Current Research (2016) Newfoundland and Labrador Department of Natural Resources
Geological Survey, Report 16-1, pages 27-38

THE LONG LAKE GROUP: AN UPDATE ON U–Pb GEOCHRONOLOGICAL STUDIES

J.G. Hinchey and V. McNicoll[1]
Mineral Deposits Section
[1] Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8

ABSTRACT

The Long Lake group forms part of the Victoria Lake supergroup of central Newfoundland and hosts one known VMS deposit. Whereas the group is characterized by continuous fractionation sequences from basalt, through andesite and rhyolite, the rocks hosting VMS associated alteration and mineralization are bimodal and are dominated by felsic volcanic rocks and lesser mafic volcanic rocks and intercalated volcano-sedimentary rocks. All of the rocks are interpreted to have formed in volcano-sedimentary basins within active volcanic arcs on the peri-Gondwanan margin of the Iapetus Ocean.

The felsic volcanic rocks of the Long Lake group were, in the 1970s and 1980s, considered to be part of the ca. *496.5 Ma Tulks Hill volcanic rocks to the west, but this stratigraphic correlation was brought into question after a geochronological investigation of the Long Lake rocks showed them to be* ca. *506 Ma.*

New age data presented herein indicate that the felsic rocks of the Long Lake group can, in fact, be subdivided into two sequences: 1) a lower stratigraphic division, hosting the VMS deposit, of ca. *514 Ma fine-grained to aphyric rhyolite and felsic tuff that displays high concentrations of high-field strength and rare-earth elements, and 2) an upper stratigraphic division of* ca. *506 Ma blue-quartz-phyric felsic to intermediate tuff having significantly lower concentrations of high-field strength and rare-earth elements.*

The age similarity between the Long Lake and ca. *514–509 Ma Tally Pond VMS systems points to a temporal, and perhaps genetic link between the two volcanic edifices, and negates a correlation with the younger Tulks Hill mineralizing system.*

INTRODUCTION AND REGIONAL SETTING

The Cambrian Long Lake group is situated within the Victoria Lake supergroup (VLSG) of central Newfoundland (Figure 1). It is composed of felsic, to intermediate, 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 (*e.g.*, Zagorevski *et al.*, 2007, 2010). 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.

The Victoria Lake Group (*of* Kean and Jayasinghe, 1980) had, until the early 1980s, been traditionally divided into two main volcanic sequences, termed the Tulks Hill volcanic rocks and the Tally Pond volcanic rocks, plus extensive unnamed volcaniclastic and sedimentary units. The Victoria Lake Group was interpreted to be bound by the Red Indian Line (*e.g.*, the fundamental suture zone of the Newfoundland Appalachians (Williams *et al.*, 1995)) to the west, and was interpreted to be stratigraphically overlain by Llandeilo–Caradocian black shales and cherts to the northeast, which are, in turn, overlain by Middle Ordovician–Early Silurian sedimentary rocks of the Badger group (*see* Kean and Jayasinghe, 1980; Williams *et al.*, 1995, pages 403-413).

Work undertaken by the Geological Survey of Newfoundland and Labrador (GSNL) in the 1970s and 1980s (Kean, 1977, 1982) led to the inclusion of the rocks around Long Lake, herein referred to as the Long Lake group, in the Victoria Lake Group. Specifically, the Long Lake rocks were considered to be a subdivision of the Tulks Hill volcanic rocks. Geochronological investigations of the Tulks Hill volcanic rocks revealed that they comprised two dis-

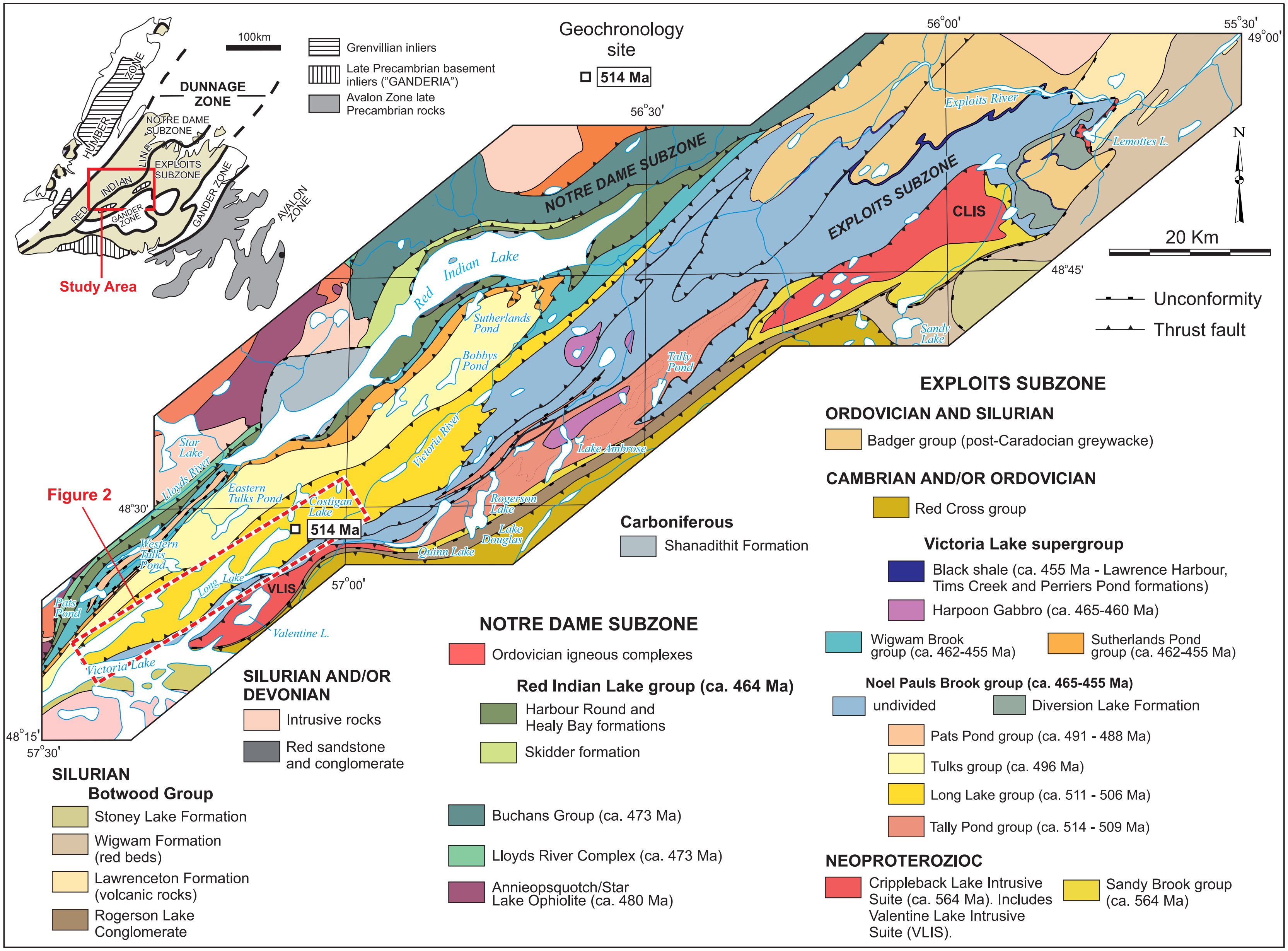

Figure 1. *Location (inset) and generalized geology of the area surrounding Red Indian Lake, including rocks of the Victoria Lake supergroup. CLIS – Crippleback Lake intrusive suite; VLIS – Valentine Lake intrusive suite. Geochronological results from this study are indicated, but other ages quoted in the text are omitted for the sake of clarity. Diagram modified from McNicoll* et al. *(2010).*

tinct, geographically separated, age divisions, *viz.* a *ca.* 462 Ma sequence in the west (Dunning *et al.*, 1987) and a *ca.* 496.5 Ma sequence in the centre (G. Dunning, personal communication 2008; a re-interpretation of isotopic age data originally provided by Evans *et al.*, 1990). Subsequent mapping and geochronological investigations (*e.g.*, Evans *et al.*, 1990; Evans and Kean, 2002, and references therein; Rogers and van Staal, 2002) indicated that the Victoria Lake Group was a composite, and included volcanic rocks that have a wide range of ages and geochemically inferred tectonic environments of formation. Hence, Evans and Kean (2002) proposed that the Victoria Lake Group be informally elevated to supergroup status (Victoria Lake supergroup, VLSG) to reflect this composite nature.

Geological mapping and related studies undertaken 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), augmented by investigations by the GSNL (*e.g.*, Hinchey 2007, 2008; Hinchey and McNicoll, 2009) suggested that the regional tectonostratigraphic sequence showed a westward-decreasing age pattern. This pattern was implied by extant geochronology, which showed the stratigraphic and temporal progression from west to east as: the Tally Pond group (*ca.* 514–509 Ma; McNicoll *et al.*, 2010), the Long Lake group represented by felsic volcanic rocks on the southeast shore of Long Lake (506 ± 3 Ma; Zagorevski *et al.*, 2010), the Tulks group (496.5 ± 1 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 (453 ± 4 Ma; van Staal *et al.*, 2005; Zagorevski *et al.,* 2007; Figure 1). Statistical errors of the ages show a temporal overlap between the Long Lake group (506 ± 3 Ma) and the volcanic rocks of the Tally Pond group (508.7 ± 3.3 – 514 ± 7 Ma) to the east. Hinchey (2014) suggested that the spatial order and westward-younging age progression of the internal components of the VLSG may not be indicative of a simple temporal sequence, but could, instead, be a fortuitous orderly tectonic juxtaposition of volcanic groups that had originally been geographically distal.

PROJECT DESCRIPTION AND RATIONALE

After conducting follow-up work to the previous mapping (*e.g.*, Kean, 1977; van Staal *et al.*, 2005) and exploration programs (*e.g.*, Noranda, 1998), Hinchey (2014) suggested, based upon field relationships and preliminary U–Pb Sensitive High Resolution Ion Microprobe (SHRIMP) geochronology, that the Long Lake group could be divided into two lithological sequences (Figure 2): 1) a 'lower stratigraphic' division of *ca.* 511 Ma, fine-grained to aphyric, rhyolite and felsic tuffs that host the Long Lake VMS deposit and have high concentrations of high-field strength and rare-earth elements, and 2) an 'upper stratigraphic' division of *ca.* 506 Ma blue-quartz-phyric felsic to intermediate tuff having significantly lower concentrations of high-field strength and rare-earth elements. The U–Pb SHRIMP age of 511 ± 4 Ma from the Long Lake main deposit (lower stratigraphic division) noted above overlaps, in error, with the younger Isotope Dilution Thermal Ionization Mass Spectrometry (ID-TIMS) age of 506 ± 3 Ma reported in Zagorevski *et al.* (2010) for the Long Lake group. Nevertheless, Hinchey (2014) presented detailed lithogeochemistry and isotopic data that, along with field observations, supported the notion that there are lithological sequences within the Long Lake group that have been juxtaposed by regionally imbricated fold and thrust belts.

Because of the stratigraphic ambiguity implied by the overlap, in error, of the two U–Pb ages noted in the foregoing paragraph, the original dated sample, JHC-12-027, which had been collected from the immediate footwall host rocks to the Long Lake deposit, was re-analyzed using ID-TIMS methods in an attempt to improve the precision of the age. The new work was undertaken to better define the stratigraphy of the Long Lake group and to constrain the timing of VMS mineralization. Herein, we report the ID-TIMS data from the host rocks of the Long Lake deposit and discuss the relevance of the age in terms of the lithostratigraphic architecture of the Long Lake group and its VMS potential. Detailed descriptions of the local geology, VMS deposits and occurrences, as well as lithogeochemical signatures associated with the two proposed volcanic stratigraphic sequences and related VMS deposits and occurrences are presented in an earlier report by Hinchey (2014) to which the reader is referred for additional information. Only summary information from the aforementioned report will be provided below.

LONG LAKE GROUP

LOCAL GEOLOGY

The Long Lake group volcanic rocks display continuous fractionation sequences from basalt, through andesite, and rhyolite. However, in the vicinity of the Long Lake deposit, the rocks are bimodal and have felsic (to felsic-intermediate) compositions predominating over mafic compositions. Just the felsic volcanic rocks will be described herein. These felsic volcanic rocks are divided, as indicated above, into two sequences consisting of, 1) light-grey to white, quartz ± feldspar phyric, felsic to intermediate, and medium- to coarse-grained pyroclastic rocks that occur in

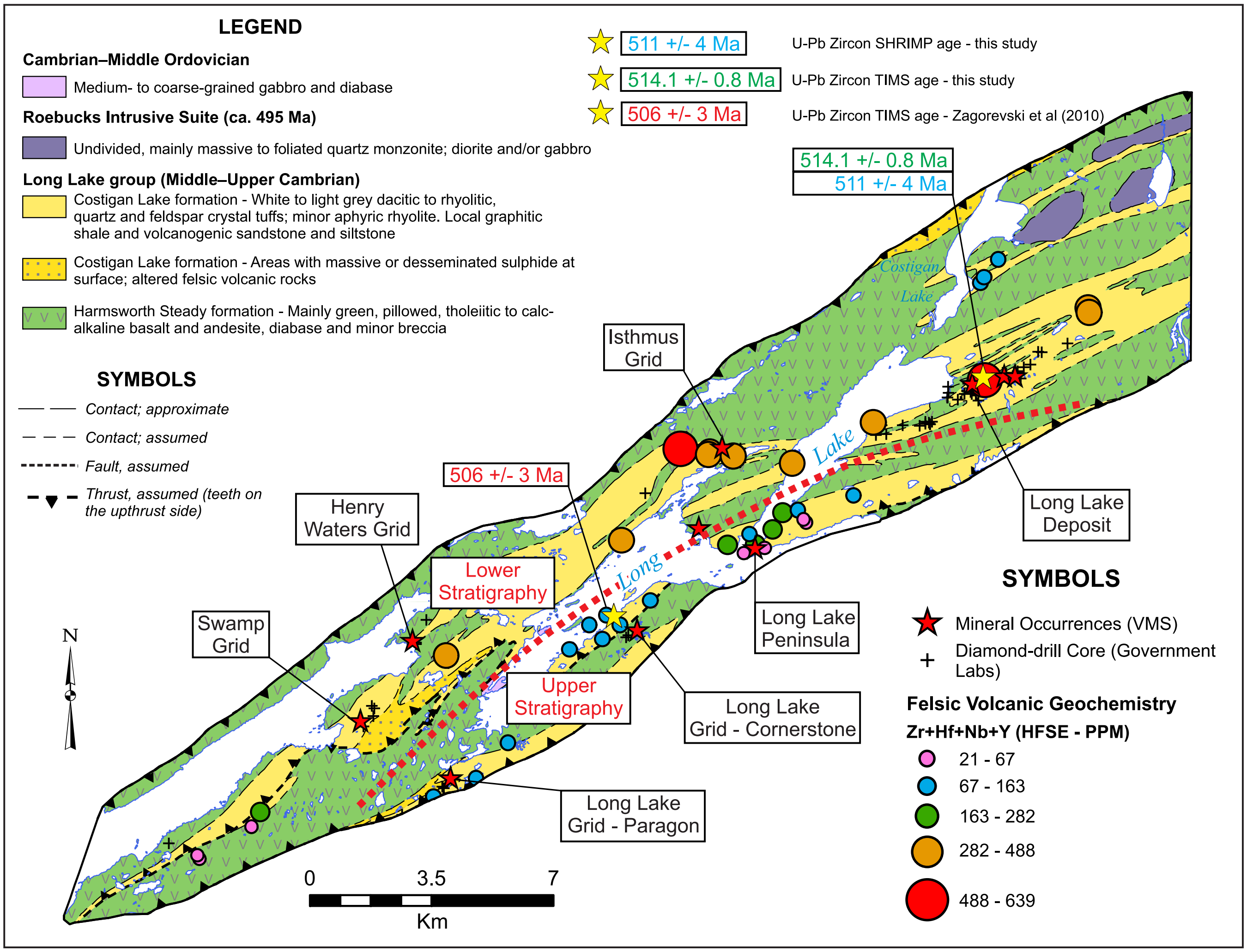

Figure 2. *General geology of the southwestern portion of the Long Lake group as portrayed by van Staal* et al. *(2005) and Lissenberg* et al. *(2005). Also shown are the locations of the Long Lake main deposit and other areas of exploration focus and the location of the dated samples from the group. 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 dashed red line trending from southwest to northeast is illustrative and represents the approximate location proposed for the division of the upper and lower stratigraphy as discussed in the text.*

the southeastern part of the group, *e.g.*, the upper stratigraphy of Figure 2 (Plate 1C, D), and 2) white to grey to pink, aphyric to quartz ± feldspar porphyritic, magnetite-bearing, massive rhyolite, and local fine-grained, magnetite-bearing, felsic tuff occurring in the northern part of the group, *e.g.*, the lower stratigraphy of Figure 2 (Plate 1A, B). Variations in dip directions and reversals in stratigraphic younging directions are interpreted as being indicative of folding and/or thrusting in the group (*see* Hinchey, 2014) and, when combined with the regional structural and geophysical relationships, provide evidence to argue that the stratigraphy is more complex than apparent from a cursory examination of the rocks.

In common with other parts of the VLSG, the Long Lake group contains a strongly developed penetrative fabric expressed as a northeast-striking foliation. Foliation dip directions vary from steeply northwest where the stratigraphy is upward facing, to steeply to the southeast where it is overturned. This contrast in foliation attitude coincides with variable stratigraphic facing directions in similar stratigraphic successions, and can be linked to the folding observed throughout the group. Detailed structural interpretations in the group are hindered by the poor outcrop, but local relationships, such as the foliation and stratigraphic facing directions referred to above, in addition to geochemical and geochronological data (*see* below), point to polyphase deformation, conceptually illustrated by Hinchey

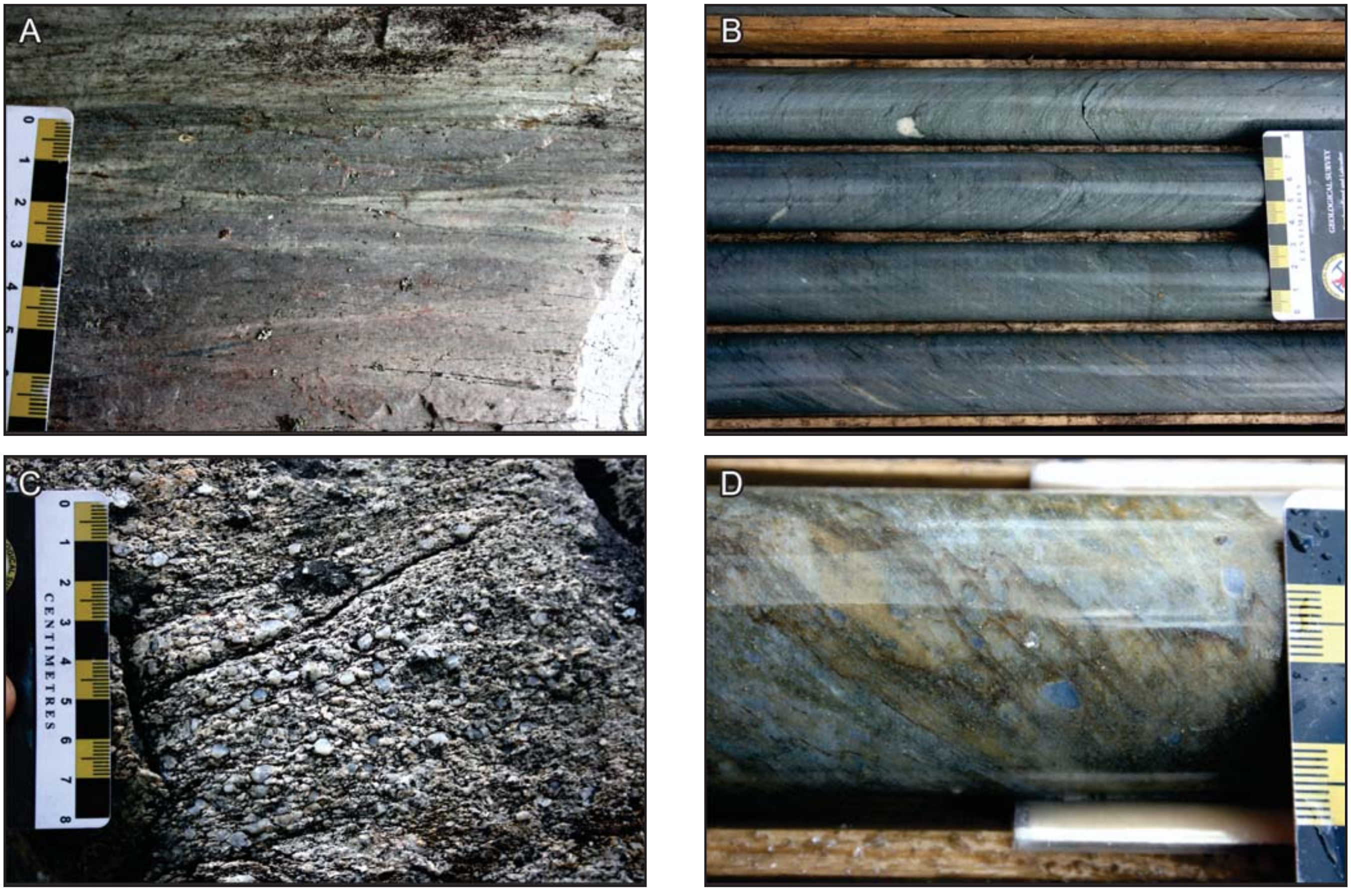

Plate 1. *A) Very fine-grained to aphyric, pink, flow-banded rhyolite; 'lower stratigraphy', B) fine-grained, massive and homogeneous feldspar phyric felsic volcanic; 'lower stratigraphy' (DDH LL-94-18; approximately 490 m depth), C) medium- to coarse-grained blue-quartz-eye phyric felsic tuff; 'upper stratigraphy', D) blue-quartz-eye phyric felsic tuff; 'upper stratigraphy' (DDH LL-06-01; approximately 170 m depth). (Same as Plate 1 of Hinchey, 2014.)*

(2014) as a series of early (D_1) thrusts reoriented by open to isoclinal F_2 folds. The rocks exhibit lower to middle greenschist-facies metamorphism.

VMS MINERALIZATION

The Long Lake group hosts one known significant VMS deposit, named the Long Lake main deposit, occurring in the lower stratigraphic division, along with several VMS occurrences located throughout the lower and upper stratigraphic divisions (Figure 2). The geochronology results reported herein are from the Long Lake main deposit.

The Long Lake main deposit is hosted by an intercalated sequence of felsic (Plate 1B) and mafic volcanic rocks, within which are minor cherty, iron-rich exhalative sedimentary rocks. The deposit consists of narrow (centimetre- to metre-scale) intervals of barite-rich high-grade massive sulphide dominated by sphalerite, chalcopyrite, galena and pyrite. The felsic volcanic rocks in the stratigraphic footwall are mainly fine-grained felsic tuff and aphyric to quartz-phyric rhyolite that are intensely altered to mineral assemblages comprising variable amounts of sericite, pyrite, chlorite, carbonate and quartz. The impact of recrystallization is evident in the rhyolitic rocks as polycrystalline quartz, and in the sulphide horizons as coarse-grained crystalline sulphide, having pyrite commonly overprinting other sulphide minerals. The stratigraphic hanging wall is composed of similar felsic volcanic rocks, but it is not intensely altered.

The deposit and its host rocks, along with early (D_1) thrusts and the concordant metamorphic foliation (S_1) are interpreted to have been isoclinally folded by subsequent deformation, and mineralization occurs on both the north and south limbs of a F_2 synform. This structural pattern is supported by the geophysical (magnetic) signatures as well as by the variations in foliation dip directions (*see* Figure 3 in Hinchey, 2014). These patterns in the vicinity of the Long Lake 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 (*see* Figure 3 in

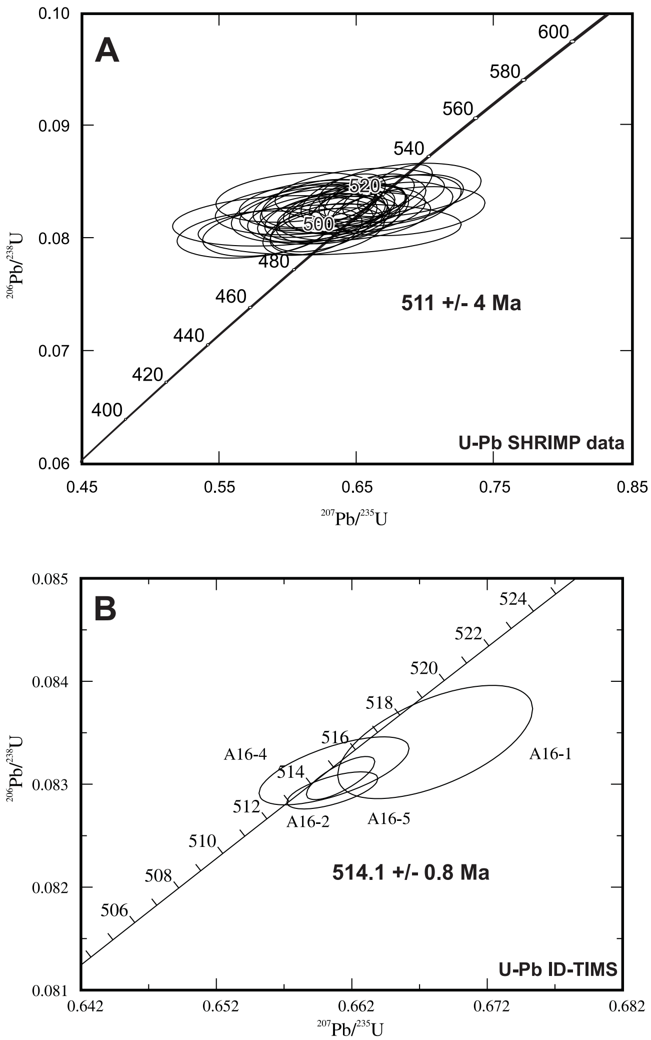

Figure 3. *A) U–Pb concordia diagram showing the isotopic results of zircons analyzed from the Long Lake felsic volcanic sample JHC-12-027 by SHRIMP II techniques. B) U–Pb concordia diagram showing the isotopic results derived from analysis of four zircons from the Long Lake felsic volcanic sample JHC-12-027 by the ID-TIMS method.*

Hinchey, 2014). The strong structural overprint on the deposit explains the attenuated and recrystallized nature of the sulphides and possibly the shape of some of the basalt lenticles. The interpretation of tight, overturned asymmetrical folding is also favored by the repetition and observed polarity of lithogeochemical alteration signatures in diamond-drill core. Additional mineralized zones have been discovered in the lower stratigraphic division 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).

LITHOGEOCHEMISTRY

Hinchey (2014) provided detailed interpretations of lithogeochemical results from all felsic volcanic rocks in the Long Lake group, and all lithogeochemical data from this project were released in an open-file report by Hinchey (2015). The geochemical results supported field observations indicating that the felsic volcanic rocks could be divided into two stratigraphic sequences, termed the 'lower stratigraphy' (that hosts the Long Lake main deposit), and 'upper stratigraphy' (Figure 2). A summary of the lithogeochemical and Sm–Nd isotopic features of the two stratigraphic sequences is given below and the reader is referred to Hinchey (2014, 2015) for data tables and geochemical plots.

The 'lower stratigraphy' felsic volcanic rocks have lithogeochemical signatures dominated by high Zr/TiO_2 and low Nb/Y, which when plotted on a discrimination diagram of Pearce (1996), are suggestive of a subalkaline affinity. Concentrations of the HFSE (*e.g.*, Zr, Hf, Y, Nb) are high and characterize the felsic volcanic rocks as ocean-ridge-type rocks on commonly used HFSE diagrams. Primitive mantle normalized plots are characterized by weak LREE enrichments, prominent negative Nb and Ti anomalies, and moderately positive Zr and Hf anomalies. On the La/Yb_N *vs* Yb_N plot of Lesher *et al.* (1986) and Hart *et al.* (2004), the rocks plot in the field for FIII felsic rocks, *i.e.*, interpreted to have formed in association with high-level magma chambers at shallow crustal levels in rift associated environments. The Sm–Nd isotopic compositions from the 'lower stratigraphy' felsic volcanic rocks range from εNd_{514} values of +4.27 to +6.19, indicative of a relatively juvenile source.

Although the felsic volcanic rocks from the 'upper stratigraphy' also display low Nb/Y values, classifying them as having subalkaline affinity on a modified Zr/TiO_2 *vs* Nb/Y discrimination diagram of Pearce (1996), the Zr/TiO_2 values are much lower and plot close to the andesite-basalt boundary. 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) rocks on commonly used HFSE diagrams. 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. On the La/Yb_N *vs* Yb_N plot of Lesher *et al.* (1986) and Hart *et al.* (2004), the rocks plot in the field for FIV felsic rocks, *i.e.*, interpreted to have formed in association with high-level magma chambers at shallow crustal levels with similar P-T conditions as described for FIII felsic rocks, but with a more depleted source. The Sm–Nd isotopic compositions from the 'upper stratigraphy' felsic volcanic rocks range from εNd_{506} values of +2.84 to +3.58, a contrast with the 'lower stratigraphy' division, and indicative of a more evolved source.

U–Pb ZIRCON GEOCHRONOLOGY

BACKGROUND

Prior to the present study, there was an U–Pb age determination for the entire Long Lake group, a felsic volcaniclastic rock dated by ID-TIMS at 506 ± 3 Ma (Zagorevski *et al.*, 2010; *see* Figure 2 for location) and considered to be 'upper stratigraphy' by Hinchey (2014). The age was interpreted by Zagorevski *et al.* (2010) to indicate the time of formation of all the felsic volcanic rocks in the Long Lake group.

The field work conducted during this study suggested that there are at least two distinctive sequences of felsic volcanic rocks within the Long Lake group, and that these might account for the previously inferred contrasts in whole-rock lithogeochemistry (*e.g.*, Noranda, 1998). Hence, a sample was collected from the immediate footwall to the Long Lake main (VMS) deposit to constrain the age of the 'lower stratigraphy', and the VMS mineralization.

Sample JHC-12-027 was collected from 575.1–598.5 m in diamond-drill hole LL-94-018 from the Long Lake VMS deposit. This rock yielded a small number of euhedral zircon grains (Plate 2A), and initial data collected by SHRIMP U–Pb methods revealed a single age population forming a cluster of concordant, overlapping data points (Figure 3A). The crystallization age of the rock was interpreted to be 511 ± 4 Ma. This age is within statistical error of the 506 ± 3 Ma age from the 'upper stratigraphy' (Zagorevski *et al.*, 2010); nevertheless, the difference was believed to be significant in the context of local relationships. A second examination of zircons from the rock that yielded the SHRIMP age of 511 ± 4 Ma was undertaken using ID-TIMS techniques as an exercise to improve the statistical precision of the foregoing age. The methods and results of the TIMS study are presented below.

U–Pb ID-TIMS GEOCHRONOLOGY

ANALYTICAL METHODS

The U–Pb ID-TIMS analysis was conducted at the Geochronology Laboratory of the Geological Survey of Canada. Heavy mineral concentrates were prepared by standard crushing, grinding, Wilfley table, and heavy liquid separation techniques. Mineral separates were sorted by magnetic susceptibility using a Frantz™ isodynamic separator and hand-picked using a binocular microscope. Analyses were carried out on single zircon grains that were chemically abraded following the techniques of Mattinson (2005), including annealing for 48 hours at 1000°C prior to leaching with HF at 180°C for 16 hours. Details of zircon morphology and quality are summarized in Table 1 and representative grains are illustrated in Plate 2B. The U–Pb ID-TIMS techniques utilized in this study are modified after Parrish *et al.* (1987), with treatment of analytical errors following Roddick (1987).

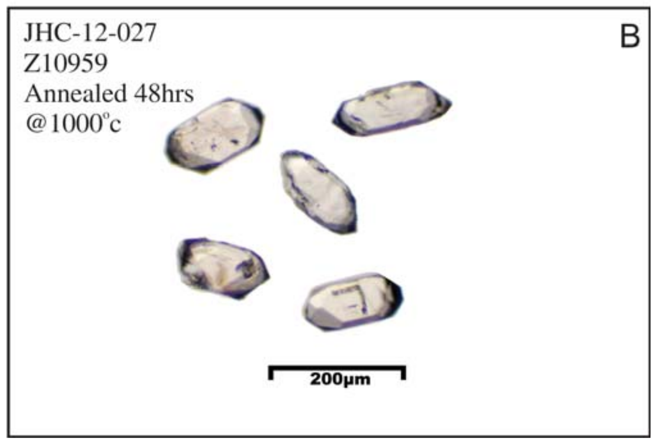

Plate 2. *A) Representative zircon grains from sample JHC-12-027, B) annealed zircon grains from which a selection were analyzed using ID-TIMS techniques.*

Table 1. U-Pb Zircon ID-TIMS analytical data

Fraction[1]	Description[2]	Wt. mg	U ppm	Pb[3] ppm	$^{206}Pb/^{204}Pb$[4]	Pb[5] pg	Isotopic Ratios[6]: $^{208}Pb/^{206}Pb$	$^{207}Pb/^{235}U$	±1SE Abs	$^{206}Pb/^{238}U$	±1SE Abs	Corr.[7] Coeff.	$^{207}Pb/^{206}Pb$	±1SE Abs	Ages (Ma)[8]: $^{206}Pb/^{238}U$	±2SE	$^{207}Pb/^{235}U$	±2SE	$^{207}Pb/^{206}Pb$	±2SE	% Disc
Long Lake deposit felsic volcanic (JHC-12-027: Z10959)																					
A16-1 (1)	Co,Clr,Eu,Pr,In,rFr,CA16	2	114	10	658	2.2	0.18	0.6681	0.0036	0.08341	0.00027	0.585	0.05810	0.00025	516.4	3.2	519.6	4.4	533.4	19.0	3.3
A16-2 (1)	Co,Clr,Eu,Pr,rIn,fFr,CA16	3	105	9	1026	1.4	0.17	0.6606	0.0017	0.08294	0.00009	0.639	0.05776	0.00012	513.6	1.1	515.0	2.1	520.8	8.9	1.4
A16-4 (1)	Co,Clr,Eu,Pr,In,fFr,CA16	3	120	11	475	4.5	0.19	0.6607	0.0028	0.08313	0.00016	0.657	0.05764	0.00019	514.8	1.9	515.0	3.4	516.3	14.2	0.3
A16-5 (1)	Co,Clr,Eu,Pr,In,rFr,CA16	2	110	10	1711	0.7	0.16	0.6612	0.0013	0.08306	0.00011	0.759	0.05773	0.00007	514.4	1.2	515.3	1.6	519.6	5.5	1.1

Notes:
1. Number in bracket refers to the number of zircon grains in the analysis
2. Fraction descriptions: Co=Colourless,Clr=Clear, Eu=Euhedral, Pr=Prismatic, rFr=Rare Fractures, fFr=Few Fractures, Fr=Fractures, rIn=Rare Inclusions, In=Inclusions, CA16=Chemically Abraded for 16 hours
3. Radiogenic Pb
4. Measured ratio, corrected for spike and fractionation
5. Total common Pb in analysis corrected for fractionation and spike
6. Corrected for blank Pb and U and common Pb, errors quoted are 1 sigma absolute; procedural blank values for this study ranged from <0.1- 0.1 pg for U and 0.5-1 pg for Pb; Pb blank isotopic composition is based on the analysis of procedural blanks; corrections for common Pb were made using Stacey and Kramers (1975) compositions
7. Correlation Coefficient
8. Corrected for blank and common Pb, errors quoted are 2 sigma in Ma

RESULTS

The zircon grains extracted from the Long Lake deposit felsic volcanic sample are predominantly euhedral, prismatic, and range in size from 75 to 200 µm, with most in the 100–150 µm range (Plate 2A, B). Many of the zircon grains are fractured and most contain inclusions and CL-SEM images reveal well-defined growth zoning (Plate 3). Some of the grains appear to have core-rim relationships in BSE and CL-SEM images (Plate 3).

The results of the U–Pb ID-TIMS analysis of the separated zircon grains are presented in Table 1, where errors on the ages are reported at the 2σ level. All four analyses points are concordant to near-concordant on the concordia plot (Figure 3B). A weighted average of the $^{206}Pb/^{238}U$ ages of the three most concordant analyses (A16-2, A16-4, A16-5) is calculated to be 514.1 ± 0.8 Ma (MSWD = 0.68). This age is 3 Ma older than that derived from the SHRIMP data, and is considered to be a reliable age for the ‘lower stratigraphy’ volcanism.

DISCUSSION AND CONCLUSIONS

The U–Pb dates and lithogeochemical data presented by Hinchey (2014) and in this paper lead to two main conclusions that have implications for modelling the tectonomagmatic conditions during VMS formation.

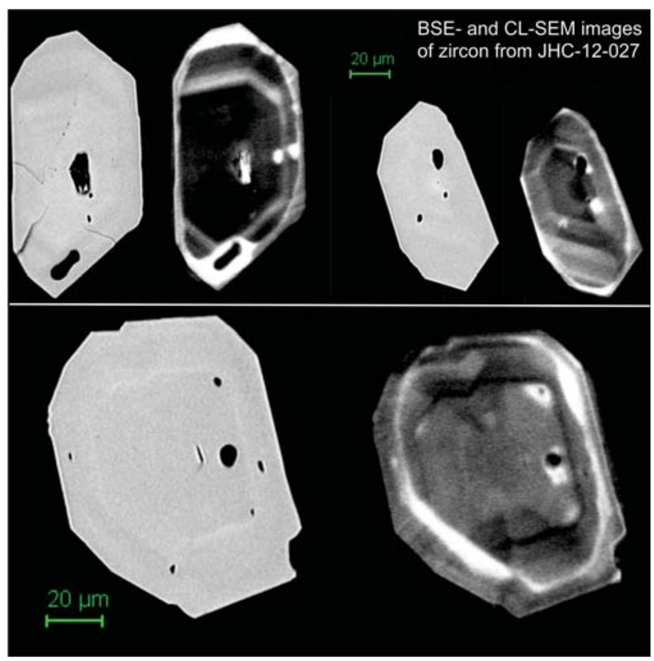

Plate 3. *Back scattered electron (BSE; left) and cathodoluminescence-scanning electron microscope (CL-SEM; right) images of representative zircons from the felsic volcanic sample JHC-12-027.*

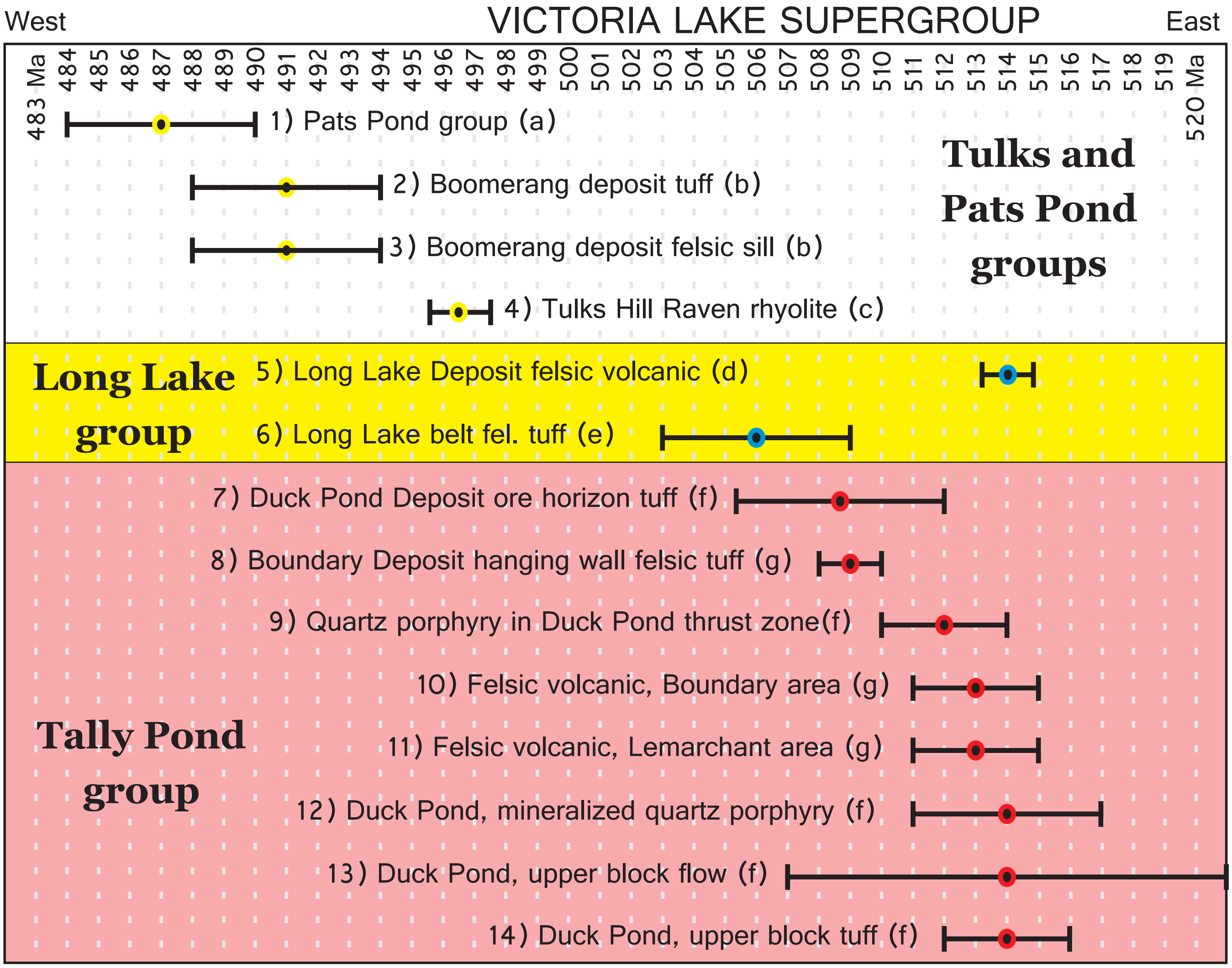

Figure 4. *Summary of ages for the VLSG subdivided by lithostratigraphic group. Data sources: (a) Zagorevski* et al.*, 2007; (b) Hinchey and McNicoll, 2009; (c) G.R. Dunning, personal communication, 2008; (d) current study; (e) Zagorevski* et al.*, 2010; (f) McNicoll* et al.*, 2010; (g) Dunning* et al.*, 1991.*

First, the new U–Pb results show that the felsic volcanic rocks included within the Long Lake group actually comprise sequences of at least two ages, namely 514 ± 0.8 Ma (*this study*) and 506 ± 3 Ma (Zagorevski *et al.*, 2010). As a first order conclusion, based on the geographical location of the dated samples and the interpreted structural history of the area, these ages dispel the long-held belief that the VLSG represents a pattern of simple age progression in which the rock units become younger to the west. Rather, the results, when taken in association with geochemical and structural interpretations (*see* Hinchey, 2014), point to a more complex tectonic regime of thrusting and folding that affected the Long Lake group rocks, and potentially the entire VLSG. The identification of the two temporally distinct, yet locally superficially similar, felsic rock lithological sequences also highlights the difficulty in recognizing intricate internal structural modifications in the poorly exposed group, and may have important implications for analogous structural complications in the VLSG.

Second, the new age from the Long Lake deposit constrains the timing of VMS formation and indicates that the formation of the Long Lake deposit is more similar in age to the VMS systems in the Tally Pond group rather than those associated with the Tulks and Pats Pond groups (Figure 4). Correlation with the Tally Pond group is supported by the fact that the host rocks to VMS deposits in the Tally Pond and Long Lake groups are composed of bimodal volcanic rocks, whereas the host to VMS deposits in the Tulks and Pats Pond groups' is dominated by felsic volcanic and volcaniclastic rocks. This similarity may also suggest an original spatial proximity of the host rocks to the Long Lake deposit with the rocks of the Tally Pond group at the time of formation, potentially having implications for the modelling of the progressive tectonic events involved in the development of the VLSG.

The two stratigraphic divisions identified herein for the Long Lake group display immobile element lithogeochemical signatures commonly interpreted to be associated with rocks formed in a continental arc environment (*e.g.*, negative Nb–Ti anomalies). However, the variable HFSE and epsilon Nd signatures, in conjunction with FIII and FIV rhyolite signatures, indicate some complexities with the relative tectonic environment of formation for the divisions. Whereas the Long Lake group (‘lower’ and ‘upper’ stratigraphic divisions combined) display continuous fractionation sequences from basalt, through andesite, and rhyolite, the rocks hosting the VMS deposit (‘lower stratigraphy’) are largely bimodal; similar to those associated with VMS deposits in the Tally Pond group to the east (*see* Piercey *et al.*, 2014). Additionally, the ‘lower stratigraphy’ felsic rocks that host the VMS deposit display relatively juvenile Sm–Nd isotopic signatures when compared to the signatures from the ‘upper stratigraphy’ felsic rocks. These geochemical characteristics suggest that while a continental arc environment may be consistent with the overall data presented, the ‘lower stratigraphy’ felsic volcanic rocks display characteristics more indicative of formation within a continental rifted arc, with the change from convergent to extensional tectonic regimes potentially corresponding with the different times of formation identified for the two stratigraphic divisions outlined herein. Similar interpretations regarding tectonomagmatic conditions within the VLSG were argued by Zagorevski *et al.* (2010), who suggested that the overall Penobscot–Victoria arc was experiencing extensional tectonics including periodic rifting during the Cambrian–Ordovician, and by Piercey *et al.* (2014) who argued a continental rifted arc tectonic environment for the development of the Boundary VMS deposit in the Tally Pond group to the east. Franklin *et al.* (2005) suggested that such rifting within continental arcs is an important condition for formation of VMS deposits in bimodal felsic environments. The rifting allows for the emplacement of co-genetic intrusions at shallow to mid-crustal levels (*i.e.*, associated with FIII to F1V rhyolites), which can potentially result in heat-induced hydrothermal convection cell systems and related reactions leading to the leaching, and potential eventual discharge and trapping of metals to form a VMS deposit. Hence, the identification of volcanic rocks that were formed through extensional tectonic processes with periodic rifting is an important aspect in the exploration for additional VMS deposits in the VLSG.

As discussed by Hinchey (2014), certain lithogeochemical characteristics of the ‘upper stratigraphy’ of the Long Lake group including lower HFSE and REE concentrations, lower Ti/Sc and higher Sc/Nb signatures compared to those from the ‘lower stratigraphy’ could alternatively be interpreted to indicate that the ‘upper stratigraphy’ felsic rocks were derived from partial melting of a more mafic and ‘juvenile’ source compared with that of the ‘lower stratigraphy’. However, this interpretation is at odds with the proposed rift-related model, and Sm–Nd isotope systematics described above. Additional information on the influences of crustal assimilation and contamination processes of the two rock divisions would be required to provide further interpretations on these apparently contradictory data.

ACKNOWLEDGMENTS

Matthew Clarke is thanked for his able assistance in the field and Gerry Hickey is thanked for assistance with logistics as well as safety. Bruce Ryan provided a very thorough and thoughtful review of an earlier version of this report and provided many constructive suggestions that greatly improved the paper.

REFERENCES

Dunning, G.R., Kean, B.F., Thurlow, J.G. and Swinden, H.S.
1987: Geochronology of the Buchans, Roberts Arm, and Victoria Lake groups and Mansfield Cove Complex, Newfoundland. Canadian Journal of Earth Sciences, Volume 24, pages 1175-1184.

Dunning, G.R., Swinden, H.S., Kean, B.F., Evans, D.T.W. and Jenner, G.A.
1991: A Cambrian island arc in Iapetus: geochronology and geochemistry of the Lake Ambrose volcanic belt, Newfoundland Appalachians. Geological Magazine, Volume 128(01): pages 1-17. doi:10.1017/S0016756800018008.

Evans, D.T.W. and Kean, B.F.
2002: The Victoria Lake Supergroup, central Newfoundland – its definition, setting and volcanogenic massive sulphide mineralization. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, Open File NFLD/2790, 68 pages.

Evans, D.T.W., Kean, B.F. and Dunning, G.R.
1990: Geological studies, Victoria Lake Group, central Newfoundland. *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 131-144.

Franklin, J.M., Gibson, H.L., Galley, A.G. and Jonasson, I.R.
2005: Volcanogenic massive sulfide deposits. Economic Geology, 100th Anniversary Volume, pages 523-560.

Hart, T.R., Gibson, H.L. and Lesher, C.M.
2004: Trace element geochemistry and petrogenesis of felsic volcanic rocks associated with volcanogenic massive Cu-Zn-Pb sulphide deposits. Economic Geology, Volume 99, pages 1003-1013.

Hinchey, J.G.
2007: Volcanogenic massive sulphides of the southern Tulks Volcanic Belt, central Newfoundland: Preliminary findings and overview of styles and environments of mineralization. *In* Current Research. Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey, Report 07-1, pages 117-143.

2008: Volcanogenic massive sulphides of the northern Tulks Volcanic Belt, central Newfoundland: Preliminary findings, overview of deposit reclassifications and mineralizing environments. *In* Current Research. Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey, Report 08-1, pages 151-172.

2014: The Long Lake group: Preliminary U-Pb geochronology and lithogeochemistry, and implications for tectonostratigraphic architecture and VMS mineralization. *In* Current Research. Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey, Report 14-1, pages 15-44.

2015: Geochemical data from the Long Lake group, central Newfoundland. Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey, Open File 012A/1580, 56 pages.

Hinchey, J.G. and McNicoll
2009: Tectonostratigraphic architecture and VMS mineralization of the southern Tulks Volcanic Belt: New insights from U-Pb geochronology and lithogeochemistry. *In* Current Research. Government of Newfoundland and Labrador, Department of Natural Resources, Geological Survey, Report 09-1, pages 13-42.

Kean, B.F.
1977: Geology of the Victoria Lake map area (12A/06), Newfoundland. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 77-4, 11 pages.

1982: Victoria Lake, Newfoundland. Map 82-009. Scale: 1:50 000. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division.

Kean, B.F. and Jayasinghe, N.R.
1980: Geology of the Lake Ambrose (12-A/10) – Noel Pauls Brook (12-A/9) map areas, central Newfoundland. Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division, Report 80-02, 33 pages, 2 maps.

Keller, G.D. and Bernier, S.
2012: Independent technical report for the Main Zone of the Long Lake volcanic massive sulphide project, Newfoundland and Labrador, Canada. Technical report conducted by SRK Consulting Inc. for Messina Minerals Inc., 130 pages.

Lesher, C.M., Goodwin, A.M., Campbell, I.H. and Gorton, M.P.
1986: Trace element geochemistry of ore-associated and barren felsic meta-volcanic rocks in the Superior Province, Canada. Canadian Journal of Earth Sciences, Volume 23, pages 222-237.

Lissenberg, C.J., Zagorevski, A., Rogers, N., van Staal, C.R. and Whalen, J.B.
2005: Geology, Star Lake, Newfoundland and Labrador. Geological Survey of Canada, Open File 1669, scale 1:50 000.

Mattinson, J.M.
2005: Zircon U–Pb chemical abrasion (“CA-TIMS”) method; combined annealing and multi-step partial dissolution analysis for improved precision and accuracy of zircon ages. Chemical Geology, Volume 220, pages 47-66.

McNicoll, V., Squires, G., Kerr, A. and Moore, P.
2010: The Duck Pond and Boundary Cu–Zn deposits, Newfoundland: new insights into the ages of host rocks and the timing of VHMS mineralization. Canadian Journal of Earth Sciences, Volume 47, pages 1481-1506.

Noranda
1998: Precious and base metal properties available for option in central Newfoundland. Summary Report, ca. 500 pages.

Parrish, R.R., Roddick, J.C., Loveridge, W.D. and Sullivan, R.W.
1987: Uranium-lead analytical techniques at the

Geochronology Labroratory, Geological Survey of Canada. *In* Radiogenic Age and Isotope Studies, Report 1. Geological Survey of Canada, Paper 87-2, pages 3-7.

Pearce, J.A.
1996: A user's guide to basalt discrimination diagrams. *In* Trace Element Geochemistry of Volcanic Rocks: Applications for Massive Sulfide Exploration. *Edited by* D.A. Wyman. Geological Association of Canada, Short Course notes, Volume 12, pages 79-113.

Piercey, S.J., Squires, G.C. and Brace, T.D.
2014: Lithostratigraphic, hydrothermal, and tectonic setting of the Boundary volcanogenic massive sulphide deposit, Newfoundland Appalachians, Canada: Formation by subseafloor replacement in a Cambrian rifted arc. Economic Geology, Volume 109, pages 661-687.

Roddick, J.C.
1987: Generalized numerical error analysis with applications to geochronology and thermodynamics. Geochimica et Cosmochimica Acta, Volume 51, pages 2129-2135.

Rogers, N., van Staal, C.R., McNicoll, V.J., Squires, G.C., Pollock, J. and Zagorevski, A.
2005: Geology, Lake Ambrose and part of Buchans, Newfoundland and Labrador. Geological Survey of Canada, Open File 4544, scale 1: 50 000.

Rogers, N. and van Staal, C.R.
2002: Toward a Victoria Lake supergroup: a provisional stratigraphic revision of the Red Indian to Victoria Lakes area, central Newfoundland. *In* Current Research. Government of Newfoundland and Labrador, Department of Mines and Energy, Geological Survey, Report 02-1, pages 185-195.

van Staal, C.R., Valverde-Varuero, P., Zagorevski, A., Rogers, N., Lissenberg, C.J. and McNicoll, V.J.
2005: Geology, Victoria Lake, Newfoundland and Labrador. Geological Survey of Canada, Open File 1667, Scale 1:50,000.

Williams, H., Lafrance, B., Dean, P.L., Williams, P.F., Pickering, K.T. and van der Pluijm, B.A.
1995: Badger Belt. *In* Chapter 4 of Geology of the Canadian Appalachian-Caledonian Orogen in Canada and Greenland. *Edited by* H. Williams. Geological Survey of Canada, Geology of Canada, No. 6, pages 403-413.

Zagorevski, A., van Staal, C.R., McNicoll, V. and Rogers, N.
2007: Upper Cambrian to Upper Ordovician peri-Gondwanan island arc activity in the Victoria Lake supergroup, central Newfoundland: Tectonic development of the northern Ganderian margin. American Journal of Science, Volume 307, pages 339-370.

Zagorevski, A., van Staal, C. R., McNicoll, V., Rogers, N. and Valverde-Vaquero, P.
2008: Tectonic architecture of an arc-arc collision zone, Newfoundland Appalachians. *In* Formation and Applications of the Sedimentary Record in Arc Collision Zones. *Edited by* A. Draut, P.D. Clift and D.W. Scholl. Geological Society of America, Special Paper 436, pages 309-334.

Zagorevski, A., van Staal, C.R., Rogers, N., McNicoll, V.J. and Pollock, J.
2010: Middle Cambrian to Ordovician arc-backarc development on the leading edge of Ganderia, Newfoundland Appalachians. *In* From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region. *Edited by* R.P. Tollo, M.J. Bartholomew, J.P. Hibbard and P.M. Karabinos. Geological Society of America Memoir 206, pages 367-396, doi: 10.1130/2010.1206(16).