsula–upper stratigraphy; D) Pararasitic folds in a chlorite-altered, quartz-phyric felsic tuff at the Long Lake Cornerstone grid location; upper stratigraphy (DDH LL-06-01 @ approximately 43 m depth).* See *Figure 2A for locations mentioned in the caption.*

rite, and silica alteration throughout, and minor sphalerite in stringer zones. The best assay returned was 1.55 % Zn over 0.2 m.

The Henry Waters Grid is located between the southern tip of Long Lake and the Henry Waters arm of Victoria Lake (Figure 2A). Identified geochemical anomalies were drilled by Noranda in the mid-1990s and again by Paragon Minerals in 2006 (DDH HW-06-01). Drillhole HW-06-01 was re-logged for this study; it contains altered quartz and feldspar phyric, to aphyric rhyolite flows and sills, metalliferous black graphitic shale, and lesser amounts of felsic tuff and mafic sills. Alteration includes chlorite, carbonate, silica and pyrite. Minor fracture controlled base-metal stringers occur within the rhyolite, and the best assayed intersection consists of 1.32% Zn, 140 ppm Pb, and 934 ppm Cu over 1 m (Sparkes, 2007). Black graphitic shale was intersected toward the base of the hole, containing numerous augen-shaped cherty fragments and disseminated sulphides (Plate 2A). The presence of these cherty fragments in this particular shale package, compared to their apparent absence in most other shales observed in the Long Lake group, may suggest a detrital, rather than a replacement, origin for the chert. Base-metal contents in the shale range up to 8393 ppm Zn, 1337 ppm Cu, 316 ppm Pb, 13 ppm Ag, and 67 ppm Au, and average 0.5% Zn over 30 m (Sparkes, 2007).

The Swamp Grid (Figure 2A) occurs approximately 3 km to the southwest of the Henry Waters Grid and intersected similar rock types. Feldspar and quartz-phyric to aphyric, white to grey rhyolite breccia is the dominant rock type, with lesser amounts of mafic tuff, mafic flows and sills, and black graphitic shale and argillite. The rhyolite breccia is variably altered to assemblages of sericite, pyrite, chlorite, carbonate and silica, and locally contains base-metal-rich stringers containing up to 1.29% Zn over 0.5 m.

Plate 4. *Photograph illustrating the typical topography in the vicinity of the Long Lake main deposit (approximate location of the deposit is marked by the yellow star). Photograph view is to the northeast.*

OTHER OCCURRENCES IN THE UPPER STRATIGRAPHY

Volcanogenic massive sulphide occurrences in the upper stratigraphy include, from north to south: 1) the Long Lake Peninsula area, 2) the Long Lake Cornerstone Grid, and 3) the Long Lake Paragon Grid (formerly known as RL 227 Grid by Noranda; Figure 2A). All three areas were examined in the field, and the latter two occurrences were examined in diamond-drill core.

The extensive alteration and gossan development in the Long Lake Peninsula area (Plate 2C) attracted the first exploration to the Long Lake area in the 1940s. Rock types are dominated by extremely foliated and cleaved quartz-phyric, fine-grained felsic to intermediate tuff having intense sericite–pyrite alteration (Plate 3C). The area contains a large copper (in soil) anomaly and historic drilling intersected 2.9% Cu over 0.3 m and 0.8% Cu over 1.8 m (Noranda, 1998).

The Long Lake Cornerstone Grid occurs on the southeast margin of Long Lake (Figure 2A). Host rocks are dominated by felsic to intermediate tuff having very prominent blue quartz crystals (Plate 2C, D). Diamond drilling by Cornerstone Resources in 2006 followed up on base metals in soil anomalies and AEM anomalies, with drillhole LL-06-01 intersecting 200 m of altered blue quartz-phyric tuff along with minor base-metal stringers. Alteration assemblages include sericite, chlorite, carbonate, and silica. Foliations are well developed in the core, with complex structural relationships observed with parasitic (Plate 3D) and isoclinal folding.

The Long Lake Paragon Grid occurs in the southeast portion of the Long Lake group (Figure 2A). Diamond-drill hole LL-06-03 was re-logged in this study and intersected variably altered felsic to intermediate tuffs for approximately 150 m, below which the volcanic rocks are in fault contact with black graphitic shale; interpreted to represent the younger Lawrence Harbour formation as mapped by van Staal *et al.* (2005) on surface. This boundary would represent the basal or sole thrust to the overlying imbricate faults within the Long Lake group. Although no significant base-metal-rich zones were intersected, the alteration zone is well developed, and includes sericite, chlorite, silica and pyrite.

U–Pb GEOCHRONOLOGY

New U–Pb geochronology data are important in the context of geological information discussed above, and geochemical data discussed in the next section.

Prior to this study there was only one U–Pb age determination for the entire Long Lake group, represented by a felsic volcaniclastic rock (taken from the upper stratigraphy) that returned an age of 506 ± 3 Ma (Zagorevski *et al.*, 2010; *see* Figure 2A for location). The result was interpreted to apply to all of the felsic volcanic rocks in the Long Lake group.

The field work conducted during this study suggested that there are at least two distinctive packages of felsic volcanic rocks within the Long Lake group, and that these might correspond with previously inferred contrasts in whole-rock lithogeochemistry. Hence, a sample was collected from the immediate footwall to the Long Lake main deposit to constrain the age of the lower stratigraphy, and the VMS mineralization.

The sensitive high-resolution ion microprobe (SHRIMP) data collected are currently being refined through isotope dilution-thermal ionization mass spectrometer (ID-TIMS) techniques in an attempt to improve precision. The initial results are discussed but may be revised later. The U–Pb analysis was conducted at the Geochronology Laboratory of the Geological Survey of Canada under the supervision of Vicki McNicoll, and the reader is referred to Stern (1997) and Stern and Amelin (2003) for the details of methods, procedures and data processing.

Sample JHC-12-027 was collected from 575.1–598.5 m in diamond-drill hole LL-94-018. It produced a small number of euhedral zircon grains, and SHRIMP data reveal a single age population forming a cluster of concordant, overlapping data points. The crystallization age of the sample is currently interpreted as 511 ± 4 Ma.

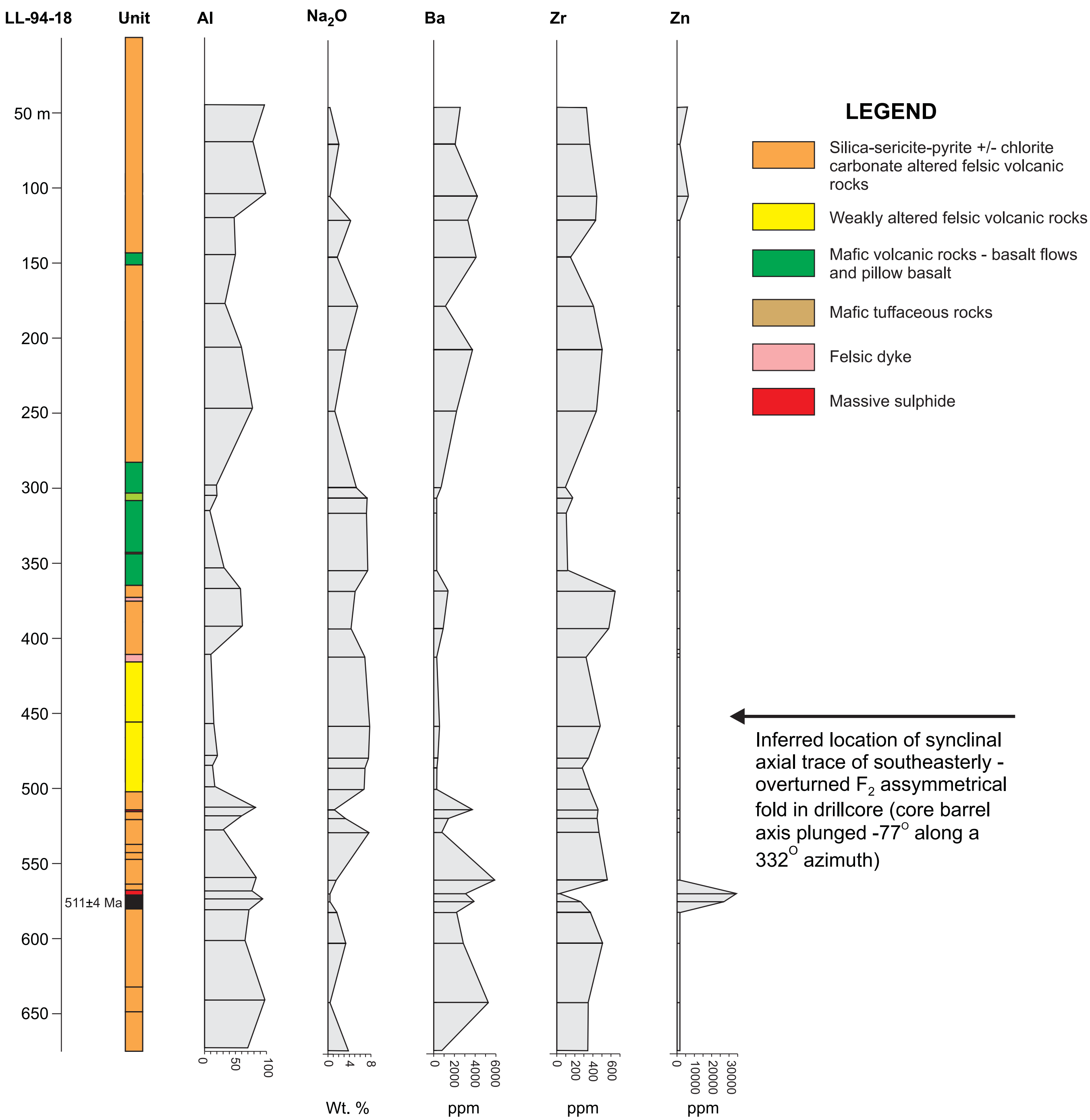


Figure 4. *Geochemical strip log for diamond-drill hole LL-94-18 (Long Lake main deposit) illustrating the repetition of alteration zones and repetition of lithogeochemical alteration signatures downhole (depth in metres). AI = Hashimoto alteration index (*see *Figure 5 caption for formula).*

This is within error margin of the 506 ± 3 Ma from the upper stratigraphy; nevertheless, the difference is believed to be significant in the context of local stratigraphy.

GEOCHEMISTRY

INTRODUCTION

A representative suite of all volcanic and volcaniclastic rocks from the Long Lake group were analyzed for major and trace elements, using ICP-ES (Inductively Coupled Plasma – Emission Spectrometry) and ICP-MS (Inductively Coupled Plasma – Mass Spectrometry) methods at the Geological Survey laboratory. To aid in discussion and for clarity for figures, these samples are separated into four groups, defined as: 1) the Long Lake main deposit area, 2) other areas studied with drillcore from the lower stratigraphy (Isthmus, Henry Waters, and Swamp grids), 3) areas studied with drillcore from the upper stratigraphy (Long Lake grids of Paragon and Cornerstone), and 4) outcrop samples examined throughout the group. Selected samples were also analyzed for Sm–Nd isotopic compositions by ID-TIMS techniques at Memorial University. The complete geochemical database from this project will be released at a later date, but Table 1 provides some key elements and ratios, and Table 2 provides Sm–Nd data. As most of the known VMS showings and occurrences are associated with the felsic volcanic rocks in the group, these rock types were favoured in the sampling, and most of the following discussion applies to these data.

ELEMENT MOBILITY CONSIDERATIONS

Whenever lithogeochemistry is used to make inferences about primary rock compositions, it is important to account for the effects of element mobility. The replacement of primary minerals (predominantly feldspar) and volcanic glass by secondary hydrothermal minerals affect some elements. The most common hydrothermal alteration process affecting the host rocks to VMS occurrences in the Long Lake group is replacement of primary feldspar by sericite. This generally results in a gain of K from hydrothermal fluids and a corresponding loss of Na and Ca from the rock. Additional replacement of feldspars and sericite by chlorite results in an addition of Mg ± Fe to the rocks. Therefore, it is assumed that the alkalis, Mg, Fe, and SiO_2 are mobile. The low-field strength elements (*e.g.*, Ba, Rb, Cs, Sr) are also considered to be mobile under the alteration conditions in this study, and are not used to discriminate between rock types. The REE (with the exception of Eu (*e.g.*, Sverjensky, 1984; Whitford *et al.*, 1988)) are generally considered to be immobile except under extreme hydrothermal alteration conditions, when the light REE may become mobile (Campbell *et al.*, 1984; MacLean and Barrett, 1993). The coherent behaviour of REE in the samples from the Long Lake group suggests that they were essentially immobile. The high field strength elements (HFSE: *e.g.*, Zr, Hf, Nb, Ta, Y, Th) are immobile in almost all cases (*e.g.*, Barrett and MacLean, 1999; Lentz, 1999). The coherent behaviour of these elements in the studied samples also suggests that they remained essentially immobile during alteration.

The geochemical data from the four groups of samples defined above are plotted on an alteration box plot in Figure 5 (Large *et al.*, 2001). This plot uses two common alteration indexes; the Hashimoto index (AI; Ishikawa *et al.*, 1976) and the chlorite–carbonate–pyrite index (CCPI; Large *et al.*, 2001; *see* Figure 5 for formulas). High AI values represent sericite and chlorite alteration products from the breakdown of plagioclase feldspars and volcanic glass; whereas high CCPI values represent chlorite, Fe–Mg carbonates, and pyrite alteration typically associated with VMS deposits. As many of the samples studied are displaced to the right of the ‘least altered box’, with relatively high AI and CCPI, it suggests that their primary geochemical compositions have been affected by hydrothermal activity. For this reason, emphasis is placed on relatively immobile REE and HFSE.

LONG LAKE DEPOSIT AREA (LOWER STRATIGRAPHY)

The host rocks to the Long Lake main VMS deposit are bimodal in composition as illustrated in the modified Winchester and Floyd (1977) Zr/TiO_2 – Nb/Y plot of Pearce (1996; Figure 6A). The aphyric to fine-grained quartz and feldspar-phyric rhyolite and tuff have relatively high Zr/TiO_2 and low Nb/Y (Figure 6a, Table 1) suggestive of a subalkaline affinity, whereas the medium-grained, quartz ± feldspar-phyric felsic to intermediate tuff has significantly lower Zr/TiO_2 (Figure 6A). The HFSE (*e.g.*, Zr, Hf, Y, Nb) contents of the aphyric to fine-grained rhyolite and felsic tuff volcanic rocks are relatively high, characterizing them as ocean-ridge type rocks on commonly used HFSE diagrams (Figure 7A); whereas the HFSE contents of the medium-grained felsic to intermediate tuff are much lower, being characterized as volcanic-arc type rocks (Figure 7A). Primitive mantle-normalized plots for all felsic rocks (Figure 8A, Table 1), are characterized by weak LREE enrichments, as shown by the Ce_N/Yb_N ratios in Table 1. The aphyric to fine-grained rhyolite and tuff display strongly negative Nb and Ti anomalies and moderately positive Zr and Hf anomalies (Table 1, Figure 8A). In contrast, the medium-grained felsic tuff is characterized by much less strongly developed Nb, Ti, Zr and Hf anomalies (Table 1, Figure 8A). The aphyric to fine-grained rhyolite and tuff have relatively higher Ti/Sc and lower Sc/Nb ratios compared to the medium-grained tuff; dictated predominantly by Sc concentrations. On the La/Yb_N versus Yb_N plot of Lesher *et al.* (1986) and Hart *et*

Table 1. Summary table of some key major- and trace-element concentrations and ratios from the four groupings discussed in the text

Long Lake Deposit Area Drillcore

	Felsic-Intermediate Tuff		Rhyolite or Tuff		Rhyolite		HFSE enriched Felsic Tuff	
	AVERAGE n=5	σ	AVERAGE n=9	σ	AVERAGE n=19	σ	AVERAGE n=38	σ
SiO_2	52.30	6.93	71.35	3.85	71.20	4.76	66.96	7.59
TiO_2	1.28	0.57	0.27	0.13	0.22	0.07	0.33	0.16
Zr	117.80	33.50	368.56	55.46	389.68	71.70	390.97	102.83
Zr+Hf+Nb+Y	160.86	39.17	464.52	64.27	487.25	79.22	496.70	123.64
Zr/Y	3.31	0.66	4.83	0.45	5.04	1.21	4.54	0.62
Zr/Nb	30.71	10.76	42.97	11.00	52.13	11.80	45.16	11.35
Zr/TiO_2	0.01	0.01	0.17	0.08	0.19	0.06	0.15	0.07
Zr/Hf	35.06	1.84	34.54	1.39	35.77	2.88	35.80	2.58
104*Ga/Al	144.67	21.00	183.45	27.57	186.45	28.77	200.14	41.38
Th/Nb	0.53	0.33	1.10	0.47	1.14	0.39	1.01	0.32
Sc/Nb	7.53	4.11	0.81	0.28	0.87	0.33	1.04	0.67
Ti/Sc	269.56	59.51	221.26	46.08	219.62	49.09	248.59	115.59
Zr/Sc	5.72	5.46	61.08	34.82	71.62	32.60	61.98	45.17
Ce/Yb_N[1]	2.12	0.76	2.13	0.45	2.09	0.81	2.06	0.43
La/Th_N[1]	0.87	0.36	0.45	0.15	0.49	0.14	0.52	0.16
La/Nb_N[1]	3.34	1.25	3.85	1.01	4.52	1.37	4.19	1.04
Zr/Sm_N[1]	0.90	0.10	1.43	0.18	1.57	0.26	1.43	0.28

Isthmus, Henry Waters, and Swamp Grids Area Drillcore

	Felsic-Intermediate Tuff		Rhyolite		FSE enriched Felsic Tu	
	AVERAGE n=1	σ	AVERAGE n=12	σ	AVERAGE n=3	σ
SiO_2	54.78		67.89	7.21	63.22	8.30
TiO_2	1		0.29	0.09	0.53	0.27
Zr	77		422.50	127.41	232.00	90.71
Zr+Hf+Nb+Y	107.6		533.42	151.24	299.65	107.50
Zr/Y	2.96		5.18	1.10	4.40	0.59
Zr/Nb	32.42		37.91	13.78	24.53	6.93
Zr/TiO_2	0.01		0.15	0.03	0.07	0.07
Zr/Hf	35.00		33.83	6.21	34.85	0.99
104*Ga/Al	111.26		205.76	78.98	150.31	19.18
Th/Nb	0.59		1.07	0.24	1.01	0.08
Sc/Nb	12.80		0.60	0.24	1.75	1.07
Ti/Sc	197.14		262.44	49.64	213.30	23.63
Zr/Sc	2.53		65.18	11.69	26.20	30.08
Ce/Yb_N[1]	1.28		2.19	0.44	5.43	2.54
La/Th_N[1]	0.50		0.36	0.06	0.50	0.05
La/Nb_N[1]	2.49		3.18	0.72	4.26	0.71
Zr/Sm_N[1]	0.92		1.63	0.40	1.01	0.29

Long Lake Paragon and Cornerstone Grids Area Drillcore

	Felsic-Intermediate Tuff	
	AVERAGE n=18	σ
SiO_2	59.66	4.96
TiO_2	0.49	0.09
Zr	69.22	15.91
Zr+Hf+Nb+Y	97.61	17.97
Zr/Y	2.99	0.64
Zr/Nb	26.32	10.39
Zr/TiO_2	0.01	0.00
Zr/Hf	29.83	2.52
104*Ga/Al	102.35	6.85
Th/Nb	0.84	0.43
Sc/Nb	10.47	2.36
Ti/Sc	102.35	15.54
Zr/Sc	2.51	0.85
Ce/Yb_N[1]	1.62	0.26
La/Th_N[1]	0.46	0.15
La/Nb_N[1]	2.94	1.09
Zr/Sm_N[1]	1.11	0.29

Outcrop Samples - Long Lake group

	Felsic-Intermediate Tuff		Rhyolite		HFSE enriched Felsic Tuff	
	AVERAGE n=20	σ	AVERAGE n=20	σ	AVERAGE n=3	σ
SiO_2	61.90	7.61	72.97	5.46	66.66	8.10
TiO_2	0.43	0.12	0.28	0.12	0.54	0.14
Zr	81.10	40.98	293.10	120.52	197.00	81.43
Zr+Hf+Nb+Y	106.56	49.61	360.91	148.70	263.90	92.88
Zr/Y	4.21	1.71	6.19	2.21	3.71	0.91
Zr/Nb	30.50	15.46	40.91	13.98	23.92	15.88
Zr/TiO_2	0.02	0.01	0.13	0.08	0.04	0.01
Zr/Hf	35.29	3.40	38.34	5.18	37.36	5.48
104*Ga/Al	101.34	22.80	161.44	67.40	145.35	34.11
Th/Nb	1.07	0.60	1.37	0.69	0.69	0.13
Sc/Nb	11.95	10.33	1.18	1.33	1.27	0.46
Ti/Sc	118.77	43.07	366.59	366.05	296.91	68.44
Zr/Sc	4.53	3.67	89.02	157.56	18.92	8.58
Ce/Yb_N[1]	2.50	2.34	2.82	2.85	2.86	1.00
La/Th_N[1]	0.44	0.28	0.33	0.15	0.56	0.18
La/Nb_N[1]	3.66	1.98	3.49	1.64	3.33	1.20
Zr/Sm_N[1]	1.39	0.60	2.08	0.75	1.11	0.40

Major-element data as weight %
Trace-element data as ppm
[1] Normalized to chondritic values after Sun and McDonough (1989)
n = number of samples
σ = standard deviation

Table 2: Sm/Nd isotopic data

Sample	Stratigraphic Unit	Sm	Nd	$^{147}Sm/^{144}Nd$ (measured)	$^{143}Nd/^{144}Nd$ (measured)	Age (Ma)	$^{143}Nd/^{144}Nd$ initial	eNd CHUR ** (T)c
12-JH-026	Upper Stratigraphy	2.859	17.14	0.1009	0.512466	506	0.512132	2.84
12-JH-007	Upper stratigraphy	2.325	9.45	0.1487	0.512662	506	0.512169	3.58
12-JH-057	Upper Stratigraphy?	2.459	10.57	0.1406	0.512578	506	0.512107	2.50
JHC-12-110	Lower Stratigraphy	6.641	29.58	0.1357	0.512651	511	0.512197	4.24
JHC-12-027	Lower Stratigraphy	7.081	29.71	0.1441	0.512778	511	0.512296	6.17

** calculated using present day chondritic uniform reservoir with 143Nd/144Nd = 0.512638 & 147Sm/144Nd = 0.1967

al. (2004), the HFSE enriched aphyric to fine-grained rhyolite and tuff plot as FIII felsic rocks whereas the medium-grained felsic rocks plot as FIV felsic rocks (Figure 9A). A Sm–Nd isotopic composition analysis of one sample of the HFSE-enriched felsic volcanic rocks yielded an epsilon εNd (511Ma) value of +6.17 (Table 2). All mafic volcanic rocks plot as volcanic arc-basalts on commonly used discrimination diagrams. Zagorevski *et al.* (2010) describe the Harmsworth Steady formation as a juvenile (epsilon εNd values of 4.3 and 6.8) island-arc tholeiite to calc-alkaline basalt to andesite; consistent with preliminary data from this study.

On the alteration box plot of Large *et al.* (2001), many samples of the aphyric to fine-grained rhyolite and tuff plot toward the top right hand corner; indicative of sericite, Fe–Mg carbonate, and pyrite alteration typically associated with VMS deposits (Figure 5A). Alteration processes are also highlighted on plots of AI (Ishikawa alteration index) versus Na_2O and AI versus Ba, whereby there is a negative and positive correlation, respectively (Figures 10A, 11A), resulting from feldspar destruction and barite precipitation.

ISTHMUS, HENRY WATERS, SWAMP GRID AREAS (LOWER STRATIGRAPHY)

Host rocks in the vicinity to the Isthmus, Henry Waters, and Swamp grid areas are bimodal in composition and are dominated by aphyric to fine-grained quartz and feldspar-phyric rhyolite and tuff, and lesser basalt (Figure 6B). The felsic volcanic rocks (all except one sample) have very similar geochemical characteristics to the aphyric to fine-grained quartz and feldspar-phyric rhyolite and tuff at the Long Lake main deposit area; with one sample resembling the low HFSE felsic to intermediate tuff. The dominant felsic volcanic rocks have high Zr/TiO_2 and low Nb/Y (Figure 6B, Table 1) suggestive of a subalkaline affinity. Aside from the one sample, concentrations of the HFSE (*e.g.*, Zr, Hf, Y, Nb) are high and characterize the felsic volcanic rocks as ocean-ridge on commonly used HFSE diagrams (Figure 7B). Primitive mantle normalized plots of the dominant felsic volcanic rocks are characterized by weak LREE enrichments, prominent negative Nb and Ti anomalies, and moderately positive Zr and Hf anomalies (Figure 8A,Table 1). The dominant felsic volcanic rocks have high Ti/Sc and low Sc/Nb ratios (Table 1). On the La/Yb_N versus Yb_N plot of Lesher *et al.* (1986) and Hart *et al.* (2004), the rocks plot in the field for FIII felsic rocks (Figure 9B). A Sm–Nd isotopic composition analysis of one sample of the HFSE-enriched felsic volcanic rocks from diamond-drill hole SG-06-04 yielded an epsilon εNd (511 Ma) value of +4.24 (Table 2). All mafic volcanic rocks plot as arc-basalts on commonly used discrimination diagrams.

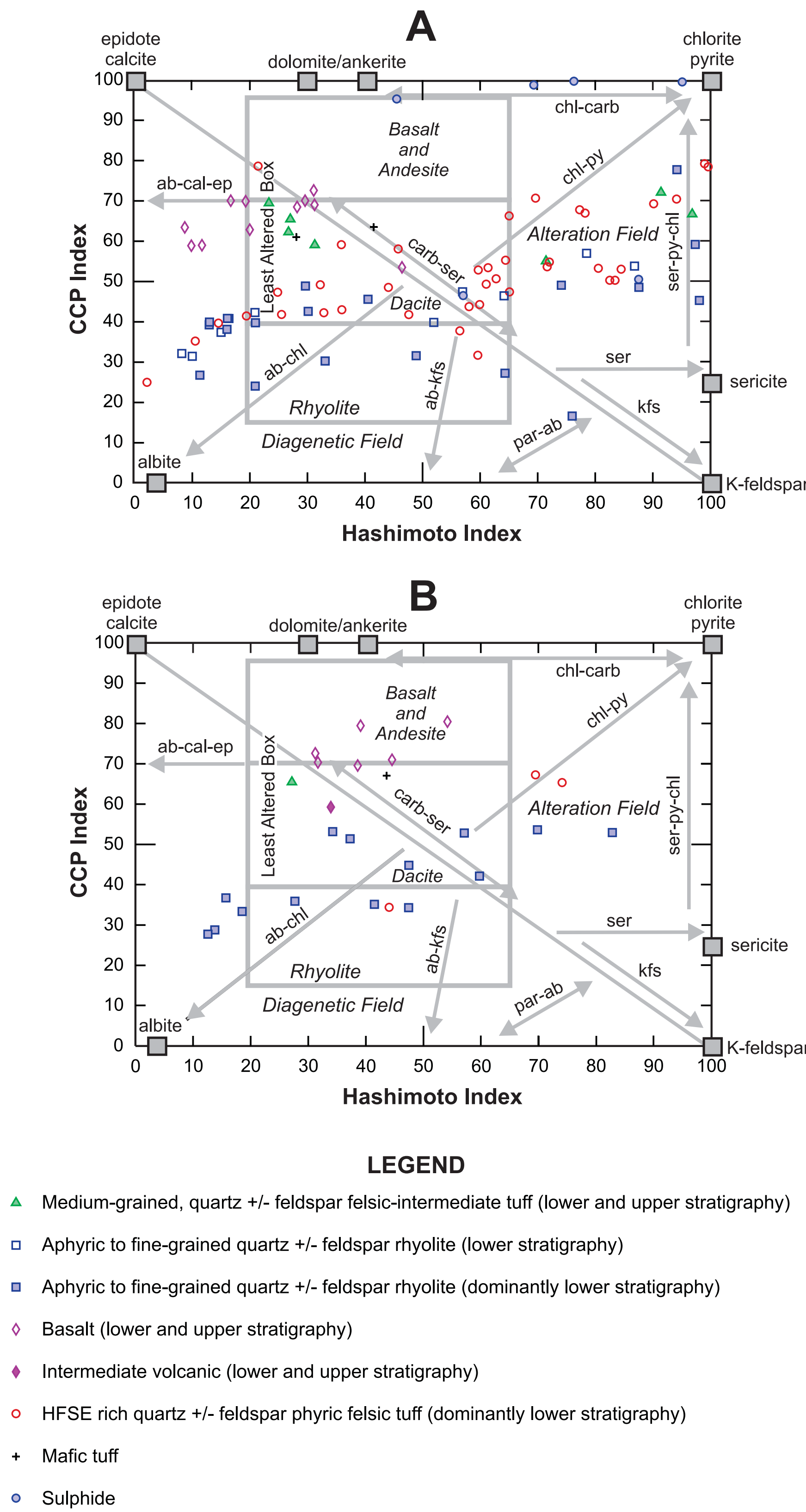
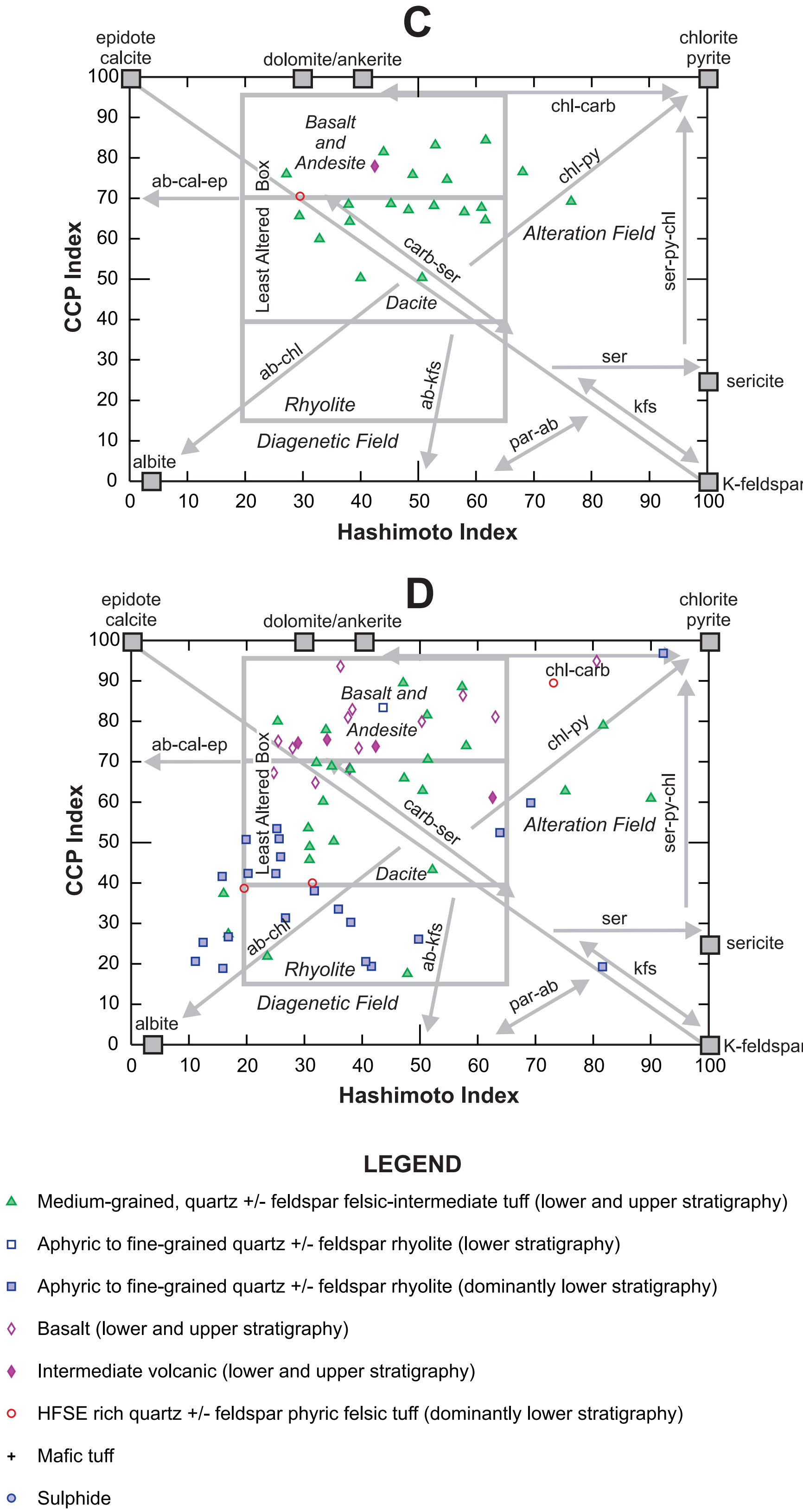


Figure 5. *Alteration box plots of Large* et al. *(2001), with vectors for various alteration minerals and alteration versus diagenetic fields. CCP index = chlorite–carbonate–pyrite index. A) Long Lake main deposit; B) Other areas in lower stratigraphy including the Isthmus, Henry Waters and Swamp grids; C) Other areas in upper stratigraphy including the Long Lake*



Cornerstone and Paragon grids; D) Outcrop samples collected in Long Lake group during this study. AI = Hashimoto index = 100[(MgO+K_2O)/(MgO+K_2O+Na_2O+CaO)] (Ishikawa* et al.*, 1976), CCPI = chlorite–carbonate–pyrite index = 100*[(MgO+FeO*0/(MgO+FeO*+K_2O+Na_2O)] (Large* et al.*, 2001).*

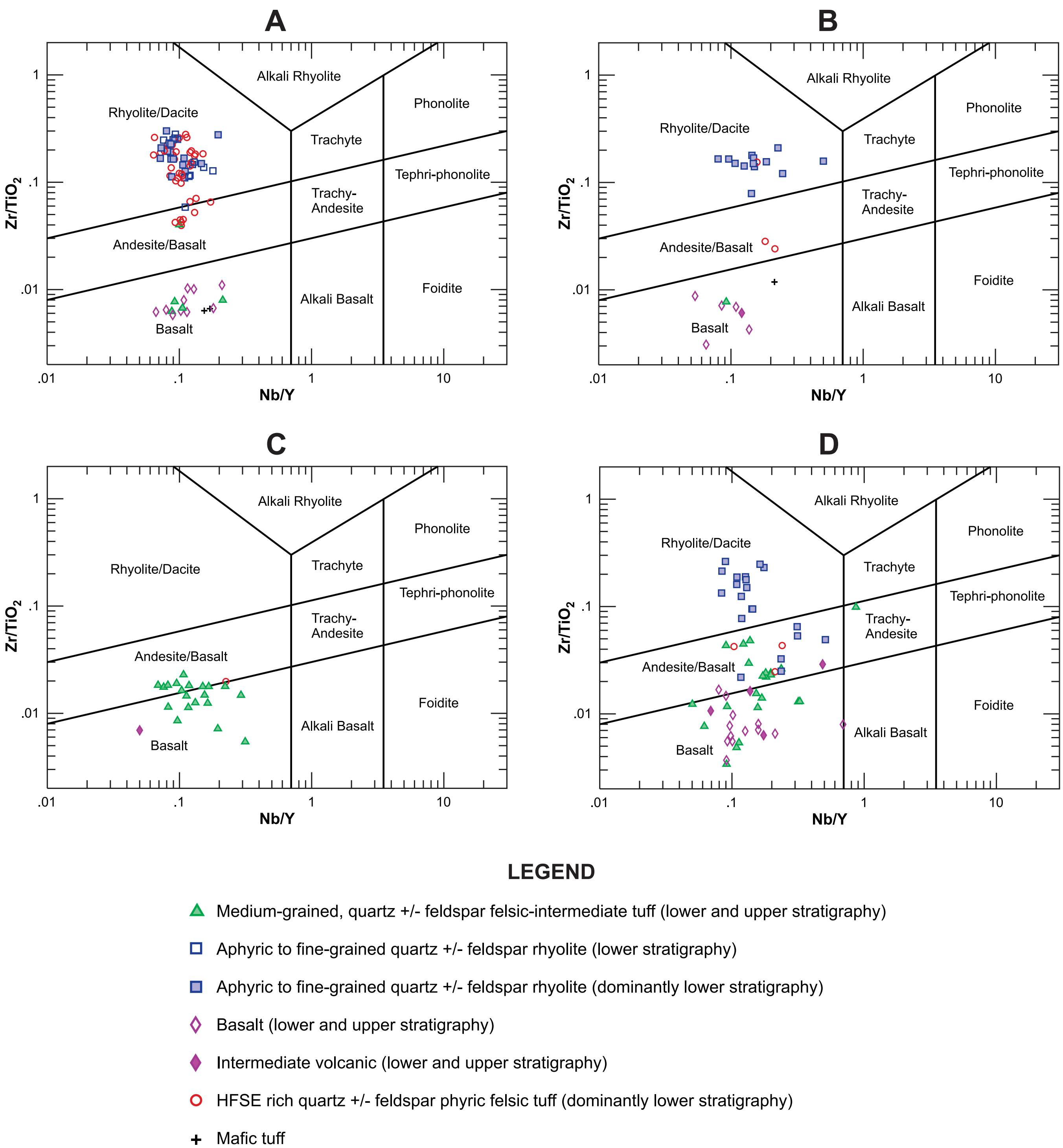


Figure 6. *Modified Zr/TiO_2 – Nb/Y plots (Pearce, 1996) of Winchester and Floyd (1977) for rocks from the four areas discussed in the text. A) Long Lake main deposit; B) Other areas in lower stratigraphy including the Isthmus, Henry Waters and Swamp grids; C) Other areas in upper stratigraphy including the Long Lake Cornerstone and Paragon grids; D) Outcrop samples collected in Long Lake group during this study.*

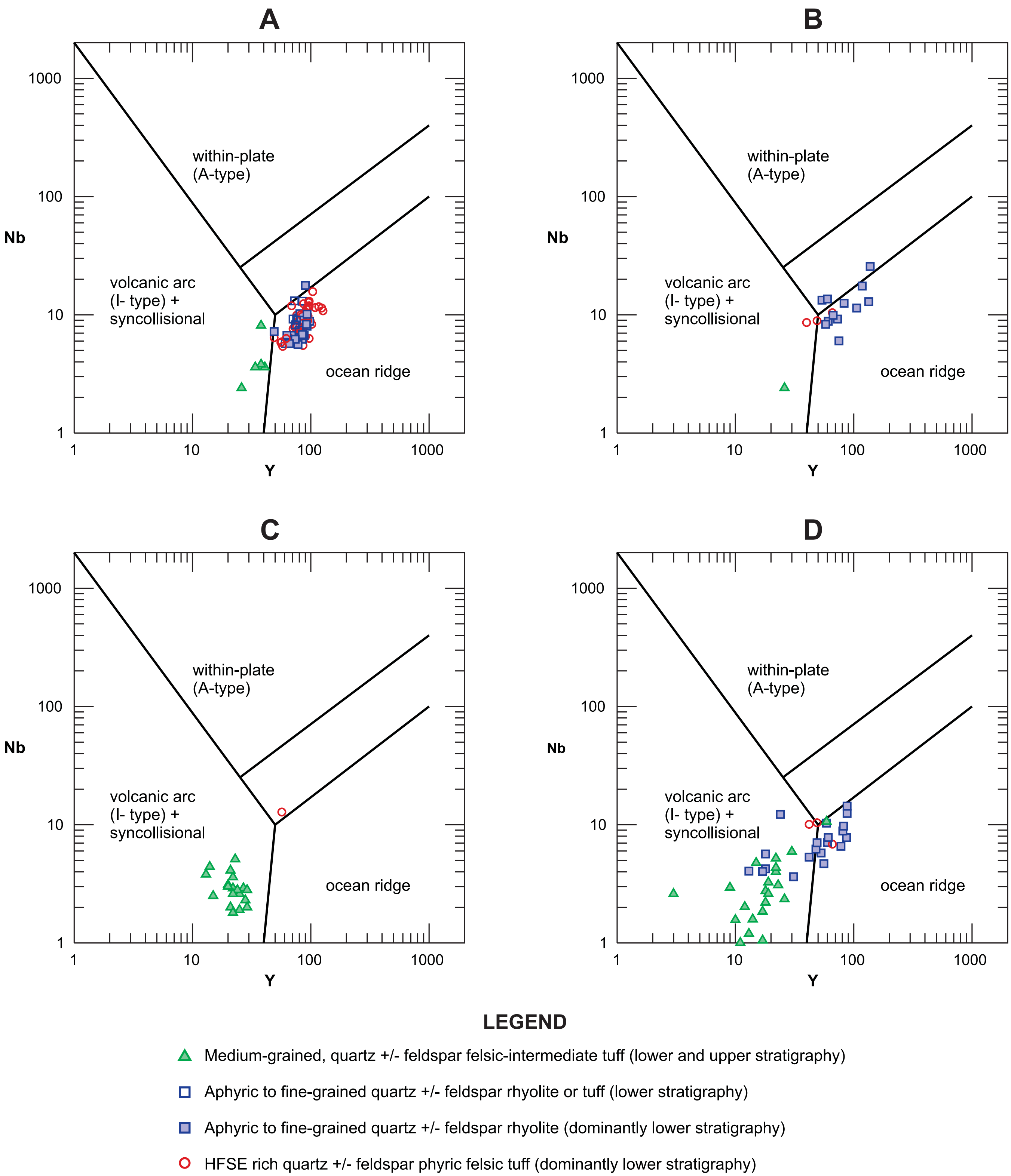


Figure 7. *Nb versus Y discrimination diagram for felsic volcanic rocks from the four areas discussed in text; after Pearce* et al. *(1984). A) Long Lake main deposit; B) Other areas in lower stratigraphy including the Isthmus, Henry Waters and Swamp grids; C) Other areas in upper stratigraphy including the Long Lake Cornerstone and Paragon grids; D) Outcrop samples collected in Long Lake group during this study.*

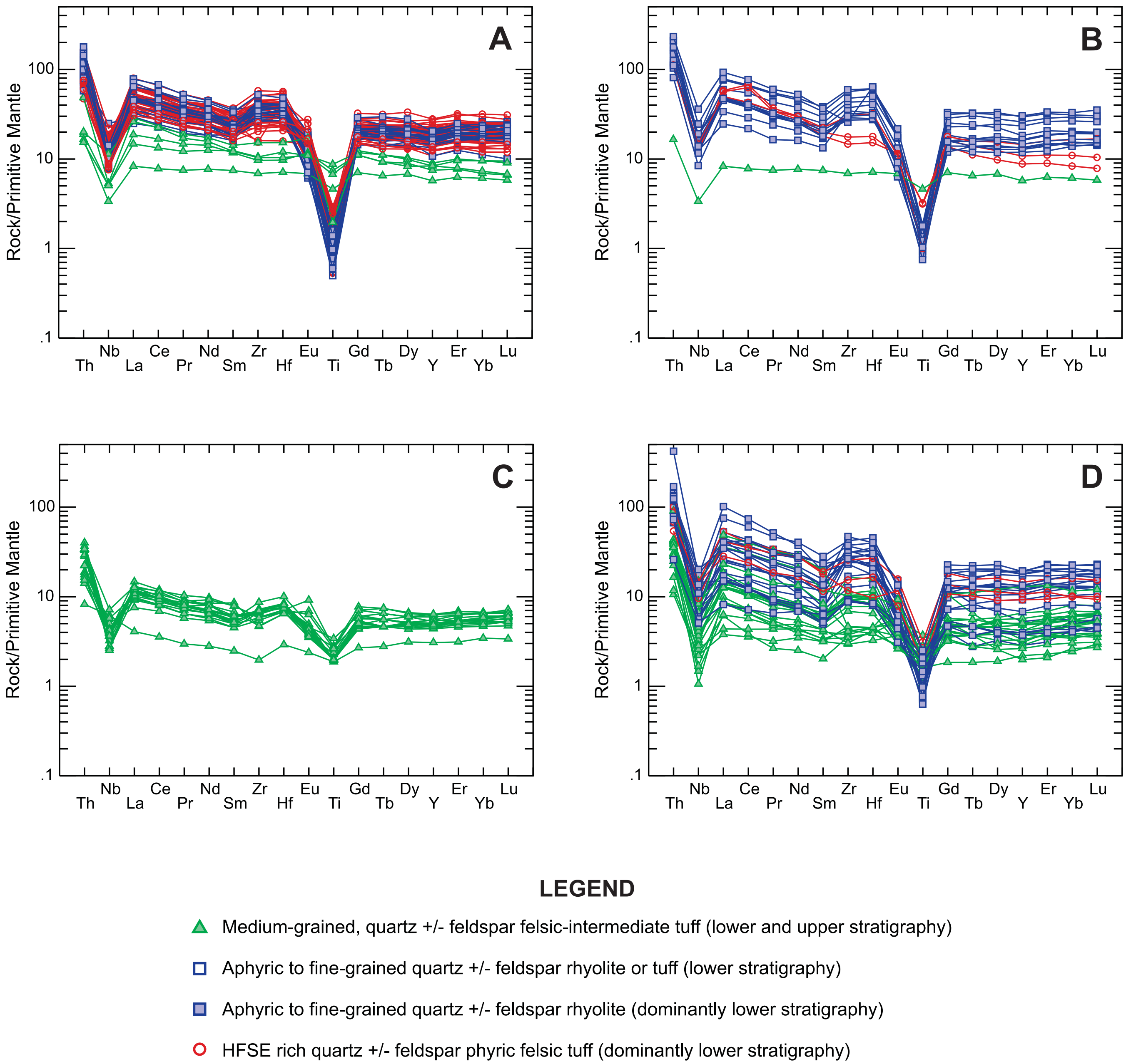


Figure 8. *Primitive mantle-normalized trace-element plots for the areas discussed in the text. A) Long Lake main deposit; B) Other areas in lower stratigraphy including the Isthmus, Henry Waters and Swamp grids; C) Other areas in upper stratigraphy including the Long Lake Cornerstone and Paragon grids; D) Outcrop samples collected in Long Lake group during this study. Primitive mantle values from Sun and McDonough (1989).*

On the alteration box plot of Large *et al.* (2001), some samples of the dominant felsic volcanic rocks plot toward the top right hand corner of the diagram; indicative of sericite, Fe–Mg carbonate, and pyrite alteration typically associated with VMS deposits (Figure 5B). In plots of AI versus Na_2O and AI versus Ba there are negative and positive correlations, respectively (Figures 10B and 11B). Overall, the results from these areas are similar to those of the Long Lake main deposit area (*see* above).

LONG LAKE PARAGON AND CORNERSTONE GRID AREAS (UPPER STRATIGRAPHY)

Host rocks in the vicinity to the Long Lake Paragon and Cornerstone grid areas are dominantly medium-grained, quartz ± feldspar-phyric felsic to intermediate tuff in composition, and plot close to the andesite–basalt boundary on the modified Zr/TiO_2 versus Nb/Y plot (Pearce, 1996) of Winchester and Floyd (1977) (Figure 6C). The tuff has low

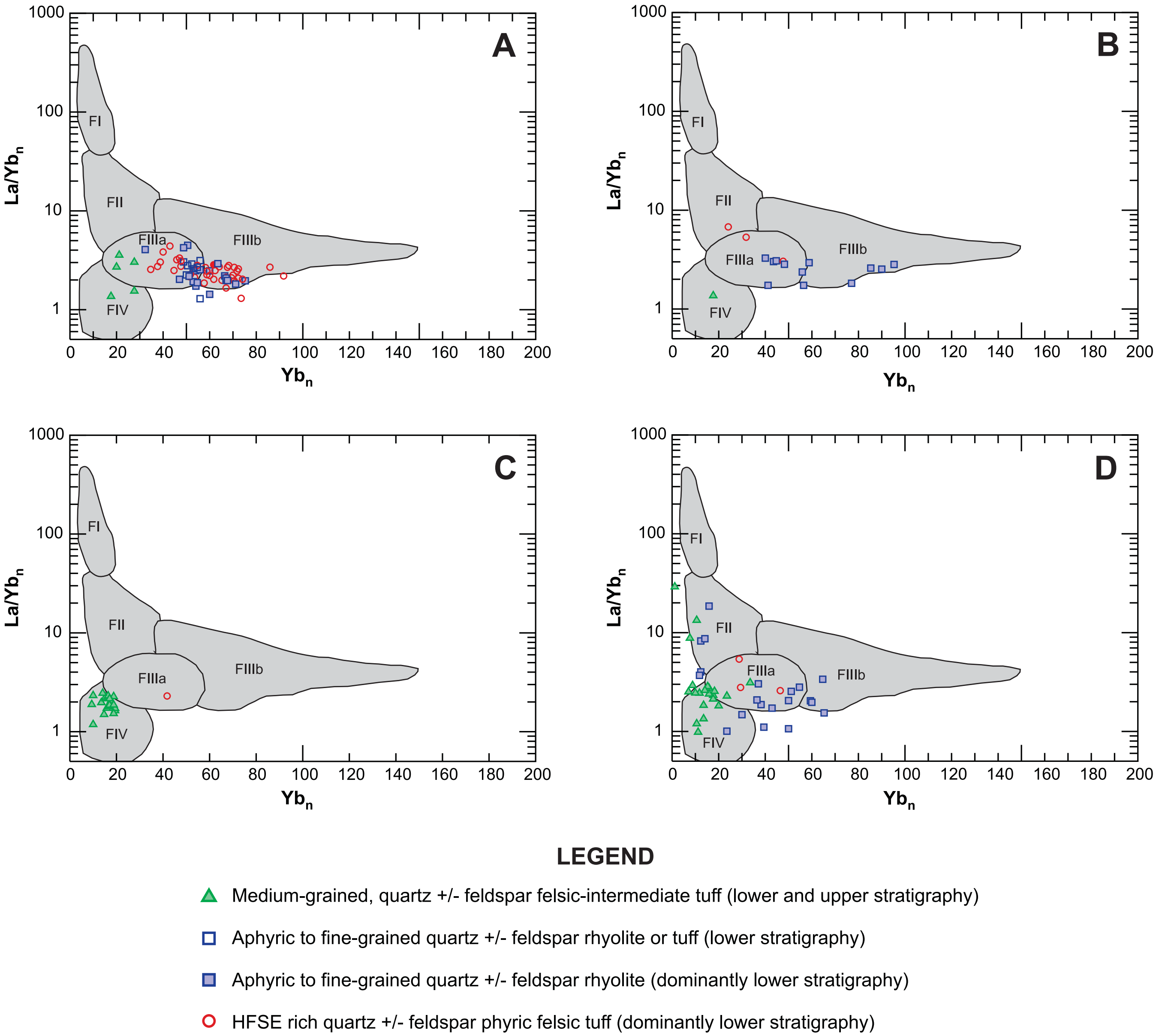


Figure 9. *Trace-element La/Yb_n – Yb_n (n = chondrite normalized) diagram for the felsic volcanic rocks from the four areas discussed in the text (diagram from Lesher* et al.*, 1986; Hart* et al.*, 2004). A) Long Lake main deposit; B) Other areas in lower stratigraphy including the Isthmus, Henry Waters and Swamp grids; C) Other areas in upper stratigraphy including the Long Lake Cornerstone and Paragon grids; D) Outcrop samples collected in Long Lake group during this study. Primitive mantle values from Sun and McDonough (1989).*

Zr/TiO_2 and low Nb/Y (Figure 6C, Table 1) suggestive of a subalkaline affinity. Concentrations of the HFSE (*e.g.*, Zr, Hf, Y, Nb) are relatively low compared to felsic volcanic rocks from the lower stratigraphy, and characterize the felsic volcanic rocks as volcanic arc (I-type) type rocks on commonly used HFSE diagrams (Figure 7C). Primitive mantle normalized plots are characterized by weak LREE enrichments, weakly developed Nb and Ti anomalies, and variably weakly developed positive Zr and Hf anomalies (Figure 8C, Table 1). The felsic rocks have relatively low Ti/Sc and high Sc/Nb ratios compared to felsic volcanic rocks from the lower stratigraphy (Table 1). On the La/Yb_N versus Yb_N plot of Lesher *et al.* (1986) and Hart *et al.* (2004), the rocks plot in the field for FIV felsic rocks (Figure 9C). A Sm–Nd isotopic composition analysis of one sample of the quartz-phyric felsic tuff from outcrop in proximity to the Long Lake Paragon Grid yielded an epsilon εNd (506 Ma) value of +3.58 (Table 2).

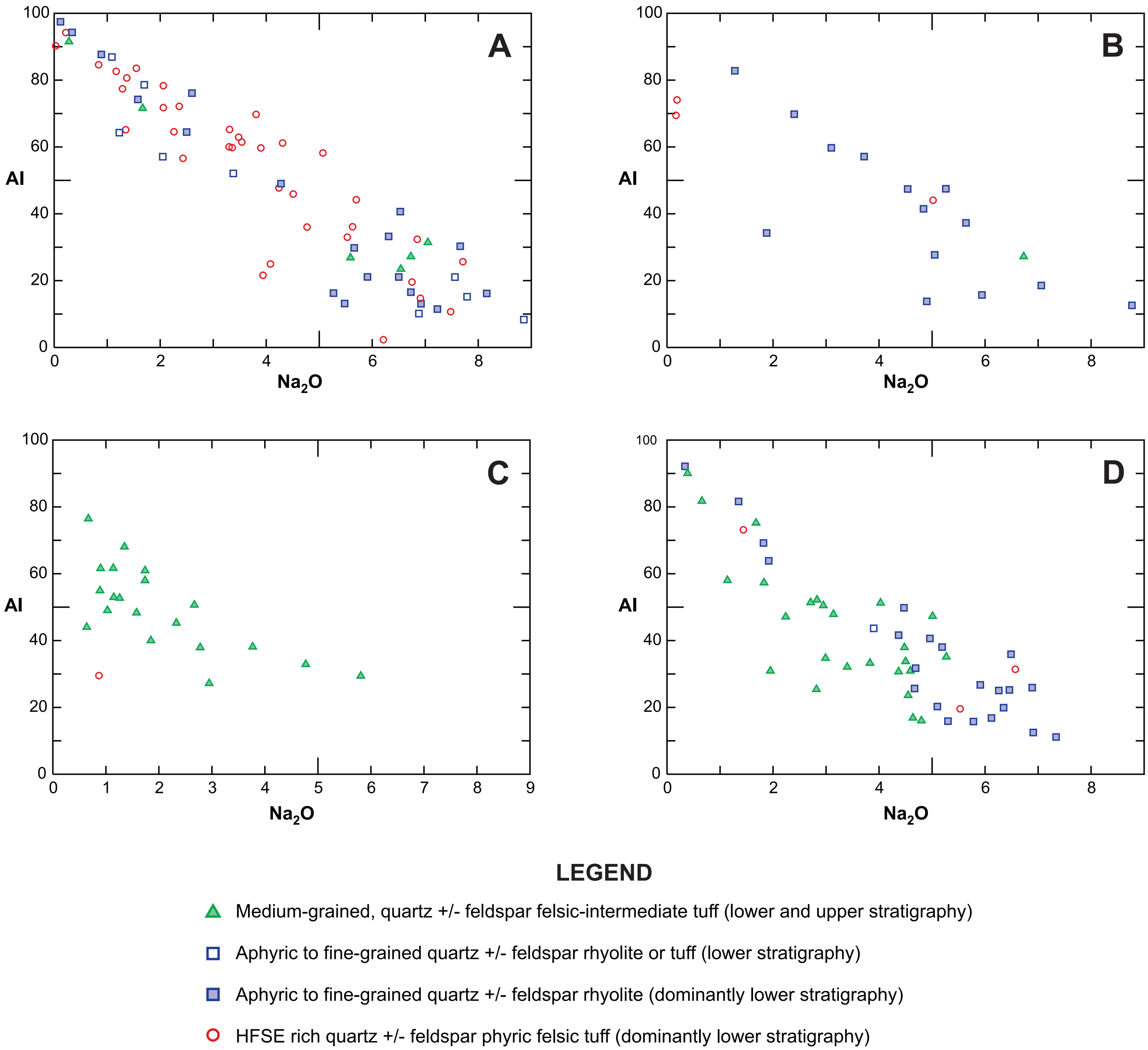


Figure 10. *Plot of AI (Hashimoto index) versus Na_2O for the four groups of felsic volcanic rocks discussed in the text. Note the negative correlation for all groups indicative of decreased Na_2O with increased AI. A) Long Lake main deposit; B) Other areas in lower stratigraphy including the Isthmus, Henry Waters and Swamp grids; C) Other areas in upper stratigraphy including the Long Lake Cornerstone and Paragon grids; D) Outcrop samples collected in Long Lake group during this study.*

On the alteration box plot of Large *et al.* (2001), most samples of the dominant felsic to intermediate volcanic rocks plot in the fields for least altered dacite and andesite, with a few samples plotting in the altered field (Figure 5C). In plots of AI versus Na_2O there is a well-developed negative correlation (Figure 10C), whereas in a plot of AI versus Ba there are no observed correlations (Figure 11C).

OUTCROP SAMPLES – LONG LAKE GROUP

As would be expected, the outcrop samples collected from the Long Lake group mirror the results described above from the individual areas of the VMS occurrences (Figures 5–11). The sample population is broadly bimodal with the quartz-phyric felsic to intermediate tuffs (*ca.* 506

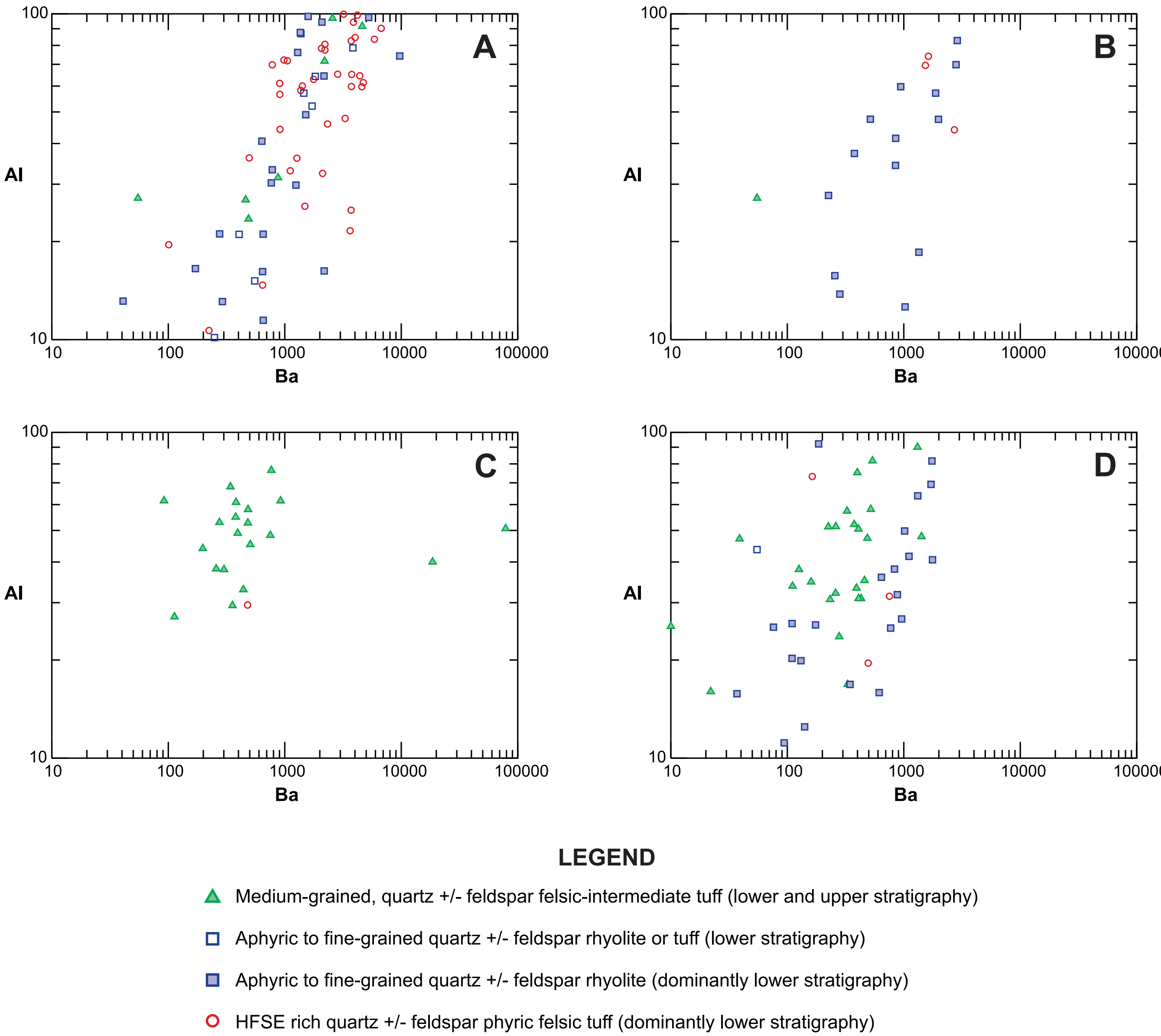


Figure 11. *Plot of AI (Hashimoto index) versus Ba for the four groups of felsic volcanic rocks discussed in the text. Note the positive correlation for felsic volcanic rocks of the lower stratigraphy (Figure 11A, B, and lower stratigraphy samples in D (e.g., blue and red symbols)), versus the lack of any correlation for the felsic volcanic rocks from the upper stratigraphy (Figure 11C and samples from upper stratigraphy in D (e.g., green triangle)). A) Long Lake main deposit; B) Other areas in lower stratigraphy including the Isthmus, Henry Waters and Swamp grids; C) Other areas in upper stratigraphy including the Long Lake Cornerstone and Paragon grids; D) Outcrop samples collected in Long Lake group during this study.*

Ma) having a somewhat broad compositional range overlapping the fields for andesite to basalt (Figure 5D). As with the descriptions above, the aphyric to fine-grained rhyolite to tuff (lower stratigraphy) and the medium-grained, quartz ± feldspar phyric felsic to intermediate tuff (upper stratigraphy) can be discriminated by higher concentrations of the HFSE and REE, deeper negative Nb and Ti anomalies, and positive Zr and Hf anomalies in the lower stratigraphy (Figures 7D and 8D; Table 1). It is noteworthy that three samples of feldspar-quartz-phyric rhyolite from the area of Costigan Lake (Figure 3A) have geochemical characteristics similar to the upper stratigraphy as defined herein (note the three blue squares with the lowest Zr/TiO_2 in Figure 6D and the three blue squares with the lowest Nb concentrations and plotting in the volcanic arc field on Figure 7D). The aphyric to fine-grained felsic volcanic rocks of the lower stratigraphy also have higher Ti/Sc and lower Sc/Nb ratios when compared to the blue quartz-phyric tuffs of the upper stratigraphy (Table 1). On the La/Yb_N versus Yb_N plot of Lesher *et al.* (1986) and Hart *et al.* (2004), the rocks of the upper and lower stratigraphy plot in the FIV and FIII fields, respectively (Figure 9D). A Sm–Nd isotopic composition analysis of an outcrop sample of quartz-phyric tuff in the vicinity of the Long Lake peninsula (*e.g.*, upper stratigraphy) yielded an epsilon εNd (506 Ma) value of +2.84 (Table 2). Two additional Sm–Nd isotopic composition analyses from the field area (Figure 2) were reported in Zagorevski *et al.* (2010); with epsilon εNd values of 3.11 from the *ca.* 506 Ma U–Pb sample location in the upper stratigraphy, and an anomalous epsilon εNd value of –4.09 from the lower stratigraphic rocks in the vicinity of Costigan Lake, located to the immediate northeast of Long Lake. Interestingly, the latter sample was found to have similar geochemical characteristics to the upper stratigraphy felsic volcanic rocks described herein, and there is no clear explanation for its anomalous Nd isotopic signature. A sample of a quartz-feldspar-phyric rhyolite from the immediate vicinity of the anomalous sample (*e.g.*, within 20 m) was analyzed to test this earlier result. The sample returned an epsilon εNd value of + 2.50 (Table 2). This result is in agreement with the other Nd isotopic results from the Long Lake group (signature is closest to that associated with the upper stratigraphy (Table 2)), and is in disagreement with the anomalously strongly negative value reported by Zagorevski *et al*. (2010). All mafic volcanic rocks plot as arc-basalts on commonly used discrimination diagrams.

On the alteration box plot of Large *et al.* (2001), some of the outcrop samples from both the lower and upper stratigraphy felsic volcanic rocks plot toward the top right hand corner of the diagram; indicative of sericite, Fe–Mg carbonate, and pyrite alteration typically associated with VMS deposits (Figure 5D). In a plot of AI versus Na_2O there is a well-defined negative correlation for all rocks (Figure 10D), whereas in a plot of AI versus Ba there is a broadly positive correlation for the lower stratigraphy rocks with no obvious pattern defined for the rocks from the upper stratigraphy (Figure 11D).

DISCUSSION

The lithogeochemical and preliminary geochronological data presented in this paper make several important conclusions. This study confirms earlier conclusions that the Long Lake group is essentially bimodal in composition, and dominated by a series of felsic to intermediate tuffs through to rhyolite, and mafic basalts and tuffs. However, contrary to previous suggestions of a single series of felsic volcanic rocks in the group (*e.g.*, Zagorevski *et al.*, 2010), this study suggests that there are two, and possibly three, packages of felsic volcanic rocks in the group. These findings build upon, and substantiate, inferences made during previous mapping (*e.g.*, Kean, 1977) and exploration (*e.g.*, Noranda, 1998). These workers also suggested that there are distinct lower and upper stratigraphic packages of felsic volcanic rocks in the group.

The felsic volcanic rocks hosting the Long Lake main deposit, as well as the other felsic volcanic rocks assigned to the lower stratigraphy, contain higher concentrations of HFSE and REE, and have different immobile element ratios than the felsic volcanic rocks in the upper stratigraphic sequence (Figures 2A, B, 7 and 8). The two packages of rocks may have entirely different sources; or could have had a similar parental source but different melting conditions (e.g., higher temperature melting processes for the lower stratigraphy (*see* Piercey *et al.,* 2003)), or different crustal contamination histories. Although neodymium isotopic results are not conclusive, there may be a slight variation between the two packages of felsic rocks. The lower stratigraphic package has a slightly higher (*e.g.*, more juvenile) epsilon εNd signature (6.17, 4.24) than the upper stratigraphic package (epsilon εNd of 2.50, 2.84, 3.11, 3.58). Note that the strongly negative value reported by Zagorevski *et al.* (2010) is excluded from this discussion, with the new +2.5 epsilon εNd value from the Costigan Lake area interpreted as the isotopic signature of that part of the group. This epsilon εNd value, along with the observed lithogeochemical patterns and structural relationships, suggests that the volcanic rocks in the vicinity of Costigan Lake may be a part of the *ca*. 506 Ma upper stratigraphy, as conceptually illustrated in Figure 3D.

The lower HFSE and REE concentrations, lower Ti/Sc and higher Sc/Nb ratios of the upper stratigraphy felsic rocks compared to the lower stratigraphy felsic rocks (note that Sc is more compatible than Ti during mantle melting; *see* Pearce and Peate (1995) and Piercey *et al.*, (2001)), and because the samples from the upper stratigraphy plot in the FIV, 'juvenile' field on the La/Yb_N versus Yb_N plot of Lesher *et al.* (1986) and Hart *et al.* (2004), suggests that the upper stratigraphy Long Lake rocks were derived from partial melting of a more mafic to intermediate source compared to that of the lower stratigraphy felsic rocks. However, the apparently more evolved Nd isotope systematics of the upper stratigraphy would refute this interpretation, or alternatively require significant influence of complex crustal assimilation and contamination processes to explain the results.

The division of the felsic volcanic rocks into a lower and upper stratigraphy is also supported by the preliminary U–Pb geochronological data presented herein. The preliminary age date of 511 ± 4 Ma obtained for altered felsic volcanic rocks in the footwall of the Long Lake main deposit directly constrains the VMS mineralization. This *ca.* 511 Ma age determination also appears to be older than that obtained from the upper stratigraphy felsic rocks to the south (*ca.* 506 Ma) reported in Zagorevski *et al.* (2010). As both age determinations overlap in error, the age date from the Long Lake deposit is currently being refined *via* TIMS analysis. Regardless of the final age determination, both dates place the Long Lake group in much closer temporal proximity with the Tally Pond group to the east than the Tulks volcanic group to the west. The age of mineralization at Long Lake is identical within error to ages obtained from the Duck Pond deposit (McNicoll *et al.*, 2010).

Work at the Long Lake main VMS deposit suggests that the sulphide mineralization is dominantly structurally attenuated, with mineralization occurring along the limbs of an inferred northerly plunging synformal structure (Figures 3A, B, and 4). This structural attenuation and folding complicate the lithogeochemical alteration studies because footwall alteration packages have also been repeated and attenuated (Figure 4). Complex faulting and folding (Plate 3), compounded by lack of outcrop density (Plate 4) hinder any detailed structural interpretations of the ore body. Highly attenuated and folded magnetite seams in a rhyolite outcrop in the vicinity of the surface projection of the Long Lake main deposit (Plate 3A) may substantiate the synformal model; if so it could suggest potential for local thickening of massive sulphide near fold closures. High concentrations of non-conductive sphalerite and barite in the ore, in conjunction with ubiquitous magnetite in the lower felsic sequence, make geophysical modelling of the ore body by EM and magnetic methods challenging.

Traditional alteration vectors used for VMS exploration appear to highlight areas of interest in both the upper and lower stratigraphy felsic volcanic rocks. Use of the Hashimoto alteration index (Ishikawa *et al.*, 1976) and the chlorite–carbonate–pyrite index of Large (2001) vector to known mineralization. Decreases in Na_2O concentrations and increases in Ba concentrations are useful exploration vectoring tools in the lower stratigraphy, but vectoring based on Ba concentrations does not appear to work well for the upper stratigraphic package.

CONCLUSION

Felsic volcanic rocks from the Long Lake group are provisionally divided into two units: 1) a HFSE- and REE-enriched lower stratigraphy of *ca.* 511 Ma age that hosts the Long Lake main VMS deposit, as well as other VMS occurrences, and 2) an upper stratigraphy of *ca.* 506 Ma that has lower HFSE and REE concentrations, and which also hosts VMS occurrences and alteration. Both groups of rocks have potential to host VMS mineralization, and target deposits would appear to have similar characteristics.

Compared to the Tally Pond group to the east and the Tulks and Pats Pond groups to the west, the Long Lake belt seems under-endowed in VMS mineralization, particularly given its relatively large geographical area and favourable rock types. All three groups of rocks were most likely derived from a continuously evolving volcanic-arc system built upon Precambrian continental crust, and the apparent discrepancy in VMS enrichment throughout the three groups is difficult to explain, aside from the Long Lake group being poorly exposed and not as intensely explored.

Future work in the area should follow up on the known VMS occurrences and alteration systems, as well as the Zn-enriched metalliferous (mid-upper Cambrian) black shales and argillites in the vicinity of the Henry Waters Grid. It is possibile that the latter could represent the distal manifestation of a seafloor exhalative event that may have associated massive sulphide accumulations. Additional structural studies to understand the locations of faults, and potential repetitions of, prospective horizons will be important for future discoveries in such a poorly exposed area.

Follow-up research from this work is ongoing and includes additional lithogeochemical interpretations, isotopic and geochronological studies, with an aim to further characterize the group and its mineral occurrences.

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