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Targeted Geoscience Initiative 4: Contributions to the Understanding of Volcanogenic Massive Sulphide Deposit Genesis and Exploration Methods Development

Geological and geochemical characteristics of the Waconichi Formation east of the Lemoine auriferous volcanogenic massive sulphide deposit, Abitibi greenstone belt, Quebec

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ABSTRACT

The Lemoine Mine exploited a small but exceptionally rich auriferous volcanogenic massive sulphide body (0.76 Mt of ore grading 4.6 g/t Au). The deposit was located in the Lower Lemoine Member of the Waconichi Formation, in the Chibougamau area of the Archean Abitibi greenstone belt. The Lower Lemoine Member, which is mostly of tholeiitic magmatic affinity, is overlain by the Upper Lemoine Member comprising transitional basalt and transitional to calc-alkaline rhyolite. Field mapping, geochemical analyses, and detailed core logging of every accessible drillhole in the study area, east of the former mine, has helped to define the Lower Lemoine Member subunits and identify their mode of emplacement. The Lower Lemoine Member is composed of multiple extrusive subunits: from the bottom of the volcanic stratigraphy, the Alpha Rhyolite followed by the Lemoine Rhyolite, the Lemoine Dacite, the Lemoine Andesite, and the Hanging-wall Quartz and Feldspar Porphyry. A second, later, component of the Alpha Rhyolite intrudes the Lemoine Rhyolite locally. The Marelle Quartz and Feldspar Porphyry and the Coco Lake Rhyolite represent subvolcanic intrusions that form concordant sills at multiple stratigraphic levels in the Lower Lemoine Member. Preliminary results also indicate the potential presence and general location of previously unrecognized volcanic vents northeast of the Lemoine deposit, which may have been the site of paleohydrothermal fluid up-flow and may host additional mineralization. The precise location of the volcanic vents is the topic of ongoing work and will have implications for exploration for volcanogenic massive sulphides in the area and in similar settings elsewhere. Moreover, our work indicates that the Lemoine auriferous volcanogenic massive sulphide deposit is hosted in a felsic-dominated volcanic sequence comprising a significant portion of shallow intrusive rocks, defining a major thermal corridor over a large synvolcanic intrusion; conditions that may have contributed in forming such a base- and precious-metal-rich deposit.

INTRODUCTION

Situated in the northeastern portion of the Abitibi greenstone belt (Fig. 1), south of Chibougamau, the Lemoine auriferous volcanogenic massive sulphide (VMS) deposit was Canada's second-richest VMS deposit in terms of net smelter return, after Eskay Creek in British Columbia, and the sixth worldwide (Lafrance and Brisson, 2006). The Lemoine Mine has produced a total of 0.76 Mt of ore grading 4.6 g/t Au, 4.2% Cu, 9.5% Zn, and 83 g/t Ag (Mercier-Langevin et al., 2014) and is the only VMS deposit in the Chibougamau district that has been mined. According to the criteria established by Mercier-Langevin et al. (2011), the Lemoine deposit classifies as an auriferous VMS deposit due to its elevated Au grade but low tonnage. Its discovery in 1973 generated VMS exploration activity in the Chibougamau region, but so far the unmined Scott Lake deposit (including the Selco prospect: Saunders and Allard, 1990; Salmon and McDonough, 2011), with total inferred resources of 5.4 Mt of rock grading 1.2 wt% Cu, 4.2 wt% Zn, 0.2 g/t Au, and 34 g/t Ag, is the only additional potentially economic VMS deposit in the district. Both deposits are hosted by felsic tholeiitic members of the Waconichi Formation (Daignault and Allard, 1990; Leclerc et al., 2012), known as the Lemoine and Scott members, respectively. The paucity of other known significant VMS deposits, despite favourable geology in the Chibougamau area (Leclerc et al., 2012), and knowing that VMS deposits usually occurs in clusters (Sangster, 1980), justifies further exploration.

The Lemoine deposit is situated in the western part of the ca. 2728 Ma (Mortensen, 1993) Lower Lemoine Member (Leclerc et al., 2011) (Fig. 2a). The Lower

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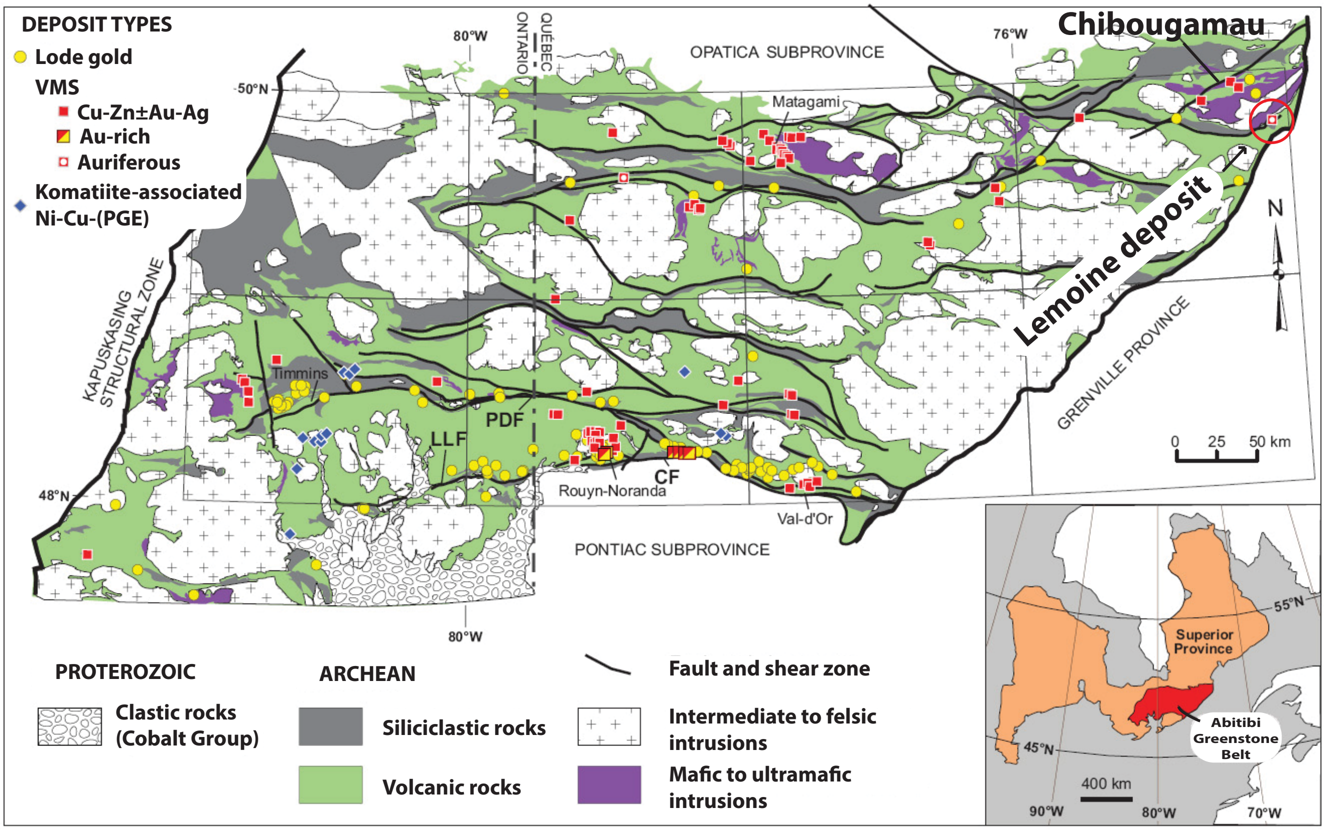


Figure 1. Map of the Abitibi greenstone belt highlighting the Chibougamau camp and the Lemoine deposit. Also shown are significant lode gold, VMS, and Ni-Cu-(PGE) deposits. Modified from Mercier-Langevin et al. (2014).

Lemoine Member is bordered to the north by the Fe-Ti-V-hosting synvolcanic (Mortensen, 1993) Doré Lake Complex and to the south by the Upper Lemoine Member, formerly known as the Gilman Formation (Daigneault and Allard, 1990; Leclerc, 2011) (Fig. 2). Extensive VMS exploration has been undertaken in prospective rocks in the vicinity of the Lemoine deposit and to a lesser extent in the eastern part of the Lower Lemoine Member. However, the geology in the east is somewhat different from that in the Lemoine deposit area, and a better understanding of the volcanic architecture in this prospective area would provide a framework for future exploration. This report presents an overview of the completed work thus far as part of an M.Sc. project at the Institut National de la Recherche Scientifique (INRS) by the first author.

Previous Work

Lafrance and Brisson (2006) summarized knowledge of the Lemoine Member and compiled a detailed geological map covering the mine area and the eastern part of the Lower Lemoine Member. They also reported several synvolcanic faults within the area (Fig. 2). Mercier-Langevin et al. (2014) characterized the various deformed and metamorphosed alteration assemblages associated with the Lemoine deposit, the spatial distributions of these assemblages, and presented a more detailed geochemical analysis of Lower Lemoine Member units in the former mine area. Ross et al. (2014) logged the physical, chemical, and mineralogical properties of drill core from five drillholes located both east and west of the former Lemoine Mine.

Objectives

The main objectives of this study of the eastern sector of the Lower Lemoine Member are (1) better geochemically and texturally define subunits within the Lower Lemoine Member; (2) determine the emplacement processes associated with each subunit; (3) provide a model for the volcanic architecture of the Lower Lemoine Member; and (4) characterize the alteration assemblages and provide an understanding of their spatial distribution in relation to the volcanic architecture, with the aim that this information can be used to vector toward VMS mineralization in the study area and in similar settings elsewhere.

Methodology

Over the course of two field seasons, 145 outcrops were visited, six were mapped in detail at decimetre-scale and 18 drillholes totalling 13,500 metres, were logged. Some 283 samples were collected for lithogeo-

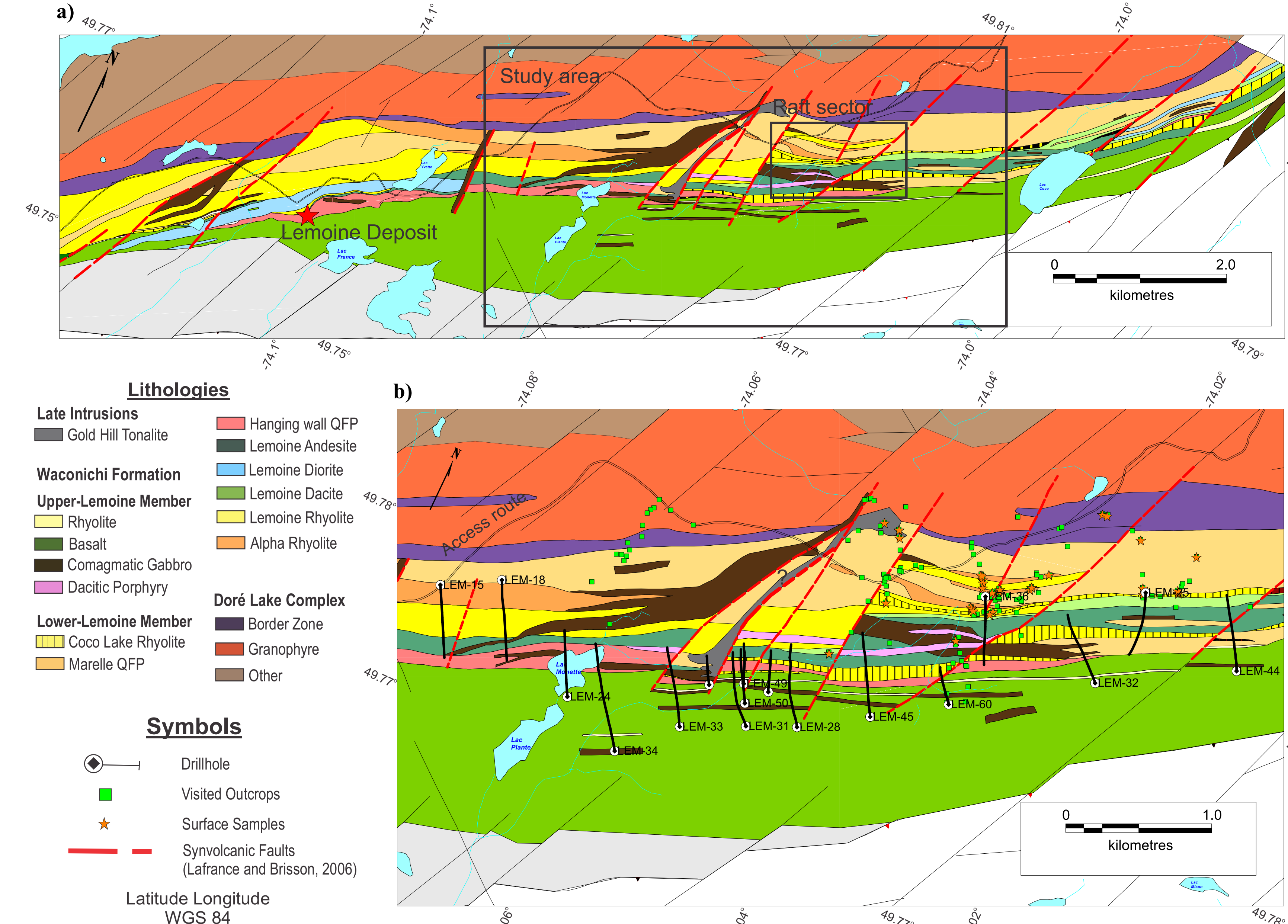


Figure 2. a) Map showing the extent of the Lemoine Member on the south limb of the Chibougamau anticline. **b)** Map of the study area on the Lemoine Property showing all studied drillholes as well as studied outcrops and field samples. Both maps show the most current modifications based on the initial map from Lafrance and Brisson (2006).

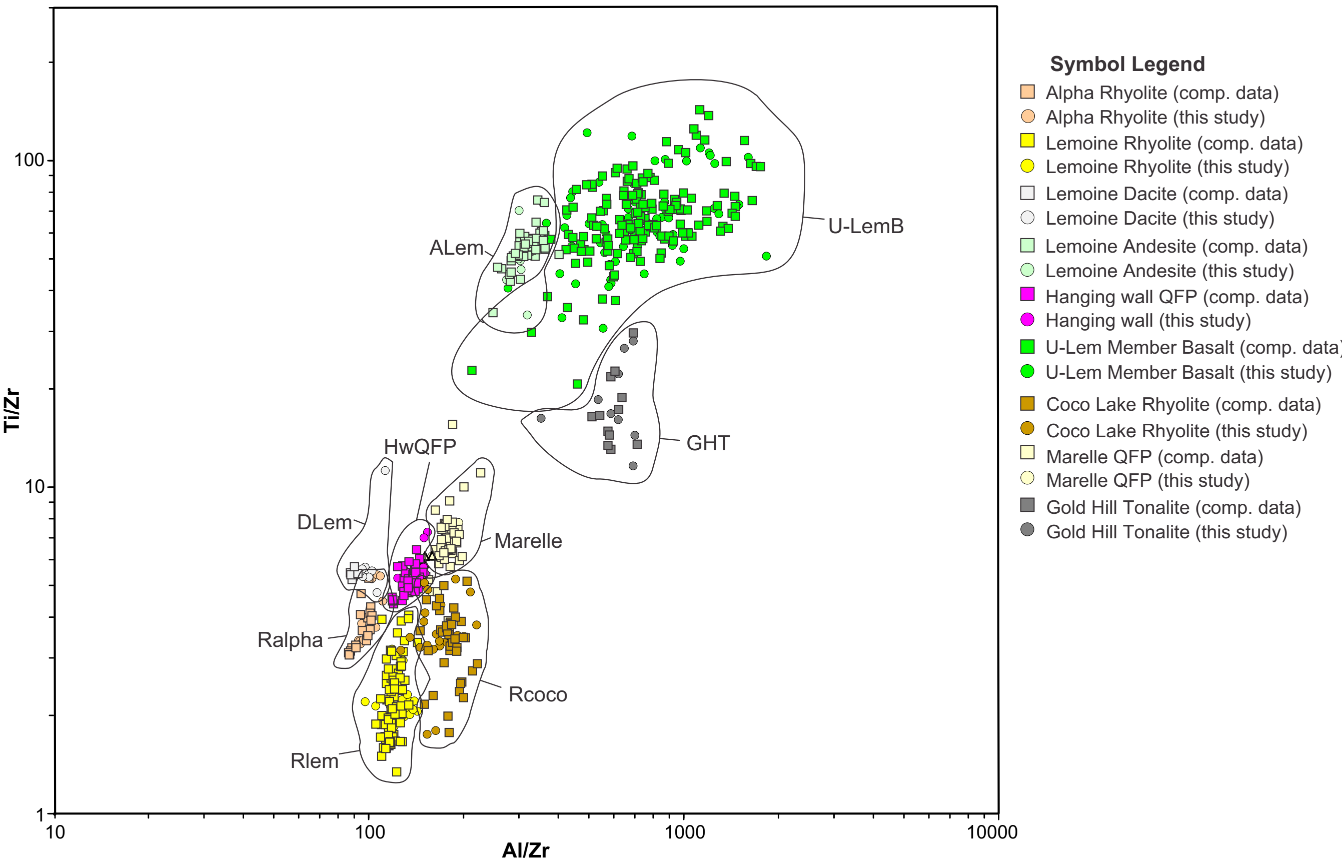


Figure 3. Plot of Ti/Zr versus Al/Zr discrimination diagram. Data represented by circles are from this study. Data represented by squares are compiled from Mercier-Langevin et al. (2014) and from Lafrance and Brisson (2006). Note: comp. = compilation.

chemistry (major and trace elements) and thin sections; 660 additional geochemical analyses were already available from company work in the study area. Bulk geochemical data were first used to discriminate the Lower Lemoine Member subunits from one another and gain a better understanding of their geochemical relationships. Immobile element ratios (e.g. MacLean and Barrett, 1993) were used to discriminate between rocks of similar mineralogical composition and textures. Volcanic textures and lithofacies (e.g. McPhie et al., 1993) helped to elucidate volcanic emplacement modes. Petrographic observations supported identification of macroscopic features and helped to characterize the different alterations assemblages present throughout the study area.

RESULTS

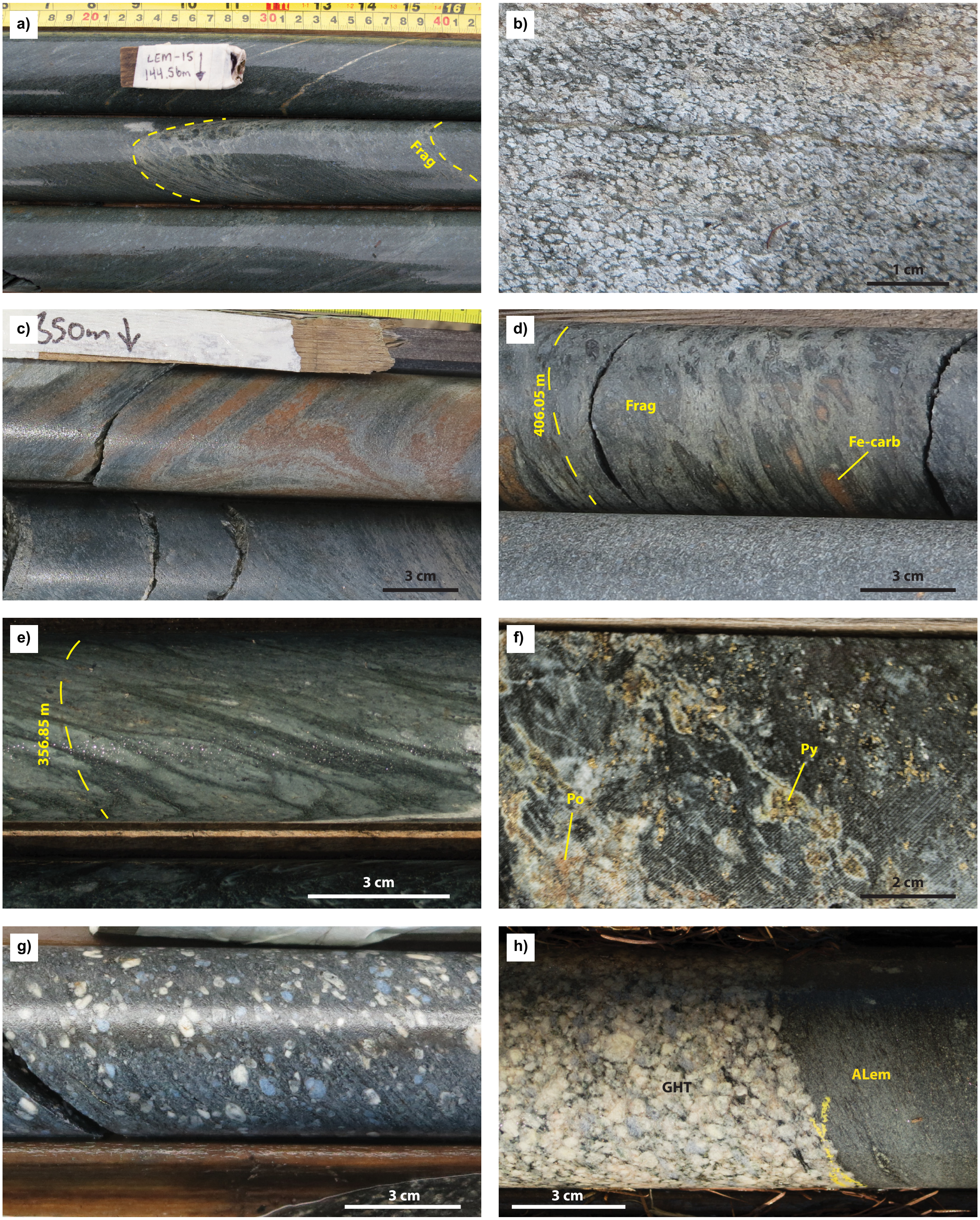
Lower Lemoine Member — Extrusive Units

In the study area, the Lower Lemoine Member contains numerous extrusive units that stratigraphically young towards the southeast. The following sections describe these subunits from the northwest to the southeast (see Fig. 2b), with an emphasis on macroscopic observations, bulk rock geochemistry, and facies identification.

Alpha Rhyolite (RAlpha)

The Alpha Rhyolite (previously the “High-Zr Marelle QFP”, Lafrance and Brisson, 2006; Mercier-Langevin et al., 2014) is present in two places in the study area.

Figure 4 opposite. Photographs of selected drill-core samples and intervals. **a)** Fragmental zone (“frag”) from 144.53 to 144.70 m in drillhole LEM-15, defined by elongated dark fragments in a lighter sericite altered groundmass within a lobe facies of the Alpha Rhyolite. Fragments are moderately chloritized with a strongly sericitized matrix. **b)** The coherent and spherulitic Alpha Rhyolite on outcrop 13-ARB-019 with the typical “leopard-rock” appearance. **c)** Flow banding in a Lemoine Rhyolite lobe defined by bands of Fe-carbonate, drillhole LEM-18, 350 m. **d)** Fragmental zone (“frag”) in the Lemoine Rhyolite, drillhole LEM-18, 406.03 to 406.18 m, defined by dark grey fragments in a lighter grey finer grained groundmass. Fragments sometimes contain an iron-carbonate core (Fe-carb). **e)** Strongly deformed lapilli in the Lemoine Dacite, drillhole LEM-25, 356.9 m. **f)** Pyrrhotite (Po) and pyrite (Py) mineralization within amygdules in the Lemoine Andesite, drillhole LEM-49, 404 m. **g)** Marelle QFP in drillhole LEM-44, 355.5 m. Note the abundant quartz (bluish) and feldspar (milky white) phenocrysts. **h)** Gold Hill Tonalite (GHT) with coarse crystalline texture in contact with the Lemoine Andesite (ALem) in drillhole LEM-28, 387.7 m.


a)
LEM-15
144.56m
Frag
b)
1 cm
c)
350m
3 cm
d)
406.05 m
Frag
Fe-carb
3 cm
e)
356.85 m
3 cm
f)
Py
Po
2 cm
g)
3 cm
h)
GHT
ALem
3 cm

In the southwest, where it is only found in drill core (LEM-15, LEM-18) and does not crop out, it is the oldest extrusive unit and borders the Doré Lake Complex, emplaced prior to formation of the Lemoine Rhyolite. The Alpha Rhyolite is also present in the Raft sector (Fig. 2), where it outcrops. There, it is underlain by the intrusive Marelle QFP (see Fig. 2) and overlain by the extrusive Lemoine Rhyolite. In the Raft sector the Alpha Rhyolite is interpreted to be intrusive.

The Alpha Rhyolite contains 3 to 7 vol.% resorbed quartz phenocrysts (1–3 mm), and locally also contains 1 to 5 vol.% feldspar phenocrysts (1–3 mm), all in a fine groundmass. It is texturally similar to other quartz and feldspar porphyritic (QFP) units in the Lower Lemoine Member (e.g. Marelle QFP and Hanging-wall QFP - see below). The Alpha Rhyolite is of tholeiitic to transitional chemical affinity and is distinguishable from all other Lemoine subunits in a plot of Ti/Zr-Al/Zr ratios (Ti/Zr averages 4.0 and Al/Zr averages 100, Fig. 3). Also the Alpha Rhyolite has less pronounced negative Nb and Ta anomalies (not shown) with an average $[La/Lu]_N$ (McDonough and Sun, 1995) of 1.4, indicating a flatter REE pattern than the Marelle QFP (average $[La/Lu]_N = 3.0$).

The southwest occurrence of the Alpha Rhyolite contains coherent (“massive”), lobate, and hyaloclastite facies; amygdules are locally preserved. The proportions of the facies are compatible with a lobe-hyaloclastite lava-flow architecture (cf. Gibson et al., 1999; Fig. 4a). Within the study area, values for Ishikawa alteration index (AI = 100(K_2O+MgO)/(K_2O+MgO+Na_2O+CaO) (Ishikawa, 1976) and chlorite-carbonate-pyrite index (CCPI = 100(MgO+FeO)/(MgO+FeO+Na_2O+K_2O) (Large et al., 2001) alteration indices (not shown) are highest in the Alpha Rhyolite, largely in samples from drillholes LEM-15 and LEM-18 (Fig. 2b).

In the Raft sector, the Alpha Rhyolite is coherent and a coarse “leopard-like” spherulitic texture is omnipresent (Fig. 4b) with up to 1 cm-wide, locally coalescing spherules. The overall map pattern, stratigraphic relationships, uniformly coherent textures, and the presence of an angular enclave of Lemoine Rhyolite within the Alpha Rhyolite suggests that the Alpha Rhyolite is intrusive in the Raft sector. It represents a second pulse of magma of Alpha Rhyolite composition, rich in quartz phenocrysts (up to 15 vol.% in drillhole LEM-36), emplaced after both the extrusive Alpha Rhyolite in the southwest and the overlying Lemoine Rhyolite.

Lemoine Rhyolite (RLem)

The Lemoine Rhyolite, which is the immediate footwall of the Lemoine deposit (Donahue, 1982; Mercier-Langevin et al., 2014), extends 10 km along strike from southwest of the former mine site to the Raft sector in the northeast. It reaches a thickness of ~200 m near the Lemoine deposit (Mercier-Langevin et al., 2014) and thins systematically to the northeast (Fig. 2a). This subunit is tholeiitic (Figs. 5, 6), with average Ti/Zr and Al/Zr ratios of 2.1 and 126, respectively (Fig. 3). The Lemoine Rhyolite varies in colour from light to dark grey-green, depending on the abundance of chlorite alteration. The subunit contains 1–5 vol.%, 1–3 mm euhedral blue quartz phenocrysts surrounded by a milky quartz corona in an aphanitic groundmass.

The Lemoine Rhyolite has substantial coherent portions with massive to flow-banded lobes (Fig. 4c), spherulitic (Fig. 4b), or amygdular zones (quartz and Fe-carbonate-filled amygdules), and lesser fragmental

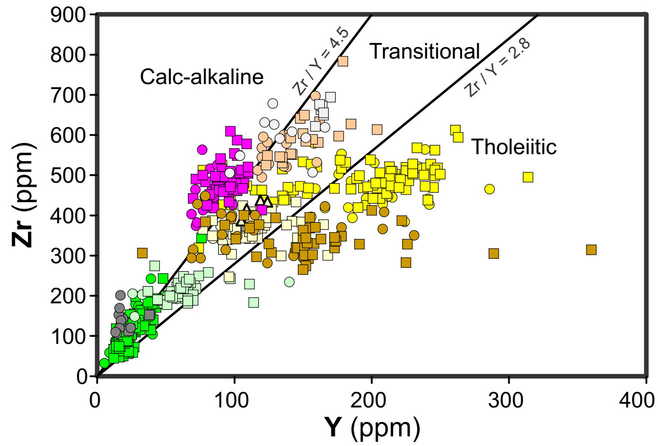


Figure 5. Zr versus Y plot of tholeiitic versus calc-alkaline magmatic affinity. Fields from Ross and Bédard (2009). Data from this study, from Mercier-Langevin et al. (2014) and from Lafrance and Brisson (2006). Symbol legend can be found on Figure 3.

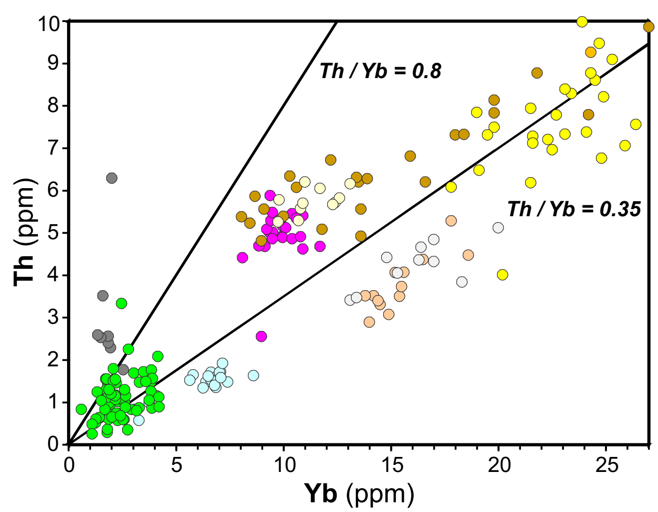


Figure 6. Th versus Yb plot of tholeiitic versus calc-alkaline magmatic affinity. Fields from Ross and Bédard (2009). Data shown are from this study, from Mercier-Langevin et al. (2014), and from Lafrance and Brisson (2006). Symbol legend can be found on Figure 3.

portions (e.g. hyaloclastite: Fig. 4d). Two major phases are present in the Lemoine Mine area (Mercier-Langevin et al., 2014) and a similar architecture is present in the study area. The first phase has a lobe-hyaloclastite flow-style basal component and an upper fragmental zone composed of lapilli-size fragments. The second phase is a mostly massive flow that is intruded by the Coco Lake Rhyolite in the Raft sector. Alteration indices are highest in drillholes LEM-15 and -18 in the southwest part of the study area, as well as in drillhole LEM-36, just south of the Raft sector (Fig. 2b).

Lemoine Dacite (DLem)

The Lemoine Dacite is a ≤60 m-thick, laterally continuous unit that is only present in the northeast part of the study area, extending between drillhole LEM-52 and the edge of the study area in the northeast (Fig. 2b). Geochemically, the Lemoine Dacite has average Al/Zr and Ti/Zr ratios of 99 and 6.0 (Fig. 3), respectively, distinguishing it from the Alpha Rhyolite. The Lemoine Dacite is transitional to calc-alkaline with an average Zr/Y ratio of 4.5 (Fig. 5). This unit does not outcrop well in the study area and is only present in drill core, where it is grey-green to dark grey-green, aphanitic, and ranges from massive to mostly fragmental and spherulitic. There is a systematic spatial variation in fragment size from 2 to 3 cm-wide fragments in drillhole LEM-25 (Fig. 4e) to millimetre-scale fragments in drillhole LEM-52, which is situated in the southwest part of the study area (Fig. 2b). Except for some chloritic alteration of the tuff matrix and late carbonate veining, the Lemoine Dacite is only weakly altered.

Lemoine Andesite (ALem)

The Lemoine Andesite forms a ≤200 m-thick lava unit that extends from east of the Lemoine Mine to the northeast termination of the Lower Lemoine Member (Fig. 2). It is differentiated from the Upper Lemoine Member basalt by being tholeiitic with an average Th/Yb ratio of 0.26 (Fig. 6). The Lemoine Andesite also has flatter REE patterns with an average $[La/Lu]_N$ of 1.6 (Upper Lemoine Member basalt averages $[La/Lu]_N = 3.6$). The Lemoine Andesite is black to dark grey-green with local amygdaloidal zones that contain 1–5 vol.%, 1–3 mm blue quartz amygdules. Light green patches of agglomerated epidotized plagioclase phenocrysts are irregularly present throughout the unit. Some 1–3 mm euhedral garnet porphyroblasts occur in narrow bands in drillhole LEM-49, between 325 and 328 m. The Lemoine Andesite is composed predominantly of massive and pillowed flows; the pillows are separated by thin (<10 cm) layers of hyaloclastite. The Lemoine Andesite contains one tuffaceous zone in the middle and a second one at the top of the subunit. The middle tuffaceous zone, composed of centimetre-scale interbedded chert and biotite-rich tuff, only occurs in the eastern part of the study area, and its thickness cannot properly be constrained as it is always in contact with an intrusion (e.g. drillhole LEM-44 at 491 m). The top tuffaceous layer is thickest in drillhole LEM-15, where it forms a 3 m-thick laminated siliceous tuff interbedded with thin centimetre-scale beds of lapilli-size hyaloclastite. The same top tuffaceous unit in drillhole LEM-31E is only 32 cm thick. The Lemoine Andesite is commonly strongly chloritic due to metamorphism to upper-greenschist facies, but alteration indices are strongest near drillholes LEM-49 and -33, where pyrite and pyrrhotite mineralization is associated with amygdules (Fig. 4f).

Hanging-Wall Quartz and Feldspar Porphyry (HwQFP)

The Hanging-wall QFP conformably overlies the Lemoine Andesite in the northeast part of the Lower Lemoine Member and sits directly on top of the Lemoine Rhyolite in the mine area, where it forms the immediate hanging-wall to VMS mineralization (Mercier-Langevin et al., 2014). It is a laterally extensive unit up to 175 m thick near the former mine site and pinches out progressively to the northeast. It is readily identified by its stratigraphic position, its transitional to calc-alkaline magmatic affinity, and lower Al/Zr ratios than the other QFPs (Fig. 3). This unit is quartz- and feldspar-phyric with similar size and abundance of quartz (3–7 vol.%, 1–4 mm) and feldspar (5–8 vol.%, 1–4 mm) phenocrysts to the Coco Lake Rhyolite and the Marelle QFP. Both coherent and fragmental facies have been documented (Lafrance and Brisson, 2006), but the emplacement mode of this subunit has not been studied in detail. Iron-carbonate amygdules, up to 5 cm across, are present in the Hanging-wall QFP in the western part of the study area, but are less abundant elsewhere. A tuffaceous layer situated at the top of the HwQFP in drillhole LEM-31 is composed of five 10–15 cm-thick, normally graded beds of lapilli-tuff to tuff in contact with the Coco Lake Rhyolite.

Upper Lemoine Member — Extrusive Units

The Upper Lemoine Member (previously known as the Gilman Formation) conformably overlies the Lower Lemoine Member. It is composed mostly of basaltic flows with lesser gabbro, rhyolitic massive flows, and a few chert layers.

Upper Lemoine Member Basalt (BuLem)

This unit forms the bulk of the Upper Lemoine Member volcanic package in the study area and is laterally continuous. It is geochemically variable but is distinct from the Lemoine Andesite based on its different stratigraphic position and its transitional to calc-alkaline magmatic affinity (Figs. 5, 6). The Upper Lemoine Basalt is composed essentially of massive and pillow facies. Texturally, the basalt is mostly aphanitic, with local areas containing up to 10 vol.% acicular amphibole crystals. The unit also locally contains 3–6 vol.% quartz-carbonate amygdules within pillows.

Upper Lemoine Member Rhyolite (RuLem)

Thin massive aphanitic rhyolite layers are intercalated with the basaltic flows, but they comprise only a minute part of the Upper Lemoine Member. Geochemical analyses indicate the calc-alkaline nature of this subunit (average Zr/Y = 5.2), and this feature, together with its position higher up in the volcanic stratigraphy, provide the basis for its identification.

Intrusions

Marelle Quartz and Feldspar Porphyry (QFP)

The Marelle QFP is a laterally extensive subunit that extends from southwest of the Lemoine Mine to beyond the study area to the east (Fig. 2). In the study area it occurs at multiple positions in the volcanic stratigraphy, but the thickest sill borders the Doré Lake Complex. The Marelle QFP is up to 350 m thick in some locations, making it the thickest subunit in the Lower Lemoine Member. The Marelle QFP crops out in multiple locations because of its great thickness, coherent texture, felsic composition, and relative minor alteration. Contacts with other units are sharp.

The Marelle QFP exhibits an average Ti/Zr ratio of 6.8 and an average Al/Zr ratio of 178, but with variable Al/Zr ratios (see Fig. 3). Texturally, the Marelle QFP contains 10–25 vol.%, 4–7 mm sub- to euheudral zoned blue quartz phenocrysts and 10–20 vol.% subeuhedral to euhedral poikiolitic plagioclase crystals in an aphanitic groundmass (Fig. 6g). Petrographically the groundmass is composed predominantly of 20–50 μm quartz and feldspar, making this groundmass coarser than that of other QFP subunits.

Coco Lake Rhyolite (RCoco)

The Coco Lake Rhyolite (previously "Upper Lemoine Rhyolite", Lafrance and Brisson, 2006; Mercier-Langevin et al., 2014) is a subvolcanic intrusive subunit present as a laterally continuous sill and dyke complex that occurs at multiple stratigraphic levels in and above the Lower Lemoine Member. The Coco Lake Rhyolite is present only in the northeast part of the Lemoine Member, mostly in and around the Raft sector. It is a quartz- and feldspar-phyric subunit with 7–10 vol.% blue quartz and 3–5 vol.% plagioclase phenocrysts. Intrusions of Coco Lake Rhyolite occur within the Lemoine Rhyolite, immediately below the Lemoine Dacite, above the Lemoine Andesite and above the HwQFP.

This subunit is difficult to distinguish visually from other QFP subunits in the Lower Lemoine Member because of subtle variations in phenocrysts populations and similar shapes and sizes thereof. Geochemically it has a tholeiitic magmatic affinity (Figs. 5, 6) and has a distinctively lower Ti/Zr ratio (average of 3.7) and a lower Al/Zr ratio (average of 169) than the Marelle QFP. The Coco Lake Rhyolite is consistently coherent throughout the study area and has sharp contact relationships with surrounding subunits. The subunit is likely subvolcanic, as it occurs at multiple stratigraphic levels, is coherent, and has sharp contacts with surrounding subunits. Where it is situated between the HwQFP and the Lemoine Andesite, it is responsible for the discontinuity of the chert horizon.

Gold Hill Tonalite (TGH)

The Gold Hill Tonalite is present in the lower part of the volcanic stratigraphy, immediately west of the Raft sector, where it is in contact with multiple subunits, ranging from the Lemoine Rhyolite to the Lemoine Andesite (Fig. 4h). Geochemically it occupies a specific area of moderate Al/Zr and high Ti/Zr by which it is readily distinguished from other lithologies (Fig. 3). Also, the Gold Hill Tonalite is strongly calc-alkaline (Figs. 5, 6) with a steep REE pattern (average $[La/Lu]_N$ = 5.8). It is pink and is phaneritic with abundant plagioclase (70 vol.%), moderate quartz (25 vol.%), and minor potassium feldspar (5 vol.%). One outcrop sample is geochemically identical to a drill-core sample, but the outcrop lacks the porphyritic to almost crystalline texture present in drill core. Contact relationships are sharp (Fig. 4h), and surrounding rocks are commonly highly magnetic up to 20 m away from the contact. The Gold Hill Tonalite is weakly altered relative to the volcanic rocks of the Lower Lemoine Member.

DISCUSSION

Volcanic Model

Our data indicate that the base of the Lower Lemoine Member is composed locally of extrusive Alpha Rhyolite, which was emplaced in one or more lobe-hyaloclastite flow(s). Based on the laterally restricted nature of this subunit, the volcanic centre is most likely situated in the western part of the study area.

A more sustained volcanic episode was necessary to produce the lava flows associated with the laterally extensive Lemoine Rhyolite. The emplacement of the Lemoine Rhyolite can be divided into two stages, as identified by Mercier-Langevin et al. (2014): coherent rhyolite at the base with overlying lobes and hyaloclastite. Based on lateral thickness variations, we suggest that the effusive centre for the Lemoine Rhyolite is situated to the west of the study area.

Overlying the Lemoine Rhyolite, but only present in the eastern part of the study area, is the Lemoine Dacite. The Lemoine Dacite also extends outside the study area to the east and thus more work is needed to pinpoint the location of the effusive centre. However, at depth this subunit becomes consistently thinner, suggesting that the volcanic vent was situated above present day erosion levels.

The Lemoine Andesite consists of massive flows and pillowed flows. It can be subdivided into at least two flows or flow packages based of the presence of a chert layer mid-level within its stratigraphy, and which marks a hiatus in volcanism. A second chert layer is located at the top of the subunit. The presence of sulphide mineralization in amygdules suggests that hydrothermal fluids were circulating within the Lemoine Andesite. Based on thickness variations, it is plausible that the Lemoine Andesite vent is located in the study area.

The HwQFP represents the last episode of volcanism associated with the Lower Lemoine Member. Lobes with flow banding present on an outcrop west of the study area confirm the extrusive nature of this subunit. Based on thickness variations alone, the HwQFP may share the same volcanic vent as the Lemoine Rhyolite west of the study area, but confirmation based on volcanic facies variations is needed. The HwQFP marks a change in magmatic affinity relative to the underlying subunits, which may indicate a change in the tectonic environment or different petrogenetic conditions; however, subsequent felsic intrusions in the Lower Lemoine Member revert to tholeiitic to transitional affinities. Above the HwQFP, the Upper Lemoine Basalt and Rhyolite become more transitional to calc-alkaline magmatic in affinity. Upper Lemoine Basalt was emplaced as massive and pillowed flows. However, the extrusive nature of the Upper Lemoine Rhyolite is unclear, as it only occurs as coherent rocks that forms thin discontinuous bands within the Upper Lemoine Basalt.

Intrusions

The timing of the multiple subvolcanic intrusions within the Lower Lemoine Member is not completely resolved. The Marelle QFP occurs at the stratigraphic base, within the Lemoine Andesite, and in contact with the Upper Lemoine Basalt in the northeast part of the property. The Coco Lake Rhyolite is also present at similar stratigraphic positions. Together, these observations suggest that the intrusions are younger than at least some Upper Lemoine Basalt (and therefore all extrusive subunits in the Lower Lemoine Member). However, it has not been established which of the two intrusive QFPs, Marelle or Coco Lake, is the youngest.

The strong calc-alkaline magmatic affinity of the Gold Hill Tonalite and the distinct magnetite alteration in the adjacent host rocks suggests it post-dates the Marelle QFP and the Coco Lake Rhyolite. It is possible that the GHT is linked with a phase of the ca. 2718–2712 Ma Chibougamau Pluton.

The results of this study indicate that the Lower Lemoine Member, which hosts the Lemoine auriferous VMS deposit, consists of a relatively thick, felsic-dominated sequence that comprises a significant portion of shallow intrusive rocks that are coeval and cogenetic with the effusive rocks. This sequence is intruded at its base by the large synvolcanic Doré Lake Complex (Mortensen, 1993; Leclerc et al., 2012; Mercier-Langevin et al., 2014). This setting indicates the development of a major thermal corridor in that area and we speculate that these conditions may have contributed in forming such a base- and precious-metal-rich deposit, as suggested by the analysis of Singer et al. (2011), who observe higher average copper and gold grades in VMS deposits that are associated with syn-VMS mineralization intrusions.

IMPLICATIONS FOR EXPLORATION

The results presented herein provide an improved volcanological, textural, geochemical, and mineralogical characterization of all subunits present within the Lower Lemoine Member, and provide key stratigraphic relationships and the overall volcanic architecture of the Lower Lemoine Member. This sets the framework for future exploration by highlighting volcanic subunits and marker horizons that can be followed and used to vector toward concealed mineralization in subsequent drillholes laterally and at depth on the property. Understanding emplacement processes of the Lower Lemoine Member subunits will help optimize exploration by providing an improved geological model and, perhaps, new exploration targets. The spatial distribution of the metamorphosed, synvolcanic hydrothermal alteration can be mapped, and the classic AI alteration index of Ishikawa et al. (1976) appears to be a robust vectoring tool. Although determination of the locations of the paleo-volcanic vents is still in progress, these vents are commonly spatially associated with synvolcanic fissures and faults. Such fissures and faults are zones of increased cross-stratal permeability along which high-temperature, VMS-mineralizing hydrothermal fluids can have been channelized (e.g. Gibson et al., 1999; Franklin et al., 2005). The information provided above, although preliminary, can be used to develop potential new targets for exploration.

FUTURE WORK

Additional work is underway by the authors of this paper to better understand the volcanic architecture of the Lower Lemoine Member, including (1) quantitative facies-variation analysis within each extrusive subunit in the Lower Lemoine Member; (2) precise U-Pb zircon geochronology to help understand the volcanic and intrusive evolution of the Lemoine Member; (3) characterization of alteration assemblages in the study area and comparisons with work done in the Lemoine deposit vicinity (Mercier-Langevin et al., 2014) to help define exploration vectors in the study area; and (4) testing the inferred synvolcanic nature of the north-northeast–south-southwest (NNE–SSW) faults in the study area identified by Lafrance and Brisson (2006) remains to be examined.

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REFERENCES

Daigneault, R. and Allard, G.O., 1990. Le Complexe du Lac Doré et son environnement géologique (région de Chibougamau - sous-province de l'Abitibi); Ministère de l'Énergie, des Mines et des Ressources du Québec, Report MM 89-03, 275 p.

Donahue, J.C., 1982. The Geology and Petrochemistry of the Patino-Lemoine Deposit and its Host Rocks, Lemoine Township, Québec; M.Sc. thesis, University of Georgia, Athens, Georgia, 275 p.

Franklin, J., Gibson, H., Jonasson, I., and Galley, A., 2005. Volcanogenic massive sulfide deposits, *In:* 100th Anniversary Volume, (ed..) J.W. Hedenquist, J.F.H. Thompson, R.J. Goldfarb, and J.P. Richards; Society of Economic Geologists, Littleton, Colorado, p. 523–560.

Gibson, H.L., Morton, R.L., and Hudak, G.J., 1999. Submarine volcanic processes, deposits and environments favorable for the location of volcanic-associated massive sulfide deposits; Reviews in Economic Geology, v. 8, p. 13–51.

Ishikawa, Y., Sawaguchi, T., Iwaya, S., and Horiuchi, M., 1976. Delineation of prospecting targets for Kuroko deposits based on modes of volcanism of underlying dacite and alteration haloes; Mining Geology, v. 26, p. 105–117.

Lafrance, B. and Brisson, T., 2006. Rapport sur le programme de forage 2005, projet Lemoine, Woodruff Capital Management Inc.; Ministère de l'Énergie et des Ressources Naturelles du Québec, Report GM 62564, 36 p.

Large, R.R., Gemmell, J.B., Paulick, H., and Huston, D.L., 2001. The alteration box plot: A simple approach to understanding the relationship between alteration mineralogy and lithogeochemistry associated with volcanic-hosted massive sulfide deposit; Economic Geology, v. 96, p. 957–971.

Leclerc, F., Bédard, J.H., Harris, L.B., McNicoll, V.J., Goulet, N., Roy, P., and Houle, P., 2011, Tholeiitic to calc-alkaline cyclic volcanism in the Roy Group, Chibougamau area, Abitibi Greenstone Belt— revised stratigraphy and implications for VHMS exploration; Canadian Journal of Earth Sciences, v. 48, p. 661-694.

Leclerc, F., Harris, L.B., Bédard, J.H., Van Breemen, O., and Goulet, N., 2012. Structural and stratigraphic controls on magmatic, volcanogenic, and shear zone-hosted mineralization in the Chapais-Chibougamau mining camp, northeastern Abitibi, Canada; Economic Geology, v. 107, p. 963–969.

MacLean, W. and Barrett, T., 1993. Lithogeochemical techniques using immobile elements; Journal of Geochemical Exploration, v. 48, p. 109–133.

McDonough, W. F., and Sun, S.-S., 1995, The composition of the Earth; Chemical Geology, v. 120, p. 223-253.

McPhie, J., Doyle, M., and Allen, R., 1993. Volcanic Textures: A Guide to the Interpretation of Textures in Volcanic Rocks; Centre for Ore Deposit and Exploration Studies, University of Tasmania, 196 p.

Mercier-Langevin, P., Hannington, M.D., Dubé, B., and Bécu, V., 2011. The gold content of volcanogenic massive sulfide deposits; Mineralium Deposita, v. 46, p. 509–539.

Mercier-Langevin, P., Lafrance, B., Bécu, V., Dubé, B., Kjarsgaard, I., and Guha, J., 2014. The Lemoine auriferous volcanogenic massive sulfide deposit, Chibougamau Camp, Abitibi greenstone belt, Quebec, Canada: geology and genesis; Economic Geology, v. 109, p. 231–269.

Mortensen, J. K., 1993. U-Pb geochronology of the eastern Abitibi Subprovince. Part 1: Chibougamau - Matagami - Joutel region; Canadian Journal of Earth Sciences, v. 30, p. 11–28.

Ross, P.-S. and Bédard, J.H., 2009. Magmatic affinity of modern and ancient subalkaline volcanic rocks determined from trace-element discriminant diagrams; Canadian Journal of Earth Sciences, v. 46, p. 823–839.

Ross, P.S., Bourke, A., Leclerc, F., and Boulerice, A.R., 2014. Analyse multiparamétrique à haute résolution de carottes de forage dans la région de Chibougamau 2012-2014, rapport final; Ministère de l'Énergie et des Ressources naturelles du Québec, in press.

Salmon, B. and McDonough, B., 2011. Technical report on the mineral resource estimate of the Scott Lake project, northern Québec, Canada, Roscoe Postle Associates Inc; Internal Report to Cogitore Resources, 102 p.

Sangster, D., 1980. Quantitative characteristics of volcanogenic massive sulphide deposits I; Canadian Institute of Mining and Metallurgy Bulletin, v. 73, p. 74–81.

Saunders, J.A. and Allard, G.O., 1990. The Scott Lake deposit: a contact-metamorphosed volcanogenic massive sulfide deposit, Chibougamau area, Quebec; Canadian Journal of Earth Sciences, v. 27, p. 180–186.

Singer, D.A., Berger, V.I., and Mosier, D.L., 2011. Effects of intrusions on grades and contents of gold and other metals in volcanogenic massive sulfide deposits; Ore Geology Reviews, v. 39, p. 116–118.