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

Geology and Au enrichment processes at the Paleoproterozoic Lalor auriferous volcanogenic massive sulphide deposit, Snow Lake, Manitoba

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Geology and Au enrichment processes at the Paleoproterozoic Lalor auriferous volcanogenic massive sulphide deposit, Snow Lake Manitoba

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ABSTRACT

The Paleoproterozoic Lalor auriferous volcanogenic massive sulphide deposit, located in the Snow Lake mining camp, Manitoba, is hosted in a complex volcanic package referred to as the Lalor volcanic succession. The deposit consists of stratigraphically and structurally stacked Zn-rich, Au-rich, and Cu-Au-rich ore lenses. The host volcanic succession comprises mafic to felsic tholeiitic to calc-alkaline extrusive to intrusive volcanic rocks of the ca. 1.89 Ga Lower Chisel subsequence, and the ore is hosted in both mafic and felsic rocks. Atypical of the other Zn-rich deposits of the Snow Lake district, the Lalor deposit is not situated at the top of the Lower Chisel subsequence, but is at a slightly lower stratigraphic position.

The volcanic rocks that host the deposit were affected by intense and laterally extensive ore-related hydrothermal alteration. These altered rocks were subsequently subjected to syndeformational amphibolite-grade metamorphism that resulted in the development of distinct minerals and metamorphic mineral assemblages of varying composition from variably altered precursor lithologies. Five distinct alteration- and metasomatism-related chemical associations (K, K-Mg-Fe, Mg-Fe, Mg-Ca, and Ca) are recognized based on mineralogical (mineral assemblages) and bulk geochemical compositions. Mapping of the host volcanic rocks and ore-related mineral assemblages and chemical associations at Lalor indicates the following: 1) the Zn-rich massive sulphide lenses are preferentially associated with the low- to high-temperature K and Mg-Ca alteration zones; 2) the Cu-Au-rich zones, which occur at depth, stratigraphically below the Zn-rich mineralization, are hosted in transposed, presumably originally discordant high-temperature Mg-Fe altered rocks; and 3) Au has been in part locally remobilized into low-strain sites that are not now spatially associated with any particular chemical association.

The Lalor volcanic succession is affected by polyphase deformation that has strongly influenced the geometry of the Lalor deposit. Pre-D₂ (synvolcanic?) deformation is evidenced by the abrupt termination of the intensely altered Lalor volcanic succession to the southwest and the presence of chemically distinctive and unaltered volcanic rocks of the Western succession. The present geometry of the deposit is largely controlled by D₂ deformational structures with important stretching (L₂), flattening (S₂), and structural staking (F₂ folding and syn- to late-D₂ transposition and shearing). The D₂ deformation and associated peak metamorphic conditions are thought to be responsible for the local remobilization of Au sulphosalts and some sulphides.

INTRODUCTION

The Paleoproterozoic Lalor auriferous volcanogenic massive sulphide (VMS) deposit, located in the Snow Lake mining camp of northern Manitoba, is currently being mined by owner and operator HudBay Minerals Inc. Combined reserves and resources are estimated at 25.3 Mt averaging 5 wt% Zn, 0.79 wt% Cu, 2.9 g/t Au,

and 25 g/t Ag (HudBay Minerals Inc., 2014), including 8.8 Mt at 4.6 g/t Au, making it the largest and richest VMS deposit of the Snow Lake camp (Mercier-Langevin et al., 2014). Based on the grade and tonnage data, Lalor belongs to a subgroup of large, Au-enriched VMS deposits termed “anomalous”, with over 31 t Au (c.f. Mercier-Langevin et al., 2011). However, with 8.8

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Mt of ore at 4.6 g/t, the Au and Au-Cu zones at Lalor exceed the 3.46 g/t Au and 31 t Au thresholds defining Au-rich VMS. Such deposits are challenging exploration targets because the Au-enrichment processes and their diagnostic characteristics are complex and variable, and can be masked by superimposed deformational and metamorphic effects that have modified or obliterated primary geological and mineralogical relationships.

The Geological Survey of Canada, in collaboration with the Manitoba Geological Survey, HudBay Minerals Inc., the Institut national de la recherche scientifique, and the University of Ottawa, conducted research at Lalor under the auspices of the VMS Ore System project of NRCan's Targeted Geoscientific Initiative 4 program. This project is largely based on extensive drill-core logging, underground mapping, 3-D modelling, and bulk geochemical, oxygen isotopic and mineral chemical analyses. The salient aims are to determine the geological and structural setting of the deformed and metamorphosed Lalor VMS deposit, its hydrothermal signature, the relative timing of volcanic, mineralizing, deformational, and metamorphic events, and to elucidate the genesis of the precious and base metal mineralization. This report summarizes some of the key aspects of the deposit geology and evolution determined so far, but our research at Lalor is ongoing.

GEOLOGICAL SETTING

The Lalor deposit is hosted in the Lalor volcanic succession (Caté et al., 2014a), which is part of the Chisel mature arc sequence of the Paleoproterozoic Snow Lake arc assemblage (Fig. 1; Bailes and Galley, 1999). The ca. 1.89 Ga Snow Lake arc assemblage occurs in the easternmost part of the Paleoproterozoic Flin Flon greenstone belt (Galley et al., 2007). The Chisel mature arc sequence consists of intercalated, geochemically fractionated, intermediate to mafic flows, volcanoclastic to volcanosedimentary units, and discrete felsic flow complexes and related subvolcanic intrusive phases. The volcanic sequence is cut by the Richards Lake synvolcanic pluton and the Chisel mafic intrusion. Zinc-rich, bimodal felsic-type VMS deposits are located at the contact between the lower and upper parts of the Chisel sequence (Bailes and Galley, 1999; Galley et al., 2007). The Chisel, Chisel North, Ghost, and Lost deposits are spatially and temporally associated with rhyolite domes and are located at the contact between the footwall Powderhouse dacite and the hanging-wall Threehouse basalt and volcanoclastic rocks (Galley et al., 2007), which marks the transition between the lower and upper parts of the Chisel sequence (Bailes and Galley, 1996; Engelbert et al., 2014).

Four discrete episodes of folding are recognized in the Snow Lake area (David et al., 1996; Kraus and

Williams, 1999). D₁ and D₂ events produced tight, isoclinal, south-verging folds, shallowly dipping thrusts, and imparted the main foliation (Kraus and Williams, 1999; Bailes et al., 2013). These structures are refolded by NNE-SSW-trending F₃ folds and an associated S₃ crenulation cleavage (Martin, 1966; Kraus and Williams, 1999). F₄ folds with east-west-trending axes locally overprint F₃ folds (Kraus and Williams, 1999).

GEOLOGY OF THE LALOR DEPOSIT

The Lalor deposit consists of at least twelve stratigraphically and structurally stacked Zn-rich massive sulphide lenses, sulphide-poor Au-rich lenses, and transposed Cu- and Au-rich semi-massive to disseminated sulphide footwall stringer zones (Caté et al., 2013; Duff et al., 2013). The mineralized lenses are strongly transposed into the main foliation in the uppermost section of the Lalor volcanic succession, which has been intensely hydrothermally altered in the deposit footwall (Caté et al., 2014b; Mercier-Langevin et al., 2014).

Volcanic Stratigraphy

The Lalor volcanic succession is in contact with the Balloch volcanic succession ("Lalor-Chisel contact": Fig. 2). The VMS-hosting succession is truncated to the west by the Lalor West fault, and is in contact with a weakly altered volcanic package referred to herein as the Western volcanic succession (Fig. 2; Caté et al., 2014a). Mafic, intermediate, and felsic volcanic and intrusive rocks are present in the Lalor volcanic succession. However, because most of the rocks located in the stratigraphic footwall of the deposit have been affected by intense alteration, deformation, and metamorphism, there has been nearly complete destruction of the primary volcanic textures and it is generally not possible to determine protoliths by visual inspection. Thus, immobile element geochemistry is essential in mapping the units and reconstructing the volcanic stratigraphy of the intensely altered and deformed Lalor volcanic succession (Caté et al., 2014a).

Nine units were defined based on their spatial distribution and geochemical characteristics. These chemostratigraphic units are mafic (M), intermediate (I), and felsic (F) and have a tholeiitic to calc-alkaline affinity (Fig. 3; Caté et al., 2014a).

Unit F1

Unit F1 is rhyolitic to rhyodacitic, transitional to calc-alkaline, and is spatially located in the footwall of the Zn-rich massive-sulphide ore lenses. The unit could occur as dykes, sills or form small extrusive bodies, as evidenced by the presence of unit F1 geochemical signatures intercalated with other chemostratigraphic units (Figs. 2, 3). Relatively weakly altered intervals of unit F1 consist of massive aphyric rhyolite.

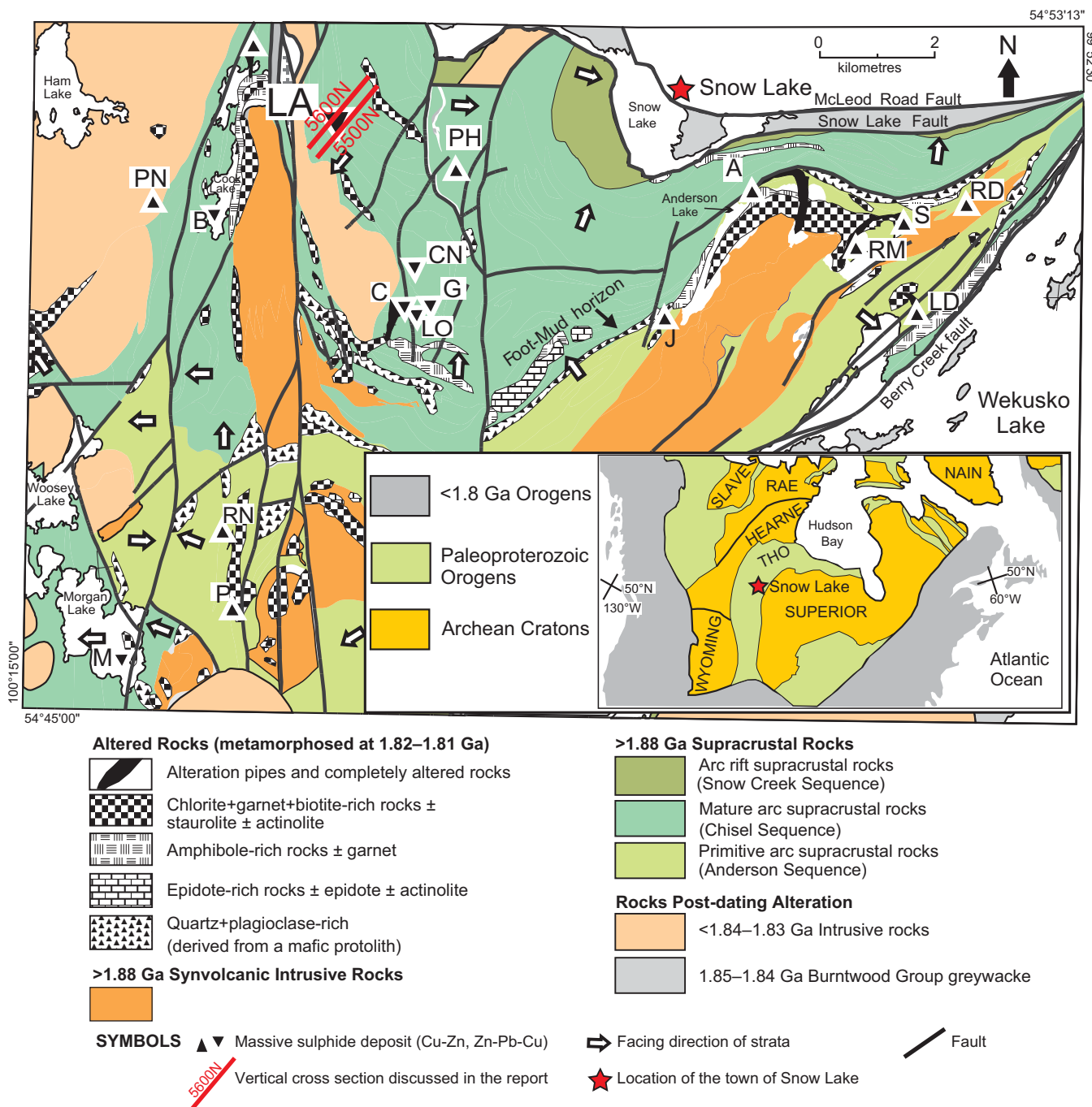


Figure 1. Simplified geological map of the Snow Lake area (from Galley et al., 2007), showing major alteration zones and VMS deposits, including the Lalor deposit (LA). Other deposits: A = Anderson; B = Bomber zone; C = Chisel Lake; CN = Chisel North; G = Ghost; J = Joannie zone; LO = Lost; LD = Linda zone; M = Morgan Lake zone; P = Pot Lake zone; PH = Photo Lake; PN = Pen zone; RD = Rod; RM = Ram zone; RN = Raindrop zone; S = Stall Lake. The location of the Snow Lake area is shown in the inset map.

Unit F2

Unit F2 is rhyolitic to rhyodacitic, transitional to calc-alkaline (Fig. 3) and forms a continuous, <50 m-thick unit (Fig. 2) that hosts the lowermost Zn-rich massive sulphide lenses (lens 20 and its underlying lenses). No primary volcanic textures are preserved. The trace element signature of unit F2 is similar to that of the

Powderhouse dacite (Caté et al., 2014a) present in the footwall of the Chisel deposit southeast of Lalor (Bailes and Galley, 1996).

Unit F3

Unit F3 is felsic and of calc-alkaline affinity (Fig. 3) and is generally intercalated with unit F2. Unit F3 is intensely altered and no primary textures are preserved.

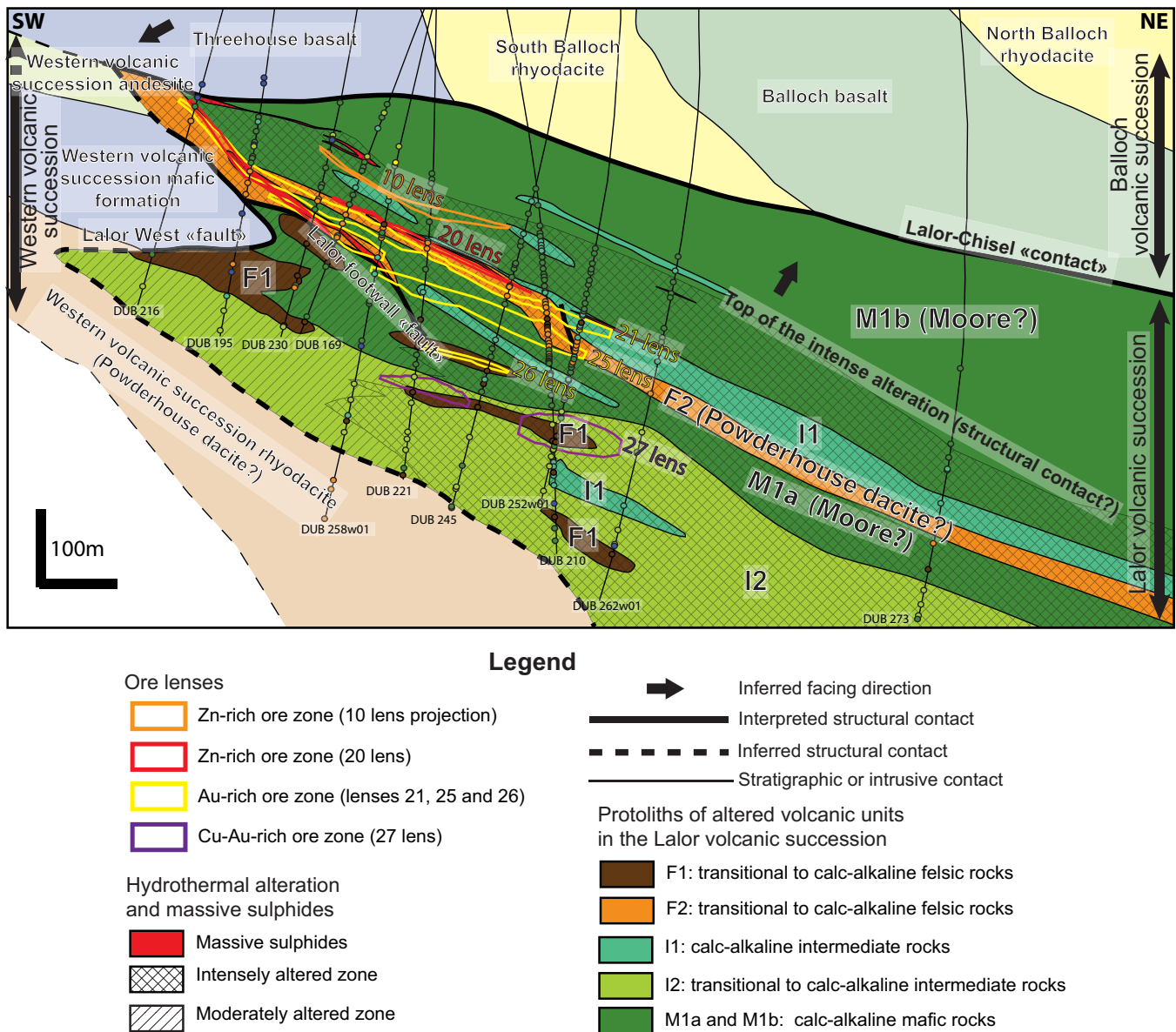


Figure 2. Simplified geological cross-section 5600 N (looking northwest) constructed subparallel to L_2 plunge and including the chemostratigraphic units of the Lalor volcanic succession (from Caté et al., 2014a). The top of the cross-section is at 600 m below surface. The Balloch and Western volcanic succession are in muted colours and the Lalor volcanic succession in brighter colours. Drillholes and samples (unit-colour filled circles along drillholes traces) are shown, together with the distribution of the interpreted units. Ore-zone morphologies are from Hudbay Minerals; 10 lens is projected from section 5500 N. Chemostratigraphic units F3, M2, and M3 are not depicted, as they are only present in narrow intervals and in minor amounts. Unit names of the Balloch volcanic succession are from Bailes (2008).

Unit I1

Unit I1 is a calc-alkaline andesite that forms discontinuous intervals throughout the entire Lalor volcanic succession (Fig. 2). Most of the least altered samples of unit I1 are aphyric to feldspar-phyric dykes that are up to 25 m thick, although some altered volcanoclastic rocks are also considered to be part of chemostratigraphic unit I1, based on their similar geochemical signature.

Unit I2

Unit I2 is a transitional to calc-alkaline andesite that

forms a 150 m-thick interval at the base of the exposed Lalor volcanic succession (Fig. 2). Least altered samples consist of biotite-rich tuff, lapilli tuff, and tuff breccia.

Units M1a and M1b

Units M1a and M1b have similar immobile element signatures, but they are located at two different stratigraphic levels (Fig. 2). Unit M1a is present in the foot-wall of the lowermost Zn-rich massive sulphide lenses (20 lens and lower), and unit M1b hosts the uppermost Zn-rich massive sulphide lenses (10 and 11 lenses).

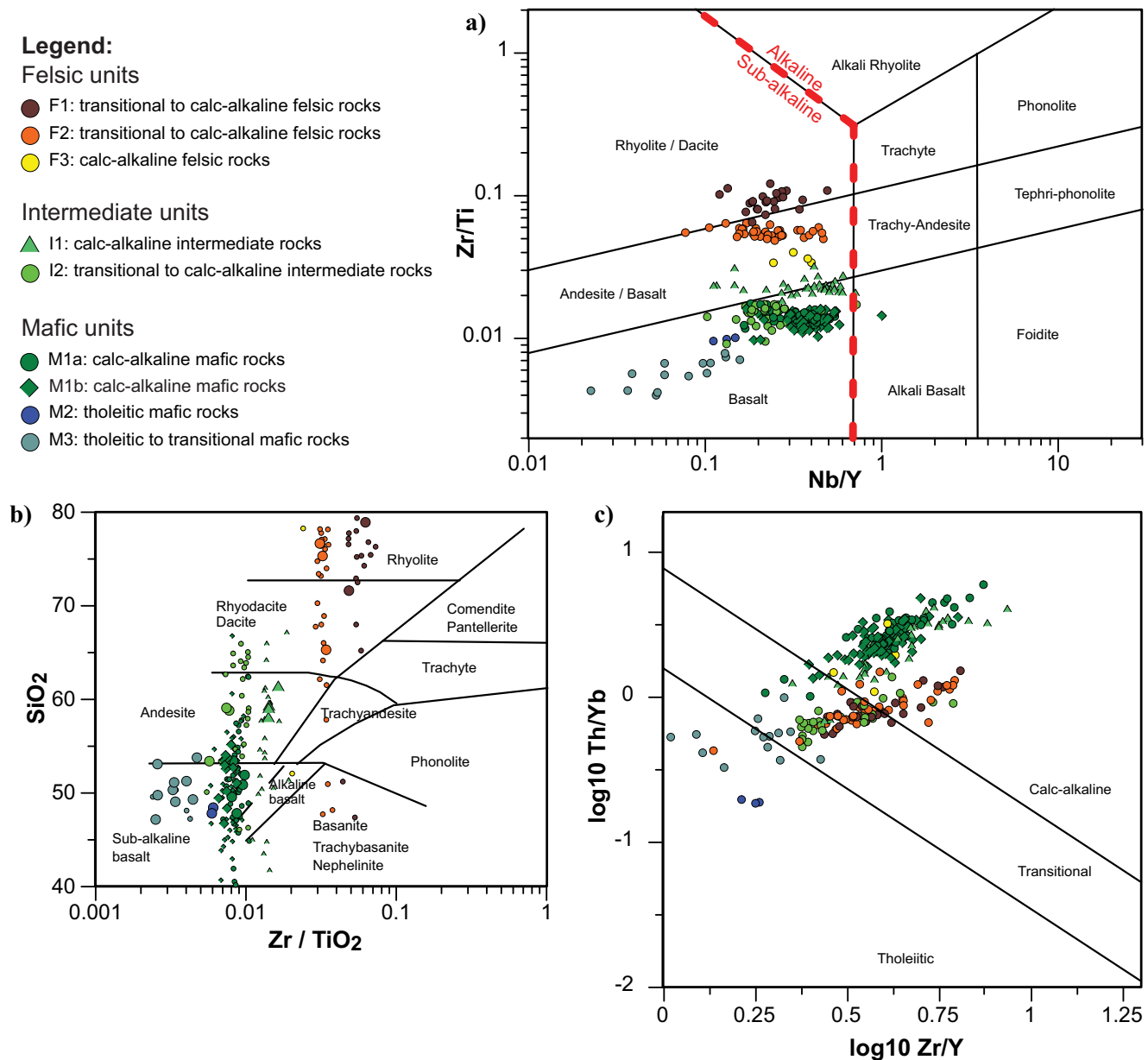


Figure 3. Discriminant geochemical diagrams of the Lalor-succession volcanic (\pm intrusive) rocks sampled from selected drill-holes along section 5600 N (Fig. 2) and two least altered samples from DUB223. **a)** Pearce (1996) classification diagram modified after Winchester and Floyd (1977). **b)** Winchester and Floyd (1977) classification diagram. Thirty-six samples with <40 wt% SiO₂ and 9 samples with >80 wt% SiO₂ have been excluded as they fall out of the diagram range. As SiO₂ has been strongly affected by VMS alteration and vertically spreads the samples, only the SiO₂ content of the less altered samples (larger symbols, with $20 < Al < 60$; $Al = 100 \cdot (MgO + K_2O) / (MgO + K_2O + Na_2O + CaO)$, $S < 1$ wt%, $CO_2 < 1$ wt%, $Na_2O > 0.5$ wt%, $LOI < 2$ wt% and unaltered-appearing texture and mineralogy) is used in this report to determine the fractionation of the units. **c)** Magmatic affinity diagram of Ross and Bédard (2009).

The upper part of the M1b unit (lenses 10 and 11 hanging wall) has not been intensely altered by the VMS hydrothermal system and is truncated by the Lalor-Chisel contact. Both units consist of calc-alkaline basalt to basaltic andesite and are very similar geochemically and texturally to the Moore basalt (Caté et al., 2014a) located in the footwall of the Chisel deposit (Bailes and Galley, 1996). Least altered samples of unit M1b are massive volcanic rock with some coarse mafic lapilli tuff.

Unit M2

Unit M2 is a tholeiitic basalt that forms post-VMS aphyric dykes that locally can be up to a few m thick.

Unit M3

Unit M3 consists of post-VMS aphyric, feldspar-phyric, and feldspar- and pyroxene-phyric dykes of tholeiitic to transitional affinity that have similar trace element signatures to that of the Treehouse basalt (Caté

et al., 2014a), which is located in the hanging wall of the Chisel deposit (Bailes and Galley, 1996).

Hydrothermal Alteration and Syn-Metamorphic Metasomatism

The host rocks at Lalor have been intensely hydrothermally altered over a large area extending to more than 350 m spatially below the ore horizon, and this alteration has modified the bulk geochemical composition and mineralogy of the volcanic rocks and obliterated most primary volcanic textures. Syn- to late D₂ peak amphibolite-grade metamorphism (Menard and Gordon, 1997) has significantly modified the VMS-related alteration mineralogy, with only minimal modification of the bulk geochemical composition of the rocks (Tinkham, 2013; Caté et al., 2014c), with the exception of some minor effects that are discussed below. Metamorphosed hydrothermally altered rocks generally contain variable proportions of coarse-grained quartz, muscovite, biotite, chlorite, Mg-Fe-amphibole, cordierite, garnet, staurolite, kyanite, sillimanite, Ca-amphibole, diopside, carbonate minerals, anhydrite, gahnite, sulphides, magnetite, and other trace minerals. The metamorphosed mineral assemblages and the relative abundance and composition of specific minerals within these assemblages can be correlated with bulk rock geochemical compositions to identify specific chemical associations and determine alteration zonation. Four distinct chemical associations (K, K-Mg-Fe, Mg-Fe, Ca-Mg) that correlate with the presence and relative abundance of key minerals have been documented in the altered rocks at Lalor (Caté et al., 2014c). A fifth chemical association (Ca) results from syndeformation and metamorphism metasomatism in the Lalor area. Dehydration and decarbonation reactions have locally modified the mineralogy, mineral textures, and bulk compositions of the hydrothermally altered rocks in the deposit footwall (Tinkham, 2013). Thus, the chemical associations are the collective result of multiple processes dominated by polyphase hydrothermal fluid flow, and localized syn-metamorphic metasomatism superimposed on volcanic rocks of varying composition.

K Chemical Association

The K chemical association occurs in muscovite-bearing (>5 vol% muscovite) rocks (Fig. 4a). Quartz, pyrite, biotite, kyanite, and sillimanite are also present in varying abundances. Minor (<5 vol%) relic plagioclase is locally preserved. The K chemical association occurs mainly in the wallrocks of the upper part of the deposit, proximal to the Zn-rich massive sulphide lenses (Fig. 5; Caté et al., 2014c). The abundance of pyrite increases toward the massive sulphide lenses up to a maximum of 40 vol%. Minor gahnite and spha-

lerite occur in the wallrocks immediately adjacent to massive sulphides. Bulk geochemical compositions and alteration indices indicate that the K chemical association corresponds to metamorphosed sericitic alteration (Fig. 6). Whole-rock oxygen isotope values indicate low- to moderate (~200–250°C) alteration temperatures (Mercier-Langevin et al., 2014).

K-Mg-Fe Chemical Association

The K-Mg-Fe chemical association occurs in biotite-bearing rocks that contain no muscovite, chlorite, Mg-Fe amphibole (anthophyllite, cummingtonite-grunerite, and gedrite series), cordierite and/or Ca amphibole (actinolite, hornblende, and tschermakite series) (Fig. 4b). Feldspar is minor or absent. These biotite-bearing rocks contain abundant Al-rich minerals (kyanite, sillimanite, staurolite, and/or garnet) and quartz. Pyrite increases in abundance toward massive sulphides, up to a maximum of 40 vol%. The K-Mg-Fe chemical association is transitional between the K and the Mg-Fe chemical associations (Fig. 5). It is present both proximal to the uppermost Zn-rich sulphide lenses in the upper part of the deposit and in the deep footwall of the deposit. Bulk geochemical compositions and alteration indices indicate that the K-Mg-Fe chemical association corresponds to a metamorphosed chlorite-sericite alteration style (Fig. 5). Whole-rock oxygen isotope values suggest moderate (~250°C) alteration temperatures (Mercier-Langevin et al., 2014).

Mg-Fe Chemical Association

The Mg-Fe chemical association occurs in rocks that contain chlorite, Mg-Fe amphibole, and/or cordierite (Fig. 4c). These rocks also contain variable amounts of biotite, quartz, garnet, and staurolite, with rare feldspar. Muscovite is absent in rocks of this chemical association. Talc is locally abundant, especially close to Mg-Ca-altered rocks (see below). The abundance of biotite in the Mg-Fe chemical association increases near K-Mg-Fe-altered rocks. Gahnite is locally present, commonly in sulphide veinlets. The Mg-Fe chemical association affects a very large volume of rocks in the deposit footwall (Fig. 5). The Cu-Au mineralization (transposed footwall stringer zones) and minor portions of the Au-rich sulphide-poor lenses are hosted in the Mg-Fe-altered rocks. The Mg-Fe-altered rocks represent a high-temperature (~200–350°C), metamorphosed chlorite-dominated alteration zone, as indicated by bulk geochemical and oxygen isotope compositions (Mercier-Langevin et al., 2014) (Fig. 6).

Mg-Ca Chemical Association

The Mg-Ca chemical association corresponds to rocks that are mainly composed of variable amounts of Mg-chlorite, Ca-amphibole (mainly actinolite series),

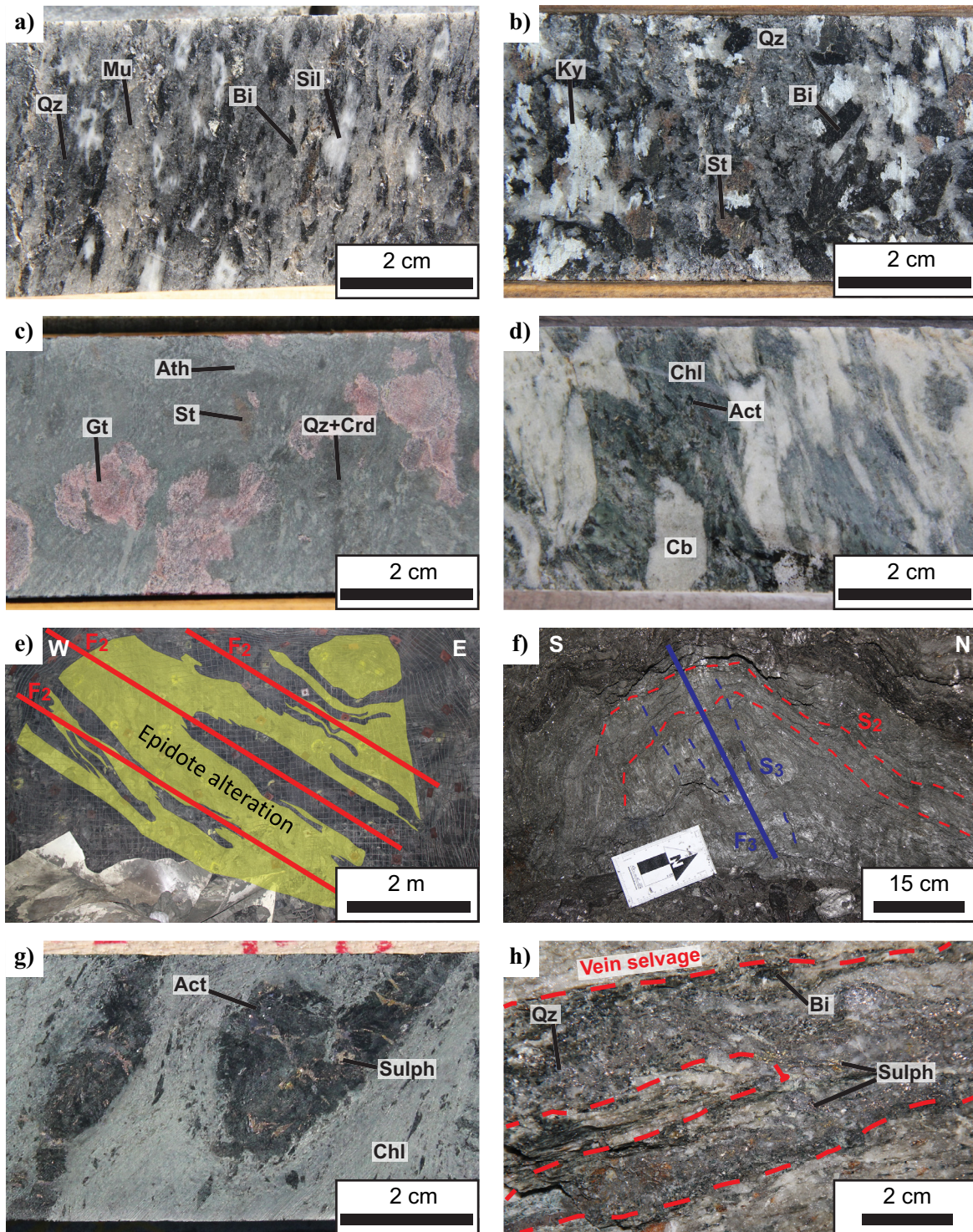


Figure 4. a) Metamorphic mineral assemblage of the K chemical association, with biotite, muscovite, and sillimanite porphyroblasts in a quartz-muscovite-biotite matrix. b) Metamorphic mineral assemblage of the K-Mg-Fe chemical association, with biotite, kyanite, and staurolite porphyroblasts in a quartz-biotite matrix. c) Metamorphic mineral assemblage of the Mg-Fe chemical association, with garnet, staurolite, and Mg-Fe amphibole porphyroblasts in a quartz-Mg-Fe amphibole-cordierite matrix. d) Metamorphic mineral assemblage of the Mg-Ca chemical association, with deformed carbonate spheroids and actinolite porphyroblasts in Mg-chlorite matrix. e) F_2 -folded epidote-rich alteration layers in moderately altered andesite. f) S_3 -crenulated S_2 foliation affected by a F_3 fold in muscovite schist. g) S_2 -perpendicular sulphide-filled fractures in F_2 -folded actinolite layers in a chlorite matrix. Sulphides are pyrrhotite, chalcopyrite, and trace galena. This mineralization is part of the Au-rich 21 ore lens. h) Quartz-sulphide-biotite vein in a quartz-phlogopite-Mg-Fe amphibole mineral assemblage. Sulphides are sphalerite, pyrite, pyrrhotite, galena, and chalcopyrite. This mineralization is located in the 25 ore lens. Abbreviations: Act = actinolite, Ath = Mg-Fe amphibole, Bi = biotite, Cb = carbonate minerals (calcite and/or dolomite), Chl = chlorite, Crd = cordierite, Gt = garnet, Ky = Kyanite, Mu = muscovite, Qz = quartz, Sil = sillimanite, St = staurolite, Sulph = sulphides.

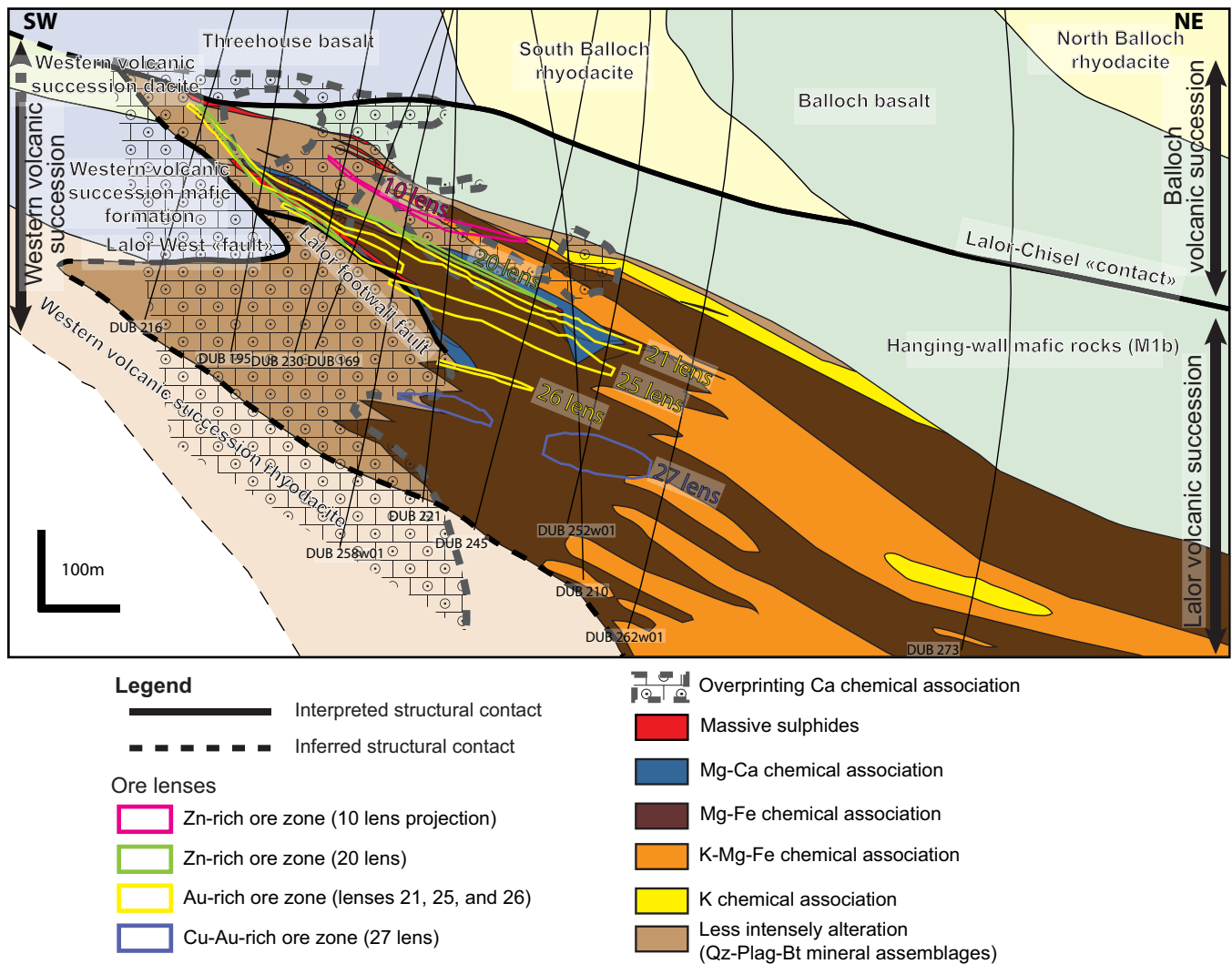


Figure 5. Simplified geological cross-section 5600 N (looking northwest) constructed subparallel to L_2 plunge with metamorphic mineral assemblages of altered volcanic rocks grouped according to chemical associations. The top of the cross-section is at 600 m below surface. Least altered volcanic rocks are in muted colours and the altered rocks of the Lalor volcanic succession in brighter colours. Traces of drillholes that have been used to interpret this section are shown. Ore-zone morphologies from Hudbay Minerals; 10 lens is projected from section 5500 N. Unit names in the Balloch volcanic succession are from Bailes (2008). Abbreviations: Bt = biotite, Plag = plagioclase, Qz = quartz.

and/or carbonate (calcite and/or dolomite) (Fig. 4d). Quartz, anorthite, biotite, talc, titanite, grossular, and anhydrite are common constituents. Diopside can be a major (>20 vol.%) component very locally. Crosscutting relationships indicate that layers (5 cm- to >1 m-thick sheet-like zones) of actinolite-rich mineral assemblages overprint the chlorite-rich and the carbonate-rich assemblages. The actinolite layers were folded during D_2 , but they also overprint S_2 in a few places. Moreover, similar actinolite-rich layers overprint the other chemical associations (K, K-Mg-Fe, and Mg-Fe) proximal to Mg-Ca-altered rocks. Tinkham (2013) concluded that hydrous and carbonic metasomatism occurred by fluid circulation in the Mg-Ca-altered rocks during amphibolite-grade metamorphism. The Mg-Ca chemical association is mostly developed around the lowermost Zn-rich massive sulphide lenses

and the sulphide-poor Au-rich zones, especially in the western part of the deposit (Fig. 5). The Mg-Ca chemical association corresponds to intense chlorite-carbonate alteration prior to amphibolite-grade metamorphism (Caté et al., 2014c). The Mg-Ca chemical association is characterized by bulk-rock $\delta^{18}O$ values similar to those of the Mg-Fe chemical association. This indicates that the Mg-Ca chemical association is the result of hydrothermal alteration at moderate to high temperatures (~200–300°C; Mercier-Langevin et al., 2014).

Ca Chemical Association

The Ca chemical association represents rocks that were metasomatized after VMS formation (pre- to post-peak D_2 ; Caté et al., 2014b). This metasomatism overprinted altered and unaltered rocks of the Lalor volcanic suc-

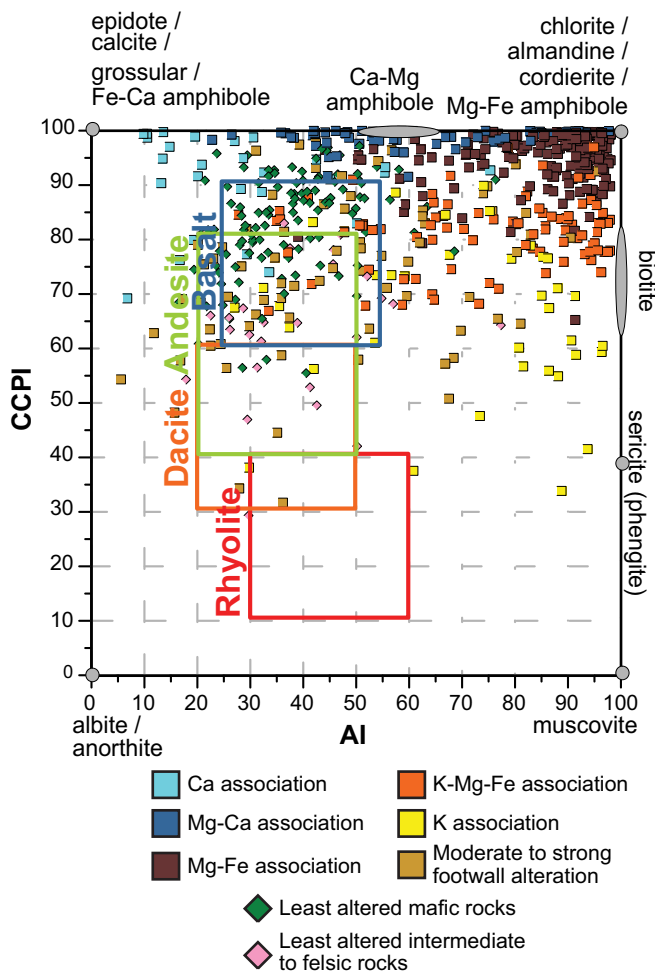


Figure 6. Box plot diagram (Large et al., 2001) with 699 samples of altered rocks classified by chemical association and least altered rocks. Classification of the samples has been done by macroscopic observation of the mineral assemblages. Fields of fresh volcanic rocks are from Gifkins et al. (2005). Main metamorphic minerals present at Lalor have been plotted. Abbreviation: CCPI = chlorite-carbonate-pyrite index ($100 \cdot (\text{MgO} + \text{FeO}) / (\text{MgO} + \text{FeO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$).

cession as well as post-VMS dykes and rocks of the Western and Balloch volcanic successions. The Ca chemical association is evidenced by pervasive layers of epidote and quartz with a halo rich in Ca-amphibole (hornblende to tschermakite series) that is generally developed after biotite. Veins of grossular, epidote, quartz, diopside, anhydrite, and/or calcite can be present in the centre of diffuse bands of Ca-rich alteration. The Ca-metasomatism tends to lower the alteration index ($\text{AI} = 100 \cdot (\text{MgO} + \text{K}_2\text{O}) / (\text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO})$) and increase the chlorite-carbonate-pyrite index ($\text{CCPI} = 100 \cdot (\text{Mg} + \text{FeO}) / (\text{MgO} + \text{FeO} + \text{Na}_2\text{O} + \text{K}_2\text{O})$) of affected rocks (Fig. 6), and it can be differentiated from the other VMS-related alteration styles on this basis.

Although intensely altered rocks largely predominate in the Lalor footwall, weakly to moderately altered rocks are locally present. They typically have preserved volcanic textures, such as feldspar phenocrysts

or phenoclasts. West of the deposit, these rocks are composed of quartz, feldspar, and biotite with variable abundances of muscovite, kyanite, and sillimanite. Tschermakite-series amphibole is present in mafic rocks; felsic rocks are richer in quartz. Despite moderate to strong alteration effects, in the deep footwall of the deposit, quartz-biotite-garnet-feldspar-altered rocks contain preserved textures of the primary volcanic rocks, such as volcanic lithic fragments.

Deformation and Metamorphism

The Lalor deposit has been affected by polyphase deformation (Kraus and Williams, 1999) and metamorphism up to amphibolite-grade (Menard and Gordon, 1997), which have had a major effect on the distribution, geometry, mineralogy, and textures of the ore zones and their host rocks (Caté et al., 2014a,b).

Main Structural Features and Structural Controls on the Geometry of the Ore Lenses and the Associated Footwall Alteration Zones

The Lalor volcanic succession is bounded at its top and to the west by structural contacts that probably formed early in the deformation history (pre- D_2 ; Caté et al., 2014b). The Lalor-Chisel contact is overprinted by the main S_2 foliation. The contact truncates the unaltered mafic volcanoclastic rocks at the top of the Lalor volcanic succession and cuts the units of the Balloch volcanic succession at a high angle (Fig. 5). The host deposit succession is bounded to the west by the Lalor West fault. This structural contact is folded by F_2 folds (Figs. 2 and 5), and displays evidence of further syn- to late- D_2 ductile shearing along the F_2 fold limbs (Caté et al., 2014b). The Lalor West fault is a sharp contact between strongly to intensely altered volcanic rocks of the Lalor volcanic succession and least (weakly) altered rocks of the Western volcanic succession. These major contacts predate main deformation (D_2 , see below) and may result from syn- D_1 fold-and-thrust-style deformation, from an early (maybe synvolcanic) extension episode, or from the combination of both deformation styles.

Structural features associated with the D_1 deformation have been largely obliterated by the subsequent deformation events (Kraus and Williams, 1999; Caté et al., 2014b). Preserved structures (S_1 foliation and F_1 folds) are generally transposed into the S_2 fabric, forming a composite S_{1-2} fabric, except in some F_2 fold hinge areas (Caté et al., 2014b).

The main deformation event in the Lalor deposit area is D_2 . Tight to isoclinal, southwest-verging, inclined F_2 folds are common (Fig. 4e). A penetrative S_2 foliation (Fig. 4f) has developed everywhere and affects most of the phyllosilicate minerals (biotite, muscovite, and chlorite). A mineral and stretching lin-

eation (L_2) is associated with S_2 and affects the phyllosilicate and some of the amphibole minerals. Shear zones have been mapped underground (Caté et al., 2014b), and they appear to be syn- to late- D_2 , but their kinematics and exact timing within D_2 remain unclear. Ore zones have been folded during D_2 deformation, transposed parallel to the S_2 foliation, and stretched parallel to the L_2 lineation (Caté et al., 2014b). Some base metal ore lenses are probably the result of structural dismemberment and stacking during F_2 folding and syn- to late- D_2 shearing/transposition.

The D_3 deformation event produced large open to locally tight upright folds (F_3) that locally affect the orientation of older features (Fig. 4f) without having a major effect at the deposit scale. An axial planar S_3 crenulation cleavage is developed in some muscovite or chlorite schists (Fig. 4f). The ore lenses are affected by broad, open F_3 folds (Caté et al., 2014b). Regional D_4 deformational effects have not been recorded in the rocks of the Lalor area.

Ore Remobilization during Metamorphism

As presented above, the geometry of ore lenses is structurally controlled by the D_2 and D_3 deformation events. The ductile behaviour of many sulphides during deformation (Kelly and Clark, 1975 and references therein) resulted in the local mechanical remobilization of sphalerite, chalcopyrite, and pyrrhotite in piercement structures, necks of boudinaged dykes, or fold hinges (Caté et al., 2014b,d). Sulphide-poor Au-Ag-Pb-Cu mineralization occurs in unaltered rocks close to massive sulphide mineralization (mafic dykes that crosscut the massive sulphides and least altered basalt in structural contact with massive sulphides). This mineralization comprises galena, chalcopyrite, pyrrhotite, pyrite, sulphosalts, and local minor arsenopyrite; it occurs in S_2 -folded veinlets and in microfractures that crosscut the S_2 foliation, or in fractures in porphyroblasts (e.g. amphibole, Fig. 4g; Caté et al., 2014d). The sulphide-poor Au-rich ore zones are characterized by a similar Au-Ag-Pb-Cu association (Duff et al., 2015) and mineralization is preferentially located in narrow (<3 mm) fractures in more competent amphibole-rich mineral assemblages or in syn- to late- D_2 quartz veins, actinolite layers, and Ca-rich metasomatized rocks (Fig. 4g,h).

DISCUSSION

Stratigraphic Setting of the Lalor Deposit

The Lalor volcanic succession comprises numerous volcanic and subvolcanic units with mafic to felsic compositions and tholeiitic to calc-alkaline affinities (Fig. 3; Caté et al., 2014a). The bulk of the intensely hydrothermally altered rocks are located below the Zn-rich sulphide lenses, and this altered volume of rocks is

the discordant footwall feeder pipe of the VMS system; whereas the Zn-rich ore lenses are the massive sulphide mineralization deposited at or below the seafloor. This overall geometry indicates that the Lalor volcanic succession, as a whole, is not overturned (Caté et al., 2014a), although there is likely structural complexity within the package and elucidating this is the subject of ongoing study. The lowermost Zn-rich massive-sulphide ore lenses (e.g. 20, 31, 32, and 40 lenses) are hosted in the felsic unit F2, whereas the uppermost lenses (e.g. 10 and 11 lenses) are hosted in the overlying mafic unit M1b. These massive sulphide bodies were most probably emplaced at or very near the paleo-seafloor. Thus, the formation of the Lalor deposit resulted either from two (or more) successive mineralizing events or more likely from protracted VMS-related hydrothermal activity that ceased during unit M1b (Caté et al., 2014a).

The trace element signatures of the various units of the Lalor volcanic succession are similar to those of units in the Lower Chisel subsequence (Caté et al., 2014a), and chemostratigraphic units M1 (a and b) and F2 may correspond to the Moore basalt and associated mafic volcanoclastic rocks, and to the Powderhouse dacite, respectively. Both the Moore basalt and Powderhouse dacite are present in the footwall of most of the other VMS deposits of the Chisel sequence (Bailes and Galley, 1996). Contrary to the Chisel, Chisel North, Ghost, and Lost VMS deposits host succession, there is no equivalent to the Threehouse mafic volcanoclastic rocks that conformably overlie the Lalor deposit. However, Threehouse-like dykes cut the Lalor volcanic succession, which suggests the presence of the Threehouse unit higher in the now truncated volcanic succession (Caté et al., 2014a). Therefore, the Lalor deposit is thought to be within the Lower Chisel subsequence (Caté et al., 2014a), and not at the contact between the Lower and Upper Chisel subsequences (i.e. at a slightly lower stratigraphic position than the other VMS deposits of the Chisel sequence).

Hydrothermal Setting of the Lalor Deposit

The Lalor deposit formed from hydrothermal fluids that circulated in the host volcanic pile and deposited massive sulphides at or very near the paleo-seafloor. The VMS-associated hydrothermal alteration was subsequently metamorphosed during deformation, resulting in the development of metamorphic mineral assemblages that largely reflect the bulk geochemical compositions of the initial alteration styles (Caté et al., 2014c). The wide variety of metamorphic mineral assemblages and their associated bulk geochemical compositions can be translated into, and mapped as, chemical associations to determine the primary alteration styles and their zonation (Caté et al., 2014c); this

allows for a better understanding of the primary geometry of the ore-forming system.

The uppermost Zn-rich massive-sulphide lenses (10 lens; Fig. 5) are mainly associated with the low-temperature K chemical association, whereas the lowermost massive-sulphide lenses (20 lens; Fig. 5) are dominantly associated with the high-temperature Mg-Ca and Mg-Fe chemical associations. The different alteration styles of the two groups of Zn-rich massive-sulphide lenses may indicate that these Zn-rich ore lenses formed in distinct hydrothermal environments and that they are stratigraphically (i.e. not structurally) stacked.

The Au-rich sulphide-poor ore lenses are dominantly associated with rocks attributed to the Mg-Ca chemical association, and to a lesser extent to rocks attributed to the Mg-Fe chemical association (Fig. 5), or to rocks unaffected by the VMS alteration but which are proximal to massive sulphide lenses. This could imply (1) the Au-rich ore lenses are syn-VMS and formed in primary alteration zones corresponding to the Mg-Ca chemical association (together with some syn-metamorphic remobilization) or (2) the rocks of the Mg-Ca chemical association are chemically and/or rheologically favourable host rocks for Au-rich mineralization emplaced during metamorphism by remobilization of metals present in the syn-VMS sulphide-rich ore lenses (Caté et al., 2014c).

The Cu-Au ore lenses occur in rocks of the high-temperature Mg-Fe chemical association (Fig. 5). These rocks correspond to a metamorphosed intense chloritic alteration that is generally present in the footwall alteration pipe of most VMS deposits. Thus, we interpret the Cu-Au mineralization to be the deformed equivalent of the high-temperature stringer zone located in the footwall of VMS deposits (Franklin, 1993).

The presence of actinolite-rich layers (part of the Mg-Ca chemical association) that overprint the Mg-Ca and less commonly the K, K-Mg-Fe, and Mg-Fe chemical associations, and Ca-rich metasomatism during deformation and metamorphism shows that, despite an overall preservation of the pre-metamorphism bulk-rock geochemical compositions, syn-metamorphic metasomatism locally occurred and led to changes in the bulk geochemical compositions and textures of the metamorphosed altered rocks. Moreover, the circulation of H₂O- and CO₂-rich fluids during metamorphism (Tinkham, 2013) may have remobilized Au along with minor amounts of Pb, Cu, Zn, and Ag.

Remobilization of Au and Formation of Au-rich Ore Lenses

Gold-rich sulphide-poor mineralization at Lalor occurs dominantly in rocks of the Mg-Ca chemical associa-

tion. However, several Au-rich mineralization occurrences are situated in rocks of the Mg-Fe chemical association and rocks unaffected by the VMS-related alteration, including post-VMS mafic dykes that cross-cut the sulphide lenses. Moreover, Au-rich mineralization preferentially occurs in competent amphibole-rich rocks, and ore textures suggest that the timing of this mineralization is late- to post-D₂. Collectively this indicates that the Au-rich, sulphide-poor mineralization was formed, at least in part, by the remobilization of Au along with minor amounts of Ag, Zn, Cu, and Pb during deformation and metamorphism. The scale of this remobilization remains unresolved, but it may have been in the range of centimetres to tens of metres. Importantly, Au-rich, sulphide-poor ore zones are always located in close proximity (within tens of metres) to VMS mineralization, and are entirely enclosed in the intensely altered footwall halo, which suggests that the Au was introduced into the rocks as part of the VMS-forming hydrothermal system. The Au-rich sulphide-poor ore zones may be the result of a pre-deformation, epithermal-style overprint on the VMS system, but most of the diagnostic characteristics of epithermal systems are lacking. The confinement of the Au mineralization within the VMS system also indicates that the bulk of the Au input probably occurred during the formation of the VMS deposit and not during metamorphism.

Various processes can lead to the remobilization of Au during metamorphism (Tomkins, 2007). At Lalor, Au-rich sulphide-poor mineralization is characterized by a specific metallic association (Duff et al., 2013, 2015). Specific mineral assemblages attributed to syn-deformation metamorphic metasomatism are commonly associated with Au mineralization (actinolite-rich layers of the Mg-Ca chemical association or Ca-rich metasomatism; Caté et al., 2014b,c); however, this association is not systematic (universal) and this could be due to the more competent nature of these amphibole-rich mineral assemblages. Moreover, the presence of sulphosalts in the Au mineralization indicates that the remobilization may have (partly or wholly) occurred during sulphide anatexis (Frost et al., 2002; Tomkins et al., 2006). However, hydrothermal remobilization may also have been important, and further work is needed to assess the contribution of the various remobilization processes.

IMPLICATIONS FOR EXPLORATION

The results presented here have various implications for mineral exploration at the deposit to regional scales, not only at Lalor but also elsewhere in metamorphosed volcanic belts. Prospectivity in the Chisel sequence is not limited to the Lower – Upper Chisel subsequences contact (Caté et al., 2014a). As in other districts (e.g.

Blake River Group: McNicoll et al., 2014), VMS deposits can occur at multiple stratigraphic levels in the Snow Lake camp. Volcanogenic massive sulphide deposits in the Chisel sequence are not necessarily preferentially associated with felsic volcanic rocks (e.g. Chisel, Chisel North, Ghost, Lost, and Photo deposits and Lalor lowermost lenses; Bailes and Galley, 1996; Caté et al., 2014a), but can be associated with mafic volcanic rocks (Lalor uppermost lenses; Caté et al., 2014a).

The bulk geochemical compositions of hydrothermally altered rocks have undergone only minor and local changes during post-ore deformation and metamorphism, and exploration vectors adapted from less metamorphosed rocks can be applied to deposits metamorphosed at amphibolite grade (e.g. Caté et al., 2014c). Moreover, the $\delta^{18}\text{O}$ signature of the hydrothermally altered rocks has been preserved through metamorphism and can be used as an exploration vector toward high-temperature reaction zones (Mercier-Langevin et al., 2014).

The presence of atypical metamorphic mineral assemblages (metamorphosed hydrothermally altered volcanic rocks), and changes in the nature and relative abundance of metamorphic minerals can be used to vector toward mineralization (Caté et al., 2014c). The wide variety of mineral assemblages and their coarse-grained nature allows for a better identification of the variations in primary alteration styles and paleo-hydrothermal alteration pathways in the field (Galley et al., 1993). The use of geochemistry and mineralogy (chemical association) can further help navigate within paleo-hydrothermal systems.

The present-day geometry of the Lalor deposit is dominantly structurally controlled by the D_2 deformation (Caté et al., 2014b,d), and the local D_2 foliation and stretching lineation must be taken into account at all scales. Moreover, local mechanical remobilization of ductile ore minerals (e.g. sphalerite and chalcopyrite) occurred, and led to the formation of structurally controlled mineralization at various scales.

The Au-rich zones result predominantly from local metamorphic remobilization of Au, most likely from the primary VMS mineralization (Caté et al., 2014d). The silicate gangue minerals are probably not genetically associated with the Au mineralization but likely served as a competent trap for locally remobilized Au. Exploration for Au-rich ore zones in VMS deposits affected by high-grade metamorphism should not be restricted to rocks affected by intense hydrothermal alteration, and drilling should be extended around the main massive sulphide bodies as shown by the presence of Au-rich sulphide-poor zones at Lalor.

FUTURE WORK

Results presented here are part of an ongoing Ph.D. thesis project by the senior author. Current and future work include the following: 1) a complete structural analysis of the deposit host sequence and structural influences on the geometry of the ore lenses and distribution of metals; 2) a 3-D reconstruction of the volcanic architecture and hydrothermal alteration system; and 3) the integration of all available data and information to complete a genetic model of the deposit, including the timing and processes of Au enrichment.

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