Introduction

The Neoarchean Bird River Belt (BRB) in southeastern Manitoba is part of an east-trending supracrustal belt that extends for 150 km from Lac du Bonnet in the west to Separation Lake (Ontario) in the east (***Figure 1***). The BRB is host to both a rare-element-bearing pegmatite resource (TANCO mine) and base metal (+PGE) ore deposits at the Maskwa-Dumbarton mine, where additional mineral resources are currently under development (Makwa Project, Mustang Minerals Corp., 2010). Mustang Minerals is also engaged in exploration for additional base metal (+PGE) ore deposits in the north part of the BRB (Mayville project, Mustang Minerals Corp., 2011).

In support of exploration in the BRB, Manitoba Geological Survey (MGS) carried out a collaborative mapping project (2005-2008), involving detailed stratigraphic mapping, geochemical investigations and focused research projects by postgraduate students at the University of Waterloo. These research projects received financial support from NSERC as well as Gossan Resources Ltd., Marathon PGM Corp., North American Palladium Ltd., Mustang Minerals Corp. and Tantalum Mining Corporation of Canada Ltd. (TANCO). Geochronological investigations concurrent with the mapping have yielded U-Pb zircon ages for key geological units. The new age data, together with geochemical, tectonic and metamorphic studies, have led to reappraisals of the stratigraphy, structure and regional setting of the BRB. Recent publications include a 1: 50 000 scale compilation map of the BRB with extensive notes, based on 2005-2007 mapping (Gilbert et al., 2008), and two 1: 20 000 scale preliminary maps of the Bird River Belt (Gilbert 2008; Gilbert and Kremer 2008). A more comprehensive report on the geology of the BRB is in preparation.

Major findings of the project include the following ~

(1) The BRB occurs in a transitional oceanic–continental-margin setting between older cratonic blocks–the North Caribou Superterrane to the north and the Winnipeg River Subprovince to the south.

(2) The predominant arc-type rocks in the BRB are separated into north and south panels by the Booster Lake Formation–a succession of orogenic turbidite deposits. These turbidites occur as a major, fault-bounded enclave and several smaller fault slivers that occupy a tectonic zone extending laterally for over 40 km through the central part of the greenstone belt.

(3) The south panel arc-type rocks are stratigraphically and geochemically distinct from those in the north panel (***Table 1***). In addition to the contrasting geochemical affinities, the two panels are also distinguished by differences in their overall volcanic rock composition: basalt-andesite constitutes over half of the south panel but less than 10% of the north panel, in which rhyolite and dacite make up over 80% of the volcanic rock component (***Figure 2***).

(4) Late sanukitoid intrusive rocks (± associated fragmental deposits) are found in all the volcanic formations within the north panel of the BRB, as well as within the Booster Lake Formation, indicating the youngest volcanic rocks are penecontemporaneous with the Booster Lake turbidite deposits.

(5) Volcanogenic massive sulphide (VMS)-type mineralization has not yet been positively identified in the BRB, but numerous stratigraphically-controlled base metal sulphide occurrences and zones of hydrothermal alteration are positive indicators in favour of the potential for VMS mineralization within the BRB.

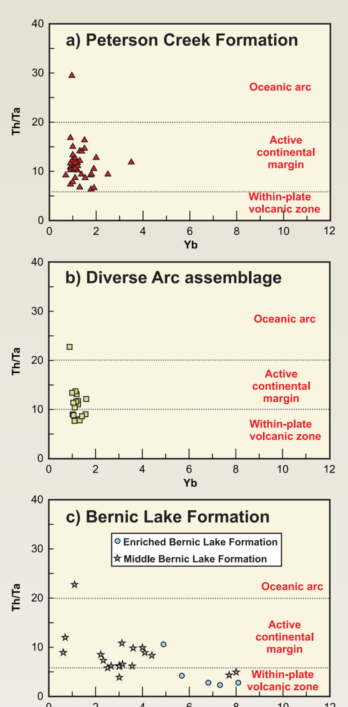

Figure 4: Th/Ta versus Yb diagram (Gorton and Schandl, 2000) of intermediate to felsic volcanic rocks from the BRB: a) Peterson Creek Formation; b) Diverse Arc assemblage; c) Bernic Lake Formation (middle and enriched divisions).

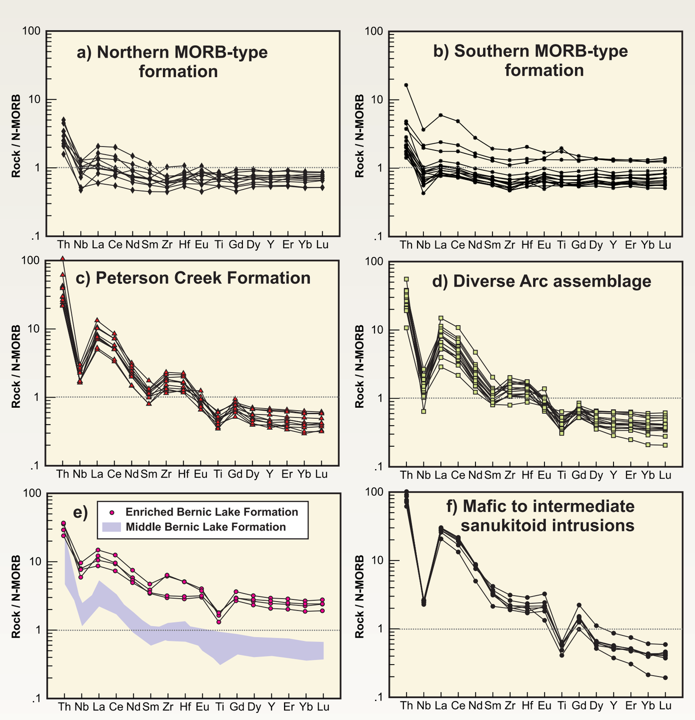

Figure 6: Normal mid-ocean-ridge basalt (N-MORB)–normalized incompatible element plots of mafic to intermediate volcanic rocks from the Bird River Belt (normalizing values from Sun and McDonough, 1989): a) Northern MORB-type formation; b) Southern MORB-type formation; c) Peterson Creek Formation; d) Diverse Arc assemblage; e) Bernic Lake Formation (middle and enriched divisions); f) mafic to intermediate sanukitoid intrusions.

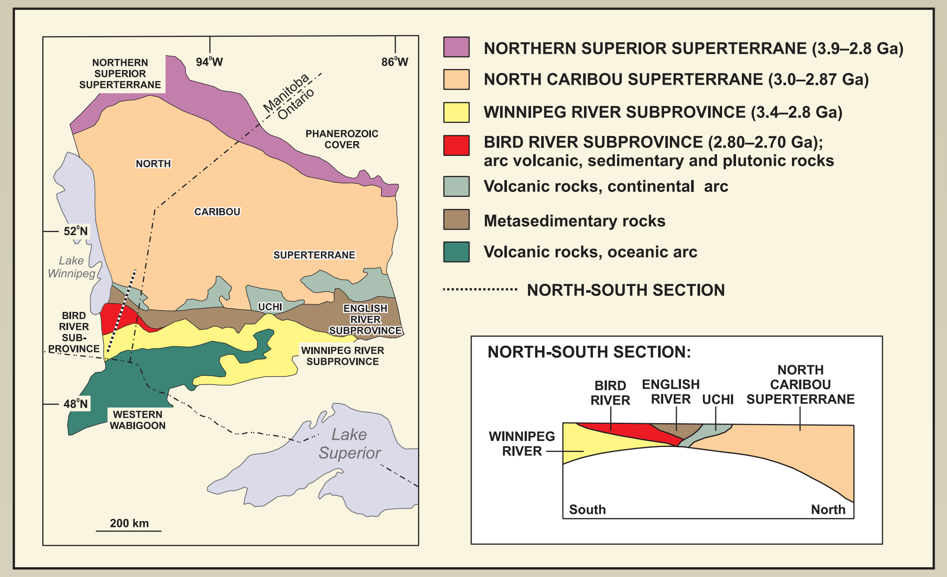

Figure 1: Regional map showing the Bird River Belt and geological subprovinces in southeastern Manitoba. The north-south section represents a possible post-collisional model (<2.70 Ga) for the setting of the Bird River Belt on the north flank of the Winnipeg River Subprovince.

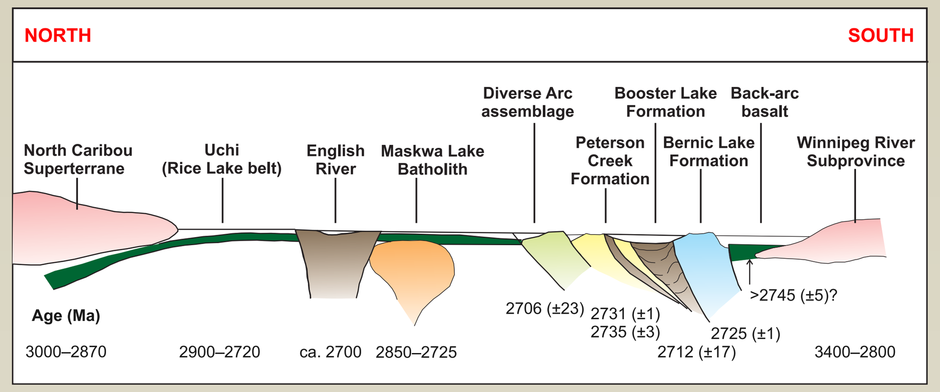

Figure 3: Cross-section from the North Caribou Superterrane in the north to the Winnipeg River Subprovince in the south, post-Booster Lake turbidite deposition (see north-south section line in ***Figure 2***). This transect shows the spatial relationships between the main formations in the Bird River Belt (BRB) and the English River and Uchi subprovinces, prior to continental collision. Note that crustal underplating to the south and deformation of supracrustal rocks assumed to have accompanied convergence of the North Caribou Superterrane and Winnipeg River Subprovince are not indicated, although convergence was probably underway during turbidite deposition (Lemkow et al., 2006). LITHOPROBE studies indicate underplating of the BRB by the Winnipeg River Subprovince to the south (as shown in the cross-section in ***Figure 1***), as well as the presence of a subduction zone to the north.

Regional setting

The BRB occurs in a transitional oceanic–continental-margin setting between flanking older cratonic blocks to the north and south (***Figure 3***). Mid-ocean-ridge basalt (MORB)-type rocks that extend along the north margin of the belt are intruded by the 2745 (±5) Ma Bird River Sill and appear to be the oldest volcanic rocks in the BRB (***Table 2***). Continental-arc magmatism and orogenic sedimentation in the Bird River Subprovince spanned approximately 100 Ma (2.80–2.70 Ga; Percival et al., 2006). North panel rocks–Peterson Creek Formation (PCF) and Diverse Arc assemblage (DAA)–are compositionally akin to arc volcanic rocks at active continental margins, whereas volcanic rocks in the south panel (Bernic Lake Formation) appear to document incipient rifting of the continental-arc rocks (***Figure 4 a-c***).

Orogenic sedimentation (2712–2697 Ma) subsequent to continental-arc volcanism resulted in the deposition of turbidites (Booster Lake Formation) and penecontemporaneous fluvial-alluvial deposits (Flanders Lake Formation). The turbidites may be stratigraphically equivalent to the fluvial-alluvial rocks, but relatively more distal from the source terrane. These orogenic sedimentary rocks, which are invariably fault bounded, have been widely assumed to be equivalent to epiclastic deposits and metamorphic derivatives in the west- to northwest-trending English River Subprovince, which lies between the Bird River Subprovince and the Uchi Subprovince to the northeast (***Figure 1, 3***; Hrabi and Cruden, 2006). Subduction-related volcanic activity and orogenic sedimentation came to an end due to collision of the Uchi continental-margin succession with the Winnipeg River Subprovince, which followed 2.72–2.71 Ga convergence of the North Caribou and Winnipeg River cratonic blocks (Lemkow et al., 2006). The tectonic collision was associated with regional deformation, metamorphism and granitoid plutonism.

Geology of the Bird River area

The BRB, extending for over 50 km from Lac du Bonnet in the west to Flanders Lake in the east, consists mainly of ca. 2.73 Ga arc-type volcanic rocks divided into north and south panels by the relatively younger, turbiditic Booster Lake Formation (***Figure 2, Table 2***). Extrusive, MORB-type volcanic rocks (Lamprey Falls Formation of Cerný et al., 1981) extend along both the north and south margins of the belt. Whereas these MORB-type volcanic rocks are lithologically and geochemically similar, they are tectonically distinct and thus identified separately as 'Northern MORB-type' and 'Southern MORB-type', respectively (Gilbert et al., 2008).

MORB-type formations

The 2–3 km wide Northern MORB-type formation is a south-facing, monoclinal sequence of aphyric pillowed basalt (***Figure 5a, b***) and extensive, synvolcanic gabbro. The Southern MORB-type formation, 2.5 km wide and predominantly north-facing, also consists mainly of pillowed basalt (***Figure 5c***) and gabbro, as well as minor siltstone-chert formations (± base-metal sulphide mineralization). Both Northern and Southern MORB-type basalts exhibit flat, slightly depleted rare earth element (REE) patterns, consistent with a back-arc basin environment of eruption (***Figure 6a, b***). The Northern MORB-type formation is characterized by relatively juvenile ε_{Nd} values (+1.3 at 2.7 Ga), suggesting the basalt was derived from a primitive, depleted mantle source.

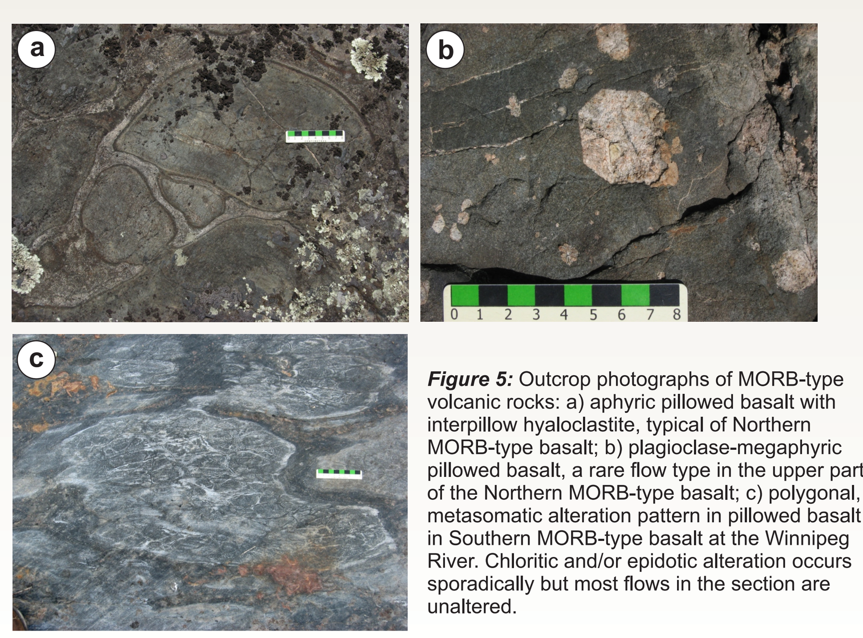

Figure 5: Outcrop photographs of MORB-type volcanic rocks: a) aphyric pillowed basalt with interpillow hyaloclastite, typical of Northern MORB-type basalt; b) plagioclase-megaphyric pillowed basalt, a rare flow type in the upper part of the Northern MORB-type basalt; c) polygonal, metasomatic alteration pattern in pillowed basalt in Southern MORB-type basalt at the Winnipeg River. Chloritic and/or epidotic alteration occurs sporadically but most flows in the section are unaltered.

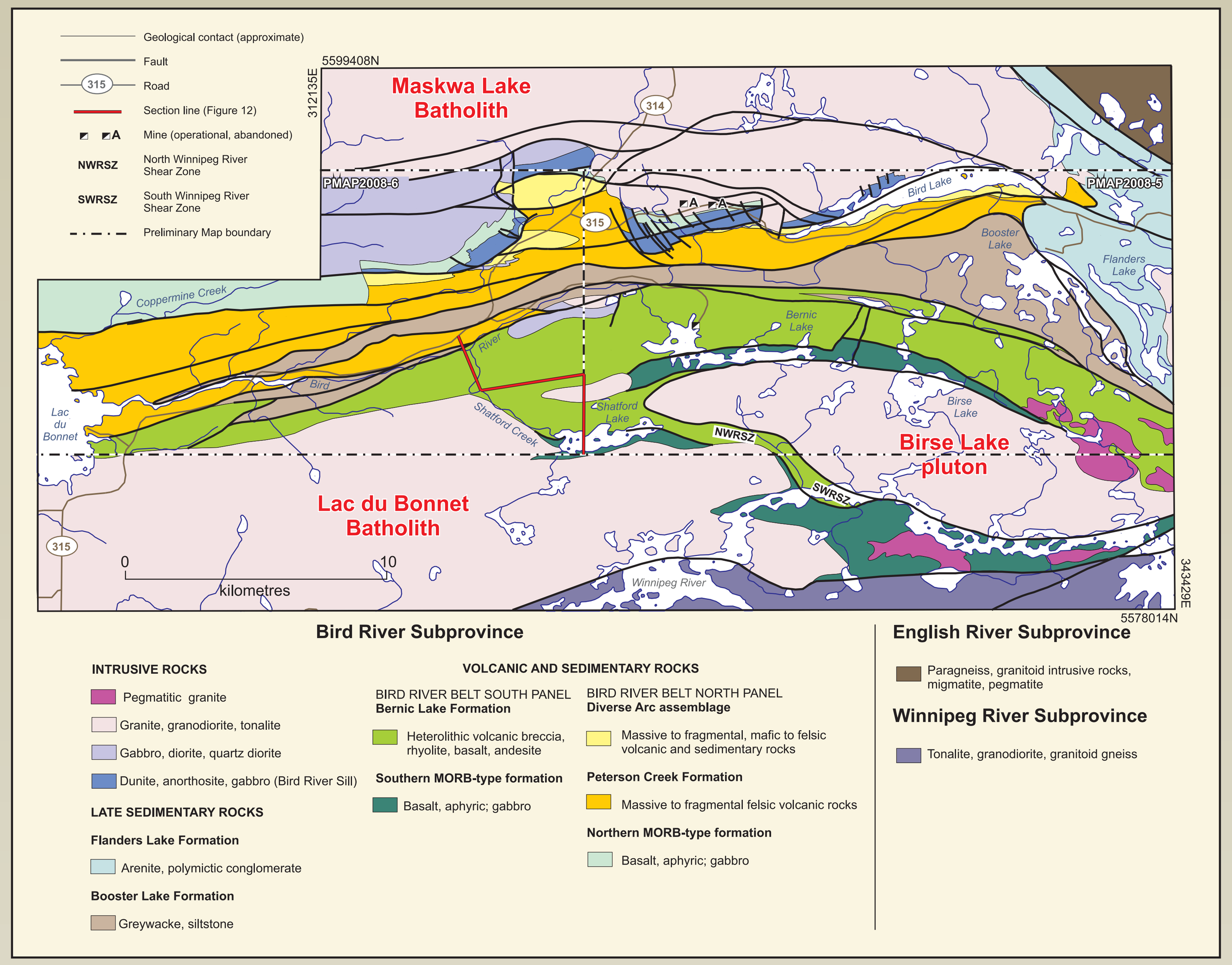

Figure 2: Geology of the Bird River Belt, showing the main stratigraphic and structural features.

North panel of Bird River Belt					South panel of Bird River Belt				
	Geochemical affinity	Litho-stratigraphy	Structure	Age		Geochemical affinity	Litho-stratigraphy	Structure	Age
Diverse Arc assemblage	Calcalkaline; convergent tectonic regime	Mafic to felsic, massive to fragmental volcanic rocks; turbidite, conglomerate, chert and oxide-facies iron formation.	Central part of BRB: repeated folding at north margin; overturned major fold in section farther to south.	> 2706 ±23 Ma[1]	**Bernic Lake Formation**	Transitional tholeiitic to calcalkaline. Progression from lower to upper stratigraphic levels coincident with transition from convergent to extensional crustal settings (incipient arc-rift).	Mafic to felsic, massive to fragmental volcanic rocks; minor oxide-facies iron formation. In western BRB: 3-fold subdivision: lower –- felsic volcanic rocks; middle –- mainly basalt-andesite flows; upper –- diverse mafic-felsic flows and fragmental rocks.	Overall north-facing sequence. In western BRB: synclinal to synclinorial structure in middle subdivision of Bernic Lake Fm.	2724.6 ±1.1 Ma[1]
Peterson Creek Formation		Felsic volcanic rocks, massive to fragmental. Monolithic to heterolithic felsic crystal-tuff ± lapilli		2731.1 ±1 Ma[1]; 2734.6 ±3.1 Ma[2]					

Geochronology references: [1] Gilbert et al., 2008; [2] Gilbert, unpublished data, 2007

Table 1: Comparison of north and south panels of the Bird River Belt.

Late intrusive rocks

Granite, pegmatite, granodiorite, tonalite, quartz diorite
(TANCO pegmatite, **2640 ±7 Ma**[1]; Marijane Lake pluton, **2645.6 ±1.3 Ma**[2]; Lac du Bonnet Batholith, **2660 ±3 Ma**[3])

Diabase, gabbro and andesitic to dacitic intrusive rocks

Sedimentary rocks

FLANDERS LAKE FORMATION **(2697 ±18 Ma[4])**
Lithic arenite, polymictic conglomerate

======== ***Fault, inferred*** ========

BOOSTER LAKE FORMATION **(2712 ±17 Ma[4])**
Greywacke-siltstone turbidite, conglomerate

======== ***Fault, inferred*** ========

Intrusive rocks

MISCELLANEOUS INTRUSIONS
Gabbro, diorite, quartz-feldspar porphyry; granodiorite
(Birse Lake pluton, **2723.2 ±0.7 Ma**[2]; Maskwa Lake Batholith II, **2725 ±6 Ma**[3]; Pointe du Bois Batholith, **2729 ±8.7 Ma**[3]; TANCO gabbro, **2723.1 ±0.8 Ma**[2])

Metavolcanic and metasedimentary rocks

BERNIC LAKE FORMATION **(2724.6 ±1.1 Ma[2])**
Basalt, andesite, dacite and rhyolite (massive to fragmental); related intrusive rocks and heterolithic volcanic fragmental rocks

PETERSON CREEK FORMATION **(2731.1 ±1 Ma[2]; 2734.6 ±3.1 Ma[5])**
Dacite, rhyolite (massive to fragmental); felsic tuff and heterolithic felsic volcanic fragmental rocks

DIVERSE ARC ASSEMBLAGE (**2706 ±23 Ma**[2])
Basalt, andesite, rhyolite, related fragmental and intrusive rocks; heterolithic volcanic fragmental rocks; greywacke-siltstone turbidite, chert, iron formation; polymictic conglomerate (contains clasts derived from Bird River Sill)

~~~~~~~~ ***Unconformity, inferred*** ~~~~~~~~

Intrusive rocks

BIRD RIVER SILL **(2744.7 ±5.2 Ma[3])**
Dunite, peridotite, picrite, anorthosite and gabbro

======== ***Fault, inferred*** ========

Metavolcanic and metasedimentary rocks

MORB-TYPE VOLCANIC ROCKS
Basalt (aphyric to plagioclase-phyric; locally pillowed, amygdaloidal or megacrystic); related volcanic breccia and gabbro; oxide-facies iron formation

======== ***Fault, inferred*** ========

EAGLENEST LAKE FORMATION
Greywacke-siltstone turbidite

Older intrusive rocks

Granodiorite, diorite (Maskwa Lake Batholith I, **2782 ±11 Ma**[3], **2852.8 ±1.1 Ma**[2], **2844 ±12 Ma**[3])

References for geochronological data: [1] Baadsgaard and Cerny, 1993; [2] Gilbert et al., 2008; [3] Wang, 1993; [4] Gilbert, 2006; [5] Gilbert, unpublished data, 2007.

Table 2: Principal geological formations, their ages and contact relationships in the Bird River Belt.

North panel arc-type rocks

North panel arc-type rocks are subdivided into the predominantly felsic volcanic PCF and the volcano-sedimentary DAA (Gilbert, 2007). Intermediate to felsic, massive and fragmental volcanic rocks of the PCF (***Figure 7a, b***) constitute over 80% of the entire north panel arc succession. The DAA includes a wide variety of mafic to felsic, calcalkaline volcanic rocks, reworked volcanic fragmental deposits, epiclastic detritus, sporadic chert and iron formation (***Figure 7c; 8a-f***).

Incompatible element plots of north panel arc rocks exhibit the characteristic negative-sloping profile typical for rocks with a subduction-modified mantle source (***Figure 6c, d***).

Discriminant geochemical plots (***Figure 4a, b; 9***) and the predominant felsic-intermediate composition of volcanic rocks in the north panel indicate these rocks have a continental-arc affinity and correlate well with modern arc-type rocks in an 'active continental-margin' (ACM) setting. The ε_{Nd} values (+1.0 to –1.1 at 2.7 Ga) indicate that a limited amount of recycled continental lithosphere was incorporated into the mantle source magma.

An interval of at least 10 Ma separated arc volcanism (2731–2735 Ma PCF, ***Table 2***) from the cessation of MORB-type extrusion that occurred prior to the emplacement of the Bird River Sill (2744.7 ±5.2 Ma; Wang, 1993); this intrusion was unroofed prior to deposition of the DAA conglomerate (***Figure 10a, b***). The relative age relationship between the DAA and PCF is uncertain. Lithostratigraphic and structural data indicate the DAA may be contemporaneous with the upper part of the PCF, but geochronological data and the intrusive relationships of late sanukitoid dikes suggest the DAA is relatively younger. The 2731–2735 Ma age of the PCF and concordant 2706 ±23 Ma age (2σ error) obtained for the youngest detrital zircon grain in greywacke within the DAA (Gilbert et al., 2008) suggests the volcano-sedimentary north panel spanned as much as 25 Ma, and may thus overlap with the age of the turbiditic Booster Lake Formation (2712 ±17 Ma; Gilbert, 2006).

South panel arc-type rocks

The BRB south panel arc-type sequence (Bernic Lake Formation, BLF) consists of abundant felsic and mafic volcanic rocks, unlike the mainly intermediate to felsic north panel (***Figure 11a-f***). The south panel is mainly north-facing, but several major folds are indicated by pillow-facing directions in the central and western BLF. Geochemically, south panel rocks have a transitional, tholeiitic to calcalkaline affinity, in contrast to the calcalkaline affinity of the north panel sequence. As in the BRB north panel, geochemical indices of the BLF volcanic rocks suggest a continental-arc affinity (***Figure 9***). The ε_{Nd} values of the south panel rocks (+0.7 to –2.4 at 2.7 Ga) indicate limited contamination by continental lithosphere occurred during ascent of the source magma through the crust. The BLF consists predominantly of basalt to andesite flows (middle BLF, ***Figure 12***), which extend laterally through the south panel for over 40 km; the true thickness of this 2.5 km wide mafic volcanic sequence is uncertain because it is deformed by several major folds. A 750 m wide section of diverse, massive to fragmental volcanic rocks (upper BLF) apparently overlies the basaltic sequence in the western BRB. Farther east, north of Birse Lake, felsic-intermediate volcanic rocks are tectonically juxtaposed and/or intercalated with the middle BLF basaltic rocks. The BLF contains a lower, felsic-intermediate subdivision (lower BLF) that extends between Shatford and Bernic lakes (***Figure 2, 12***); these rocks have no known counterpart in the eastern BRB. Contacts between the lower, middle and upper BLF divisions are interpreted as conformable. A 500 m wide fault-slice of geochemically distinctive, rare earth element enriched, mafic to felsic volcanic rocks (enriched BLF) extends along the north margin of the BLF in the eastern part of the belt (***Figure 2***). These enriched rocks are interpreted as the youngest, most evolved part of the Bernic Lake Formation (Gilbert et al., 2008).

Figure 7: Outcrop photographs of massive and fragmental volcanic rocks in the BRB north panel: a) anastomosing fractures attributed to thermal contraction during cooling of a massive rhyolite flow, Peterson Creek Formation; b) heterolithic crystal–lithic-tuff with mainly felsic clast types, Peterson Creek Formation; c) mass-flow deposit with pyroclastic and epiclastic detritus, Diverse Arc assemblage.

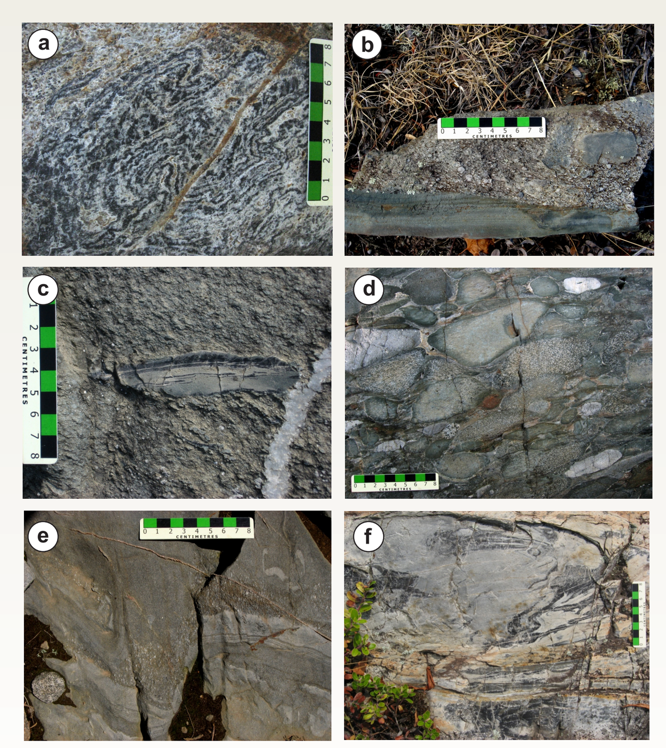

Figure 8: Outcrop photographs of massive to fragmental volcanic and epiclastic rocks in the Diverse Arc assemblage, BRB north panel: a) spherulitic rhyolite flow with contorted flow lamination; b) laminated tuff scoured by mass-flow that deposited the overlying lapilli-tuff bed; c) chert rip-up in lapilli tuff, interpreted as a reworked volcaniclastic deposit; d) polymictic conglomerate with volcanic, sedimentary, gabbroic and sporadic anorthositic fragments; e) greywacke-siltstone turbidite showing graded bedding, scour and synsedimentary deformation; f) laminated chert, partly disrupted by synsedimentary deformation.

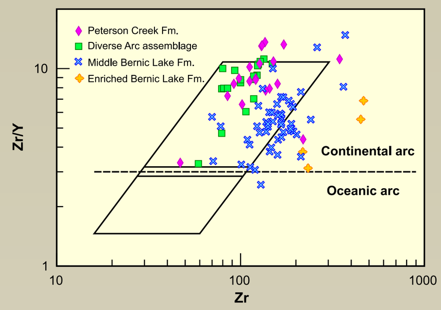

Figure 9: Zr/Y vs Zr diagram showing the continental-arc affinity of the Peterson Creek Formation, Diverse Arc assemblage and Bernic Lake Formation (BLF), as well as the relatively high Zr and Y contents of enriched BLF division rocks (approximately 2x-5x those of other BRB volcanic rocks).

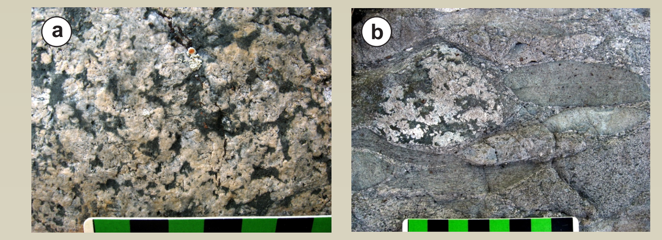

Figure 10: Outcrop photographs indicating the provenance of clasts in DAA polymictic conglomerate: a) leucogabbro from the south (upper) part of Bird River Sill, b) leucogabbro clast in DAA conglomerate (also contains volcanic, sedimentary, and other gabbroic fragment types).

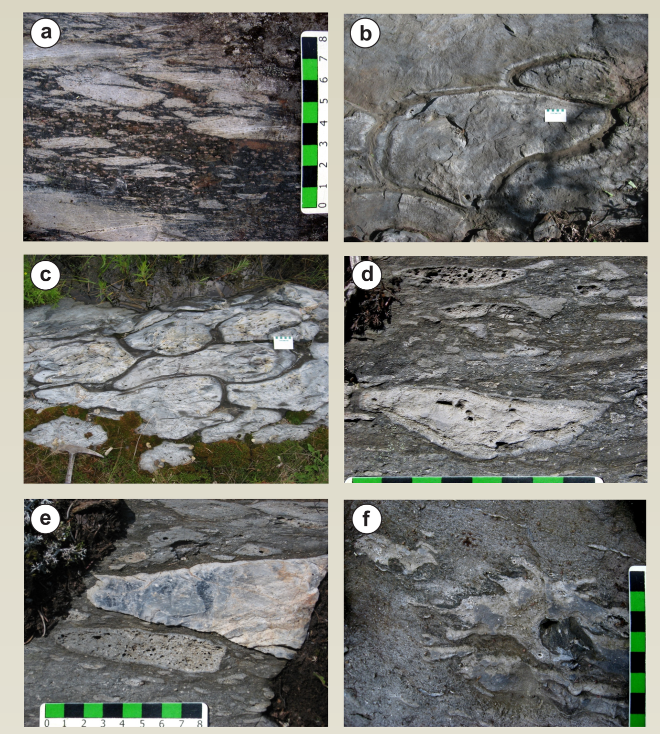

Figure 11: Outcrop photographs of massive and fragmental volcanic rocks in Bernic Lake Formation, BRB south panel: a) monolithic felsic volcanic breccia with garnetiferous, chloritic matrix, gradational with fragmental to massive rhyolite (lower BLF, close to the west end of the Birse Lake pluton); b) undeformed pillows in moderately altered basalt (middle BLF); silicification occurs at pillow margins and locally within pillows; c) white-weathered, silicified pillowed basalt at the top of the middle BLF. Base of photo is the upper (north) part of the flow unit. The flow is gradational with dark-weathered hyaloclastic tuff; d) pyroclastic breccia with a pale-weathered clast showing both rounded and pointed terminations, suggesting a projectile origin (upper BLF). The fragment margin is gray (possibly chilled). Clasts in this breccia deposit are variously massive to vesicular; e) angular felsic clast in heterolithic breccia, showing truncation of both the marginal bleached zone and the internal structure of the fragment (upper BLF). This unit is interpreted to contain pyroclastic detritus derived from previous volcanic rocks as well as primary, magma-derived clasts; f) irregular amoeboid clasts, possibly deformed while still hot and plastic during transportation by a debris flow (upper BLF). The unit is interpreted as pyroclastic in origin, derived from previously deposited volcanic rocks as well as primary, magma-derived clasts.

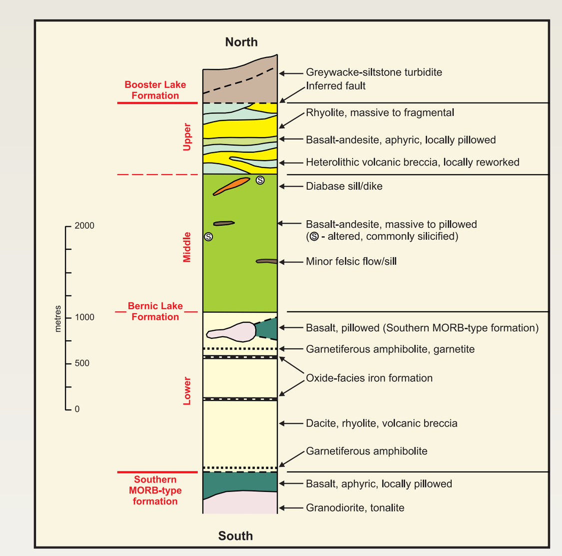

Figure 12: Composite section through the Bernic Lake Formation from Shatford Lake to the junction of Bird River and Shatford Creek (section line is shown in ***Figure 2***).

Geochemical evolution of BRB volcanic rocks

Arc to arc-rift setting

The north and south panels are distinguished by diagnostic element ratios indicating that Bernic Lake Formation rocks represent a transitional, convergent to extensional, arc-rift–type tectonic setting, in contrast to the predominantly convergent, subduction-type tectonic regime of the north panel rocks. Bird River Belt north panel volcanic rocks plot within the ACM field in the Th/Ta versus Yb diagram of Gorton and Schandl, 2000 (***Figure 4a, b***), whereas south panel rocks extend from the ACM field (convergent, subduction-type setting) into the 'within-plate volcanic zone' field (***Figure 4c***). ***Figure 4a-c*** displays a progressive gradation from PCF to DAA to middle BLF to enriched BLF fields. This pattern is coincident with the increasing levels of incompatible elements in the same rock suites shown in MORB-normalized plots (***Figure 6c-e***), and suggests a transition from convergent to extensional crustal settings (Gorton and Schandl, 2000), consistent with a model of incipient arc-rifting.

Sanukitoid suite rocks and stratigraphic relationships

Late, mafic to intermediate intrusive rocks of the large-ion-lithophile element (LILE)-enriched sanukitoid suite occur in the Booster Lake and Peterson Creek Formations, the Diverse Arc assemblage and the Northern MORB-type formation. Dikes (1–3 m wide) and sills up to several 10`s of metres thick are typically massive and undeformed, and exhibit a variety of textures. The most common type (***Figure 13a***) is plagioclase-phyric, with abundant, locally flow-oriented euhedral feldspar laths (± hornblende pseudomorphs after pyroxene, ± sporadic quartz amydules). The same porphyritic texture is displayed by sporadic cobbles within conglomerate of the Diverse Arc assemblage (***Figure 13b***) that are geochemically akin to the intrusive rocks. Some intrusive sanukitoid rocks are, however, sparsely porphyritic or aphyric. High-Th diabase and gabbro intrusions (***Figure 13c***), which are compositionally similar to the sanukitoid types, have been found in both the Peterson Creek and Booster Lake formations and may represent transitional magmatic types between the calkalkaline arc volcanic rocks of the north panel and late sanukitoid intrusive rocks.

Sanukitoid rocks are low-silica adakites (Martin et al., 2005) of late Archean age that are associated with subduction of oceanic lithosphere. Their unusual composition appears to be a result of a subduction zone environment that differed from those both in earlier Archean times and the present day, with respect to crustal thickness, pressure-temperature conditions and the depth of melting of the subducted slab. In the model of Martin et al. (2005), melts derived from the descending slab are consumed by metasomatic reaction with the ambient mantle peridotite, which yields subsequent melts with very high, light rare earth element (LREE) and LILE contents (especially Th and Sr), although heavy REE remain low, as in arc volcanic rocks (***Table 3***). $La/Yb_{(ch)}$ values in BRB sanukitoids (average 42, range 25 to 80) far exceed those of north panel arc-type rocks with similar SiO_2 content ($La/Yb_{(ch)}$ average of 13). The sanukitoid suite of rocks has been of particular significance for studies of crustal history, rate of earth cooling etc. In the BRB, this suite of geochemically distinct rocks is of special significance in the context of the stratigraphic relationships between the various hostrocks in which they occur. In particular, the occurrence of sanukitoid rock types within the DAA as 1) intrusive dikes/sills, 2) conglomerate clasts (***Figure 13a, b***), and 3) possible fragments in volcanic breccia, suggests that the sanukitoid magmatism was penecontemoraneous with DAA volcanism. Furthermore, the occurrence of sanukitoid intrusive rocks in the Booster Lake Formation suggests continental arc magmatism (DAA) overlapped orogenic sedimentation, represented by the Booster Lake turbidite deposits. The ages of detrital zircons are consistent with this model (2712 ±17 Ma and 2706 ±23 Ma, respectively, for Booster Lake Formation and DAA youngest zircons; Gilbert, 2006; Gilbert et al., 2008). It is hoped that a recently collected sample of a sanukitoid intrusion will yield an igneous age of emplacement and thus further constrain these stratigraphic relationships.

Figures 14 and ***15*** illustrate the extreme LILE and LREE enrichment of sankitoid rocks in the BRB. Compositions of the average sanukitoid rock (Martin et al., 2005), average BRB intrusive sanukitoid and a lithologically equivalent DAA conglomerate clast are all very similar (***Figure 14***), in contrast to DAA volcanic rocks. Several high-Th diabase and gabbro intrusions in the Peterson Creek and Booster Lake formations, which are more enriched in LILE and LREE than DAA volcanic rocks but less enriched than sanukitoid types, may be part of a gradational magmatic series between the DAA and sanukitoid suite rocks in the BRB (***Figure 15***). Such a genetic relationship appears likely in view of the approximate age equivalence of sanukitoid and DAA rocks, indicated by sanukitoid rocks that occur both as detritus in DAA conglomerate and as intrusive dikes.

Rock suite	SiO_2	TiO_2	Ba	Sr	Zr	Rb	Nb	La	Ce	Nd	Sm	Eu	Th	Y	$La/Yb_{(ch)}$	Ni	Cr	Mg#
Sanukitoid <62% SiO_2 (Martin et al., 2005)	58.8	0.74	1543	1170	184	65	10	60	126	55	9.8	2.3	9.0[1]	18	30	72	128	0.57
Average Bird River Belt sanukitoid rock	59.0	0.67	999	754	167	55	6	65	137	55	8.2	2.1	9.0	15	42	98	150	0.61
Average high-Th diabase and gabbro	52.3	0.61	1001	610	110	90	4	34	70	30	5.5	1.5	10.5	17	17	100	403	0.66
Average DAA volcanic rock	59.3	0.52	408	317	107	19	4	20	42	17	3.0	0.9	4.1	12	13	147	274	0.62

[1] Data from Martin et al., 2010

Table 3: Geochemical data and element ratios for sanukitoid, high-Th mafic intrusive and calcalkaline arc volcanic rocks in the Diverse Arc assemblage (DAA), compared with averages for sanukitoid rocks after Martin et al., 2005.

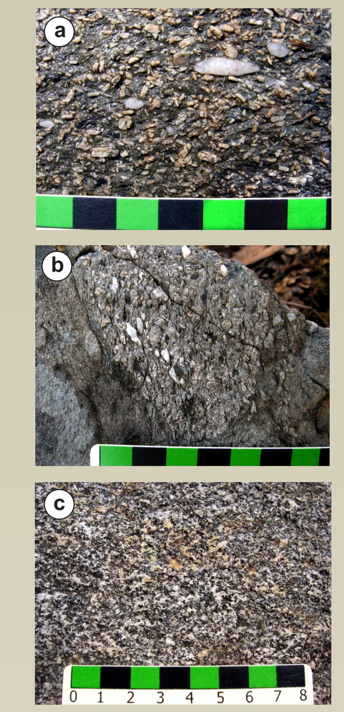

Figure 13: Outcrop photographs indicating the provenance of sanukitoid clasts in DAA polymictic conglomerate: a) sanukitoid sill (dacitic), emplaced between the PCF and DAA, showing distinctive plagioclase-phyric texture with hornblende pseudomorphs and quartz amygdules, b) texturally similar sanukitoid cobble in DAA conglomerate.
Sanukitoid-like intrusive rock: c) high-Th gabbro sill in Booster Lake Formation, compositionally similar to BRB sanukitoid rocks.

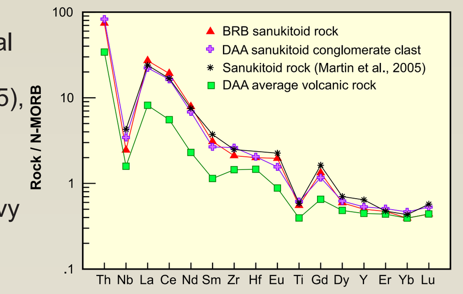

Figure 14: Normal mid-ocean-ridge basalt (N-MORB)-normalized incompatible element plots of BRB sanukitoid-type rocks (average for the intrusive rock type; clast in DAA conglomerate) compared with 1) the average sanukitoid composition of Martin et al. (2005) and 2) the average composition of DAA mafic to intermediate, calcalkaline volcanic rocks.

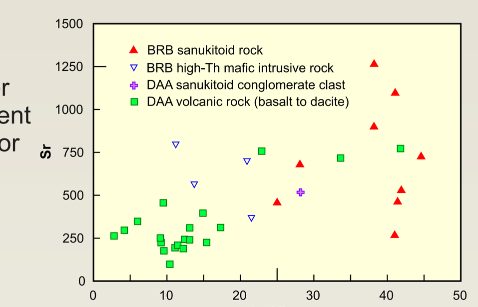

Figure 15: Sr vs $La/Yb_{(ch)}$ plot of BRB sanukitoid-type intrusive rocks and a sanukitoid clast in DAA conglomerate, compared with DAA mafic to intermediate, calcalkaline volcanic rocks. High-Th diabase and gabbro (inverted triangle symbols) that intrude the Peterson Creek and Booster Lake formations, respectively, occupy a field midway between the sanukitoid and DAA volcanic rocks, and may represent a link between continental-arc volcanism (DAA) and sanukitoid-type magmatism. Note: one BRB sanukitoid rock with $La/Yb_{(ch)}$ of 80 is not shown in this plot.

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