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Abstract: Massive basaltic flows stratigraphically overlie aphyric felsic rocks in the hanging wall of the Wolverine volcanic-hosted massive-sulphide deposit. The geochemical signatures of these flows are similar to those of normal and enriched mid-ocean-ridge basalt; however, some have elevated Th contents similar to back-arc-basin basalt. These features suggest that Wolverine basalt was derived from depleted to weakly enriched mantle sources with minor subduction-zone metasomatic input and/or a crustal component via crustal contamination. The presence of such rocks in close primary association and juxtaposition with crustally derived felsic volcanic rocks, together with their bulk compositions, indicate that the Wolverine deposit formed within an ensialic back-arc rift to nascent back-arc-basin setting. The flat heavy rare-earth-element signatures on chondrite-normalized plots require that the Wolverine basalt formed from low-pressure mantle melting (spinel stability field) with a minimal lithospheric cap.

Résumé : Des coulées massives de basalte surmontent des roches felsiques aphyriques dans l'éponte supérieure du gisement de Wolverine, une minéralisation de sulfures massifs encaissés dans des roches volcaniques. Les signatures géochimiques de ces coulées sont semblables à celles des basaltes de dorsale médio-océanique normaux et enrichis; certaines coulées présentent cependant une teneur élevée en Th, à la manière des basaltes de bassin d'arrière-arc. Ces caractéristiques semblent indiquer que les basaltes du gisement de Wolverine proviennent de sources mantelliques appauvries à légèrement enrichies, auxquelles se sont ajouté, en faibles quantités, des éléments métasomatiques associés à une zone de subduction ou des composants crustaux résultant d'une contamination crustale. La composition globale de ces basaltes ainsi que leur étroite association primaire et leur juxtaposition à des roches volcaniques felsiques d'origine crustale indiquent que le gisement de Wolverine s'est formé dans un cadre ensialique de rift d'arrière-arc ou d'arrière-bassin naissant. Le profil plat des terres rares lourdes dans les spectres normalisés aux valeurs chondritiques requiert que les basaltes du gisement de Wolverine se soient formés par fusion du manteau dans des conditions de faible pression (champ de stabilité du spinelle), sous une couche lithosphérique d'épaisseur minimale.

INTRODUCTION

The Finlayson Lake volcanic-hosted massive sulphide (VHMS) district is one of Canada's recent VHMS discovery regions, with ~34 Mt of massive sulphide discovered since the mid-1990s. Volcanic-hosted massive-sulphide deposits within the district are of varied style (Shultze, 1996; L.C. Pigage, unpub. data, 1997; Foreman, 1998; Bradshaw et al., 2001) and are interpreted to occur at different stratigraphic positions and in different tectonic settings (Murphy and Piercey, 2000; Murphy, 2001; Piercey, 2001). Since the discovery of the deposits in the mid-1990s, numerous studies have been initiated to understand the stratigraphic and tectonic setting of the district (Murphy and Piercey, 2000; Murphy, 2001; Piercey et al., 2001a, b).

Geochemical studies are underway to understand the setting and large-scale tectonic controls on the formation of VHMS deposits in the Finlayson Lake district. In this paper, we present geochemical data for basaltic rocks that stratigraphically overlie the Wolverine VHMS deposit. These data provide insight into the genesis and petro-tectonic setting of the basaltic rocks in the Wolverine VHMS deposit.

REGIONAL SETTING

The Yukon–Tanana Terrane in the Finlayson Lake district (Fig. 1) comprises deformed and greenschist- to lower amphibolite-grade metasedimentary, metavolcanic, and metaplutonic rocks (e.g. Mortensen and Jilson, 1985; Murphy, 1998; Murphy and Piercey, 1999, 2000; Murphy, 2001). Regional mapping at scales of 1:250 000 to 1:50 000 has identified a stratigraphically intact sequence consisting of three middle to late Paleozoic unconformity-bound successions — the Grass Lakes, Wolverine, and Campbell Range successions (Murphy, 1998; Murphy and Piercey, 1999, 2000; Murphy, 2001). Since premetamorphic and predeformation features can be observed in many places, we herein omit the prefix 'meta' throughout the description of the stratigraphy for the purpose of simplifying the text.

The Grass Lakes succession consists of unit 1, the Fire Lake unit (unit 2), the Kudz Ze Kayah unit (unit 3), and unit 4 (Fig. 2). The lowermost part of the Grass Lakes succession consists of pre-365 Ma, quartz-rich, noncarbonaceous clastic rocks of unit 1, which are overlain by the ~365 to 360 Ma (Mortensen, 1992, and pers. comm., 2000), mafic-dominated arc- and back-arc-related Fire Lake unit (unit 2) (Mortensen, 1992; Grant, 1997; Murphy and Piercey, 1999, 2000; Piercey et al., 2001a). Boninitic rocks of the Fire Lake unit host the Besshi-type Fyre Lake Cu-Co-Au VHMS deposit (Fig. 2; Murphy, 1998; Murphy and Piercey, 2000).

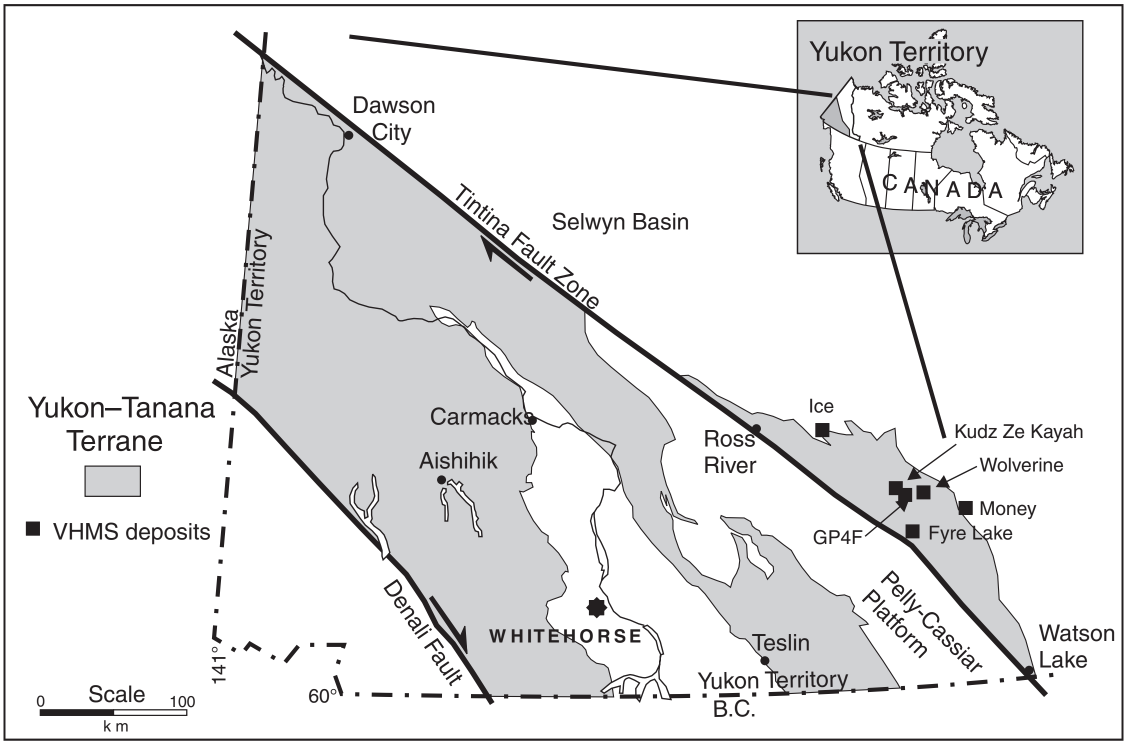


*Figure 1. Location map of the Finlayson Lake VHMS district, Yukon Territory (*modified from *Hunt, 1998).*

Stratigraphically overlying the Fire Lake unit is the Kudz Ze Kayah unit (unit 3) (Murphy, 1998), which hosts the Kudz Ze Kayah and GP4F VHMS deposits and consists predominantly of ~360 to 356 Ma (Mortensen, 1992) felsic volcanic and volcaniclastic rocks and variably carbonaceous sedimentary rocks. Near the top of the Grass Lakes succession are the alkalic basalt and carbonaceous sedimentary rocks of unit 4 (Murphy, 1998; Fig. 2). Coeval with to slightly younger than the Kudz Ze Kayah unit and unit 4 is the ~360 Ma (Mortensen, 1992), K-feldspar-porphyritic to -megacrystic granite of the Grass Lakes suite of intrusions is inferred to be the subvolcanic intrusive complex to the Kudz Ze Kayah unit felsic volcanic and volcaniclastic rocks (Fig. 2).

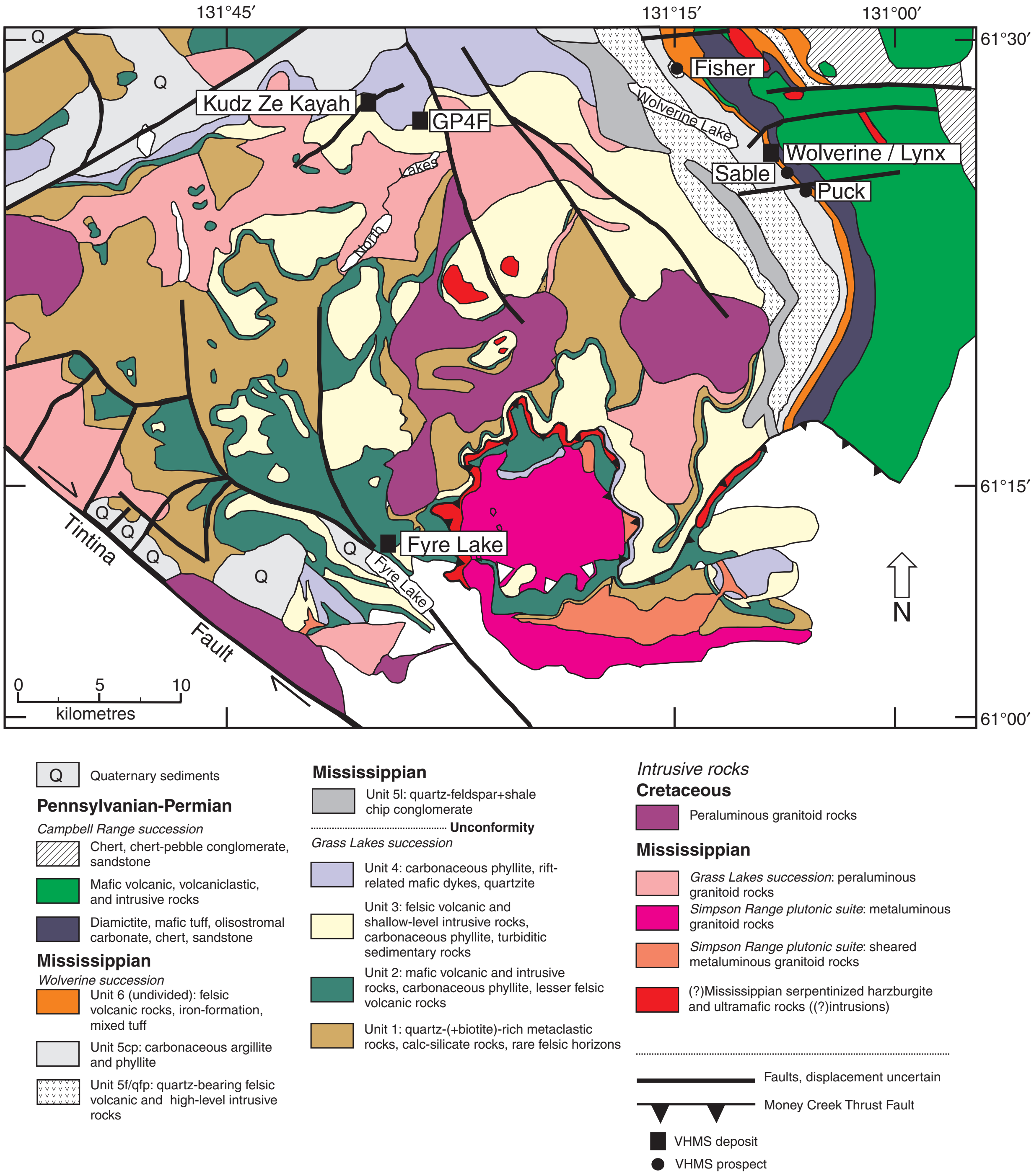


***Figure 2.** Geological map of the Finlayson Lake district with locations of VHMS deposits* (modified from *Murphy and Piercey, 2000).*

The Wolverine succession (Fig. 3) unconformably overlies the Grass Lakes succession and consists predominantly of Early Mississippian (~356–346 Ma; Mortensen, 1992; Piercey, 2001) felsic volcanic and carbonaceous sedimentary rocks (Murphy and Piercey, 1999, 2000); it hosts the Wolverine VHMS deposit (6.2 Mt @ 13.0% Zn, 1.5% Pb, 1.4% Cu, 359 g/t Ag, 1.8 g/t Au; Bradshaw et al., 2001; Fig. 2). The succession contains, from oldest to youngest, a lower conglomerate unit (unit 5l), a lower felsic-volcanic-dominated unit (unit 5f/qfp), a regional carbonaceous argillite unit (unit 5 cp), the immediate footwall felsic volcanic and subvolcanic rocks to the Wolverine deposit (unit 6-fw), and a hanging-wall sequence consisting of aphyric rhyolitic rocks and carbonaceous sedimentary rocks, which, near their top, contain basalt flows (unit 6-hw) (Fig. 2; Murphy and Piercey, 1999, 2000; Bradshaw et al., 2001). The Wolverine deposit occurs at the contact between footwall felsic volcaniclastic rocks and either hanging-wall carbonaceous argillite or carbonate-rich exhalite (Bradshaw et al., 2001). The Wolverine succession is unconformably overlain by Pennsylvanian–Permian (Plint and Gordon, 1997) mafic volcanic and clastic sedimentary rocks of the Campbell Range succession (Fig. 2; Murphy and Piercey, 1999; Murphy, 2001).

DEPOSIT STRATIGRAPHY AND STRATIGRAPHIC SETTING OF WOLVERINE BASALTIC ROCKS

The geology of the Wolverine VHMS deposit presented here is a synopsis of Tucker et al. (1997) and Bradshaw et al. (2001). The deposit is hosted by felsic volcanic rocks and carbonaceous sedimentary rocks, contains several intercalated exhalative carbonate±magnetite±barite±pyrite horizons, and is stratigraphically overlain by mafic volcanic flows. The deeper footwall to the deposit consists predominantly of

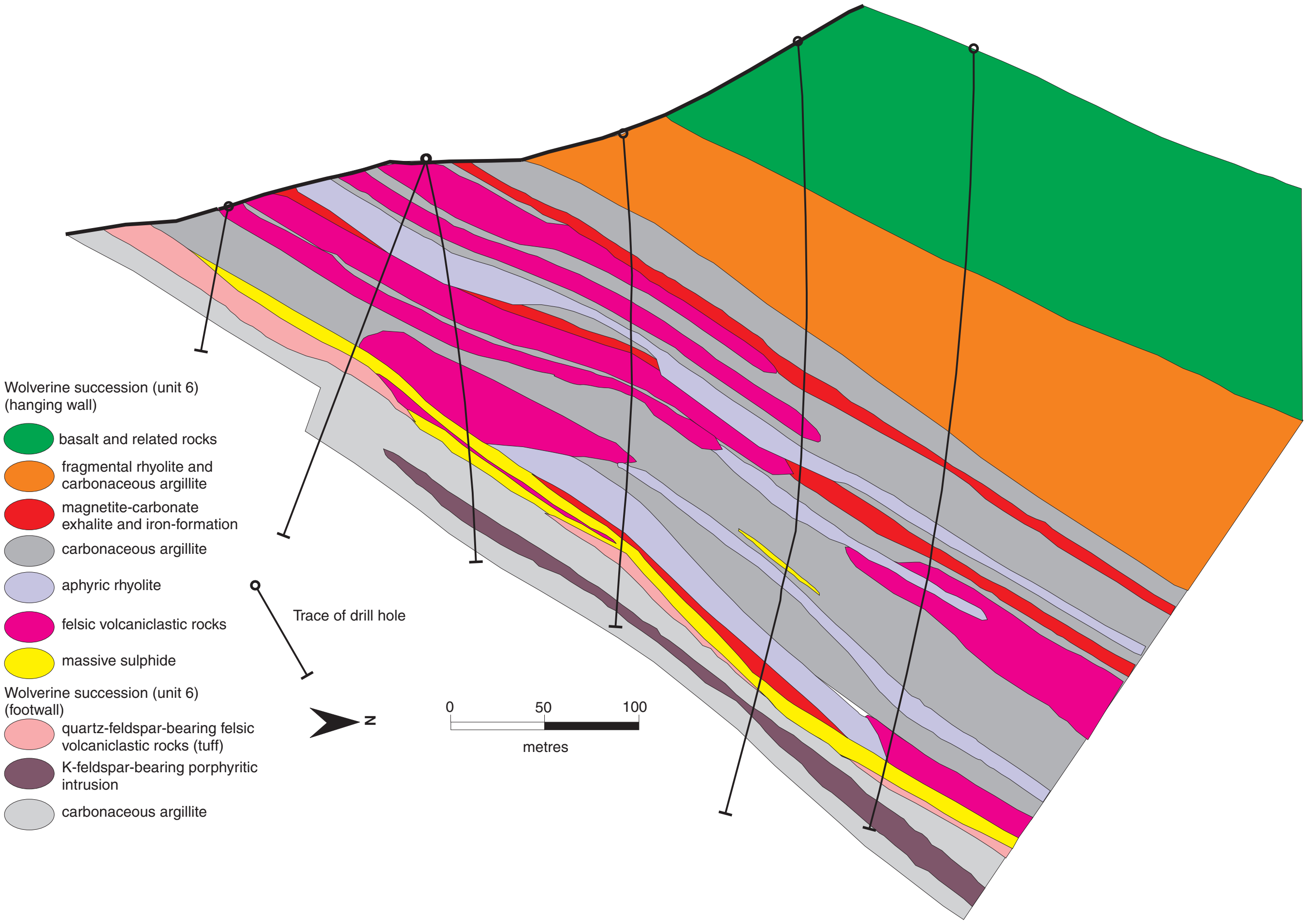


***Figure 3.** Cross-section 16250E through the Wolverine VHMS deposit depicting stratigraphic relationship of basalt to VHMS mineralization* (modified from *Bradshaw et al., 2001).*

carbonaceous sedimentary rocks with lesser felsic volcaniclastic (tuffaceous) rocks (unit 5cp of Murphy and Piercey, 1999; Fig. 3). The immediate footwall to the massive sulphides consists of variably altered, fine- to coarse-grained K-feldspar- and quartz-phyric felsic volcaniclastic rocks (tuff) (Bradshaw et al., 2001). High-level K-feldspar-porphyritic rhyolite intrusions also occur in the immediate footwall at an average of 10 m below the massive sulphides (Fig. 3; Piercey et al., 2001b; Bradshaw et al., 2001). The immediate hanging wall to the massive sulphides is either carbonaceous shale or, less commonly, carbonate-bearing exhalative rocks (Bradshaw et al., 2001). Forming the bulk of the hanging wall to the deposit are aphyric rhyolitic flows and related volcaniclastic rocks, aphyric rhyolite breccia, and variably carbonaceous sedimentary rocks (Fig. 3; Bradshaw et al., 2001). Magnetite-rich exhalite (iron-formation) and carbonate-rich exhalite form regional units (up to 13 km in strike length) and are interbedded with aphyric rhyolite (Fig. 3; J.M. Peter, unpub. data, 2001; Peter, in press).

Basaltic lava flows, volcaniclastic rocks, and lesser sedimentary rocks (~200 m thick) overlie the aphyric rhyolite flows (Bradshaw et al., 2001). Basaltic rocks are predominantly massive and do not exhibit pillowed forms. In places, the flows have minor hyaloclastite along their margins and lack peperitic margins, indicating massive-flow rather than intrusive emplacement. Bradshaw et al. (2001) reported that individual flows could be up to 40 m thick. Igneous minerals and textures within the basalt flows are moderately well preserved. Chlorite-albite-epidote±carbonate are common and are attributed to greenschist-facies metamorphism and possibly seawater alteration.

SAMPLING AND ANALYTICAL METHODS

Basaltic rocks from the Wolverine succession were sampled from drillhole WV-97-90 (439895E, 6811314N) and analyzed at the laboratories of the Geological Survey of Canada, using fused-bead X-ray fluorescence for most major elements. Water (H_2O_T) and CO_{2T} were analyzed by infrared spectroscopy, and FeO was analyzed by modified Wilson titration. Trace elements were analyzed by combined inductively coupled plasma emission spectrometry (ICP-ES) and mass spectrometry (ICP-MS). Analytical precision calculated from repeat analyses of internal basaltic reference materials is given as per cent relative standard deviation (= 100*standard deviation/mean) and yielded values of 0.43% to 6.52% for the major elements, 0.72% to 8.80% for the transition elements (V, Ni, Cr, Co), 2.21% to 5.92% for the high-field-strength elements (HFSE: Nb, Zr, Hf, Y, Sc) and Ga, 2.35% to 6.96% for the large-ion lithophile elements (LILE: Cs, Rb, Th, U) and slightly higher for Ba and Sr (1.49–15.75%), 2.15% to 6.47% for the rare-earth elements (REE: La-Lu), and 1.12% to 98.12% for Cu, Pb, and Zn (Piercey, 2001). However, Cu, Pb, and Zn concentrations were close to detection limits in the internal reference materials leading to decreased precision and high per cent relative standard deviation values (Piercey, 2001). Further details on analytical methods can be obtained from the GSC website at http://132.156.95.172/chemistry.

Given that the basaltic rocks of this study have undergone greenschist-facies metamorphism and possibly seafloor alteration, the choice of elements that can be used to assess their original geochemical attributes is limited. For this reason, we have used the immobile elements (e.g. REE, HFSE) to elucidate the petrological attributes and geochemical affinities of the basaltic rocks.

GEOCHEMICAL RESULTS

The preliminary geochemical data for the Wolverine basalt flows are presented in Table 1 and Figures 4 to 7. The SiO_2 content of the flows varies and likely reflects SiO_2 mobility resulting from hydrothermal alteration and/or regional metamorphism; however, the SiO_2 content is broadly basaltic in composition and consistent with the Zr/TiO_2 values (Fig. 4a). The TiO_2 content of the flows is low to moderate (0.67–1.23 weight per cent; Table 1) and is accompanied by moderate Al_2O_3/TiO_2 values (11–23) that are slightly higher than those of normal mid-ocean-ridge basalt (N-MORB; Table 1). The Wolverine basalt flows have Nb/Y values (0.07–0.23) typical of subalkalic volcanism (Fig. 4a, Table 1) and low Zr/Y values (1.29–2.81) typical of tholeiitic basalt (Fig. 4b, Table 1). The HFSE content is moderate to low (Fig. 5, Table 1). The Ti/V values are typical of N-MORB to back-arc-basin basalt (Fig. 5a, Table 1; e.g. Hawkins, 1995). On the Zr-Nb-Y plot, the basalt flows lie within the fields for N-MORB and volcanic-arc basalt (Fig. 5b), consistent with their low to moderate HFSE contents. The Th-Zr-Nb plot (Fig. 5c) also shows N-MORB to enriched MORB (E-MORB) signatures for most samples; however, one sample lies within the field for arc basalt with higher Th content (Fig. 5c), which suggests a possible subduction-zone-fluid influence or crustal contamination. The Wolverine basalt flows have varied REE patterns ranging from LREE depleted to LREE enriched (La/Sm_n = 0.46–1.29) and are similar in this regard to N-MORB and E-MORB (Fig. 6a). Primitive-mantle-normalized trace-element plots of the rocks (Fig. 6b) are similar to N-MORB and E-MORB; however, one sample has weakly negative Nb anomalies typical of back-arc-basin basalt.

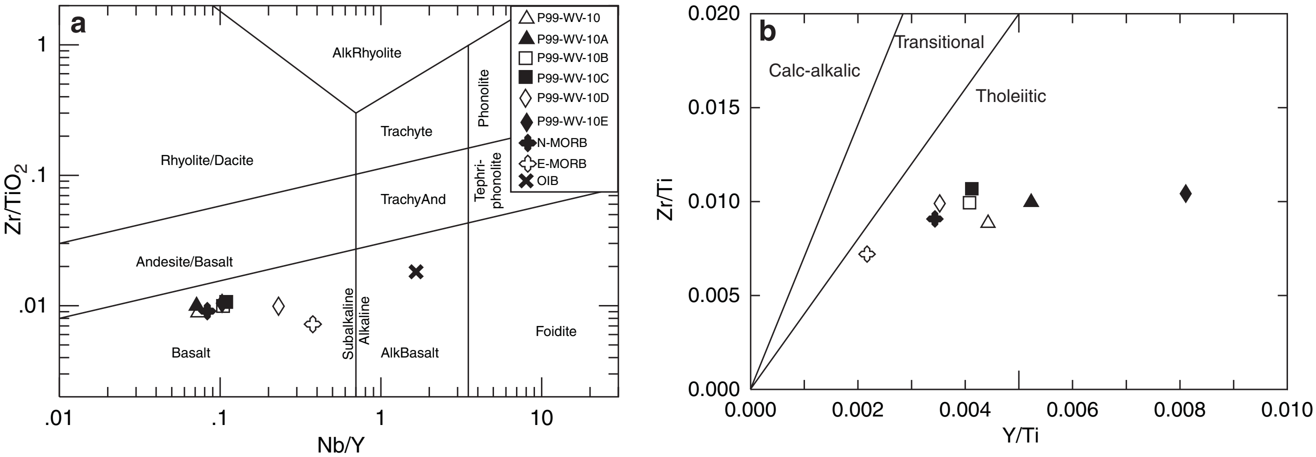
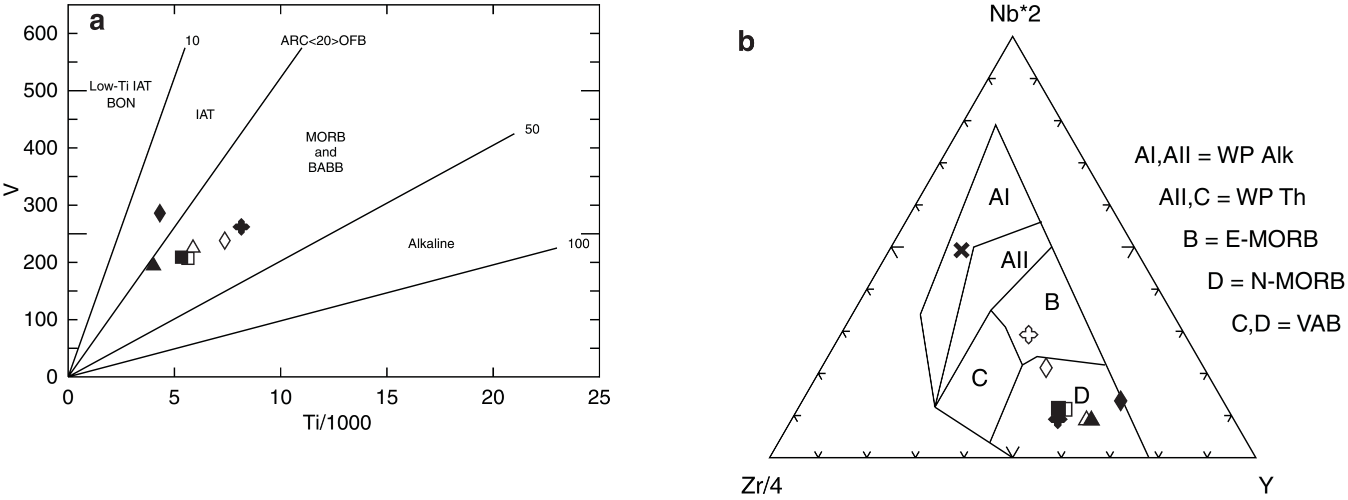


Figure 4. *Trace-element classification diagrams for Wolverine basalt.* ***a****) Modified Zr/Ti-Nb/Y plot (Pearce, 1996) of Winchester and Floyd (1977);* ***b****) Zr/Ti-Y/Ti plot for the discrimination of tholeiitic through calc-alkalic affinities, based on the premises of Barrett and MacLean (1999) with diagram modified from Lentz (1999). Values for N-MORB, E-MORB, and OIB modified from Sun and McDonough (1989). N-MORB = normalized mid-ocean- ridge basalt, E-MORB = enriched mid-ocean-ridge basalt, OIB = oceanic island basalt*



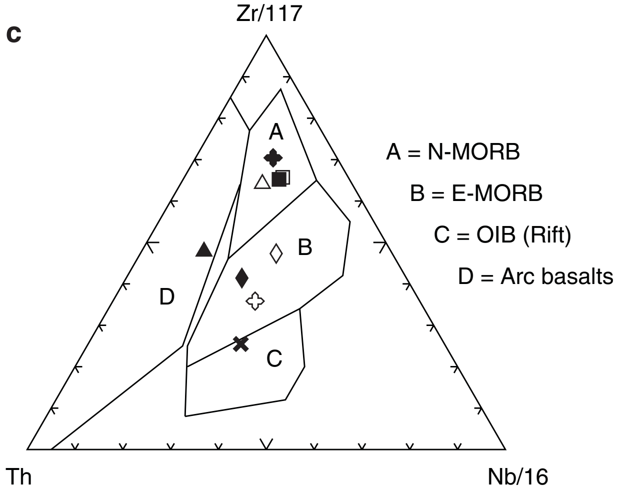


Figure 5. *Discrimination plots for Wolverine basalt.* ***a****) Ti-V plot (data from Shervais, 1982); BON = boninite, IAT = island-arc tholeiite, MORB = mid-ocean- ridge basalt, BABB = back-arc-basin basalt.* ***b****) Zr-Nb-Y plot (data from Meschede, 1986); WP Alk = within-plate alkaline, WP Th = within-plate tholeiite, N-MORB = normal mid-oceanic-ridge basalt, E-MORB = enriched mid-oceanic-ridge basalt, VAB = volcanic-arc basalt.* ***c****) Th-Zr-Nb plot modified from Wood (1980). Symbols as in Figure 4.*

Table 1. Geochemical data for mafic rocks from the Wolverine VHMS deposit and comparisons with compiled global average values for modern N-MORB, E-MORB, and OIB (Sun and McDonough, 1989). LD = limit of detection, N-MORB = normal mid-ocean-ridge basalt, E-MORB = enriched mid-ocean-ridge basalt, OIB = oceanic island basalt

Sample name	**P99-WV-10**	**P99-WV-10A**	**P99-WV-10B**	**P99-WV-10C**	**P99-WV-10D**	**P99-WV-10E**	**N-MORB**	**E-MORB**	**OIB**
Drillhole	**WV-97-90**	**WV-97-90**	**WV-97-90**	**WV-97-90**	**WV-97-90**	**WV-97-90**			
depth	**54.3**	**7**	**18.2**	**31.9**	**44**	**52.3**			
Rock type	**basalt**	**basalt**	**basalt**	**basalt**	**basalt**	**basalt**			
SiO_2 (wt. %)	46.90	47.00	47.10	42.90	47.60	31.60	50.40	51.20	49.20
TiO_2	0.98	0.67	0.94	0.89	1.23	0.72	1.36	1.69	2.57
Al_2O_3	16.20	15.10	14.80	14.80	13.00	14.00	15.20	16.00	12.80
Fe_2O_3T	10.10	9.00	10.70	13.20	11.70	10.20			
Fe_2O_3	1.60	2.10	2.60	2.70	3.10	1.70	1.30	9.40	
FeO	8.50	6.90	8.10	10.50	8.60	8.50	8.14		11.40
FeO*	9.09	8.10	9.63	11.88	10.53	9.18			
MnO	0.18	0.16	0.18	0.22	0.19	0.23	0.18	0.16	0.17
MgO	9.03	11.73	11.46	14.84	12.42	8.03	8.96	6.90	10.00
CaO	5.78	10.21	9.98	6.76	8.42	16.67	11.40	11.50	10.80
Na_2O	4.80	1.80	2.20	1.70	2.50	2.40	2.30	2.74	2.12
K_2O	0.12	0.60	0.07	0.06	0.05	0.05	0.09	0.43	0.51
P_2O_5	0.08	0.05	0.06	0.07	0.11	0.06	0.14	0.15	0.25
H_2O	4.30	4.40	3.90	5.60	4.10	4.40			
CO_2	2.80	0.70	0.20	0.10	0.30	10.30			
Cr (ppm)	522	571	327	751	705	349	346		
Ni	276	309	219	536	398	225	177		
Co	51	45	53	71	57	40	50		
Sc	43	36	42	41	37	32	40		
V	225	194	207	209	238	286	262		
Cu	125	112	211	61	62	34			
Pb	3	2	<LD	<LD	<LD	3			
Zn	67	59	67	89	79	69			
Rb	4.0	22.0	1.2	1.7	0.6	1.2	0.6	5.0	31.0
Cs	0.39	0.77	0.14	0.35	0.09	0.18	0.007	0.063	0.387
Ba	160	1200	150	99	46	100	6	57	350
Sr	100	190	120	140	150	460	90	155	660
Tl	0.03	0.10	<0.02	<0.02	<0.02	<0.02			
Ga	14.0	15.0	12.0	14.0	11.0	20.0			
Ta	0.1	0.1	0.2	0.2	0.4	0.2			
Nb	1.9	1.5	2.4	2.4	6.0	3.6	2.3	8.3	48.0
Hf	1.3	1.1	1.5	1.5	1.9	1.2	2.1	2.0	7.8
Zr	52.0	40.0	56.0	57.0	73.0	45.0	74.0	73.0	280.0
Y	26.0	21.0	23.0	22.0	26.0	35.0	28.0	22.0	29.0
Th	0.13	0.28	0.10	0.11	0.32	0.32	0.12	0.60	4.00
U	0.06	0.06	0.03	0.06	0.10	0.21	0.05	0.18	1.02
La	1.50	1.80	1.50	1.00	4.50	6.80	2.50	6.30	37.00
Ce	4.40	4.90	4.80	3.20	11.00	15.00	7.50	15.00	80.00
Pr	0.80	0.86	0.81	0.58	1.60	2.30	1.32	2.05	9.70
Nd	4.80	4.70	4.60	3.50	8.40	12.00	7.30	9.00	38.50
Sm	2.00	1.60	1.70	1.40	2.60	3.40	2.63	2.60	10.00
Eu	0.78	0.70	0.73	0.53	0.94	1.80	1.02	0.91	3.00
Gd	3.20	2.50	2.50	2.50	3.70	4.80	3.68	2.97	7.62
Tb	0.63	0.49	0.50	0.49	0.65	0.82	0.67	0.53	1.05
Dy	4.20	3.30	3.30	3.30	4.30	5.10	4.55	3.55	5.60
Ho	0.93	0.73	0.79	0.76	0.94	1.10	1.01	0.79	1.06
Er	2.70	2.10	2.20	2.30	2.70	3.30	2.97	2.31	2.62
Tm	0.42	0.36	0.38	0.35	0.43	0.53	0.46	0.36	0.35
Yb	2.70	2.50	2.50	2.50	3.00	3.70	3.05	2.37	2.16
Lu	0.40	0.39	0.40	0.40	0.46	0.63	0.46	0.35	0.30
Al_2O_3/TiO_2	17	23	16	17	11	19	11	9	5
Ti/Sc	137	112	134	130	199	135	204	-	-
Ti/V	26	21	27	26	31	15	31	-	-
Sc/Yb	16	14	17	16	12	9	13	0	0
Zr/Y	2.00	1.90	2.43	2.59	2.81	1.29	2.64	3.32	9.66
Zr/Sc	1.21	1.11	1.33	1.39	1.97	1.41	1.85	-	-
Zr/Nb	27.4	26.7	23.3	23.8	12.2	12.5	31.8	8.8	5.8
Zr/TiO_2	53	60	60	64	59	63	54	43	109
Zr/Hf	40.00	36.36	37.33	38.00	38.42	37.50	36.10	35.96	35.90
Nb/Y	0.07	0.07	0.10	0.11	0.23	0.10	0.08	0.38	1.66
Nb/Ta	15.83	15.00	16.00	15.00	16.22	15.65	-	-	-
Nb/U	32	25	80	40	60	17	50	46	47
Th/Nb_{pm}	0.57	1.57	0.35	0.38	0.45	0.75	0.43	0.61	0.70
La/Sm_n	0.48	0.73	0.57	0.46	1.12	1.29	0.61	1.56	2.39
La/Yb_n	0.40	0.52	0.43	0.29	1.08	1.32	0.59	1.91	12.29
Ce/Yb_n	0.45	0.54	0.53	0.36	1.02	1.13	0.68	1.76	10.29
Eu/Eu*	0.94	1.07	1.08	0.87	0.93	1.36	1.00	1.00	1.05
Nb/Nb*	1.44	0.71	2.00	2.45	1.63	0.74	1.29	1.43	1.33
Zr/Zr*	1.15	1.01	1.38	1.77	1.08	0.49	1.17	1.04	0.98
Hf/Hf*	1.04	1.00	1.34	1.69	1.02	0.47	1.17	1.05	0.99
Ti/Ti*	1.12	0.87	1.20	1.43	0.94	0.40	1.11	1.24	0.46

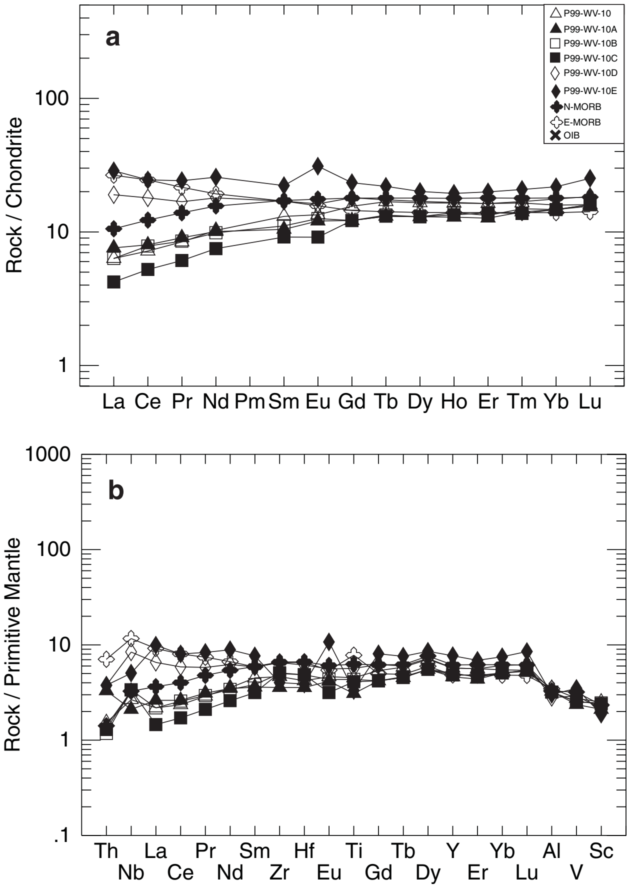


Figure 6. *a) Chondrite-normalized and* ***b****) primitive-mantle-normalized trace-element plots for Wolverine basalt. Shown for comparison are values for N-MORB and E-MORB (Sun and McDonough, 1989). Chondrite and primitive-mantle values are modified from Sun and McDonough (1989). Symbols as in Figure 4. N-MORB = mid-ocean-ridge basalt, E-MORB = enriched mid-ocean-ridge basalt*

DISCUSSION

Mantle source(s)

Some insights regarding the mantle source(s) for the Wolverine basalt flows and the role of subduction-zone influence and/or crustal contamination can be provided using trace-element data. The low to moderate HFSE contents (Fig. 5, Table 1) and varied LREE abundances (Fig. 6a, b) are similar to those of N-MORB to E-MORB and suggest derivation from a depleted to weakly enriched mantle source (e.g. McKenzie and Bickle, 1988; Sun and McDonough, 1989). To examine this further, we have plotted key immobile HFSE ratios (Nb/Yb, Zr/Yb, and Th/Yb) in two bivariate plots (Fig. 7a, b); these ratios were chosen because Zr, Nb, and Yb are moderately incompatible during mantle partial melting and also relatively immobile during subsequent hydrothermal alteration. As a result, these element ratios are not affected by any absolute element variation due to mass change. Furthermore, because of the moderately incompatible nature of these elements in basaltic systems, the HFSE ratios are relatively unaffected by partial melting and fractional crystallization, and reflect the mantle sources of the basalt (e.g. Pearce, 1983; Pearce and Peate, 1995). In the plot of Zr/Yb versus Nb/Yb (Fig. 7a), the Wolverine basalt flows lie within the field for N-MORB with one sample trending intermediate between N-MORB and E-MORB, consistent with derivation from depleted to weakly enriched mantle (e.g. Sun and McDonough, 1989).

Similarly, in Figure 7b, the samples lie between the fields for global compilations of N-MORB and E-MORB (Sun and McDonough, 1989). However, some samples have notably higher Th at a given Nb content relative to the fields for N-MORB and E-MORB (Fig. 7b). This suggests that at least one other process has influenced the Th content of the basalt.

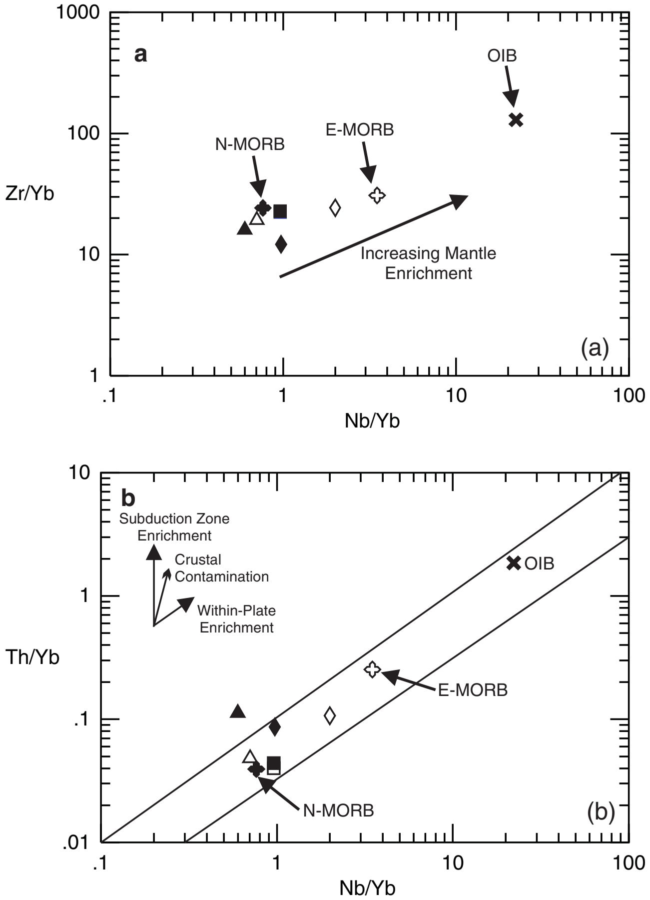


Figure 7. *Immobile high-field-strength element ratio plots.* ***a****) Zr/Yb-Nb/Yb and* ***b****) Th/Yb-Nb/Yb. Diagrams modified from Pearce (1983) and Pearce and Peate (1995). Symbols as in Figure 4.*

Numerous workers have shown that high Th and other low-field-strength elements (LFSE) can be quantitatively transferred from the subducted slab to the mantle wedge above subduction zones (Pearce, 1983; Brenan et al., 1995; Pearce and Peate, 1995). Back-arc basins proximal to subduction zones typically contain basalt with elevated LFSE contents, and such basalt has been interpreted to originate by subducted-slab LFSE metasomatism of the back-arc mantle source (e.g. Hawkins, 1995). Similarly, we suggest that the elevated Th content in some Wolverine basalt flows may reflect metasomatism of a N-MORB- to E-MORB-type mantle source with Th from subducted-slab fluids.

Equally viable, however, is that the Th enrichment (and possibly LREE) in the Wolverine basalt flows is due to crustal contamination. For example, all the felsic volcanic and volcaniclastic rocks below the Wolverine basalt flows are enriched in Th and LREE (Piercey et al., in press), and basalt interaction with the felsic substrate is highly probable. Further Nd-isotopic and geochemical studies of the Wolverine basalt flows are required to test whether crustal contamination was the source of Th- and LREE-enrichment in the Wolverine basalt flows.

Tectonic setting

An understanding of the petro-tectonic setting of the Wolverine VHMS deposit requires integration of the geological and geochemical attributes of the volcanic, sedimentary, and intrusive rocks. Previous workers have largely considered rocks of the Yukon–Tanana Terrane in the Finlayson Lake district to be the product of continental-arc magmatism (e.g. Mortensen, 1992). More recent refinements have delineated subsettings within this broadly continental ‘arc’ environment. For example, Piercey et al. (in press) suggested that the compositions of the felsic volcanic rocks of the Kudz Ze Kayah unit (unit 3) and Wolverine succession were emplaced within an ensialic back-arc-basin environment.

The geochemical attributes of the Wolverine basalt flows with N-MORB< E-MORB and back-arc-basin basalt signatures are all features common to basalt forming within modern back-arc-basin settings (e.g. Hawkins, 1995) and support a back-arc-basin setting for the Wolverine VHMS deposit. These basalt flows are located stratigraphically above felsic volcanic rocks, suggesting a progression from crust-derived felsic magmatism (Piercey, 2001; Piercey et al., in press) in the lower parts of the Wolverine succession to mantle-derived mafic magmatism (this study) in the upper part of the succession. The N-MORB to weakly E-MORB characteristics of the Wolverine basalt flows also suggest that crustal attenuation and extension must have occurred. For example, the lack of HREE depletion and the flat HREE patterns (Fig. 6) of the Wolverine basalt flows require formation from low-pressure (spinel stability field) melting at shallow levels (<60 km) within the mantle, with a minimal lithospheric cap (McKenzie and Bickle, 1988; Ellam, 1992; Williamson et al., 1995). Furthermore, a Wolverine basalt sample with N-MORB composition (P99-WV-10A) yielded an εNd_t value of +6.8 (Piercey, 2001), which indicates little crustal interaction (contamination) and suggests significant crustal attenuation. These geological and geochemical features suggest that the Wolverine basalt flows likely represent generation within an ensialic back-arc rift to nascent ensialic back-arc basin. The timing of this rift to incipient basin development is not well constrained. However, the footwall felsic volcanic rocks to the Wolverine deposit are Early Mississippian (~346 Ma; Piercey, 2001) and the Wolverine basalt flows are unconformably overlain by Pennsylvanian–Permian (Plint and Gordon, 1997) rocks of the Campbell Range. Together, these constraints provide a broad age range during which spreading could have occurred. Nevertheless, because the felsic volcanic and volcaniclastic host rocks to the Wolverine deposit likely formed from ensialic back-arc-basin magmatism, the Wolverine basalt flows most likely represent a Mississippian ((?)~345–346 Ma) progression to seafloor spreading within this evolving back-arc basin.

SUMMARY

Massive basalt flows stratigraphically overlie aphyric rhyolite flows in the hanging wall of the Wolverine VHMS deposit. The HFSE and REE geochemical attributes of the flows are similar to those of N-MORB and E-MORB. This suggests that the flows were produced from a depleted to weakly enriched mantle source. Many samples have elevated Th values compared to N-MORB and have signatures similar to back-arc-basin basalt, suggesting that Th was added to their mantle source via subducted-slab metasomatic fluids. The flat to LREE-depleted chondrite-normalized signatures require that the basalt flows formed by low-pressure mantle melting within the spinel stability field under a minimal lithospheric cap (<60 km depth). The Wolverine basalt flows likely formed during the latter stages of evolution of an ensialic back-arc basin to seafloor spreading. Initial stages are represented by felsic volcanism and formation of the Wolverine deposit. The basin underwent continued crustal attenuation and low-pressure mantle melting that culminated in the emplacement of the Wolverine basalt flows in an ensialic back-arc rift to nascent ensialic back-arc basin.

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