Mapping magma prospectivity for Cordilleran volcanogenic massive sulphide (VMS) deposits using Nd-Hf isotopes: Preliminary results

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ABSTRACT

Preliminary whole rock Nd-Hf isotopic data for porphyritic rhyolitic intrusive rocks from the Wolverine volcanogenic massive sulphide (VMS) deposit are presented herein. Pre-VMS (~352 Ma) quartz-feldspar porphyritic intrusive rocks (QFP) have Nb/Ta ratios (~12) and lower εNd_t and εHf_t values, compared to syn-VMS (~347 Ma) feldspar porphyritic intrusive rocks (FP), which have higher Nb/Ta ratios (~17) and lower εNd_t and εHf_t. Both suites have Proterozoic to Archean depleted mantle model ages indicative of crustal inheritance; however, the FP suite has a more juvenile signature. The progression from the crustal-dominated QFP suite, to a more basalt-influenced FP suite reflects the progressive opening of the Wolverine back-arc rift where early QFP magma was dominated by continental crustal melting, whereas the FP magma reflects greater back-arc basin extension, upwelling of basaltic magma beneath the rift, and enhanced continental crust-juvenile basalt mixing. Basalt upwelling beneath the Wolverine basin likely created the elevated geothermal gradient required for Wolverine VMS deposit formation.

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INTRODUCTION

Volcanogenic massive sulphide (VMS) deposits are important sources of base (Cu, Zn, Pb) and precious metals (Ag, Au) to the Canadian economy (*e.g.*, Galley *et al.*, 2007). Volcanogenic massive sulphide deposits in Yukon have been the focus of past exploration and production (e.g., Wolverine), and are the current focus of exploration in some locales (*e.g.*, BMC Minerals Ltd. at Kudz Ze Kayah, Finlayson Lake district). Both globally and in Yukon examples, VMS deposits are associated with specific geodynamic environments and specific magma clans (*e.g.*, Piercey, 2011). In particular, VMS deposits are associated with extensional geodynamic environments (*e.g.*, ridges, arc rifts, back arc basins) and with magma that was emplaced at high temperatures (T>900°C; Piercey, 2011). More generally, extensional geodynamic environments provide the structural conduits and permeability required for hydrothermal fluid recharge, and eventual discharge onto the seafloor (*e.g.*, Franklin *et al.*, 2005; Galley *et al.*, 2007; Piercey, 2011), whereas high temperature magmatism provides the heat engine required to drive hydrothermal circulation critical to VMS formation (Lesher *et al.*, 1986; Barrie, 1995; Lentz, 1998; Piercey *et al.*, 2001, 2008; Hart *et al.*, 2004; Piercey, 2010, 2011).

In the Wolverine deposit, recent research illustrates that even in felsic-dominated successions mantle heat and upwelling of juvenile basaltic magma beneath a rift may be an important driver of VMS hydrothermal circulation (Piercey *et al.*, 2008). Furthermore, the signature of mantle upwelling and juvenile crust-mantle mixing is recorded in the trace element signature of felsic rocks, and could be used as a proxy for heat flow of a given VMS environment. In particular, Piercey *et al.* (2008) illustrated that higher temperature felsic rocks have elevated high field strength element (HFSE) and rare earth element (REE) contents, but also have element ratios (*e.g.*, Nb/Ta, Ti/Sc) indicative of evolved crust – juvenile basalt mixing. These authors also argued that this record of juvenile basalt involvement may be a critical feature for delineating prospective "hot" rifts in felsic dominated successions.

To test the significance of juvenile magmatism and "hot" rifts, a project was initiated at the Wolverine deposit utilizing bulk rock Sm-Nd and Lu-Hf tracer isotopes, and *in situ* mineral-scale analyses of Lu-Hf and U-Pb in zircon, to identify the "mantle" trace element signatures recorded in Wolverine porphyritic rhyolite, and to determine if resistant minerals (*e.g.*, zircon, monazite, apatite) record similar geochemical and isotopic signatures. Presented herein are preliminary results from bulk rock Nd and Hf isotope geochemistry of pre and syn-VMS high-level (~synvolcanic) footwall porphyritic intrusive rock (*i.e.*, porphyries) from the Wolverine deposit, which provide initial data to test the "hot" rift hypothesis.

GEOLOGICAL SETTING

The Finlayson Lake district is located northeast of the Tintina fault in southeastern Yukon (Fig. 1). The district is underlain by pericratonic rocks of the Yukon-Tanana terrane and oceanic rocks of the Slide Mountain terrane, which are juxtaposed against rocks of the North American continental margin along the Inconnu thrust of post-Late Triassic age (Fig. 2; Murphy *et al.*, 2006). The Finlayson Lake district is subdivided into several informal fault and unconformity-bounded groups and formations; the Wolverine deposit is hosted by the Wolverine Lake group within the Big Campbell thrust sheet (Fig. 2; Murphy *et al.*, 2006). The Wolverine Lake group consists of Mississippian felsic metavolcanic and high level meta-intrusive rocks, metasedimentary units, and locally mafic metavolcanic and metaplutonic rocks (Figs. 2 and 3; Murphy *et al.*, 2006).

In the Wolverine deposit area, the Wolverine Lake group consists of a footwall dominated by felsic tuffaceous rocks, meta-intrusive rocks, and interlayered black shale (Figs. 3 and 4; Bradshaw *et al.*, 2008; Piercey *et al.*, 2008, 2016). The hanging wall consists of interlayered felsic siltstone, black shale, iron formation, carbonate exhalative rocks, felsic siltstone breccia, and mafic intrusive and lesser volcanic rocks (Figs. 3 and 4; Bradshaw *et al.*, 2008; Piercey *et al.*, 2008, 2016).

In the immediate footwall to the deposit there are very distinctive felsic porphyritic intrusive rocks. These coherent intrusive rocks occur at the Wolverine deposit proper, as well as along strike at other VMS prospects, including the Fisher, Puck, and Sable zones (Figs. 3 and 4). Previous work has documented the field relationships and ages of the porphyries and documented an older, ~352 Ma pre-VMS suite of quartz feldspar porphyries, and a younger ~347 Ma, syn-VMS suite of feldspar porphyritic rocks (Figs. 4 and 5; Piercey *et al.*, 2008).

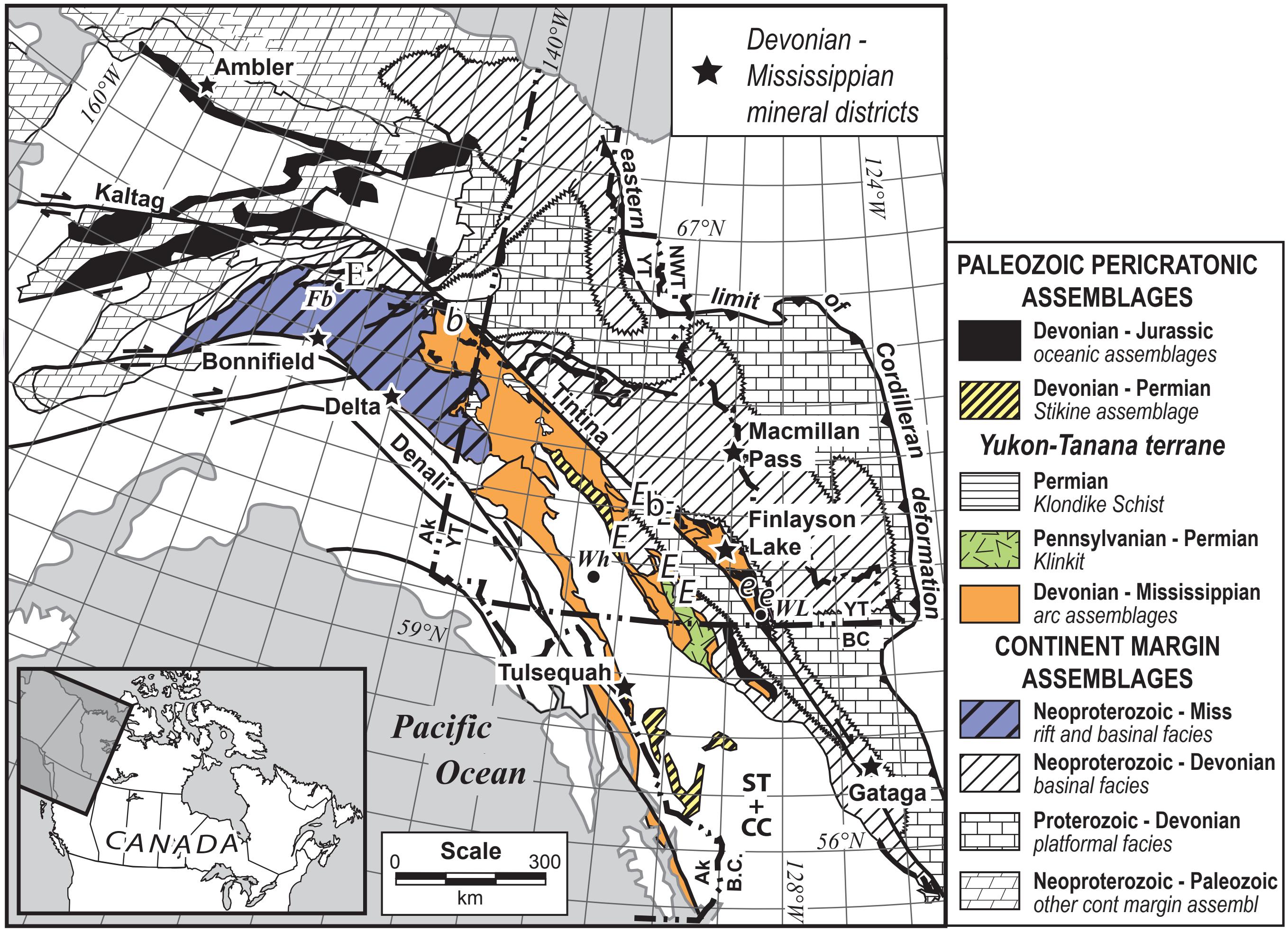

Figure 1. *Terrane map of northern Cordillera showing location of Finlayson Lake district. Modified from Colpron et al. (2006). Abbreviations: Wh=Whitehorse; Fb=Fairbanks; WL=Watson Lake; ST+CC=Stikine and Cache Creek; E=eclogite (Permian); e=eclogite (Mississippian); and b=blueschist (Permian).*

LITHOGEOCHEMISTRY AND RADIOGENIC ISOTOPE GEOCHEMISTRY

Samples of the quartz-feldspar and feldspar porphyries were analyzed previously for lithogeochemistry as part of the study by Piercey *et al.* (2008). The samples were taken from drill core from the footwall in various zones of the Wolverine deposit (Fig. 4), and the full dataset will be released in future publications. A subsample of this dataset were subsequently analyzed for Sm-Nd and Lu-Hf isotopes at Memorial University of Newfoundland following the methods outlined in Phillips (2015). For Sm-Nd, standard methods of spiking, sample dissolution, column chemistry and subsequent analysis by isotope dilution thermal ionization mass spectrometry (ID-TIMS) were undertaken. Throughout the course of the study repeat analysis of the JNDi-1 reference material yielded an average $^{143}Nd/^{144}Nd$ value of 0.512100±6 (1 s.d, n=27); the published value of Tanaka *et al.* (2000) is 0.512115. Lu-Hf isotopes were prepared using standard method of spiking, sample dissolution, column chemistry and subsequent analysis by multi-collector inductively coupled plasma mass spectrometry (MC-ICP-MS) following the methods of Vervoort *et al.* (2004). During the course of this study the JMC-475 Hf standard yielded an average value of $^{176}Hf/^{177}Hf$ = 0.282171±17 (1 s.d, n=12); the published values are $^{176}Hf/^{177}Hf$=0.282160 (Vervoort and Blichert-Toft, 1999). Initial $^{143}Nd/^{144}Nd$ ratios and εNdt were calculated at 350 Ma, the mid-point between the ages of the two porphyry suites presented in this paper. The chondritic uniform reservoir (CHUR) values used for

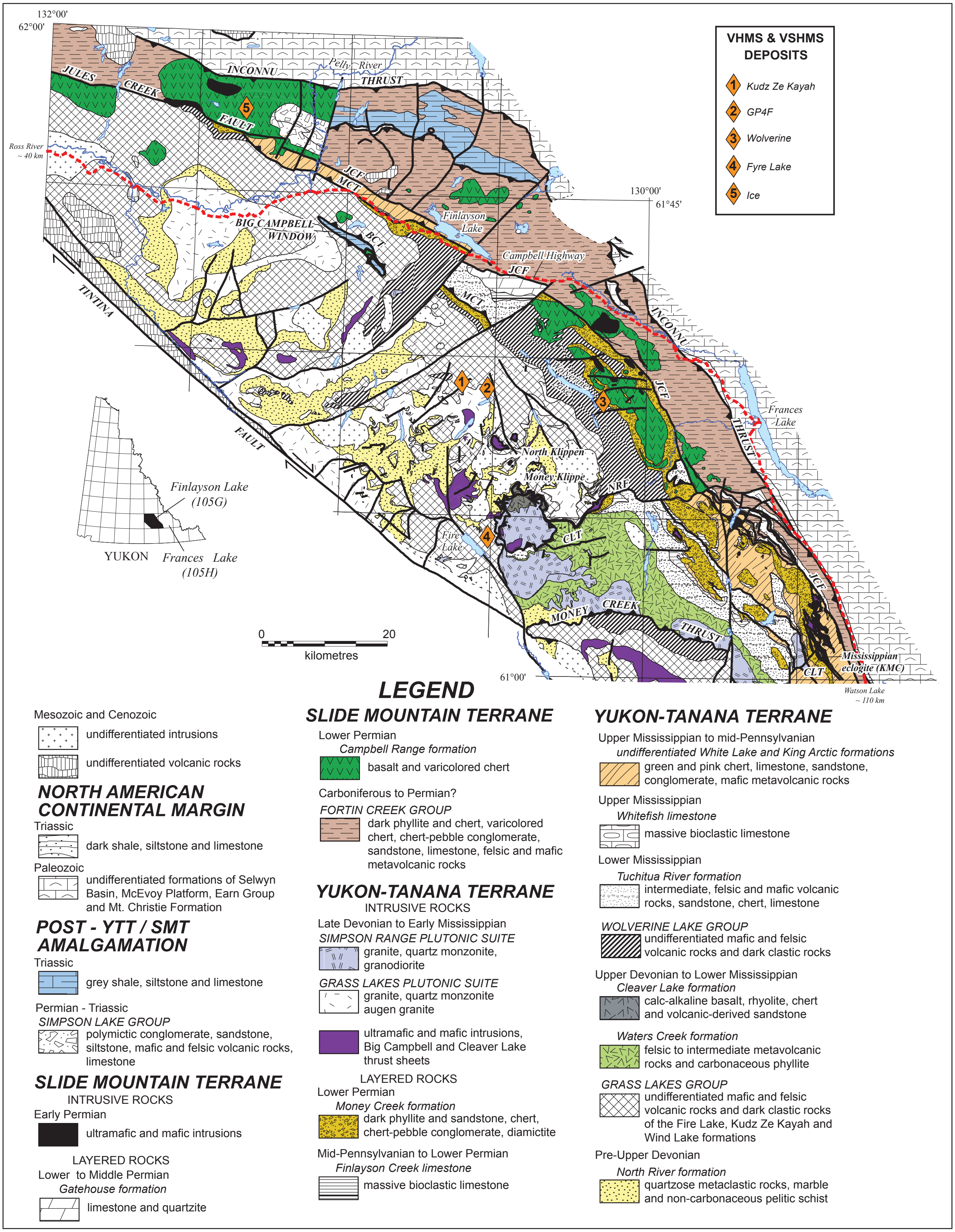

Figure 2. *Geological map of Finlayson Lake district showing locations of volcanogenic massive sulphide deposits (from Murphy et al., 2006).*

εNd_t calculations are $^{143}Nd/^{144}Nd = 0.512638$ and $^{147}Sm/^{144}Nd = 0.1967$ (Hamilton *et al.*, 1983). Depleted mantle model ages (T_{DM}) are calculated using the values of $^{143}Nd/^{144}Nd = 0.513163$ and $^{147}Sm/^{144}Nd = 0.2137$ (Goldstein *et al.*, 1984). Initial $^{176}Hf/^{177}Hf$ ratios and εHft were calculated at 350 Ma similar to the Nd isotopic data. The chondritic uniform reservoir (CHUR) values used for εHft calculations are $^{176}Hf/^{177}Hf = 0.282772$ and $^{176}Lu/^{177}Hf = 0.0332$ (Blichert-Toft and Albarede, 1997). Depleted mantle model ages (T_{DM}) are calculated using the values of $^{176}Hf/^{177}Hf = 0.28325$ and $^{176}Lu/^{177}Hf = 0.0334$ (Vervoort and Blichert-Toft, 1999).

RESULTS

Sm-Nd and Lu-Hf results are shown in Figures 6 and 7. In Figure 6 Wolverine quartz-feldspar and feldspar porphyritic rhyolite samples are plotted against the whole-rock Nb/Ta ratio. The Nb/Ta data are from Piercey *et al.* (2008) and are shown as they are reflective of the source region (*i.e.*, upper crust vs. juvenile basalt) for the felsic rocks. Nb and Ta are geochemical twins and rarely fractionated from one another during partial melting and fractional crystallization, with upper crustal rocks and rocks derived therefrom having Nb/Ta ~12, whereas Nb/Ta ~17 for rocks derived from more juvenile,

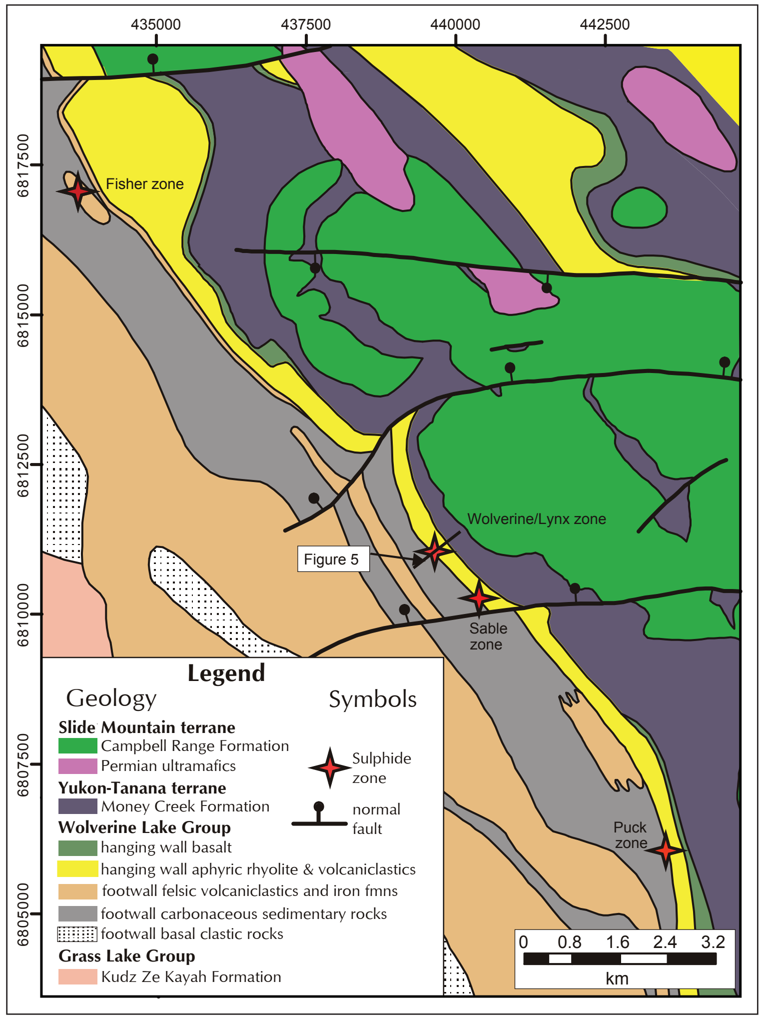

Figure 3. *Geology of local Wolverine deposit area, illustrating locations of different zones. Geology from Murphy et al. (2006).*

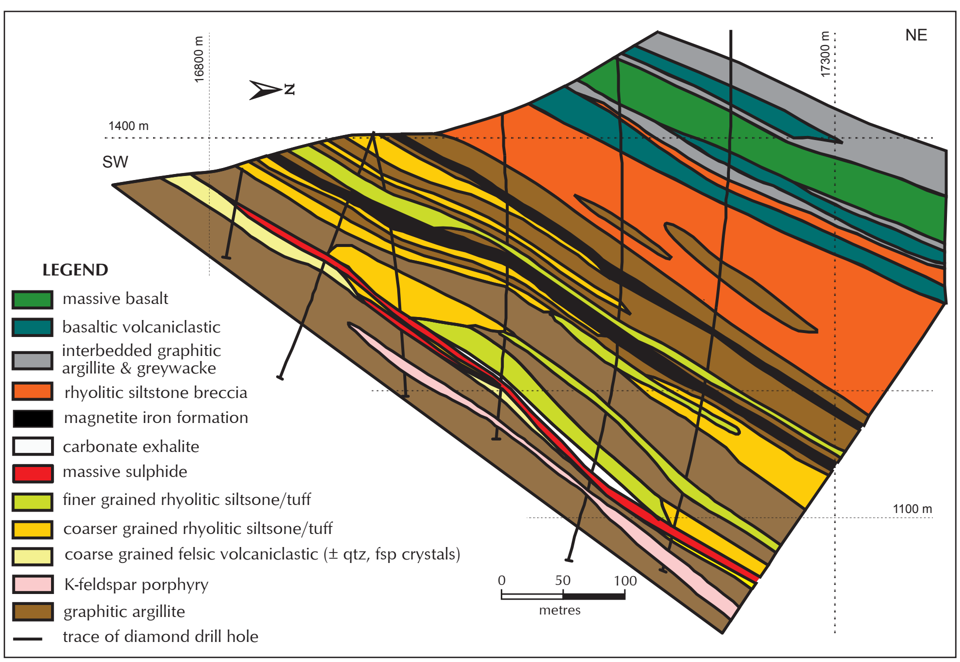

Figure 4. *Geological cross sections Wolverine deposit illustrating deposit stratigraphy and the presence of feldspar porphyritic rhyolites in the deposit footwall. Sections modified from Bradshaw et al. (2008).*

mantle sources (e.g., basalt; Green, 1995; Barth *et al.*, 2000; Kamber and Collerson, 2000; McLennan, 2001). The pre-VMS QFP (352 Ma) suite have Nb/Ta ~12 and εNd_t ranging from -7.7 to -11.5, εHf_t ranging from -12.4 to -19.0, and with T_{DM}(Nd) ages of 1.66-2.58 Ga and T_{DM}(Hf) ages of 1.59-2.22 Ga (Figs. 6 and 7). The younger, syn-VMS FP (347 Ma) suite of porphyries have higher Nb/Ta ratios and εNd_t ranging from -7.9 to -8.1, εHf_t ranging from -13.4 to -18.0, and with T_{DM}(Nd) ages of 1.59-1.67 Ga and T_{DM}(Hf) ages of 1.62-1.97 Ga (Figs. 6 and 7).

DISCUSSION AND SUMMARY

Porphyritic rocks from the Wolverine deposit have distinct variations in Nd-Hf isotopic signatures that are indicative of varying contributions of upper crust vs. juvenile (basaltic) material to their genesis. Both suites of high level intrusive rocks have been influenced by upper crustal materials as indicated by their negative εNd_t and εHf_t values and Proterozoic to Archean depleted mantle model ages (Figs. 6 and 7); it is implied that these rocks melted continental crustal sources, or assimilated continental crustal material during emplacement (Lentz, 1998; Piercey *et al.*, 2008). These data are also consistent with previously reported data for the felsic rocks throughout the Yukon-Tanana terrane, which show strong evidence of crustal inheritance from Laurentian-derived, peri-continental material (e.g., Piercey *et al.*, 2006). There are notable differences between the suites, however. The older QFP suite has lower Nb/Ta ratios, lower εNd_t and overlapping, but generally lower εHf_t, compared to the younger FP suite (Figs. 6 and 7). Piercey *et al.* (2008) suggested that the lower Nb/Ta in the QFP suite reflected a greater upper crustal contribution relative to the FP suite, which had a greater juvenile contribution, likely derived from underplated basaltic magma at the base of the Wolverine back-arc rift. The isotopic results herein support this hypothesis and the FP suite is shifted towards higher εNd_t and εHf_t, consistent with a greater juvenile contribution to its genesis relative to the QFP suite.

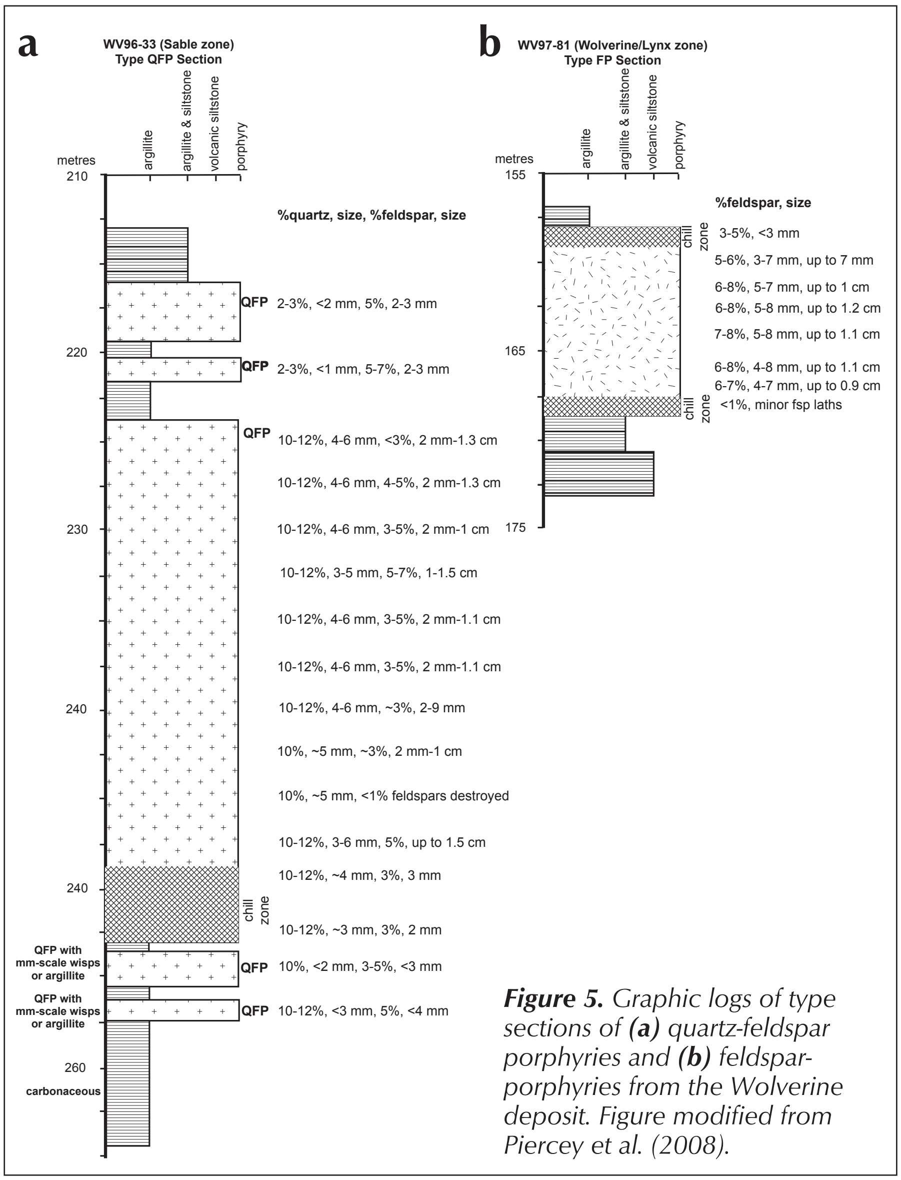

Figure 5. *Graphic logs of type sections of **(a)** quartz-feldspar porphyries and **(b)** feldspar-porphyries from the Wolverine deposit. Figure modified from Piercey et al. (2008).*

The progression from the more crustally-derived QFP suite at 352 Ma to the FP suite with a greater juvenile contribution at 347 Ma is interpreted to represent the progressive opening of the Wolverine back-arc basin, upwelling of juvenile basaltic magma beneath the rift, and greater crust-basalt mixing as the basin widened (Piercey *et al.*, 2008). The latter authors also argued that the upwelling of mantle-derived magma beneath the rift was also critical in increasing heat flow to the basin, which in turn enhanced hydrothermal circulation and ultimately led to the formation of the Wolverine deposit.

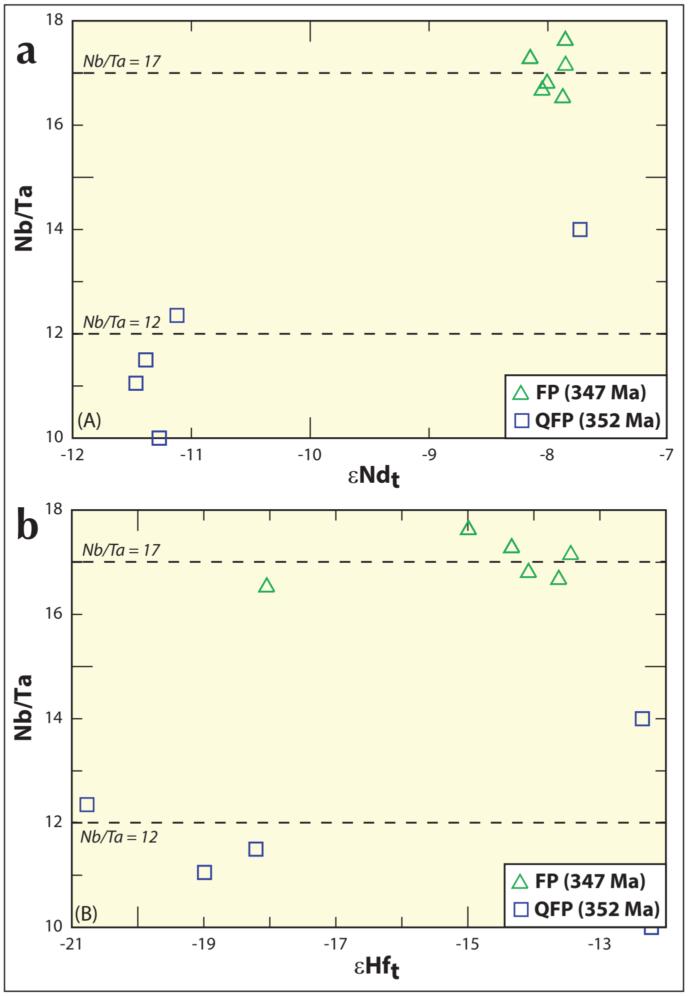

***Figure 6. (a)** Nb/Ta versus εNd_t and **(b)** Nb/Ta versus εHf_t for porphyritic rhyolitic rocks from the Wolverine VMS deposit. Nb/Ta values ~12 reflect crustal sources, whereas Nb/Ta ~17 reflect more basaltic/juvenile sources. While all samples have negative εNd_t and εHf_t, the younger, FP suite tends towards more juvenile signatures relative to the QFP suite.*

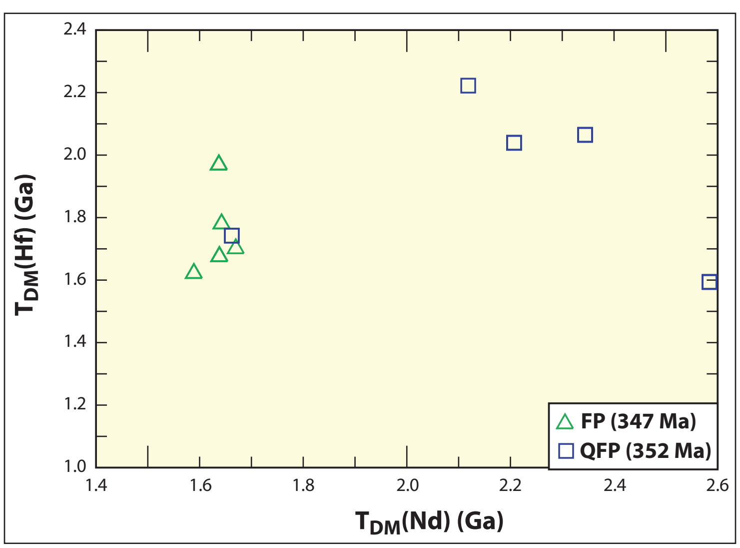

***Figure 7.** Depleted mantle model ages for Hf and Nd for the Wolverine porphyritic rhyolites. Notably all samples have Proterozoic to Archean model ages indicative of crustal inheritance from old upper crustal sources.*

The presence of distinctive, more juvenile εNd_t-εHf_t signatures in the FP suite, which is intimately associated with mineralization and syn-VMS formation, suggests that rhyolitic rocks with similar juvenile signatures within the Yukon-Tanana terrane and other pericratonic terranes may also be prospective for VMS mineralization. This hypothesis requires further testing and will be the focus of ongoing research by the authors. Moreover, future work will focus on comparing both bulk rock Nd-Hf and *in situ* Hf-Nd-U-Pb signatures of heavy mineral phases (e.g., zircon, monazite, apatite) within the pericratonic terranes to see if there are important isotopic differences between barren and VMS-bearing assemblages, testing geochemical and isotopic relationships as a function of VMS deposit grade and tonnage, and seeing if such methods allow mapping of VMS potential and fertility of felsic-dominated assemblages.

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