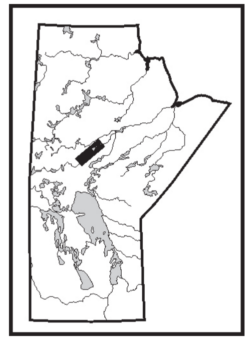
GS-6 Geochemistry, Sm-Nd isotope data and age constraints of the Bah Lake assemblage, Thompson Nickel Belt and Kisseynew Domain margin: relation to Thompson-type ultramafic bodies and a tectonic model (NTS 63J, O and P)

by H.V. Zwanzig



Zwanzig, H.V. 2005: Geochemistry, Sm-Nd isotope data and age constraints of the Bah Lake assemblage, Thompson Nickel Belt and Kisseynew Domain margin: relation to Thompson-type ultramafic bodies and a tectonic model (NTS 63J, O and P); *in* Report of Activities 2005, Manitoba Industry, Economic Development and Mines, Manitoba Geological Survey, p. 40–53.

Summary

New and previously unpublished geochemistry, Sm-Nd isotope data and recently published U-Pb zircon ages are used to characterize the mafic-ultramafic volcanic and intrusive rocks of the Bah Lake assemblage at the top of the Ospwagan Group continental-margin and rift succession in the Thompson Nickel Belt (TNB). These highly metamorphosed and complexly folded rocks include a high-Mg suite; a fractionated, incompatible-element–enriched mafic suite; and one or two minor suites. They are distinguished from one another by geochemical plots that indicate the involvement of different mantle sources and the presence or absence of crustal assimilation. Samarium-neodymium data are critical in establishing possible involvement of older crust in the origin of these suites.

The minimum age of the Bah Lake assemblage is newly constrained by the ca. 1890 Ma granitoid intrusions that it appears to hosts. This age, and a comparison of geochemistry and ε_{Nd} values of the Bah Lake assemblage to the 1885–1883 Ma Thompson-type ultramafic bodies and Molson dikes, suggest a new tectonic-evolution model for the TNB and other parts of the Superior craton margin. This evolution appears to involve four different episodes of crustal extension and mafic-ultramafic magmatism, and is consistent with an earlier conclusion that the Bah Lake assemblage magmatism was not directly related to deposition of the nickel ores. The high-Mg magmatism of the Bah Lake assemblage, however, may have provided the crustal and mantle conditions required for later emplacement of Thompson-type magmas with their high olivine (and nickel) contents and capacity to precipitate nickel ore. A better understanding of TNB structure and tectonics may lead to more effective exploration models.

Introduction

The Bah Lake assemblage of metamorphosed mafic-ultramafic volcanic and intrusive rocks occurs in the Thompson Nickel Belt (TNB). The TNB extends from an area 70 km northeast of Thompson, Manitoba for a distance of about 400 km to the southwest, with the southern half covered by Phanerozoic rocks (Figure GS-6-1; Thompson Nickel Belt Geology Working Group, 2001a–o). The Bah Lake assemblage forms the upper part of the Ospwagan Group, which comprises a thin Paleoproterozoic continental-margin cover on the northwestern margin of the Archean Superior craton. The Ospwagan Group unconformably overlies the Archean basement gneiss that extends southeast into granulite. The sedimentary rocks and the Bah Lake assemblage of the Ospwagan Group occur as highly metamorphosed keels in the structurally reworked Archean basement. Intrusions that are part of the Bah Lake assemblage, and others that are younger but pertinent to this study, including the Thompson-type ultramafic bodies and the Molson dike swarm, have also undergone the intense thermotectonism in the TNB.

The TNB, which is bounded to the north and west by the juvenile Paleoproterozoic rocks of the internal zone of the Trans-Hudson Orogen (THO), forms the southeastern external zone of the THO (Bleeker, 1990a). The Kisseynew Domain, which lies west of the TNB, comprises 1850–1830 Ma syncollisional metasedimentary rocks of the Burntwood and Grass River groups (Zwanzig, 1997). These are locally structurally intercalated with amphibolite of the Bah Lake assemblage (Zwanzig, 1998, 1999). The Kisseynew Domain and the adjacent margin of the TNB contain ca. 1890–1885 Ma plutons (Percival et al., 2004, 2005, GS-9, this volume) that appear to intrude western outliers of the Bah Lake assemblage (Zwanzig et al., 2003). Syn- to postcollisional granite intrudes the younger metasedimentary rocks in the Kisseynew Domain and the rocks at the margin of the TNB (Zwanzig, 1997, 1998).

In spite of extensive nickel exploration and mapping in the greater Thompson area (e.g., Thompson Nickel Belt Geology Working Group, 2001a–h), the stratigraphy, structure and regional extent of the Bah Lake assemblage are not well known (e.g., compare Zwanzig, 1997, 1998, 1999). Nor is the tectonic setting or tectonic history well understood for the TNB and other parts of the Superior craton margin in Manitoba. Three or four episodes of crustal extension with related magmatism may be identified in TNB, but these are not well constrained in time. The first episode is ca. 2.1 Ga dike intrusion northeast of the TNB (Heaman and Corkery, 1996). The second is mafic-ultramafic magmatism that produced the Bah Lake assemblage, bracketed between ca 1974 and 1890 Ma (Bleeker and Hamilton, 2001; Percival et al., 2005). The third episode is represented by the 1885–1883 Ma

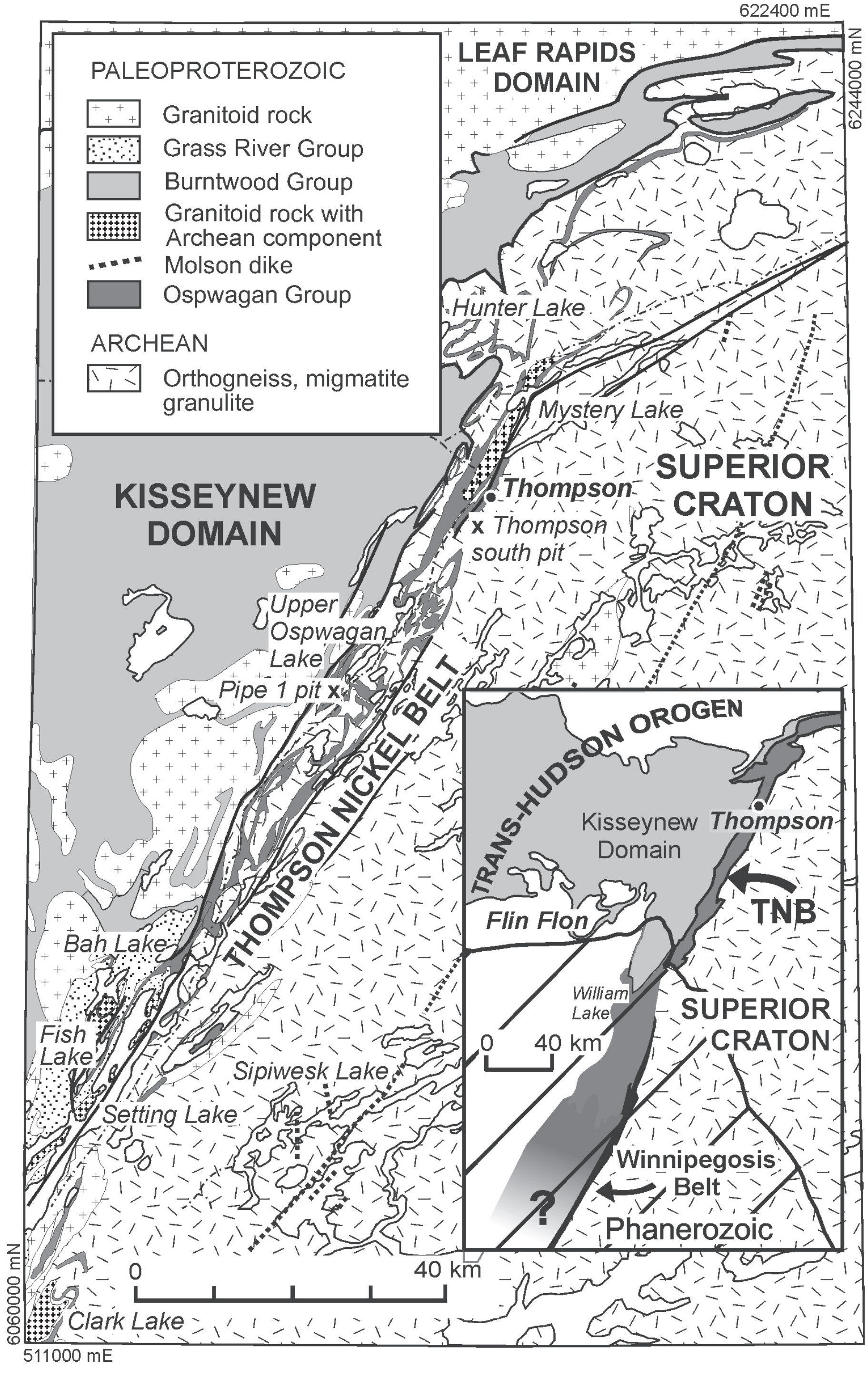


Figure GS-6-1: *Tectonic setting and regional geology of the Bah Lake assemblage and metasedimentary units in the Thompson Nickel Belt (TNB), at the northeastern boundary of the Superior craton. Areas of geochemical sampling discussed in this report are identified using the nearest lakes.*

intrusion of Molson dikes and the Thompson-type ultramafic bodies (Hulbert et al., 2005). The fourth, ca. 1860 Ma, involved mafic dikes in the TNB and ultramafic to mafic magmatism in the Winnipegosis komatiite belt (Bleeker and Hamilton, 2001; Hulbert et al., 1994).

This report uses geochemistry, Sm-Nd isotope ratios and the recently obtained absolute ages of adjoining rocks to further elucidate the origin of Bah Lake assemblage, and compare and contrast it with the mafic-ultramafic intrusions formed during the younger episodes of crustal extension. The most rigorous conclusions are drawn from normalized plots and ratio plots of trace and minor elements not highly subject to alteration. They include the rare earth elements (REE), Th, Nb, Zr, Hf, Ti and

Y, elements that are progressively less compatible with the common rock-forming minerals as their ionic radius increases and they are partitioned more into melts. Their element ratios and the shape of their mantle-normalized patterns are little affected by crystal fractionation and they provide important clues to the origin of melts. Interpretation of these plots confirms and extends the understanding of the relation between the Bah Lake assemblage and the Thompson-type ultramafic bodies. This is important, as the latter host the major nickel deposits in the TNB.

The data for this report were compiled from analyses of recently collected samples (Zwanzig, 2004), a growing database of chemistry and Sm-Nd isotope ratios (e.g., Zwanzig and Böhm, 2002), and selected earlier data collected mainly by the author, D. Peck[1] and P. Theyer of the Manitoba Geological Survey during Canadian Mining Industry Research Organization (CAMIRO) Project 97E-02. Comparative data are from two exploration drillcores included in the unpublished CAMIRO database from Inco Technical Services Ltd. and Falconbridge Ltd.

Tectonostratigraphy

A mafic volcanic succession is recognized as forming the uppermost unit in the Ospwagan Group (Macek and Bleeker, 1989; Bleeker, 1990b). Although the rocks are metamorphosed at amphibolite facies and folded in a large-scale interference pattern, homoclinal sections are relatively well preserved on the northwest shore of Upper Ospwagan Lake (Zwanzig, 2004) and between Setting Lake and Bah Lake (Figure GS-6-1b in Zwanzig, 1999). This mafic succession was renamed the Bah Lake assemblage (Burnham et al., 2004). The Setting Lake–Bah Lake and Upper Ospwagan Lake sections comprise pillowed and massive basalt with abundant sheets of gabbro that may include dikes, sills and thick flows. The rocks are very mafic and appear to grade into ultramafic compositions (for descriptions, *see* Zwanzig, 1997, 1998, 2004). Sheets of metapicrite with olivine megacrysts are abundant at Upper Ospwagan Lake; more schistose equivalents occur locally on Setting Lake and elsewhere.

The Bah Lake assemblage overlies the quartz-rich metagreywacke-mudstone turbidite of the Setting Formation throughout the TNB. Although this lower contact is not exposed, there is local interlayering of clastic rocks with the Bah Lake assemblage. Moreover, abundant sills in the Setting Formation at Setting Lake have the same appearance as overlying gabbro in the Bah Lake assemblage, thus suggesting that the lower sills may be feeders to the flows and that the lower contact of the Bah Lake assemblage is generally stratigraphic. At Bah Lake and to the southwest, however, the mafic rocks are in fault contact with several different units and occur in two or three structural positions with uncertain stratigraphic position (Zwanzig, 1999). The succession at Bah Lake is most schistose at the top (northwest), where it has a different chemical composition than in the main section. This foliated upper amphibolite extends southwest into the Kisseynew Domain beyond Fish Lake (Figure GS-6-1), where it is in fault contact with the younger metaturbidite of the Burntwood Group. Thus, the Bah Lake–type flows and intrusions in the Setting Lake–Fish Lake area may form a structural assemblage that represents more than one stratigraphic unit. This relationship is tested using chemostratigraphy (*see* below).

The Bah Lake assemblage is unconformably overlain by the metasandstone of the Grass River Group (Zwanzig, 1997, 1998). A basal metaconglomerate is locally preserved, although the unconformity is highly sheared and the clasts highly flattened. This relation occurs in the Setting Lake–Fish Lake area, but the top of the Bah Lake assemblage is not preserved in the main part of the TNB where the Grass River Group is not exposed.

Age constraints

The absolute age of the Bah Lake assemblage is uncertain. No direct isotopic dating has been attempted for apparent lack of rocks suitable for obtaining zircon or baddeleyite. The underlying Setting Formation metagreywacke has yielded an age of 1974 ±50 Ma from a single grain of detrital zircon, the remaining ages being Archean (Bleeker and Hamilton, 2001). Recent U-Pb zircon dating by thermal ionization mass spectrometry (TIMS) and sensitive high-resolution ion microprobe (SHRIMP) has isolated a suite of large granitoid calc-alkaline plutons yielding crystallization ages of 1891 ±5 Ma to 1885 ±5 Ma (Percival et al., 2004, 2005, GS-9, this volume). One of these plutons has an amphibolite roof pendant interpreted by Zwanzig et al. (2003) to be derived from the basalt of the outboard or upper part of the Bah Lake assemblage. The amphibolite in the roof pendant is unconformably overlain by the Grass River Group. An adjacent pluton dated at 1891 ±5 Ma (Percival et al., 2004) has a contact interpreted by Zwanzig et al. (2003) as intrusive into the main part of the Bah Lake assemblage but overprinted by mylonitic fabric. Thus, the Bah Lake assemblage is loosely bracketed between ca. 1974 and 1890 Ma.

If the oldest Paleoproterozoic dikes northeast of the TNB represent an early episode of crustal rifting, then their age of ca. 2.1 Ga (Heaman and Corkery, 1996) may provide an approximate age for the coarse quartz-rich clastic rocks at the base of the Ospwagan Group. These rocks, which contain only Archean zircons (Zwanzig et al., 2001), could be significantly older than those of the Bah Lake assemblage at the top of the group.

[1] presently with Anglo American Ltd.

A pyroxenite from a Thompson-type ultramafic intrusion in the Ospwagan Group on Setting Lake has yielded a TIMS U-Pb zircon age of 1885 ±5 Ma (Hulbert et al., 2005). This ultramafic intrusion is apparently coeval within error (2σ) of 1883 ±2 Ma Molson dikes dated east of the TNB (Hulbert et al., 2005 and references therein). Undated dikes, identical to the Molson dikes, cut the Ospwagan Group in the TNB. This mafic-ultramafic magmatism likely represents a third episode of crustal extension or rifting. The age constraints of the Bah Lake assemblage indicate that it is older than the Molson- and Thompson-type intrusions. The apparent absence of these intrusions in the Bah Lake assemblage may be a consequence of an inability to distinguish them from their host rocks at high metamorphic grade. Alternatively, the high density of the Thompson-type intrusion may have prevented them from reaching high stratigraphic levels in the Ospwagan Group.

The only other mafic intrusion into the Ospwagan Group dated in the TNB is a gabbro dike with a quartz diorite core. This dike, which is from the Thompson south pit, yielded a TIMS U-Pb age of 1855 ±13 Ma (Bleeker and Hamilton, 2001), within error of an 1864 Ma (Hulbert et al., 1994) gabbro in the Winnipegosis komatiite belt. These rocks may represent a fourth episode of crustal extension and mafic-ultramafic magmatism along the margin of the Superior craton.

Geochemistry

The flows and intrusions of the Bah Lake assemblage are tholeiitic to picritic or komatiitic and show a wide range in MgO, Fe_2O_3 and TiO_2 (Table GS-6-1)[2]. The volatile free content of MgO ranges from 4.8 to 15.9% for basalt or gabbro, and from 17.8 to 26.4% for picrite or komatiite. The TiO_2 contents are moderate and fall into the range of mid-ocean ridge basalt (MORB) or back-arc basin basalt (BABB) or low-Ti continental basalt (Figure GS-6-2). This indicates an origin in a tectonic environment with crustal extension.

Major and trace-element geochemistry indicates that the Bah Lake assemblage includes two major mafic to ultramafic suites: 1) a high-Mg suite, and 2) an incompatible-element–enriched suite. The high-Mg suite includes several minor rock types. These suites can be distinguished by extended-element plots. Their study leads to the interpretation (discussed below) that the major suites had different mantle sources, whereas the minor suites involved different amounts of crystal fractionation or crustal contamination. Samarium-neodymium data and careful sampling are critical in establishing possible involvement of older crust in the origin of these suites.

High-Mg suite

High-Mg basalt with relatively flat primitive-mantle–normalized extended-element plots is most common in the main part of the TNB from Setting Lake to Mystery Lake (Figure GS-6-3). The basalt is slightly depleted in middle to heavy REE compared to modern normal mid-ocean ridge basalt (N-MORB), but not as strongly depleted as N-MORB in light REE (LREE) and low-field-strength elements (LFSE), such as Th. Although Th shows anomalously high values in some individual plots, indicating LFSE mobility, it shows consistent depletion on most plots where it represents a magmatic value. Zirconium and titanium have negative anomalies for the high-Mg flows and the intercalated sheets of picrite. The unique and regionally persistent extended-element pattern of high-Mg basalt allows it to be identified, compared and contrasted to other types of flows and various mafic and ultramafic intrusions throughout the TNB.

The similar patterns in Figure GS-6-3a, b, c and e strongly suggest that the high-Mg basalt, picrite and high-Mg gabbro are comagmatic or were derived from the same mantle source under similar conditions. The average ratio of La/Yb is 1.4 for all of these units and the Zr trough in the pattern is ubiquitous. A sample of apparently aphyric ultramafic rock at the top of a picrite sill has Al_2O_3/TiO_2 = 17 and CaO/Al_2O_3 = 1.0, typical values for Al-undepleted Archean komatiite (Kerrich and Wyman, 1996). The entire high-Mg suite may have been fractionated from similar komatiite during the Paleoproterozoic in the TNB.

Small local variations in geochemistry do exist in this common suite. Flows at Bah Lake and on parts of Setting Lake have slightly higher trace-element contents, averaging five times primitive mantle compared to three times for the main high-Mg suite at nearly the same range of MgO. Niobium forms a small peak for the basalt near Bah Lake. It is uncertain whether these small variations from the main high-Mg suite are significant. They may indicate a slightly smaller degree of partial melting.

Another minor type of high-Mg basalt includes flows at Mystery Lake that have a fractionated REE pattern with strong negative Nb and Ti anomalies but small peaks in Zr and Hf (Figure GS-6-3h). These rocks are interpreted as being contaminated with granitic crust and are discussed with the Sm-Nd isotope data (below). They are considered to be derived from the parent magma for the high-Mg suite because of the same low content of heavy REE (three times primitive mantle), which are least affected by crustal assimilation.

[2] MGS Data Repository Item 2005005, containing the complete data set for the Bah Lake assemblage used to compile this report, is available on-line to download free of charge at www2.gov.mb.ca/itm-cat/freedownloads.htm, or on request from minesinfo@gov.mb.ca or Mineral Resources Library, Manitoba Industry, Economic Development and Mines, 360–1395 Ellice Avenue, Winnipeg, MB R3G 3P2, Canada.

Table GS-6-1: Average and selected typical whole-rock, major- and trace-element analyses and ε_{NdT} values, Bah Lake assemblage.

Sample	Rock type	Location	εNdT	La/Yb	SiO_2	Al_2O_3	Fe_2O_3	MnO	MgO	CaO	Na_2O	K_2O
Bah L flows	*Hgh-Mg basalt*	*Average of 23, (4)[1]*	*(2.40)*	*1.4*	*48.9*	*13.61*	*11.64*	*0.17*	*10.00*	*10.77*	*2.08*	*0.21*
12-99-1037	Basalt	Setting Lake NE		1.4	48.6	15.11	12.07	0.19	7.86	11.08	2.37	0.27
12-04-4436-2	Pillow basalt	Upper Ospwagan Lake	2.90	1.4	48.0	12.06	11.66	0.17	11.46	11.99	1.82	0.14
12-99-973	Komatiitic basalt	Setting Lake S		1.7	48.7	9.19	11.24	0.18	15.40	11.31	1.26	0.25
CC98-004-1	Mafic flow	Bah Lake		1.3	48.8	14.22	12.49	0.18	10.41	7.63	3.47	0.24
Bah L flows	*Enriched basalt*	*Average of 12, (3)*	*(2.45)*	*3.0*	*49.0*	*13.72*	*13.73*	*0.20*	*6.55*	*10.64*	*2.62*	*0.52*
12-03-4175	Amphibolite	Five Mile Lake	2.30	3.2	49.7	12.95	17.03	0.21	4.75	9.00	2.27	0.60
12-98-551-5	Pillow basalt	Fish Lake	1.45	2.1	48.0	13.62	13.97	0.18	7.72	10.75	2.62	0.31
12-03-4323	Amphib.(pillows?)	Setting Lake SW	3.61	4.7	50.2	14.04	12.14	0.18	8.44	10.65	2.27	0.63
Picrite	*High-Mg sills*	*Average of 9 (3)*	*(2.54)*	*1.4*	*44.2*	*7.86*	*11.15*	*0.15*	*21.31*	*8.46*	*0.81*	*0.07*
12-04-4433-2	Aphyr. picrite (top)	Upper Ospwagan Lake	2.83	1.3	45.2	7.55	10.96	0.15	22.93	7.71	0.24	0.08
12-04-4442-2	Picrite flow?	Upper Ospwagan Lake	2.45	1.5	46.3	10.56	10.28	0.16	17.26	10.30	1.43	0.06
51-98-25-1	Porhyritic picrite	Upper Ospwagan Lake	2.41	1.5	43.2	6.32	10.64	0.14	23.28	7.83	0.78	0.08
Komat. baslt	*High-Mg basalt*	*Average of 2, (2)*	*(-4.61)*	*2.5*	*49.9*	*10.22*	*10.56*	*0.18*	*14.49*	*8.48*	*1.60*	*0.43*
51-99-19	Pillow basalt	Mystery Lake	-4.04	2.0	48.0	10.50	11.18	0.18	15.15	8.91	1.15	0.48
51-99-24	Pillow basalt	Mystery Lake	-5.18	3.1	51.8	9.94	9.94	0.19	13.83	8.05	2.04	0.38
Mafic dikes/sills	*Hgh-Mg gabbro*	*Average of 11, (1)*	*(2.48)*	*1.4*	*48.4*	*14.50*	*12.31*	*0.18*	*8.86*	*9.72*	*2.84*	*0.35*
12-99-2036-A	Leucogabbro	Setting Lake centre		1.3	50.2	14.29	12.99	0.21	6.91	9.04	3.63	0.21
12-98-392	Ampholite/gabbro	Five Mile Lake		1.3	47.1	13.86	12.45	0.22	8.25	10.91	3.11	1.00
CC98-017-1B	Gabbro	Bah Lake		1.2	48.3	13.69	12.96	0.19	9.92	8.44	3.62	0.27
CC98-001-1A	Melagabbro	Bah Lake	2.48	1.6	47.2	14.58	12.31	0.17	10.14	10.30	2.23	0.34
Mafic dikes/sills	*Enriched gabbro*	*Average of 5, (2)*	*(2.04)*	*3.1*	*51.1*	*14.36*	*13.78*	*0.20*	*6.46*	*7.49*	*2.74*	*0.83*
12-97-101-7	Gabbro	Setting Lake NE		3.5	48.2	12.89	16.30	0.22	8.16	7.14	3.40	0.45
12-03-4177	High-Mg flow/sill	Setting Lake, centre	1.84	3.2	45.9	10.15	18.27	0.24	11.91	7.45	1.87	0.36
12-04-4453-3	Amphibolite/gabbro	Upper Ospwagan Lake		4.34	49.6	14.37	14.60	0.22	6.57	10.91	2.30	-0.01

(4)[1] number in average εNdT

Sample	TiO_2	P_2O_5	LOI	TOTAL	Sc	V	Cr	Ni	Sr	Y	Zr	Nb	Cs	Ba	La	Ce
Bah L flows	*0.89*	*0.07*	*1.73*	*98.1*	*43.6*	*294*	*377*	*159*	*128*	*20.22*	*42.0*	*2.81*	*0.23*	*32*	*2.76*	*7.44*
12-99-1037	0.96	0.07	1.76	97.5	46.3	327	348	106	184	21.08	47.1	2.58	0.11	60	2.88	7.84
12-04-4436-2	0.78	0.06	1.17	99.3	40.0	233	581	240	96	17.70	38.0	2.18	0.61831	23	2.23	6.07
12-99-973	0.55	0.02	1.86	97.1	40.5	238	1303	434	24	14.82	30.3	1.06	0.46	8	2.05	5.22
CC98-004-1	1.03	0.08	0.98	97.4	47.6	319	183	98	194	22.99	48.4	4.19	0.05	6	3.03	8.53
Bah L flows	*1.45*	*0.13*	*1.48*	*97.6*	*44.2*	*363*	*139*	*58*	*172*	*26.66*	*80.7*	*6.83*	*0.18*	*57*	*7.86*	*18.38*
12-03-4175	2.16	0.21	0.25	99.2	41.0	428	75	39	140	36.54	115.4	9.93	-0.1	147	12.44	29.87
12-98-551-5	1.14	0.08	1.32	97.1	45.8	320	202	90	136	22.04	63.1	4.56	0.15	24	4.59	11.60
12-03-4323	0.98	0.08	0.57	100.1	42.0	301	192	118	117	20.14	53.9	3.87	0.36351	38	10.46	18.79
Picrite	*0.51*	*0.04*	*5.13*	*99.4*	*32.0*	*185*	*1999*	*850*	*28*	*11.45*	*22.1*	*1.45*	*0.28*	*9*	*1.55*	*4.19*
12-04-4433-2	0.46	0.03	4.46	99.7	26.0	145	1590	801	12	10.48	26.4	1.49	2.20491	6	1.24	3.68
12-04-4442-2	0.66	0.05	2.01	99.0	34.0	192	1300	588	30	14.21	31.2	1.86	-0.1	15	1.91	5.10
51-98-25-1	0.43	0.03	7.08	99.2	28.0	179	2614	1021	19	9.76	16.7	1.18	0.09	4	1.43	3.70
Komat. baslt	*0.49*	*0.06*	*3.52*	*99.1*	*24.0*	*188*	*1531*	*289*	*80*	*12.34*	*43.4*	*2.27*	*0.55*		*3.21*	*7.65*
51-99-19	0.52	0.06	3.78	99.1	23.0	197	1473	419	60	12.41	40.1	2.19	0.61		2.49	5.84
51-99-24	0.45	0.05	3.25	99.2	25.0	179	1589	159	100	12.26	46.7	2.34	0.49		3.92	9.45
Mafic dikes/sills	*0.94*	*0.08*	*1.81*	*98.1*	*41.8*	*308*	*206*	*131*	*155*	*18.79*	*41.2*	*2.77*	*0.18*	*37*	*2.69*	*7.42*
12-99-2036-A	1.05	0.08	1.14	99.8	45.8	362	104	35	100	18.97	44.6	2.52	0.03	2	2.44	6.93
12-98-392	1.04	0.07	2.23	96.9	47.0	318	266	110	210	19.73	36.6	2.72	0.41	123	2.49	7.37

Table GS-6-1: Average and selected typical whole-rock, major- and trace-element analyses and ε_{NdT} values, Bah Lake assemblage. *(continued)*

Sample	TiO_2	P_2O_5	LOI	TOTAL	Sc	V	Cr	Ni	Sr	Y	Zr	Nb	Cs	Ba	La	Ce
CC98-017-1B	1.02	0.07	1.62	97.3	41.3	314	202	230	267	21.74	47.3	3.83	0.07	32	2.79	7.99
CC98-001-1A	0.78	0.07	2.02	97.0	43.6	248	196	228	172	17.72	36.3	2.95	0.13	1	2.95	7.74
Mafic dikes/sills	*1.35*	*0.19*	*1.25*	*98.0*	*30.8*	*237*	*97*	*76*	*171*	*39.57*	*121.8*	*9.78*	*0.76*	*171*	*12.02*	*29.38*
12-97-101-7	1.81	0.18	1.62	97.3	32.7	363	131	90	213	32.37	133.6	8.17	0.8	239	9.44	24.46
12-03-4177	1.65	0.14	0.79	98.7	31.0	312	118	261	70	22.57	89.0	7.35	0.94257	73	7.34	19.24
12-04-4453-3	1.45	0.14	0.77	100.1	42.0	338	65	65	160	23.7	98	12.10	0.23075	67	11.70	26.81

Sample	Pr	Nd	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu	Hf	Ta	Th	U
Bah L flows	*1.20*	*6.19*	*2.01*	*0.77*	*2.72*	*0.50*	*3.20*	*0.72*	*2.06*	*0.31*	*1.95*	*0.31*	*1.42*	*0.16*	*0.30*	*0.10*
12-99-1037	1.34	6.46	2.12	0.83	2.78	0.55	3.32	0.82	2.07	0.35	2.02	0.34	1.60	0.16	0.28	0.07
12-04-4436-2	0.97	5.16	1.65	0.73	2.40	0.44	2.66	0.57	1.74	0.26	1.59	0.25	1.21		0.20	0.07
12-99-973	0.87	4.24	1.37	0.56	1.82	0.34	2.16	0.52	1.36	0.20	1.24	0.22	0.95	0.10	0.15	0.03
CC98-004-1	1.41	7.28	2.44	0.92	3.16	0.56	3.67	0.83	2.39	0.35	2.28	0.36	1.79		0.54	0.15
Bah L flows	*2.66*	*12.24*	*3.44*	*1.18*	*4.12*	*0.73*	*4.52*	*1.00*	*2.85*	*0.42*	*2.67*	*0.42*	*2.56*	*0.43*	*1.00*	*0.31*
12-03-4175	3.88	19.07	5.40	1.86	6.27	1.14	6.92	1.39	4.10	0.61	3.84	0.61	3.85		1.05	0.30
12-98-551-5	1.75	8.50	2.56	0.88	3.20	0.56	3.56	0.79	2.30	0.34	2.21	0.35	1.95	0.35	0.76	0.18
12-03-4323	2.46	10.37	2.20	0.87	3.04	0.56	3.65	0.78	2.33	0.35	2.21	0.35	1.81		0.29	0.09
Picrite	*0.67*	*3.53*	*1.16*	*0.43*	*1.58*	*0.28*	*1.82*	*0.40*	*1.16*	*0.17*	*1.08*	*0.17*	*0.78*	*0.08*	*0.12*	*0.04*
12-04-4433-2	0.59	3.30	0.99	0.46	1.49	0.27	1.63	0.35	1.07	0.16	0.97	0.15	0.79		0.13	0.04
12-04-4442-2	0.80	4.20	1.33	0.64	1.98	0.36	2.19	0.46	1.42	0.21	1.29	0.21	1.03		0.17	0.06
51-98-25-1	0.60	3.10	1.04	0.32	1.34	0.24	1.58	0.35	1.01	0.15	0.94	0.14	0.66	0.07	0.11	0.04
Komat. baslt	*1.13*	*5.07*	*1.49*	*0.53*	*1.79*	*0.31*	*2.02*	*0.46*	*1.27*	*0.20*	*1.27*	*0.20*	*1.38*	*0.24*	*1.32*	*0.36*
51-99-19	0.89	4.42	1.45	0.50	1.84	0.31	2.07	0.47	1.30	0.20	1.26	0.20	1.30	0.23	1.00	0.28
51-99-24	1.36	5.72	1.52	0.56	1.74	0.30	1.96	0.44	1.23	0.19	1.27	0.20	1.45	0.25	1.64	0.43
Mafic dikes/sills	*1.20*	*6.17*	*2.03*	*0.75*	*2.62*	*0.46*	*3.09*	*0.69*	*1.97*	*0.30*	*1.90*	*0.30*	*1.40*	*0.18*	*0.26*	*0.08*
12-99-2036-A	1.18	6.16	2.07	0.80	2.66	0.46	3.07	0.69	1.96	0.28	1.86	0.31	1.38	0.18	0.28	0.07
12-98-392	1.21	6.41	2.17	0.78	2.88	0.51	3.37	0.74	2.10	0.31	1.99	0.31	1.31	0.22	0.04	0.02
CC98-017-1B	1.35	6.93	2.25	0.82	2.94	0.55	3.49	0.80	2.29	0.34	2.24	0.34	1.71		0.43	0.12
CC98-001-1A	1.21	6.01	1.96	0.69	2.42	0.45	2.91	0.65	1.89	0.28	1.79	0.28	1.38		0.31	0.08
Mafic dikes/sills	*4.27*	*19.96*	*5.51*	*1.85*	*6.42*	*1.13*	*6.83*	*1.46*	*4.22*	*0.64*	*3.90*	*0.63*	*3.81*	*0.69*	*1.26*	*0.34*
12-97-101-7	3.49	17.30	4.75	1.41	4.95	0.85	5.56	1.10	3.03	0.52	2.68	0.47	3.46	0.54	0.93	0.24
12-03-4177	2.63	13.08	3.80	1.30	4.15	0.74	4.30	0.87	2.53	0.38	2.28	0.35	2.92		0.78	0.18
12-04-4453-3	3.54	15.58	3.92	1.42	4.83	0.82	4.76	0.97	3.03	0.44	2.69	0.42	2.90		1.41	0.42

Major elements by XRF, trace elements by ICP-MS at Actlabs. Analyses with Ta data by Geoscience Labs, Ontario Geological Survey.

Enriched suite

This major suite of basalt and gabbro occurs in the northwestern part of Setting Lake, near the southeast shore of Bah Lake and along the margin of the Kisseynew Domain to the west (Figure GS-6-1). It is characterized by higher trace-element contents than the high-Mg suite and by fractionated REE, as indicated by the negative slopes in Figure GS-6-3d and f. The average La/Yb ratio is 3.0 for flows and intrusions of this suite, compared to 1.4 for the high-Mg suite. The lower content of MgO, higher contents of Fe_2O_3 and TiO_2 (Figure GS-6-2) and general trace-element enrichment indicate that this suite has experienced greater high-level crystal fractionation than the high-Mg suite. Gabbroic anorthosite associated with the enriched suite is also interpreted to be a product of high-level fractionation. The range of MgO contents for the suite of enriched basalt and gabbro, however, is 4.8–12.2%, overlapping the MgO content of the high-Mg suite (5.7–27.5%). The content of Fe_2O_3 is 10.3–18.7%, compared to 10.2–14.4% for the high-Mg suite. Moreover, analyses with identical MgO contents show the two different geochemical patterns for the two suites. Even the most mafic analyses in the enriched suite have an LREE content of seven times primitive mantle, compared to about four times for similar analyses of high-Mg basalt. Heavy REE are greater than five times primitive mantle, compared to four times for the high-Mg suite. These characteristics are the result of melting of a different

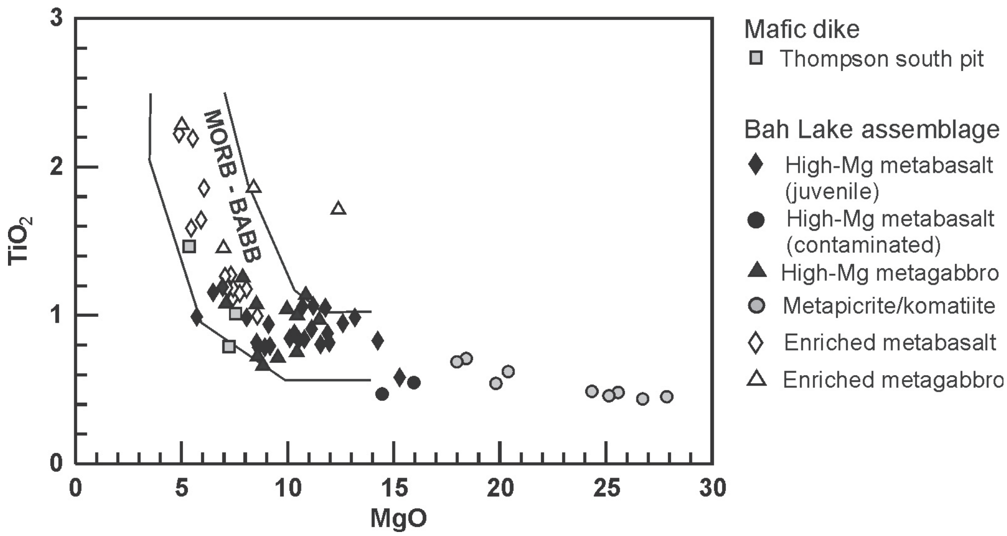


***Figure GS-6-2:** TiO_2 vs. MgO plot (after Stern et al., 1995) of samples from the Bah Lake assemblage. Symbols represent units distinguished by trace-element patterns in Figure GS-6-3.*

mantle source and/or during different conditions than for the high-Mg suite. The higher Nb and Ti values, which show no prominent negative anomalies, are inherited from the mantle source. The extended-element pattern of the enriched suite is similar to modern enriched mid-ocean ridge basalt (E-MORB) but has a negative Zr anomaly like the high-Mg suite (Figure GS-6-3d). Archean tholeiitic basalt with these characteristics has been interpreted by Kerrich and Wyman (1996) to be associated with Al-depleted komatiite, melted deep within a mantle plume.

Consistent northwest-facing pillow tops in the section at Bah Lake indicate that the enriched suite forms a younger part of the Bah Lake assemblage or was thrust over the main succession from the margin of the Kisseynew Domain, where this suite forms the only mafic rocks. Poor exposure and a complex fold pattern have prevented any early major thrust fault from being identified within the mafic section.

Younger mafic-ultramafic dikes/sills

Using the extended-element plots (Figure GS-6-3), comparisons can be made between the Bah Lake assemblage and younger mafic intrusions, including 1) Molson dikes on the west margin of the granulite terrane and within the granulite; 2) Thompson-type ultramafic intrusions at the Pipe 1 mine and at William Lake (to the south, beneath the Phanerozoic cover); and 3) a younger mafic dike exposed in the Thompson south pit.

The Molson dikes show a variety of geochemical patterns. For example, samples from Bear Island on Sipiwesk Lake are very similar to those from the Bah Lake high-Mg suite, whereas the geochemical pattern of other large Molson dikes (from the Nelson River and Molson Lake) resembles that of ‘contaminated’ flows at Mystery Lake. The pattern for crustal contamination with fractionated REE and a deep Nb trough is also present in many of the Thompson-type ultramafic intrusions, suggesting that these have also assimilated granitic crust.

The younger mafic dike exposed at the Thompson south pit is geochemically similar to the depleted Bear Island dike (Figure GS-6-3g), both showing no obvious contamination. These apparent variations in crustal assimilation are tested with Sm-Nd isotope data (Burnham et al., 2004 and below).

Crustal assimilation

Values of $\varepsilon_{Nd(T)}$, calculated at T = 1.90 Ga, have the limited range of +1.5 to +3.6 for most tested rocks from the Bah Lake assemblage (Table GS-6-1). Average values for the various units range from +2.0 to +2.5, within error of the data, which is about ±0.5 (Table GS-6-2). These values are very close to the mantle array calculated for the Flin Flon Belt (Stern et al., 1995). They indicate that the rocks are juvenile, without significant assimilation of older crust. Lines of approximate percent of crustal recycling were calculated using the Nd isotopic mantle values of Stern et al. (1995) and data from 11 samples of Archean basement gneiss from the TNB (Zwanzig and Böhm, 2002; Zwanzig and Böhm, unpublished data, 2004). They suggest that the Bah Lake assemblage generally has less than 1% Archean component (Figure GS-6-4). The wide ε_{Nd} interval between small fractions of crustal assimilation is the result of the ancient mantle-separation age, which yields strongly negative ε_{Nd} values for the basement gneiss. The average ε_{Nd} at 1.90 Ga is –17 for the basement gneiss. Uncertainty is introduced by the large range of Nd isotope ratios used to calculate the basement average, and by the absence of data from the lower crust.

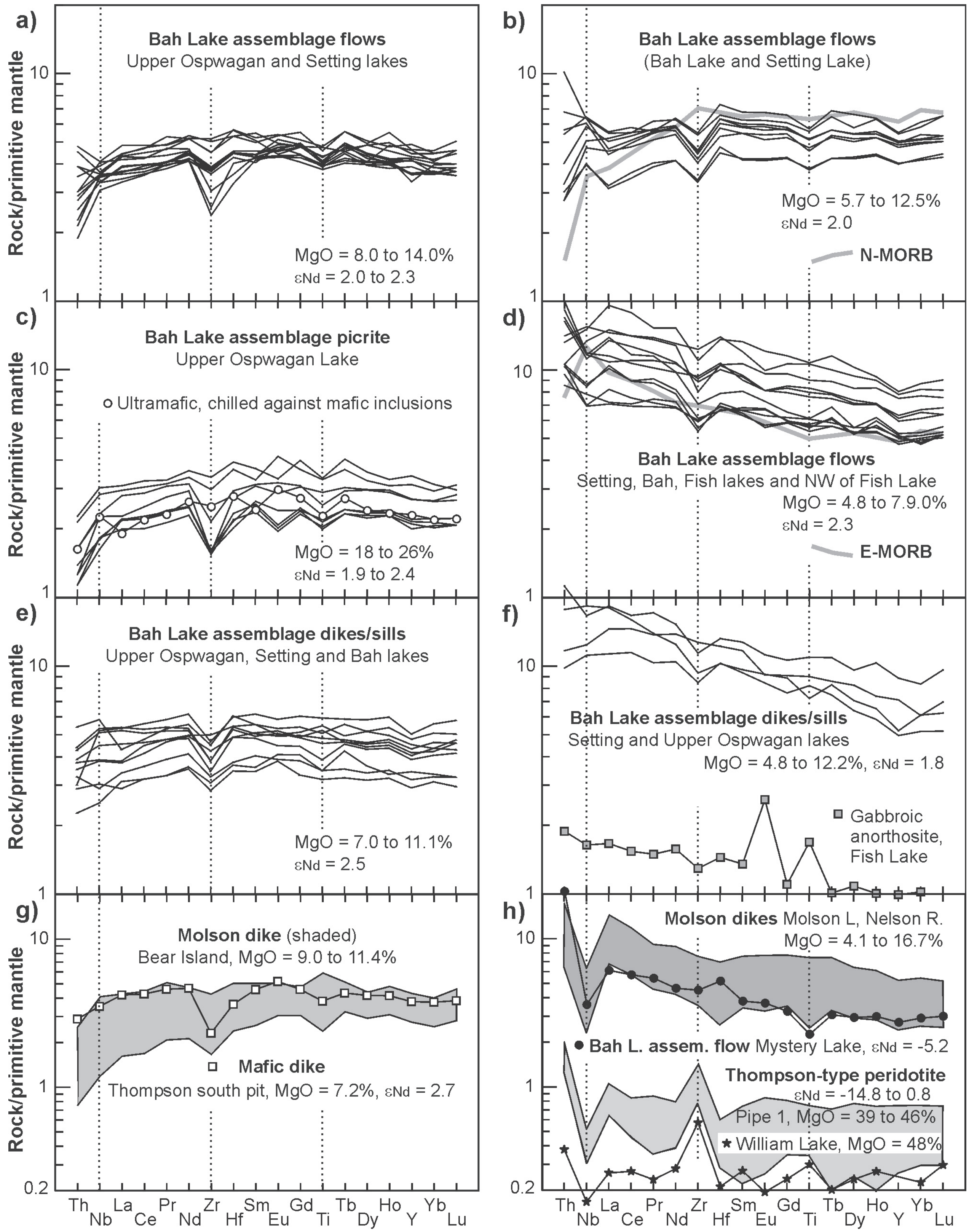


***Figure GS-6-3:** Primitive-mantle–normalized extended-element plots (after Stern et al., 1995) of samples from the Bah Lake assemblage and mafic-ultramafic intrusions in the TNB and adjacent Superior craton.*

Table GS-6-2: Sm-Nd isotope data for samples from selected flows, dikes and sills of the Bah Lake assemblage.

Sample	Rock type	Area	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	εNd(1.90)	Lab
51-98-18	Pillow basalt (altered)	Upper Ospwagan Lake	2.21	7.67	0.51224	0.17387	-2.25	1
12-04-4436-2	Pillow basalt	Upper Ospwagan Lake	1.97	5.87	0.20265	0.51286	2.90	2
12-04-4452-2	Spinifex Mg-basalt	Upper Ospwagan Lake	2.32	6.95	0.20198	0.51283	2.49	2
12-98-779	Pillow basalt	Setting L SW	1.79	5.22	0.20757	0.51289	2.18	1
CC98-012-2	Mafic flow	Bah Lake	2.37	7.22	0.19870	0.51277	2.04	1
12-03-4175	Amphibolite	Five Mile Lake	5.13	18.55	0.16731	0.51239	2.30	1
12-98-552	Pillow basalt (altered)	Fish Lake	4.32	14.83	0.17602	0.51237	-0.28	1
12-98-551-5	Pillow basalt	Fish Lake SE shore	2.74	9.12	0.18136	0.51252	1.45	1
12-03-4323	Amphibolite	Setting Lake SW	2.18	6.46	0.20417	0.51292	3.61	1
51-99-24	Komatiitic basalt	Mystery Lake	1.48	5.62	0.15963	0.51191	-5.18	1
12-04-4433-2	Aphyr picrite (top)	Upper Ospwagan Lake	1.97	5.87	0.20265	0.51286	2.90	2
12-04-4442-2	Picrite flow?	Upper Ospwagan Lake	1.82	5.42	0.20247	0.51284	2.45	2
51-98-25-1	Porhyritic picrite	Upper Ospwagan Lake	2.41	1.11	0.20168	0.51282	2.41	1
12-03-4177	High-Mg sill	Setting Lake	3.56	13.03	0.16517	0.51234	1.84	1
CC98-001-1A	Melagabbro	Bah Lake	1.89	5.84	0.19559	0.51275	2.47	1

Laboratories: 1, University of Saskatchewan (unpublished CAMIRO data); 2, University of Alberta

Assuming that the data represent the old crustal component involved in melting, then assimilation will produce a significant spread along the Y-axis of Figure GS-6-4. The lack of scatter in the data points suggests that the Bah Lake assemblage data represent the isotopic composition calculated at 1.90 Ga of the continental mantle beneath Archean basement of the TNB. The presence of the younger dike (ca. 1.86 Ga) in this array indicates that the same mantle source was intermittently involved in melting for >40 m.y.

Two samples in Table GS-6-2 were excluded from these considerations because they show evidence of alteration and were taken close to late pegmatite dikes

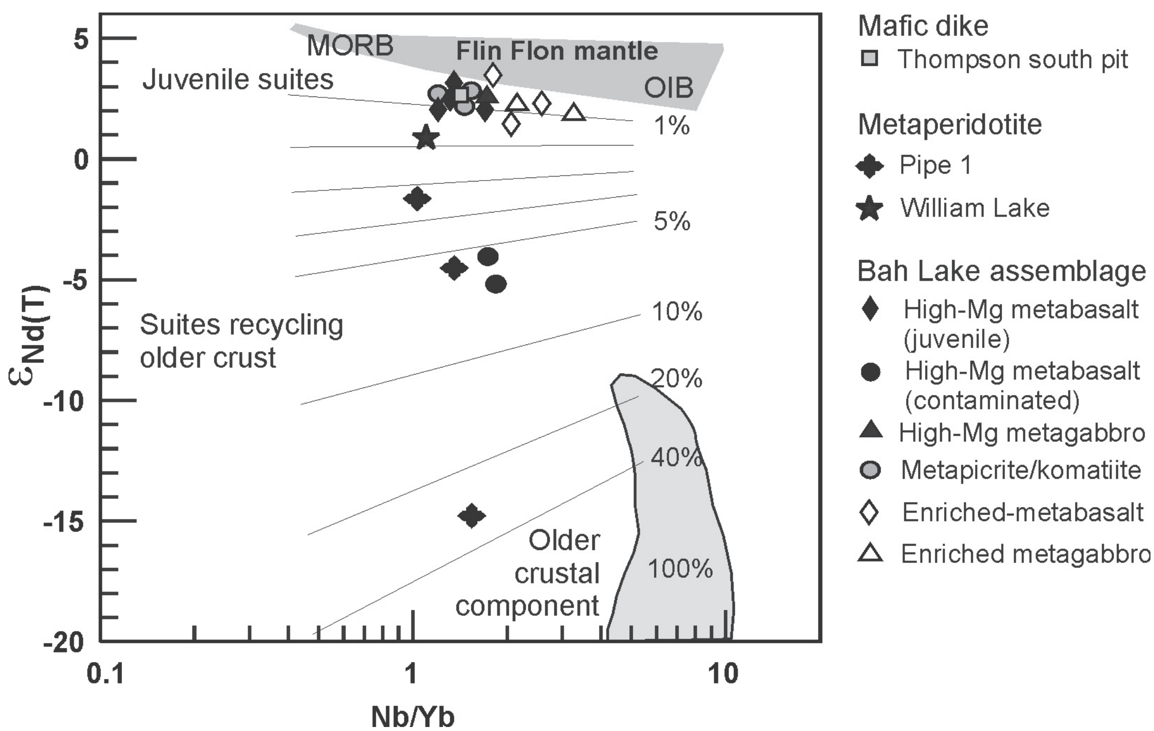


Figure GS-6-4: *Plot of $\varepsilon_{Nd(T)}$ vs. Nd/Yb, showing approximate lines of proportion of recycling of older crust and enrichment of the mantle source of the Bah Lake assemblage and younger mafic and ultramafic intrusions in the TNB.*

that may have introduced an Archean component into the basalt (Zwanzig, 2004). Samples of Mg-rich basalt from Mystery Lake, however, show consistently higher Archean crustal involvement than the main high-Mg suite (Figure GS-6-4). These rocks also have slightly elevated SiO_2 and K_2O (Table GS-6-1). The Thompson-type ultramafic intrusions show a wider range of $\varepsilon_{Nd(T)}$ (+0.8 to –15) than the older high-Mg suite. The highly negative values are probably a product of the isotopic composition of the crustal component and the high content of cumulate olivine, which contains only compatible elements. Thus, the small amount of matrix can contain a high crustal component without significantly affecting the major-element chemistry of the whole rock. Although the low contents of trace elements also make the ultramafic rocks prone to high analytical error, persistent patterns are present.

The extended-element pattern of these rocks (elevated light REE and Th) is consistent with the presence of a crustal component, which is enriched in these elements. Niobium, however, which is less affected by assimilation, forms a sharp trough (Figure GS-6-3h). The most negative and the only positive $\varepsilon_{Nd(T)}$ values (–15, +0.8) correspond to the highest and lowest La/Sm ratios (4.7, 1.5), and thus provide a good correlation between isotope ratios and crustal chemical characteristics. A moderately contaminated flow at Mystery Lake has intermediate values: $\varepsilon_{Nd(T)}$ = –4.0, La/Sm = 2.6. Elevated Zr and Hf in these rocks are also consistent with crustal assimilation. Because the Bah Lake assemblage shows very rare and limited crustal assimilation and the Thompson-type ultramafic intrusions show common and strong assimilation, the respective magma suites are interpreted as having formed under different conditions.

Discussion and economic considerations

The new and previously acquired geochemical and Sm-Nd isotopic data suggest that two types of mantle were the main source for the protracted magmatism in the TNB, and that the Archean continental crust provided an additional melt component for some of the rocks. One mantle source yielded the high-Mg depleted suite and the other the moderately enriched suite. The similar distribution of volcanic and geochemically identical intrusive rocks in both the high-Mg suite and the enriched suite is strong evidence that the sills and dikes were synvolcanic. At Setting and Bah lakes, the suites occur together but major early faults between them cannot be ruled out.

The main mantle source of the volcanic and intrusive rocks of the Bah Lake assemblage throughout the greater part of the TNB was moderately depleted in the more incompatible elements. Rocks from this source constitute the high-Mg suite of basalt to komatiite and gabbro to picrite. This suite has low incompatible-element contents (two to six times primitive mantle, depending on crystal fractionation and degree of melting). The suite is slightly less depleted in Th, Nb and LREE than modern N-MORB (Figure GS-6-3a–c). Niobium/ytterbium ratios (Figure GS-6-4) also show that its composition is close to N-MORB but skewed toward E-MORB. There was little or no contribution from the TNB granitic crust except very locally: $\varepsilon_{Nd(T)}$, calculated at T = 1.90 Ga, ranges from +2.0 to +2.9. At Mystery Lake, however, contaminated samples yielded $\varepsilon_{Nd(T)}$ values of –4.0 and –5.2.

Fractionated enriched basalt and gabbro form the second mafic suite in the Bah Lake assemblage, which is restricted to the western margin of the TNB and extends into the eastern side of the Kisseynew Domain. It was deposited on, or thrust over, the high-Mg suite at Bah Lake and the northwestern part of Setting Lake. The suite is more enriched by a transitional mantle component that is more akin to oceanic-island basalt than the high-Mg basalt and picrite. Fractionation of REE (Figure GS-6-3d, f), higher Nb/Yb ratios (Figure GS-6-4) and negative Zr anomalies suggest that this was derived from deeper, hotter mantle beneath more strongly stretched crust (Kerrich and Wyman, 1996). This origin is consistent with normal faulting at the TNB boundary during the deposition of the coarse turbidite of the Setting Formation. The same highly stretched Archean crust may also have been the main source of the nearly wholesale crustal melts that later formed the ca. 1890–1885 Ma granitoid plutons intruding the Bah Lake assemblage (Zwanzig et al., 2003; Percival et al., 2004, 2005, GS-9, this volume). The chemically enriched basalt in the Bah Lake assemblage, however, was isotopically juvenile, with $\varepsilon_{Nd(T)}$ ranging from +1.5 to +3.6, similar to the high-Mg suite. Enrichment was entirely from the mantle source. A large volume of ultramafic cumulate rock may have remained in the upper mantle or mafic crust for a time to generate the Fe-rich tholeiite without contamination. The presence of a structural sliver of gabbroic anorthosite at the margin of the Kisseynew Domain is also consistent with higher level fractionation.

The high-Mg suite is geochemically very similar to some of the mafic-ultramafic dikes of the younger Molson suite and the mafic part of a bimodal gabbro–quartz diorite dike exposed in the Thompson south pit. Other Molson dikes, however, show an extended-element pattern typical of crustal assimilation. These appear to be more common than contaminated bodies in the Bah Lake assemblage. If the small sample of Molson dikes is representative, the most contaminated bodies are east of the TNB in weakly stretched Archean crust.

The origin of the Thompson-type ultramafic bodies and the coeval Molson dikes is beyond the scope of this report. Compared to the Bah Lake assemblage, these rocks contain far more contaminated members (Figure GS-6-3h). Consideration of the cumulate nature of the ultramafic intrusions indicates that crustal assimilation can be detected mainly in the trace-element data. The high degree of crustal assimilation indicates that these bodies probably resided in lower or middle crust that was previously heated, and moderately extended. Heating may have occurred during the Bah Lake assemblage magmatism, which was highly mafic, produced komatiitic liquids chilled in the margins of picrite bodies and required a high melt fraction derived from hot mantle. Subsequently the crust was probably thickened during the F_1 deformation prior to intrusion of the Molson dikes (Bleeker, 1990b) and ultramafic bodies. These tectonic conditions may have led to the evolution of abundant ultramafic cumulates and their emplacement in the lower part of the Ospwagan Group during the subsequent (third) episode of extension.

These speculations are consistent with the earlier conclusion (Burnham et al., 2004) that the Bah Lake assemblage magmatism is not directly related to the deposition of nickel ores in the TNB. The early magmatism, nevertheless, may have established the crustal conditions for the emplacement of magmas with high olivine (and nickel) contents that were capable of assimilating sulphidic sedimentary rocks and precipitating nickel ore. The crustal structure and history were not uniform along the Superior Boundary Zone. More attention paid to these tectonic factors may yet lead to more effective exploration models.

Further work on the Molson dikes and granitic intrusions, which are apparently coeval with the Thompson-type ultramafic intrusions, is required. A full inventory of their geochemical and isotopic composition may be needed to aid exploration. The source of water required to produce the granitoid calc-alkaline magma, whether subduction related (Percival et al., GS-9, this volume), from hydrous continental mantle or from biotite breakdown in subgranulite-facies crust, may be tested using geochemistry. The Molson dikes were probably the feeders to the large volumes of contaminated mafic flows that must have complemented the Thompson-type ultramafic intrusions but were apparently eroded (Burnham et al., 2004). The Fox River and Winnipegosis belts (Figure GS-6-1) are probably good models for what covered much of the northwestern Superior craton before the collision with the Trans-Hudson Orogen internal zone.

The published and recently acquired isotopic ages used in this report to suggest the existence of four episodes of crustal extension and magmatism also provide a new tectonic model for the TNB (Figure GS-6-5). The ca. 2.1 Ga episode of rifting probably led to the deposition of the lower, fining-upward, clastic to chemical sedimentary succession of the Ospwagan Group on a newly formed passive margin and shelf (Zwanzig et al., 'Geochemistry of the high-grade metasedimentary rocks in the Thompson Nickel Belt and adjacent Kisseynew Domain, Manitoba: implications for a nickel exploration', in prep.). The second episode (bracketed by ca. 1974–1890 Ma), which produced the Bah Lake assemblage, was directly

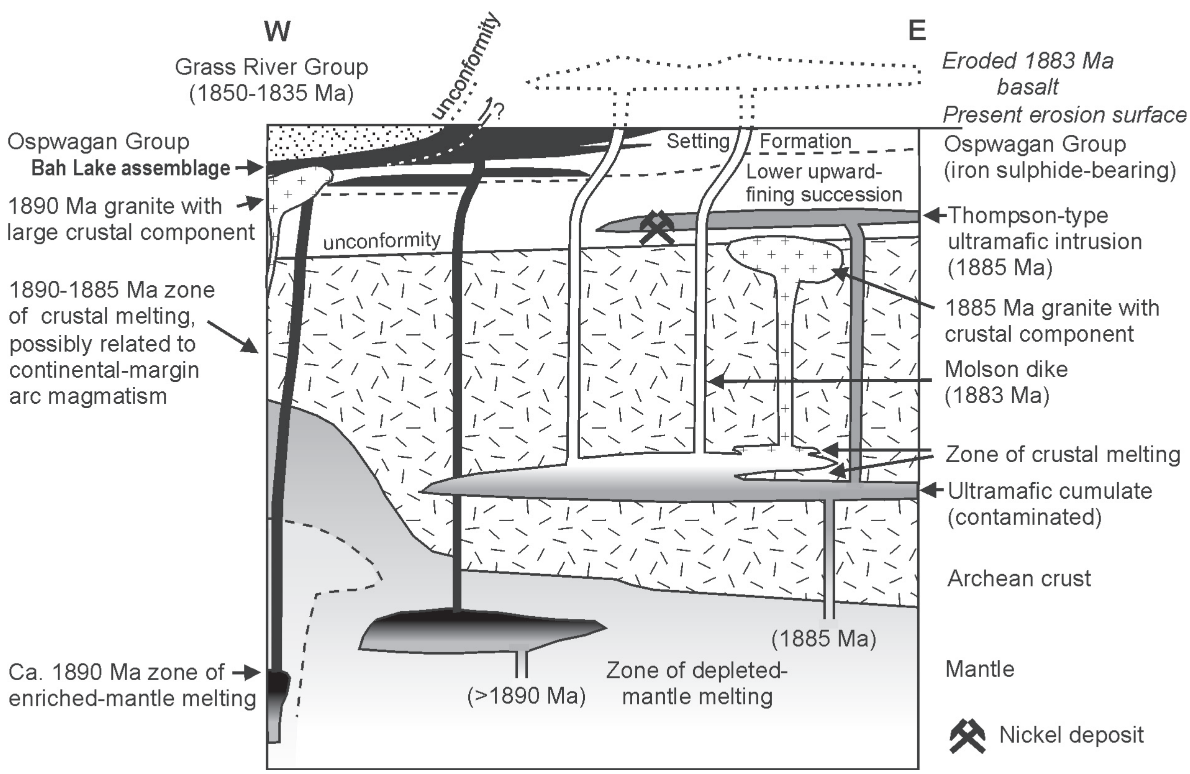


Figure GS-6-5: *Schematic crustal section from the margin of the Kisseynew Domain (W) into the TNB (E), illustrating the probable mantle sources of the Bah Lake assemblage and the relation between younger (ca. 1885 Ma) granitoid crustal melts and mafic-ultramafic mantle melts, including those that generated the Thompson-type ultramafic bodies.*

preceded by the deposition of the coarse marine turbidite of the Setting Formation, probably during normal faulting in a marine environment near the continental margin. The mafic-ultramafic magma of the Bah Lake assemblage apparently traversed the Archean crust rapidly, generally without contamination, and probably along major normal faults. The third episode (1885–1883 Ma) was directly responsible for the nickel mineralization. This ultramafic magmatism must have involved considerable fractionation and assimilation in magma chambers in the Archean crust. Coeval contaminated granitoid plutons may have formed in a back-arc environment while highly contaminated plutons formed in a fringing arc at the margin of the Kisseynew Domain. The west side of the TNB may have been an active continental margin with easterly-directed subduction from ca. 1890 to 1885 Ga or possibly longer (Zwanzig et al., 2003; Percival et al., 2005, GS-9, this volume). Thus, the third episode of extension and the nickel mineralization may have occurred in a continental back-arc environment.

The importance of the Bah Lake assemblage magmatism is its probable association with moderately enriched upwelling lithosphere in the adjacent part of the Kisseynew Domain, producing the enriched suite and significant crustal extension. In the main part of the TNB, normal faulting and weak extension may have occurred with the magmatism of the high-Mg suite. Early normal faults, which have not yet been identified in the highly appressed rocks of the TNB, may have focused the later intrusion of ultramafic magma from chambers deeper in the crust. The earlier (Bah Lake assemblage) melt extraction would have produced a more refractory mantle that subsequently yielded high-temperature ultramafic magma capable of assimilating Archean crust and sulphide-bearing rock of the Ospwagan Group, thus leading to nickel sulphide deposition.

Acknowledgments

The author thanks C. Böhm and P. Theyer of the Manitoba Geological Survey and D. Peck (now with Anglo American Ltd.) and M. Burnham for sharing their data, as well as Inco Technical Services Ltd. and Falconbridge Ltd. for their contribution to the CAMIRO Project 97E-02 database used to support this report. A. Bailes kindly edited this report.

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