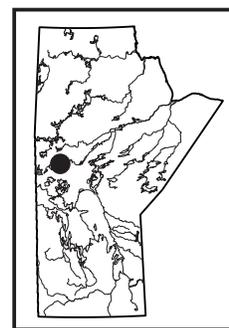


GS-7 Whole-rock oxygen-isotope mapping of the footwall alteration zones at the Lalor auriferous VMS deposit, Snow Lake, west-central Manitoba (NTS 63K16)

by P. Mercier-Langevin¹, A. Caté² and P.-S. Ross²



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Summary

The Paleoproterozoic Lalor auriferous volcanogenic massive-sulphide (VMS) deposit (25.3 Mt grading 2.9 g/t Au, containing ~70 t Au) is the largest and richest VMS deposit of the Snow Lake camp. The deposit has been intensely deformed and metamorphosed to amphibolite facies, and is associated with a transposed zone of intense footwall alteration that extends hundreds of metres underneath and laterally away from the stacked ore lenses. Whole-rock oxygen-isotope mapping of the footwall mineralogical alteration assemblages and related chemical associations indicates a partly transposed, laterally extensive, high-temperature ($\leq 350^{\circ}\text{C}$, $\delta^{18}\text{O} \leq 6\text{‰}$) reaction zone. There is a direct correlation between the $\delta^{18}\text{O}$ signature and the intensity of the alteration at Lalor, suggesting that whole-rock oxygen isotopes were not reset during metamorphism, and that they can be used to vector toward ore.

Introduction

The Paleoproterozoic Lalor volcanogenic massive-sulphide (VMS) deposit has combined reserves and resources estimated at 25.3 Mt of ore averaging 5% Zn, 0.79% Cu, 2.9 g/t Au and 25 g/t Ag (HudBay Minerals Inc., 2014), and thus potentially containing more than 70 t Au, making it the largest and richest VMS deposit of the Snow Lake camp. The Lalor deposit therefore belongs to a subgroup of large, precious metal-enriched VMS deposits (cf. Mercier-Langevin et al., 2011). Such deposits represent prime exploration targets, as they usually combine large amounts of base metals and important concentrations of precious metals, making for particularly profitable mining operations. However, these deposits also represent challenging exploration targets, as the precious metal-enrichment processes and their diagnostic characteristics are complex and variable, and often difficult to translate into exploration guides. Moreover, significant deformation and metamorphism are commonly superimposed on these deposits, making it difficult to recognize primary relationships and patterns, and thus identify prospective targets.

In 2011, the Geological Survey of Canada, in collaboration with the Manitoba Geological Survey, HudBay

Minerals Inc., the Institut national de la recherche scientifique–Centre Eau Terre Environnement and the University of Ottawa, initiated a research project at Lalor as part of Natural Resources Canada’s Targeted Geoscientific Initiative 4 program (VMS project). This research activity, which comprises a Ph.D. study (geology of the Lalor deposit) and an M.Sc. study (ore mineralogy and geochemistry), aims to define the geological and structural setting of the deformed and metamorphosed Lalor VMS deposit, its hydrothermal signature, the relative timing of events and the genesis of the base and precious metal-rich mineralization.

Geological setting

The Flin Flon belt, which is about 200 km in strike length and 70 km in width, is part of the juvenile internal portion of the Trans-Hudson orogen (Corrigan et al., 2009). The belt is bordered to the north by high-grade paragneiss and granitoid rocks of the Kisseynew domain and overlain to the south by Paleozoic sedimentary rocks. The Flin Flon belt is divided into three distinct areas: the western Hanson Lake block, the central Amisk collage and the eastern Snow Lake allochthon (Galley et al., 2007). The belt consists of accreted 1.92–1.88 Ga arc and ocean-floor assemblages, postaccretion 1.87–1.83 Ga successor-arc assemblages and related plutons, broadly syncollisional 1.85–1.83 Ga sedimentary rocks, and 1.82–1.76 Ga syn- to postcollision granites (David et al., 1996; Lucas et al., 1996; Syme et al., 1996; Zwanzig, 1999). These assemblages represent juvenile and continentally underlain oceanic segments, accreted during the Trans-Hudson orogen, that formed by collision between the Superior and Hearne cratons (Galley et al., 2007 and references therein).

The 1.89 Ga Snow Lake arc assemblage represents the easternmost segment of the Flin Flon belt and can be subdivided into three conformable volcanic sequences (Figure GS-7-1) that record discrete evolutionary stages (Bailes and Galley, 1999): 1) nascent or primitive arc (Anderson sequence); 2) mature arc (Chisel sequence); and 3) arc rift (Snow Creek sequence).

¹ Natural Resources Canada, Geological Survey of Canada, 490 rue de la Couronne, Québec, QC G1K 9A9

² Institut national de la recherche scientifique–Centre Eau Terre Environnement, 490 rue de la Couronne, Québec, QC G1K 9A9

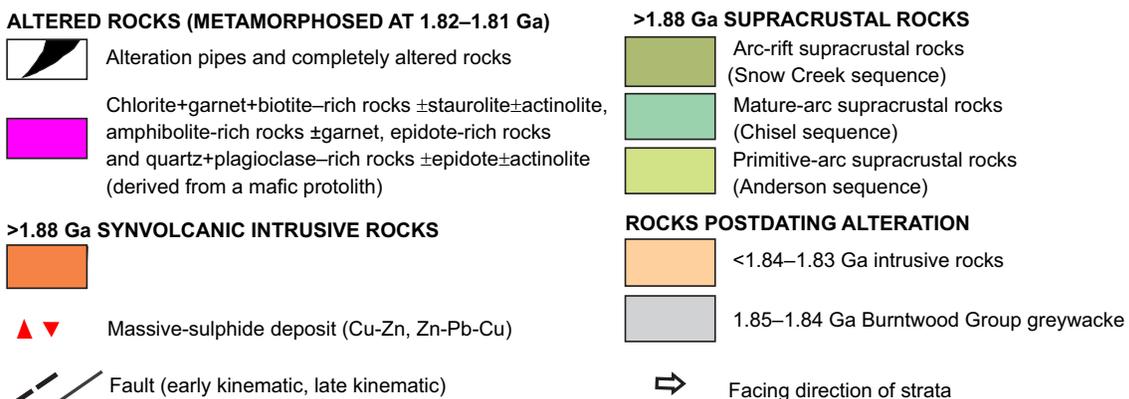
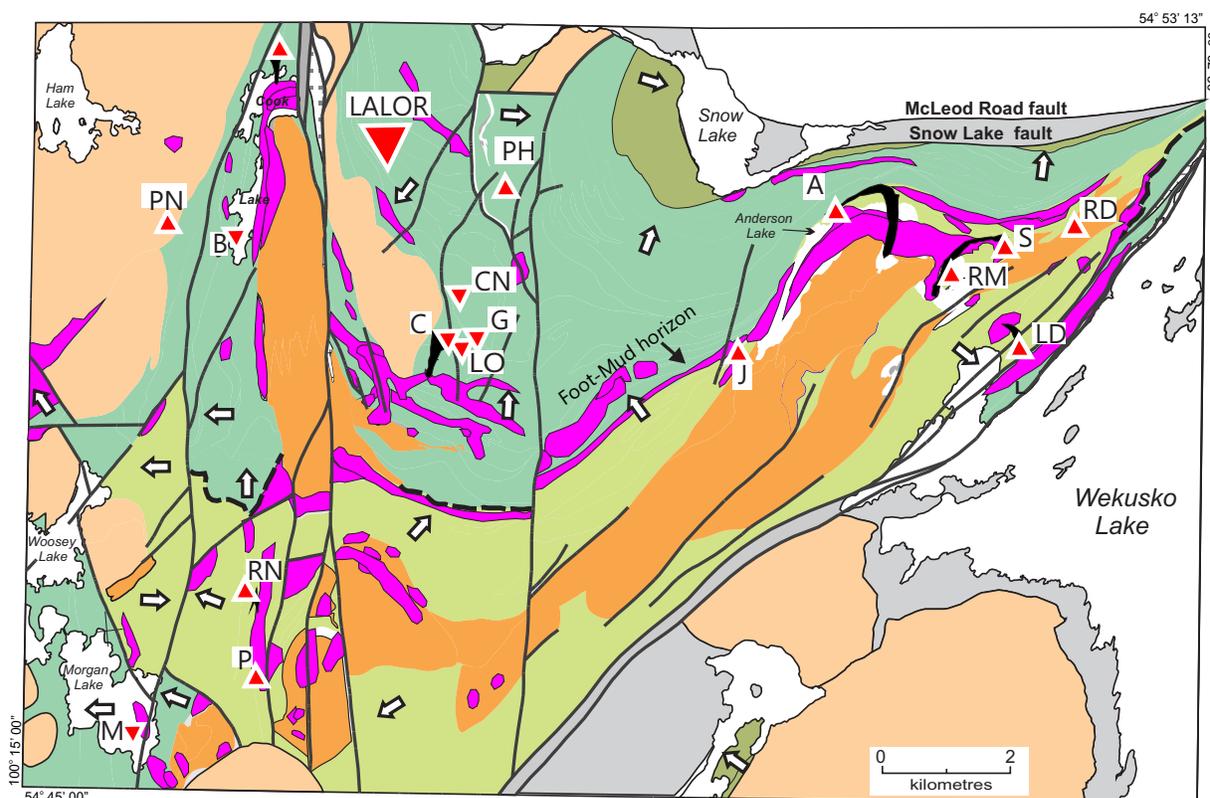


Figure GS-7-1: Simplified geology of the Snow Lake area, showing major alteration zones and VMS deposits, including the Lalor deposit (Galley et al., 2007). Abbreviations: A, Anderson; B, Bomber zone; C, Chisel Lake; CN, Chisel North; G, Ghost; J, Joannie zone; LO, Lost; LD, Linda zone; M, Morgan Lake zone; P, Pot Lake zone; PH, Photo Lake; PN, Pen zone; RD, Rod; RM, Ram zone; RN, Raindrop zone; S, Stall Lake.

The Anderson primitive-arc sequence consists largely of tholeiitic-arc basalt and basaltic andesite with isolated lobe-hyaloclastite rhyolitic complexes. The volcanic rocks were intruded by the Sneath Lake subvolcanic pluton. Copper-rich, bimodal mafic-type VMS deposits, including the Anderson Lake and Stall Lake deposits, are associated with the rhyolite complexes (Bailes and Galley, 1999; Galley et al., 2007).

The Chisel mature-arc sequence, which is about 3 km thick, conformably overlies the Anderson sequence. The Chisel sequence consists of intercalated, geochemically

fractionated, intermediate to mafic flows, turbiditic heterolithic volcanoclastic (debris flow) 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 hangingwall Threehouse basalt and volcanoclastic rocks (Galley et al., 2007), which marks the transition between the lower and upper parts of the Chisel sequence. This contact is interpreted as conformable (e.g., Engelbert et al., 2014) but appears to have been tectonized locally (i.e., Chisel-Lalor thrust; Bailes, unpublished report prepared for HudBay Minerals Inc., 2011). The Lalor deposit is also thought to be situated at this contact (Bailes et al., 2013), based on geochemical similarities between the Lalor footwall rocks and the footwall rocks at Chisel and Chisel North (Bailes, unpublished report prepared for HudBay Minerals Inc., 2009). However, detailed studies suggest some differences between the footwall successions at Lalor and those of other VMS deposits in the lower Chisel sequence (Bailes et al., 2013; Caté et al., 2013a, b, in press; Caté et al., GS-8, this volume).

The Chisel sequence is overlain by massive basalts and gabbro sills of the Snow Creek sequence that show an affinity to normal mid-ocean-ridge basalt and are interpreted to mark the end of arc volcanism and the beginning of arc rifting (Figure GS-7-1; Bailes and Galley, 1999). The Snow Creek sequence contains no VMS deposits or occurrences.

The Snow Lake arc assemblage is affected by at least four episodes of deformation, three of which are recognized in the Snow Lake area (Galley et al., 1993). The deformation events are related to fold-and-thrust-style stacking and interleaving of volcanic assemblages and younger sedimentary rocks of the Kisseynew domain during the Trans-Hudson orogeny (Kraus and Williams, 1999). The D_1 and D_2 events produced tight, isoclinal, south-verging folds; shallowly dipping thrusts; and the main foliation (Kraus and Williams, 1999; Bailes et al., 2013). These structures are refolded by north-northeast-trending F_3 folds and an associated S_3 crenulation cleavage (Martin, 1966; Kraus and Williams, 1999). The F_4 folds with east-trending axes locally overprint F_3 folds (Kraus and Williams, 1999).

In the Lalor deposit, D_{1-2} and D_3 structures largely control the geometry of the ore lenses. A detailed analysis of the main structural features at Lalor is underway as part of the current project, and preliminary results and interpretations are presented in Caté et al. (GS-8, this volume), to which readers are referred for more information.

The Chisel sequence hosts large, conformable to discordant, distal to proximal, synvolcanic alteration zones associated with Zn-rich VMS deposits (Galley et al., 2007). Regional (camp-scale) whole-rock oxygen mapping indicates that a high-temperature reaction zone ($\geq 300^\circ\text{C}$, $\delta^{18}\text{O} \leq 6\text{‰}$) coincides with subconcordant to discordant assemblages of metamorphic minerals, including varying amounts of staurolite, garnet, kyanite, Ca- and Fe-Mg-amphibole, biotite, cordierite, muscovite, Ca-plagioclase, gahnite and chlorite, in the footwall of the VMS

deposits of the Chisel sequence. The hangingwall rocks are characterized by a pronounced, low-temperature reaction zone ($\leq 250^\circ\text{C}$, $\delta^{18}\text{O} \geq 9\text{‰}$; Taylor and Timbal, 1998) that includes unaltered and muscovite±biotite-bearing rocks. The Chisel, Chisel North, Lost and Ghost deposits occur near the transition between high- and low-temperature reaction zones (Taylor and Timbal, 1998).

Geology of the Lalor deposit

The Lalor deposit consists of a number of distinct, stratigraphically and structurally stacked ore lenses (Caté et al., GS-8, this volume). The ore lenses comprise disseminated, semimassive and massive sulphides. These lenses are located in the uppermost section of a volcanic succession that contains intense hydrothermal alteration (Lalor volcanic succession; Figure GS-7-2; Caté et al., in press). The hydrothermal alteration was metamorphosed to amphibolite facies during D_{1-2} (Lam et al., 2013, 2014; Tinkham, 2013). Volcanic units in the host succession are generally oriented parallel to the main S_{1-2} foliation and dip to the northeast (Figure GS-7-2; Caté et al., GS-8, this volume). The hangingwall rocks are part of a separate volcanic succession (Balloch volcanic succession; Figure GS-7-2) that dips steeply toward the northeast (Bailes, unpublished reports prepared for HudBay Minerals Inc., 2008, 2011). The contact between these successions is structural at Lalor and dips shallowly ($<10^\circ$) toward the north-northeast, possibly representing an extension of the Chisel-Lalor thrust (Bailes et al., 2013; Caté et al., 2013a, b; Caté et al., GS-8, this volume; Engelbert et al., 2014; Gibson et al., 2014). The Lalor volcanic succession and its footwall alteration zone are structurally bounded to the west by the Western volcanic succession (Figure GS-7-2; Caté et al., GS-8, this volume), which appears to be of a different composition and much less altered than the Lalor volcanic succession (Caté et al., in press). The Lalor volcanic succession consists of at least five compositionally distinct, volcanic to volcanoclastic±intrusive units that are, for the most part, very intensely altered (Figure GS-7-2).

Syn- to late- D_2 peak amphibolite-grade metamorphism (Zaleski et al., 1991; Menard and Gordon, 1997) is responsible for the preferential development of various metamorphic-mineral assemblages in the hydrothermally altered rocks. The presence and abundance of key minerals, such as muscovite, Mg-Fe-amphibole, chlorite, cordierite, Ca-amphibole and carbonate, were used to define metamorphic-mineral assemblages and alteration zones. The mineral assemblages and the relative abundance and composition of specific minerals in those assemblages can be correlated with whole-rock lithochemistry to define specific chemical associations and to identify zonation within the alteration halo. These chemical associations result from hydrothermal alteration and subsequent metasomatism during metamorphism (Menard and Gordon, 1997; Tinkham, 2013; Caté et al., in press).

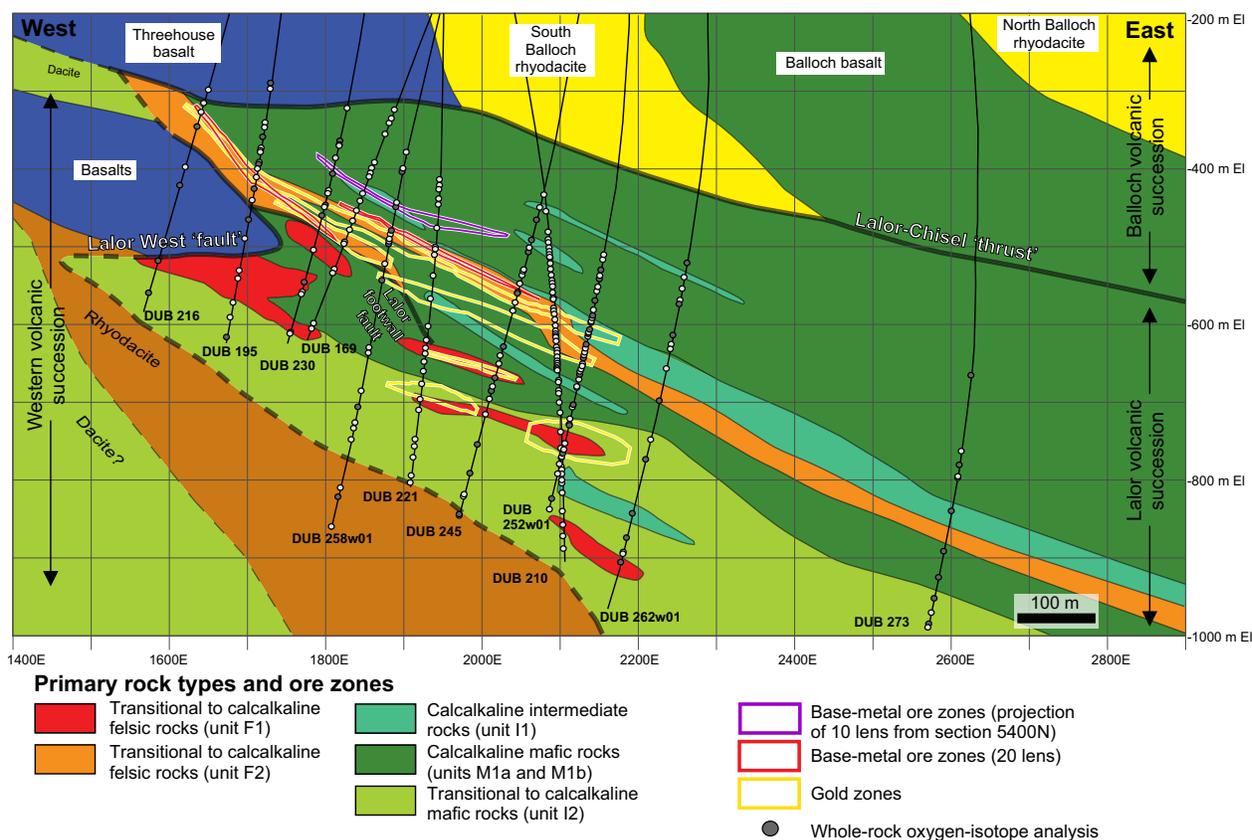


Figure GS-7-2: Simplified geological cross-section 5600N (looking northwest) of the Lalor deposit. Ore-zone shapes are as determined by HudBay Minerals Inc.; 10 lens is projected from section 5500N. Unit names in the Balloch volcanic succession are from Bailes (unpublished report prepared for HudBay Minerals Inc., 2008). Traces of the sampled drillholes are shown, with the location of the analyzed samples marked by grey dots along the sampled drillholes.

Five distinct chemical associations were defined in the Lalor alteration system (Caté et al., 2013a, b): K, K-Fe-Mg, Mg-Fe, Mg-Ca and Ca. Each of these chemical associations correlates with distinct metamorphic-mineral assemblages that reflect variations in the litho-geochemistry. Transitions from one association to the next can be gradational or sharp. The K chemical association, characterized by >5% muscovite with some biotite, kyanite, sillimanite and quartz±pyrite, is present mainly in the uppermost part of the deposit in association with the upper base-metal-rich, massive-sulphide lenses. The K-Fe-Mg chemical association (biotite, kyanite, sillimanite, staurolite±garnet and pyrite) is present in both the upper part of the deposit and the extensive footwall alteration zone. The Mg-Fe chemical association, defined by the presence of Mg-Fe–amphiboles (anthophyllite-cummingtonite series), chlorite and/or cordierite with garnet, staurolite and quartz±talc, is present mainly in the extensive footwall alteration zone. The Mg-Ca chemical association, which is heterogeneously distributed in the footwall of the Lalor ore lenses, is characterized by variable amounts of Mg-chlorite, Ca-amphiboles (mainly actinolite series), carbonates (calcite and/or dolomite),

Ca-plagioclase, biotite, quartz and talc. The Ca association, which is present in the footwall succession as well as in the Balloch and Western volcanic successions, overprints the other alteration assemblages and associations. The Ca association is characterized by the presence of carbonates, diopside, Ca-amphiboles, epidote and grossular (Caté et al., in press).

Whole-rock oxygen-isotope mapping

Analytical procedures

Whole-rock oxygen-isotope compositions were determined at the Laboratory for Stable Isotope Science at Western University (UWO), London, Ontario. Results are reported in the usual δ notation in parts per thousand (per mil or ‰), relative to Vienna standard mean ocean water (VSMOW). Oxygen was extracted from silicates and oxides using the BrF_5 method of Clayton and Mayeda (1963) and converted quantitatively to CO_2 over red-hot graphite. The oxygen-isotope composition of the evolved CO_2 was calculated using a phosphoric acid- CO_2 fractionation factor of 1.01025 (Sharma and Clayton, 1965).

The $^{18}\text{O}/^{16}\text{O}$ ratio was measured using an Optima, triple-collecting, dual-inlet, stable-isotope-ratio mass spectrometer. Precision was better than $\pm 0.31\text{‰}$ (average $\pm 0.15\text{‰}$). Laboratory reference materials calibrated to VSMOW were accurate to $\pm 0.02\text{‰}$.

Results

Whole-rock $\delta^{18}\text{O}$ values were obtained for 63 samples representing the different alteration assemblages and rock units, including ‘least-altered’ rocks, in the footwall and hangingwall of the Lalor deposit along section 5600N (Figure GS-7-3). Whole-rock oxygen-isotope signatures are preserved at amphibolite-grade metamorphism provided the water:rock ratio remained low during metamorphism (Campbell and Larson, 1998; Taylor and Timbal, 1998; Heinrich et al., 1999), which appears to have been the case for the Lalor deposit. Values of $\delta^{18}\text{O}$ for all rock and alteration types at Lalor range from 3.68 to 9.97‰ (Figure GS-7-3).

The $\delta^{18}\text{O}$ values for ‘least-altered’ rocks range from 5.44 to 9.40‰ ($n = 16$; Figure GS-7-4), which represents a slightly larger variation than expected for fresh intermediate to felsic volcanic rocks. This suggests that even rocks that are considered ‘least-altered’ were affected to some degree by hydrothermal alteration, either at low

temperature and high water:rock ratio, or at high temperature and low to moderate water:rock ratio. Except perhaps for two samples from drillholes DUB216 and DUB195 (Figures GS-7-2, -3) in the Western volcanic succession and one sample from drillhole DUB195 in the Balloch volcanic succession (Figures GS-7-2, -3), all samples in this study were collected in proximity to the ore zones (footwall and hangingwall) and therefore probably within the alteration halo of the deposit. The three samples from the Western and Balloch volcanic successions have normal $\delta^{18}\text{O}$ values that range between 6 and 7‰. The $\delta^{18}\text{O}$ values for rocks of the K chemical association range from 5.27 to 6.66‰ ($n = 3$; Figure GS-7-4), suggesting that the hostrocks interacted with moderate-temperature, neutral to weakly acidic and reduced hydrothermal fluids ($\sim 200\text{--}250^\circ\text{C}$) at water:rock ratios between 0.5 and 5 (Figure GS-7-5).

The $\delta^{18}\text{O}$ values for the K-Fe-Mg chemical association vary from 5.67 to 9.97‰ ($n = 10$; Figure GS-7-4), suggesting temperatures of $100\text{--}250^\circ\text{C}$ (Figure GS-7-5). The average temperature for that association may have been closer to 250°C in general, as only one sample yielded a heavy $\delta^{18}\text{O}$ signature (Figure GS-7-4). This isotopically heavy rock, characterized by the K-Fe-Mg chemical association, is in contact with sulphide ore, which suggests that this sample may have been affected

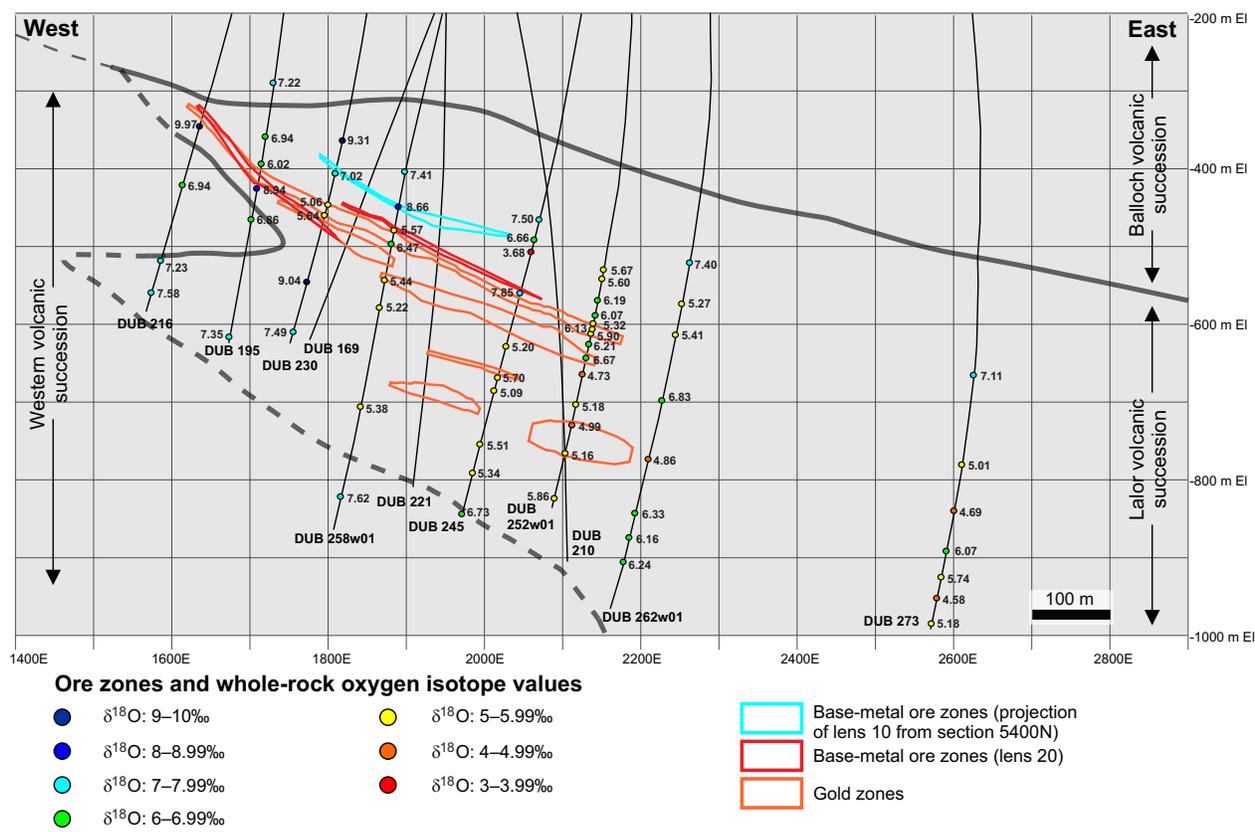


Figure GS-7-3: Section 5600N through the Lalor deposit, showing the locations and $\delta^{18}\text{O}$ values of samples ($n = 63$) obtained in this study.

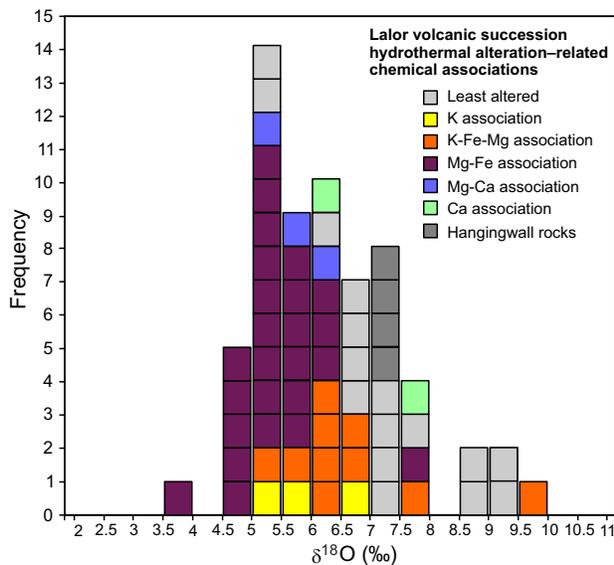


Figure GS-7-4: Histogram of whole-rock $\delta^{18}\text{O}$ values ($n = 63$) for the various hydrothermal alteration-related chemical associations in the Lalor volcanic succession.

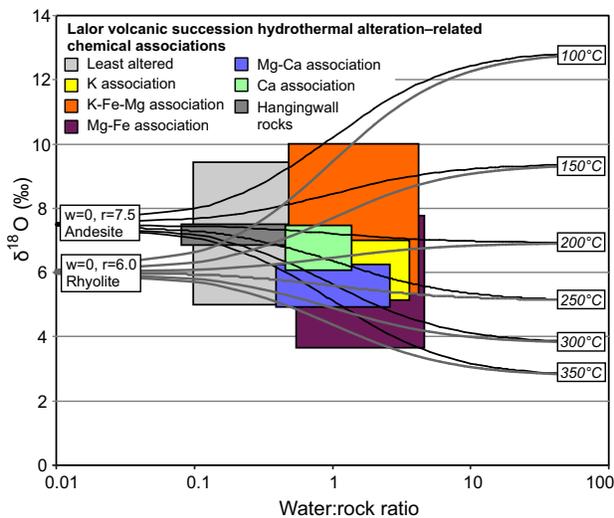


Figure GS-7-5: Plot of the final $\delta^{18}\text{O}$ values of rocks from the Lalor volcanic succession as a function of water:rock ratio. The initial water $\delta^{18}\text{O}$ value was assumed to be 0‰. The initial $\delta^{18}\text{O}$ value for felsic ('rhyolite') and intermediate to mafic ('andesite') rocks were assumed to be 6 and 7.5‰, respectively. The shaded areas represent the range of $\delta^{18}\text{O}$ values obtained for each hydrothermal alteration-related chemical association, over a range of water:rock ratios. The fractionation is calculated using the empirical rock-water fractionation proposed by Paradis et al. (1993), based on data in Harper et al. (1988).

by very low temperature ($\sim 100^\circ\text{C}$; Figure GS-7-5) alteration at or near the seafloor, or that it was overprinted by late alteration along shear zones. Oxygen-isotope values are slightly lower for the Mg-Fe chemical association, varying from 3.68 to 7.85‰ ($n = 25$; Figure GS-7-4),

requiring high-temperature alteration ($200\text{--}350^\circ\text{C}$) at high water:rock ratios (≥ 5 ; Figure GS-7-5). The lowest $\delta^{18}\text{O}$ value obtained at Lalor (3.68‰) is from this association, suggesting intense, focused hydrothermal alteration at a high temperature and water:rock ratio in the uppermost part of the footwall alteration pipe (Figure GS-7-3). Three samples from the Mg-Ca chemical association have $\delta^{18}\text{O}$ values of 5.06, 5.90 and 6.13‰, similar to those obtained from the Mg-Fe chemical association. This indicates that the Mg-Ca chemical association represents a moderate to high-temperature ($\sim 200\text{--}300^\circ\text{C}$; Figure GS-7-5) hydrothermal alteration zone at high water:rock ratios, or that it did not have a major effect on previously Mg-Fe-altered rocks. Similarly, two samples from the Ca chemical association have $\delta^{18}\text{O}$ values of 6.02 and 7.49‰, indicating that this association formed at low to moderate temperatures ($\sim 200\text{--}250^\circ\text{C}$; Figure GS-7-5), or that it only partly overprinted a previously developed alteration. The significant difference in the $\delta^{18}\text{O}$ values of these two samples supports the idea of a minor effect of Ca metasomatism on the isotopic signature of the rock. Three samples from the Balloch volcanic succession yielded values between 7.11 and 7.60‰, indicating minor, low-temperature alteration or no alteration at all. The significant overlap in the isotopic signature of all alteration-related chemical associations, including some of the 'least-altered' rocks, is due, at least in part, to the hybrid nature of many samples, as the chemical associations and mineral assemblages have gradational rather than sharp boundaries (Caté et al., in press; Caté et al., GS-8, this volume).

Preliminary interpretations

The $\delta^{18}\text{O}$ values measured for hydrothermal alteration-related chemical associations in the Lalor footwall volcanic succession indicate that the rocks were subjected to sub-seafloor alteration, likely by modified seawater, of varying intensity in terms of both temperature and water:rock ratios. There is, on average, a relatively good correlation between the Hashimoto alteration index ($\text{AI} = 100 \times [\text{MgO} + \text{K}_2\text{O}] / [\text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO}]$; Ishikawa et al., 1976) and chlorite-carbonate-pyrite index ($\text{CCPI} = 100 \times [\text{MgO} + \text{FeO}] / [\text{MgO} + \text{FeO} + \text{K}_2\text{O} + \text{Na}_2\text{O}]$; Large et al., 2001) and the $\delta^{18}\text{O}$ values; increasing alteration-index values correspond to decreasing $\delta^{18}\text{O}$ values (Figure GS-7-6). This systematic relationship indicates that the now-metamorphosed Mg-Fe, and to some extent the K-Fe-Mg, chemical associations formed at relatively high hydrothermal temperatures, whereas the K chemical association represents hydrothermal alteration at moderate to low temperatures. The Mg-Ca association represents either a high-temperature hydrothermal alteration or a late overprint of a previously Mg-Fe-altered rock. The Ca association has a mixed signature, suggesting that it either results from low to moderate temperature or overprints earlier-formed alteration without resetting

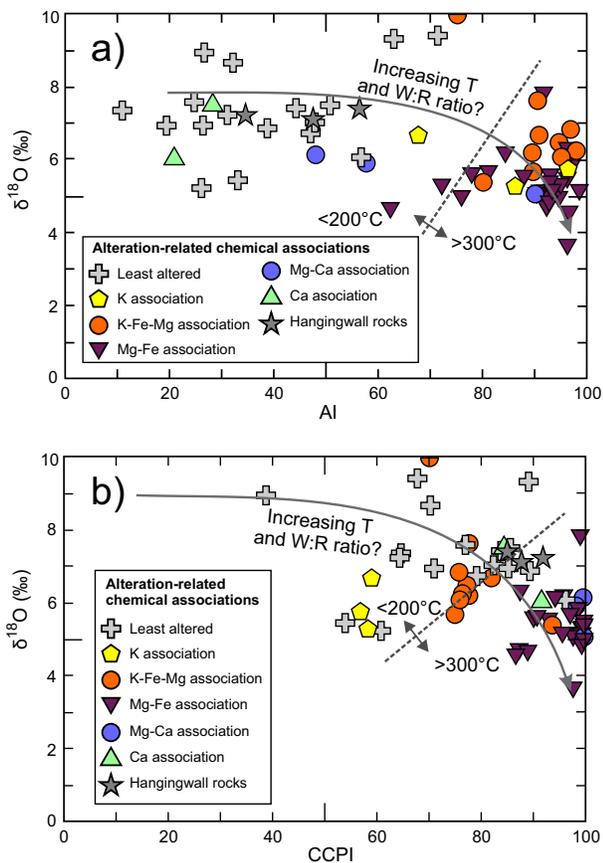


Figure GS-7-6: Plots of **a)** $\delta^{18}\text{O}$ versus AI for alteration associations in the Lalor volcanic succession; and **b)** $\delta^{18}\text{O}$ versus CCPI for alteration associations in the Lalor volcanic succession. Abbreviations: AI, Hashimoto alteration index ($= 100 \times [\text{MgO} + \text{K}_2\text{O}] / [\text{MgO} + \text{K}_2\text{O} + \text{Na}_2\text{O} + \text{CaO}]$; Ishikawa et al., 1976); CCPI, chlorite-carbonate-pyrite index ($= 100 \times [\text{MgO} + \text{FeO}] / [\text{MgO} + \text{FeO} + \text{K}_2\text{O} + \text{Na}_2\text{O}]$; Large et al., 2001); T, temperature; W:R, water:rock.

the isotopic signature completely (e.g., rock-dominated conditions).

Zones of high-temperature alteration can be traced on section 5600N by including all samples with $\delta^{18}\text{O}$ values less than or equal to 6‰ (Figures GS-7-7, -8). Similarly, zones of low temperature ($\delta^{18}\text{O}$ values equal to or greater than 9‰) can be mapped as well. All samples with $\delta^{18}\text{O}$ values varying between 6 and 9‰ are considered isotopically ‘normal’, meaning either that they were not altered or that they represent transitional areas between high- and low-temperature reaction zones, where massive-sulphide deposits would be expected (Taylor and Timbal, 1998). At Lalor, there is a very large and extensive zone of high-temperature alteration in the host succession. This high-temperature reaction zone largely mimics the distribution of the Mg-Fe footwall alteration association (Figure GS-7-7), extending for hundreds of metres beneath the deposit, and is strongly transposed parallel to the main S_{1-2} foliation. The high- and low-temperature reaction

zones appear to be largely independent of rock type (Figure GS-7-8).

Economic considerations

Despite intense, polyphase deformation and associated amphibolite-grade metamorphism, whole-rock oxygen isotopes can be used to identify and delineate paleohydrothermal upflow zones and high- versus low-temperature reaction zones in the Lalor VMS environment. The high-temperature reaction zone at Lalor, which is largely independent of protolith composition, extends for hundreds of metres in the transposed footwall succession, considerably beyond the limits of the associated ore zones. A possible implication of this is that the Lalor deposit may represent only part of a much larger system, suggesting some exploration potential along strike and at depth in the Lalor volcanic succession. There is a direct correlation between the $\delta^{18}\text{O}$ signature and the intensity of the alteration at Lalor, suggesting that whole-rock oxygen isotopes were not reset during metamorphism and that they can be used to vector toward mineralized rocks.

Data are not sufficient to speculate on the prospectivity of the Western volcanic succession, but significant tectonic transposition seems to characterize the contact between the Western and Lalor volcanic successions (Caté et al., GS-8, this volume), suggesting that some ore zones may extend beyond the area studied here.

Future work

The results of the whole-rock oxygen-isotope mapping presented here are preliminary and more work is underway as part of an ongoing Ph.D. project at Lalor to better correlate the $\delta^{18}\text{O}$ values with the precise mineral composition of the analyzed samples. A better appraisal of the potential effects of metamorphism (e.g., prograde H_2O devolatilization and associated decarbonatization and CO_2 metasomatism; cf. Tinkham, 2013) on the $\delta^{18}\text{O}$ values at Lalor has yet to be done. Some alteration assemblages may, in fact, have been produced at different times in the evolution of the deposit (e.g., Mg-Ca association); therefore, a better correlation between the whole-rock oxygen-isotope signature and the mineralogy is required. Correlation with the Au-Ag-Pb-Cu zones needs to be improved to enable a better understanding of the hydrothermal-metasomatic-metamorphic reactions involved in the genesis of these precious metal-rich zones.

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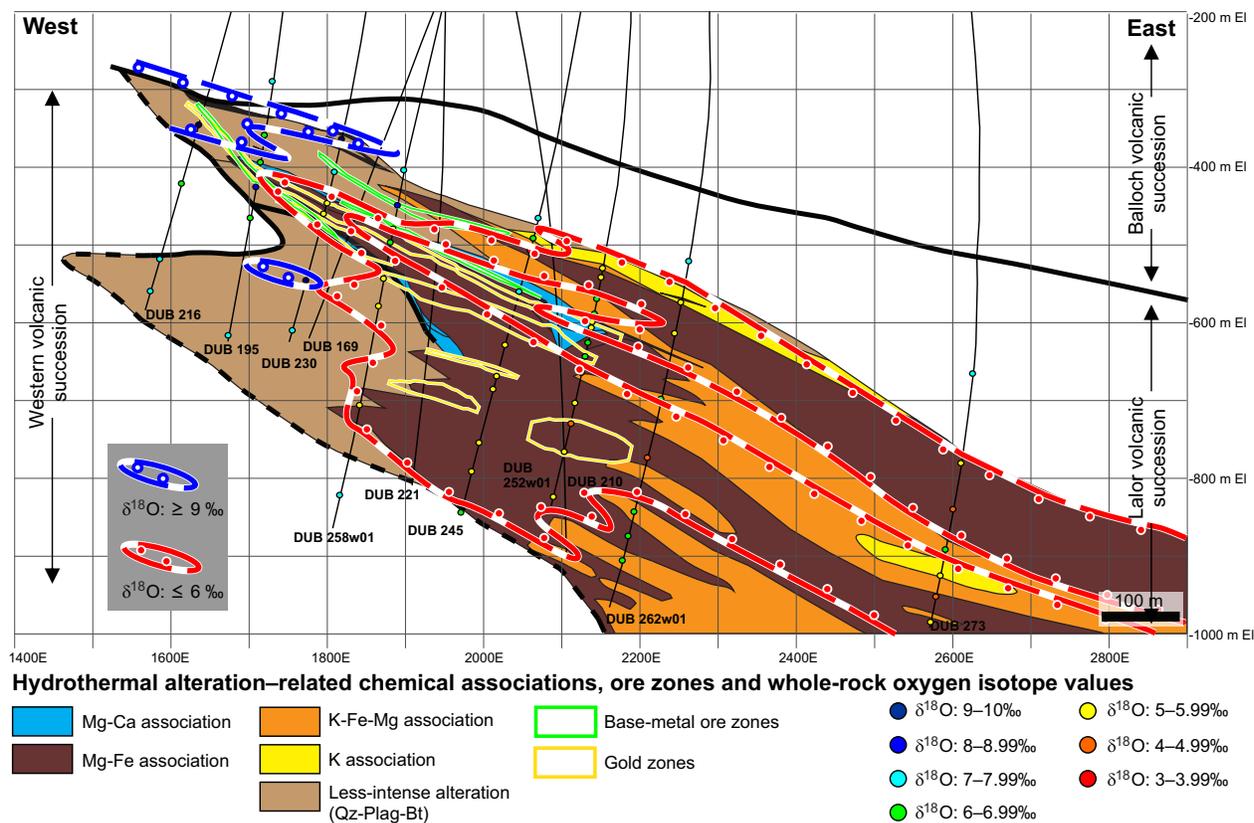


Figure GS-7-7: Simplified cross-section 5600N (looking northwest) of the Lalor deposit, showing $\delta^{18}\text{O}$ values and the distribution of the K, K-Fe-Mg, Mg-Fe and Mg-Ca alteration associations within the Lalor volcanic succession. Ore-zone shapes were determined by HudBay Minerals Inc.; the 10 lens is projected from section 5500N. A zone of high-temperature alteration ($\delta^{18}\text{O} \leq 6\text{‰}$) and zones of low-temperature alteration ($\delta^{18}\text{O} \geq 9\text{‰}$) are outlined.

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References

Bailes, A.H., and Galley, A.G. 1999: Evolution of the Paleoproterozoic Snow Lake arc assemblage and geodynamic setting for associated volcanic-hosted massive sulphide deposits, Flin Flon Belt, Manitoba, Canada; Canadian Journal of Earth Sciences, v. 36, no. 11, p. 1789–1805, doi:10.1139/e98-111.

Bailes, A.H., Rubingh, K., Gagné, S., Taylor, C., Galley, A., Bernauer, S. and Simms, D. 2013: Volcanological and structural setting of Paleoproterozoic VMS and gold deposits at Snow Lake, Manitoba, Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Winnipeg, Manitoba, May 22–24, 2013, Field Trip Guidebook; Manitoba Innovation, Energy and Mines, Manitoba Geological Survey, Open File OF2013-3, 63 p.

Campbell, A.R. and Larson, P.B. 1998: Introduction to stable isotope applications in hydrothermal systems; Reviews in Economic Geology, v. 10, p. 173–193.

Caté, A., Mercier-Langevin, P., Ross, P.-S., Duff, S., Hannington, M., Dubé, B. and Gagné, S. 2013a: The Paleoproterozoic Lalor VMS deposit, Snow Lake, Manitoba: preliminary observations on the nature and architecture of the gold- and base metal-rich ore and alteration zones; Geological Survey of Canada, Open File 7483, 19 p.

Caté, A., Mercier-Langevin, P., Ross, P.-S., Duff, S., Hannington, M., Dubé, B. and Gagné, S. 2013b: Preliminary observations on the geological environment of the Paleoproterozoic auriferous volcanogenic massive sulphide deposit of Lalor, Snow Lake, Manitoba; Geological Survey of Canada, Open File 7372, p. 13.

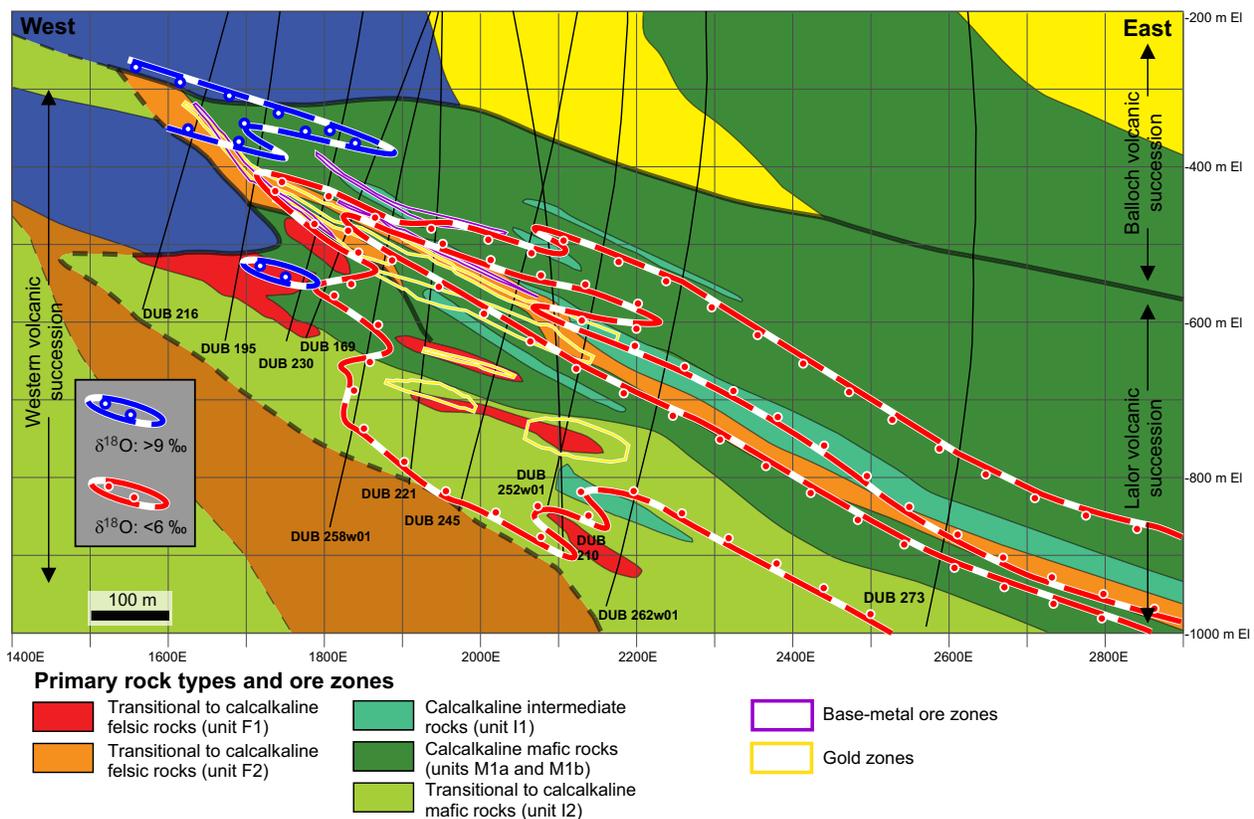


Figure GS-7-8: Simplified geological cross-section 5600N (looking northwest) of the Lalor deposit, showing zone of high-temperature alteration ($\delta^{18}\text{O} \leq 6\text{‰}$) and zones of low-temperature alteration ($\delta^{18}\text{O} \geq 9\text{‰}$). Ore-zone shapes were determined by HudBay Minerals Inc.; the 10 lens is projected from section 5500N. Unit names in the Balloch volcanic succession are from Bailes (unpublished report prepared for HudBay Minerals Inc., 2008).

Caté, A., Mercier-Langevin, P., Ross, P.-S., Duff, S., Hannington, M., Gagné, S. and Dubé, B. in press: Insight on the chemostratigraphy of the volcanic and intrusive rocks of the Lalor auriferous VMS deposit host succession, Snow Lake, Manitoba; Geological Survey of Canada, Current Research 2014-6.

Clayton, R.N., and Mayeda, T.K. 1963: The use of bromine pentafluoride in the extraction of oxygen from oxides and silicates for isotopic analysis: *Geochimica et Cosmochimica Acta*, v. 27, p. 43–52.

Corrigan, D., Pehrsson, S., Wodicka, N. and de Kemp, E. 2009: The Palaeoproterozoic Trans-Hudson Orogen: a prototype of modern accretionary processes; in *Ancient Orogens and Modern Analogues*, J.B. Murphy, J.D. Keppie and A.J. Hynes (ed.), The Geological Society of London, Special Publications, v. 327, p. 457–479.

David, J., Bailes, A.H. and Machado, N. 1996: Evolution of the Snow Lake portion of the Palaeoproterozoic Flin Flon and Kiseynew belts, Trans-Hudson Orogen, Manitoba, Canada; *Precambrian Research*, v. 80, no. 1–2, p. 107–124.

Engelbert, M.S., Friesen, V., Gibson, H. and Lafrance, B. 2014: Volcanic reconstruction of the productive VMS ore interval in the Paleoproterozoic Chisel sequence, Snow Lake, Manitoba; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Fredericton, May 20–22, 2014, Program with Abstracts, p. 83–84.

Galley, A.G., Bailes, A.H. and Kitzler, G. 1993: Geological setting and hydrothermal evolution of the Chisel Lake and North Chisel Zn-Pb-Cu-Ag-Au massive sulfide deposits, Snow Lake, Manitoba; *Exploration and Mining Geology*, v. 2, no. 4, p. 271–295.

Galley, A. G., Syme, R. and Bailes, A. H. 2007: Metallogeny of the Paleoproterozoic Flin Flon Belt, Manitoba and Saskatchewan; in *Mineral Deposits of Canada: A Synthesis of Major Deposit Types, District Metallogeny, The Evolution of Geological Provinces, and Exploration Methods*, W.D. Goodfellow (ed.), Geological Association of Canada, Mineral Deposits Division, Special Publication No. 5, p. 509–531.

Gibson, H., Engelbert, M.S., Lafrance, B., Friesen, V., DeWolfe, M., Tinkham, D.K. and Bailes, A.H. 2014: Reconstruction of the ore interval and environment for the Paleoproterozoic Lost and Ghost Lake VMS deposits, Snow Lake, Manitoba; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Fredericton, May 20–22, 2014, Program with Abstracts, p. 102.

Harper, G.D., Bowman, J.R. and Kuhns, R. 1988 A field, chemical, and stable isotope study of seafloor metamorphism of the Josephine Ophiolite, California-Oregon; *Journal of Geophysical Research*, v. 93, p. 4625–4656.

- Heinrich, C.A., Andrew, A.S. and Knill, M.D. 1999: Regional metamorphism and ore formation: evidence from stable isotopes and other fluid tracers; *Reviews in Economic Geology*, v. 11, p. 97–117.
- HudBay Minerals Inc. 2014: Hudbay provides annual reserve and resource update; HudBay Minerals Inc., press release, March 26, 2014, URL <<http://www.hudbayminerals.com/English/Media-Centre/News-Releases/News-Release-Details/2014/Hudbay-Provides-Annual-Reserve-and-Resource-Update/default.aspx>> [October 2014].
- Ishikawa, Y., Sawaguchi, T., Iwaya, S. and Horiuchi, M. 1976: Delineation of prospective targets for Kuroko deposits based on modes of volcanism of underlying dacites and alteration haloes; *Mining Geology*, v. 26, p. 105–117.
- Kraus, J. and Williams, P.F. 1999: Structural development of the Snow Lake Allochthon and its role in the evolution of the southeastern Trans-Hudson Orogen in Manitoba, central Canada; *Canadian Journal of Earth Sciences*, v. 36, no. 11, p. 1881–1899.
- Lam, J., Tinkham, D.K., and Gibson, H. 2013: Identification of metamorphic assemblages and textures associated with gold mineralization at the Lalor deposit, Snow Lake, Manitoba; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Winnipeg, May 22–24, 2013, Program with Abstracts, p. 127.
- Lam, J., Tinkham, D.K. and Gibson, H. 2014: Characterization of gold occurrences with respect to metamorphism at the Lalor deposit, Snow Lake, Manitoba; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Fredericton, May 20–22, 2014, Program with Abstracts, p. 150–151.
- Large, R.R., Gemmel, J.B., Paulick, H. and Huston, D.L. 2001: The alteration box plot: a simple approach to understanding the relationship between alteration, mineralogy and litho-geochemistry associated with volcanic-hosted massive sulfide deposits; *Economic Geology*, v. 96, p. 957–971.
- Lucas, S.B., Stern, R.A., Syme, E.C., Reilly, B.A., and Thomas, D.J. 1996: Intraoceanic tectonics and the development of continental crust: 1.92–1.84 Ga evolution of the Flin Flon Belt, Canada; *Geological Society of America Bulletin*, v. 108, no. 5, p. 602–629, doi:10.1130/0016-7606(1996)108<0602:itatdo>2.3.co;2.
- Martin, P. 1966: Structural analysis of Chisel Lake orebody; *Canadian Mining and Metallurgical Bulletin*, v. 69, p. 208–214.
- Menard, T. and Gordon, T.M., 1997: Metamorphic P-T paths from the eastern Flin Flon belt and Kisseynew domain, Snow Lake, Manitoba; *Canadian Mineralogist*, v. 35, p. 1093–1115.
- 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.
- Paradis, S., Taylor, B.E., Watkinson, D.H. and Jonasson, I.R. 1993: Oxygen isotope zonation and alteration in the northern Noranda district, Quebec: evidence for hydrothermal fluid flow; *Economic Geology*, v. 88, p. 1512–1525.
- Sharma, T. and Clayton, R.N. 1965: Measurement of O¹⁸/O¹⁶ ratios of total oxygen of carbonates; *Geochimica et Cosmochimica Acta*, v. 29, p. 1347–1354.
- Syme, E.C., Bailes, A.H. and Lucas, S.B. 1996: Tectonic assembly of the Paleoproterozoic Flin Flon belt and setting of VMS deposits; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Winnipeg, Manitoba, Field Trip Guidebook B1, 131 p.
- Taylor, B. and Timbal, A. 1998: Regional stable isotope studies in the Snow Lake area; unpublished report from CAMIRO Project 94E07 – The use of regional-scale alteration zones and subvolcanic intrusions in the exploration for volcanic-associated massive sulphide deposits, p. 271–279.
- Tinkham, D.K. 2013: A model for metamorphic devolatilization in the Lalor deposit alteration system, Snow Lake, Manitoba; Geological Association of Canada–Mineralogical Association of Canada, Joint Annual Meeting, Winnipeg, May 22–24, 2013, Program with Abstracts, p. 187.
- Zaleski, E., Froese, E. and Gordon, T. M. 1991: Metamorphic petrology of Fe-Zn-Mg-Al alteration at the Linda volcanogenic massive sulfide deposit, Snow Lake, Manitoba; *Canadian Mineralogist*, v. 29, no. 4, p. 995–1017.
- Zwanzig, H.V. 1999: Structure and stratigraphy of the south flank of the Kisseynew Domain in the Trans-Hudson Orogen, Manitoba: implications for 1.845–1.77 Ga collision tectonics; *Canadian Journal of Earth Sciences*, v. 36, no. 11, p. 1859–1880.