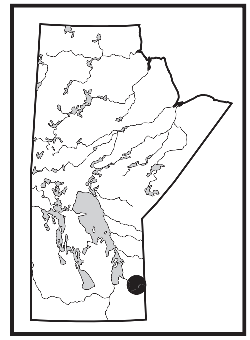
GS-12 Stratigraphic investigations in the Bird River greenstone belt, Manitoba (part of NTS 52L5, 6)

by H.P. Gilbert



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Summary

The results of detailed stratigraphic mapping and concurrent geochemical and geochronological investigations in the Neoarchean Bird River greenstone belt are now compiled and form the basis of a revised stratigraphic framework that builds on the work of previous authors. The predominant arc-type rocks of the Bird River Belt (BRB) are tectonically distinct from flanking, older, back-arc–type basaltic sequences (Lamprey Falls Formation) that are probably associated with early arc rifting. The Lamprey Falls Formation is intruded by the Bird River Sill (2.745 Ma), which hosts base-metal and platinum-group-element (PGE) mineralization. Arc-type rocks in the BRB (ca. 2.73 Ma) are separated into northern and southern structural panels by an elongate formation of fault-bounded turbidites (Booster Lake Formation). Fluvial-alluvial sedimentary rocks (Flanders Lake Formation) overlie the arc volcanic strata at the east end of the BRB. Detrital zircon data suggest that both the turbidites and the fluvial-alluvial sedimentary rocks post-date the arc-type sequence by 10–20 Ma. The arc-type north panel consists of a diverse sequence of sedimentary and volcanic rocks (‘diverse arc assemblage’) that appear to underlie a more homogeneous section of calcalkaline dacite and rhyolite (Peterson Creek Formation). Mafic to felsic arc volcanic rocks of the south panel (Bernic Lake Formation), which are slightly younger than the north panel rocks, are tholeiitic and include both normal and geochemically more evolved types. Contacts between these lithologically and geochemically distinct panels are typically faulted.

Base-metal mineralization prospects in the BRB include both magmatic types and stratigraphically associated occurrences. The magmatic type is exemplified by the Maskwa deposit, located within the basal part of the Bird River Sill. Stratigraphically associated mineralization includes a variety of occurrences that are located either at lithological contacts (e.g., at the margins of basaltic units or within iron formations) or within stratigraphic members, such as felsic volcanic rocks of the Bernic Lake Formation and basalt of the Lamprey Falls Formation.

Introduction

A geological mapping program was initiated by the Manitoba Geological Survey (MGS) in 2005 in the Bird River greenstone belt of southeastern Manitoba (Figure GS-12-1). Concurrent with detailed mapping by the author, several undergraduate and graduate research projects were initiated to conduct thematic studies on both regional tectonic aspects and localized topics related to the economic geology of the area. At this time, M.Sc. projects by C. Mealin and P. Kremer at the University of Waterloo, which focused on the geology of the PGE-bearing Bird River Sill and the setting of rare-element-bearing pegmatite bodies, respectively, are close to completion. A post-doctoral research project on the tectonic setting and history of the Bird River area by M. Duguet (GS-13, this volume) will be concluded by mid-2008.

Stratigraphic mapping and related geochemical investigations by the author in the eastern part of the Bird River Belt (BRB) were initiated in 2005 and completed during the summer of 2006, coincident with a western extension of geological mapping (Gilbert, 2006a). Fieldwork in 2007 focused on the north half of the greenstone belt in the area between Bird Lake and Lac du Bonnet (Figure GS-12-2). This detailed mapping, together with the results of geochemical and geochronological investigations, has led to the revised stratigraphic framework for the BRB presented in this report. Mapping in the southwestern part of the greenstone belt planned for 2008 will represent the last phase of the Bird River Project.

Previous work and current exploration

Mineral exploration and geological investigations in the Bird River area span the past century, dating from the pioneering work of Tyrrell (1900). Economic interest in the region has focused largely on two resource types: rare-element–bearing pegmatite bodies and mafic to ultramafic intrusive rocks containing base metals and PGE (Gilbert, 2006b). Investigation of a Cr showing on the Bird River in 1942 led to the discovery of a base-metal ore deposit at the north margin of the Bird River Sill, where Cu and Ni were produced for a decade until the mid-1970s at the Maskwa-Dumbarton mine (Figure GS-12-2). Feasibility studies are currently underway with the aim of reopening a new mine at Maskwa that will extract more than 9 million tons of ore over a period of 8 years (Mustang Minerals Corp., 2007). In addition, Marathon PGM Corporation is prospecting for base metals and PGE in the vicinity of the Bird River Sill, on ground formerly held by Gossan Resources Ltd. (Marathon PGM Corporation, 2007). Current exploration also includes ongoing investigations for new sources of rare elements in settings similar to that of the Tanco pegmatite.

The first systematic geological mapping of the BRB

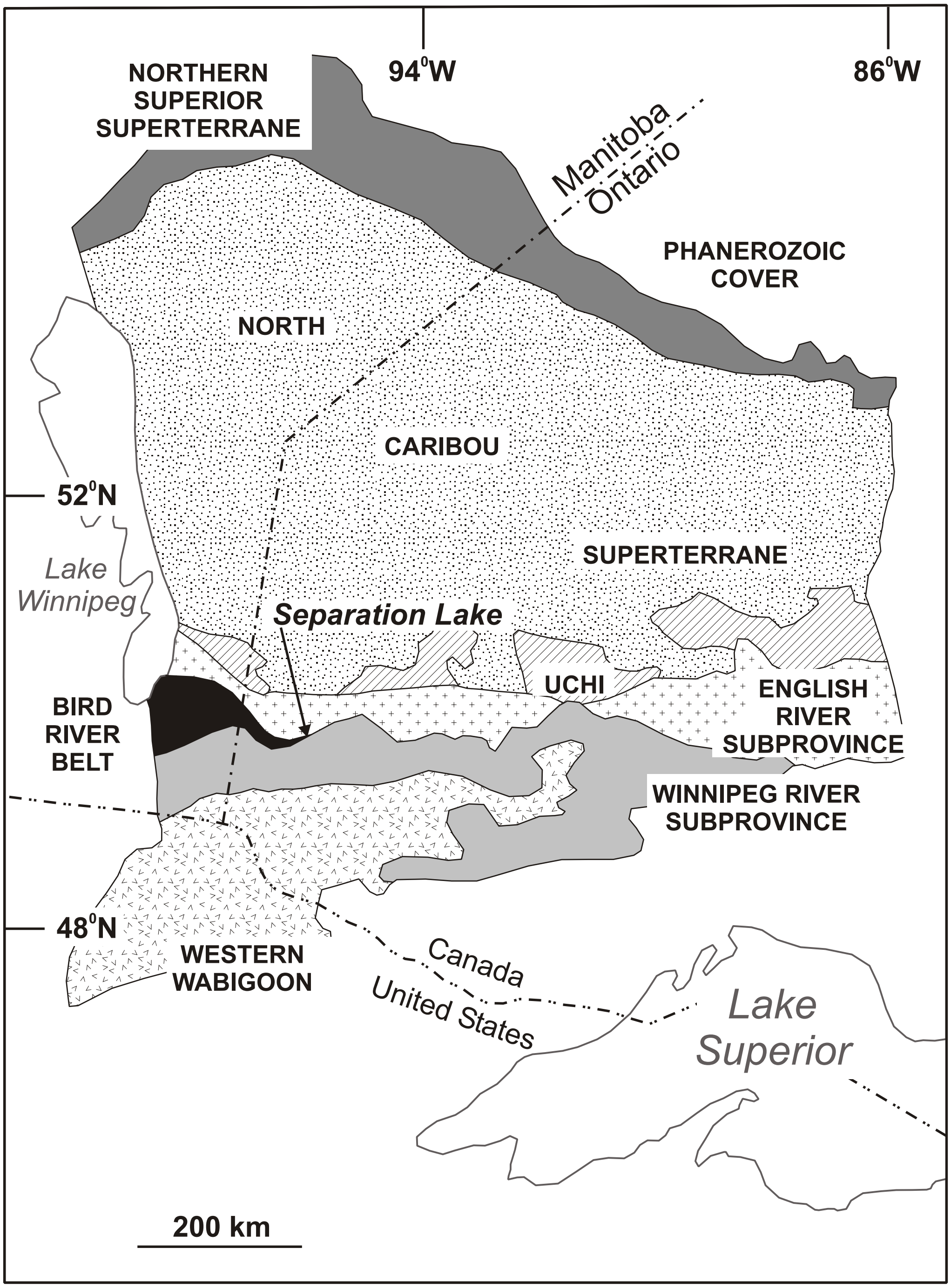

Figure GS-12-1: *Simplified geology of the western Superior Province, showing the location of the Bird River Belt.*

was undertaken more than 50 years ago (Springer, 1948; Davies, 1952). Geological investigations were subsequently carried out by Trueman (1971), who completed a study of the Bird River Sill, and by Theyer (1981), Scoates (1983) and Scoates et al. (1987). The Bird River greenstone belt was mapped by Trueman (1980) as a Ph.D. thesis. Cerny et al. (1981) provided a comprehensive study of the abundant pegmatite intrusions of the region, as well as a synthesis and interpretation of the regional geology. Prior to the current project, the most recent compilation of the geology of the area consisted of a Manitoba Geological Survey 1:250 000 scale geological map (Manitoba Energy and Mines, 1987).

Regional setting

The Neoarchean BRB is located between the English River and Winnipeg River subprovinces in the southwestern part of the Superior Province (Figure GS-12-1). The BRB is part of a 150 km long, east-trending supracrustal belt that extends east to Separation Lake in Ontario. The

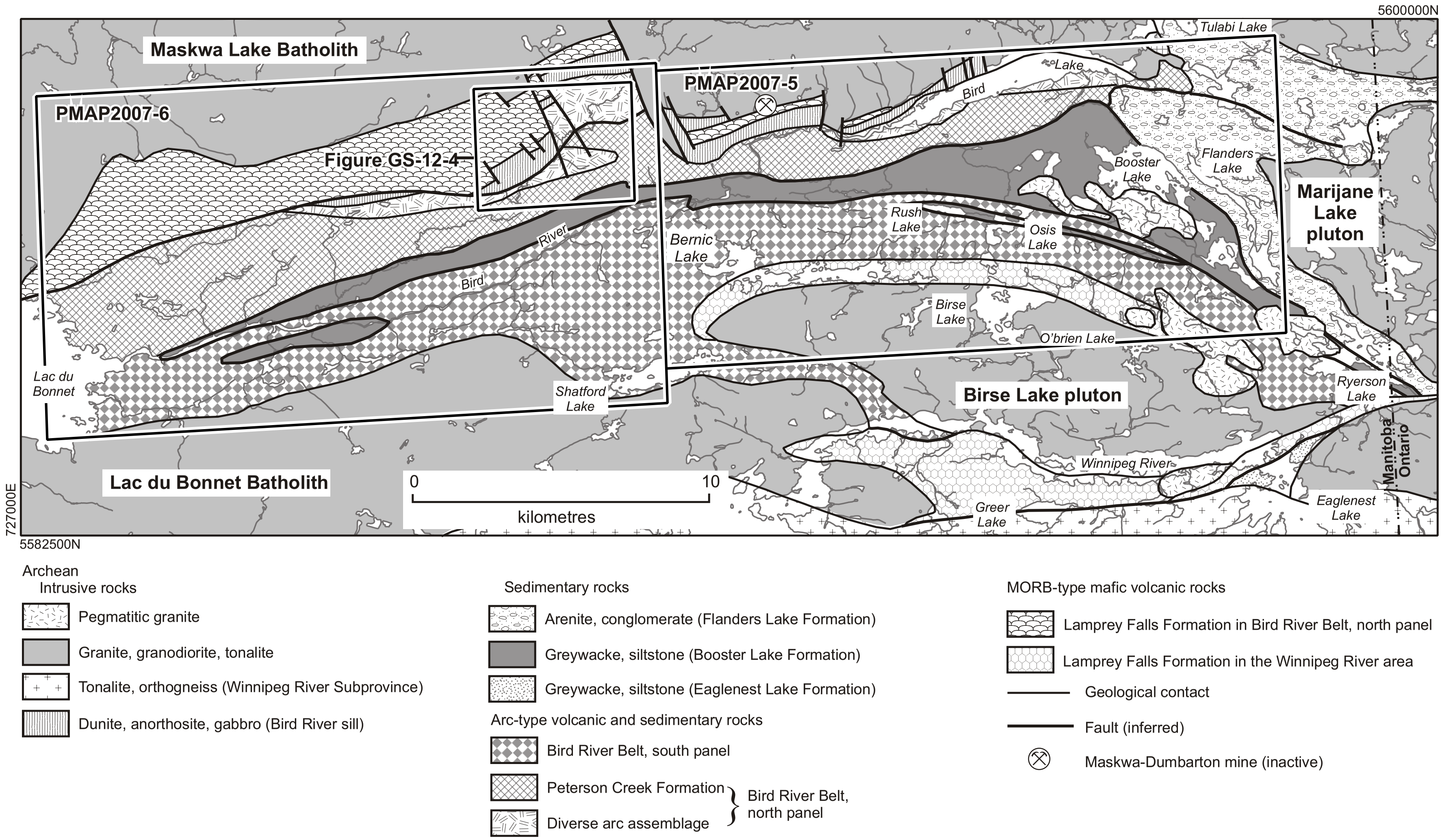

Figure GS-12-2: *Generalized geology of the Bird River Belt.*

oldest known rocks in the BRB are mid-ocean-ridge basalt (MORB)–like, back-arc volcanic sequences (Lamprey Falls Formation) along the north and south flanks of the central part of the belt. The latter consists predominantly of ca. 2.73 Ma arc volcanic rocks (Gilbert, 2006b). The greenstone belt is separated into north and south structural panels by a fault-bounded, east-trending turbidite sequence (Booster Lake Formation, 2.712 ±17 Ma; Gilbert, 2006b; Figure GS-12-2). Fluvial-alluvial sedimentary rocks of similar age (Flanders Lake Formation, 2.697 ±18 Ma; Gilbert, 2006b) overlie the arc volcanic strata at the east end of the BRB. Turbidite and fluvial-alluvial sedimentary rocks to the north in the English River Subprovince are similar in depositional age and may be stratigraphically equivalent to the Booster Lake and Flanders Lake formations (Gilbert, 2007a).

Stratigraphy

Arc-type rocks of the north and south panels of the BRB are geochemically distinct (Gilbert, 2007a) and separated in age by approximately 6 Ma (M. Duguet and D.W. Davis, pers. comm., 2006; P. Kremer and D.W. Davis, pers. comm., 2006; Table GS-12-1). Consequently, a given lithostratigraphic unit cannot occur in both the north and south panels, as had been proposed by Cerny et al. (1981). The revised stratigraphy of the BRB proposed here consists of six main supracrustal formations, described in order of decreasing age:

- 'Lamprey Falls Formation' (predating the 2.745 Ma Bird River Sill; Wang, 1993) consists almost entirely of N-MORB–type, back-arc basaltic rocks and associated gabbro. These rocks occur along the margins of both the north and south structural panels of the BRB, flanking the arc-type rocks that constitute the main part of the belt (Gilbert, 2006b). The N-MORB–type sequence in the south is subdivided into two panels that wrap around the granitoid Birse Lake pluton in the area between Birse Lake and the Winnipeg River (Figure GS-12-2; Gilbert, 2007b).
- 'Diverse arc assemblage' encompasses a variety of calcalkaline arc-type rocks in the north panel that include mafic to felsic volcanic flows, volcaniclastic and epiclastic rocks (commonly reworked by subaqueous mass flows), and minor chert and iron formation.
- 'Peterson Creek Formation' (2.731.1 ±1 Ma; M. Duguet and D.W. Davis, pers. comm., 2006) is a calcalkaline sequence of massive and fragmental dacite, rhyolite and volcaniclastic rocks within the north panel that is interpreted to overlie the diverse arc assemblage.
- 'Bernic Lake Formation' (2.724.6 ±1.1 Ma; P. Kremer and D.W. Davis, pers. comm., 2006) consists of all arc-type volcanic rocks that occur within the tholeiitic south panel of the belt.
- 'Booster Lake Formation' (2.712 ±17 Ma; Gilbert, 2006b) is a sequence of turbiditic greywacke and siltstone.
- 'Flanders Lake Formation' (2.697 ±18 Ma; Gilbert, 2006b) is a fluvial-alluvial sedimentary sequence. Detrital zircon analysis suggests the Booster Lake and Flanders Lake formations contain detritus eroded from both the BRB and the flanking granitoid terranes (Gilbert, 2006b).

Lamprey Falls Formation

Lithological details of the N-MORB–type basalt and subordinate, intercalated iron formation in the Lamprey Falls Formation have been described previously (Duguet at al., 2006; Gilbert, 2006b). New data from mapping in 2007 are summarized as follows:

- Synvolcanic gabbro is subordinate to basalt in the Lamprey Falls Formation south of the greenstone belt, whereas gabbro is more conspicuous at the north flank of the BRB. Meso- to melanocratic gabbro constitutes 30–90% of the Lamprey Falls Formation over a width of 2 km in the area northwest of the Bird River Sill (Gilbert, 2007c).
- The aphyric pillowed flows along the north flank of the BRB are predominantly south facing and locally characterized by thick interpillow masses of hyaloclastic tuff (Figure GS-12-3a). At least one pillowed unit of plagioclase-megaphyric basalt (>70 m thick) is interlayered with these aphyric flows (Figure GS-12-3b).
- Minor felsic volcanic rock units occur within the Lamprey Falls Formation basaltic sequences along both the north and south flanks of the BRB.
- A major, early fold structure in the Lamprey Falls Formation is defined by variable basaltic flow trends in the area northwest of the Bird River Sill (Gilbert, 2007c). This steeply southeast-plunging, regional open fold appears to predate emplacement of the Bird River Sill.

Diverse arc assemblage

The diverse arc assemblage, with an estimated true thickness of 750 m, extends laterally through the BRB north panel for at least 24 km, from the east end of Bird Lake to the area west of the junction of Provincial Roads (PR) 314 and 315. To the north, the assemblage is assumed to be in fault contact with the Lamprey Falls Formation, whereas its contact with the Peterson Creek Formation to the south is interpreted as either conformable or disconformable.

The widest and most complete sequence of arc-type rocks within the BRB north panel occurs in the central part of the greenstone belt, near the junction of PR 314 and 315 (Figure GS-12-4; Figure GS-12-5; 'Highway Junction section' *in* Gilbert, 2006b). The main part of this section is south facing and monoclinal, but localized folding occurs in the north part and an east-trending

Table GS-12-1: Geological formations in the Bird River Belt.

Late intrusive rocks

Granite, pegmatite, granodiorite, tonalite, quartz diorite

(Marijane Lake pluton, **2645.6 ±1.3 Ma**(1); Lac du Bonnet batholith, **2660 ±3 Ma**(2); Birse Lake pluton, **2723.2 ±0.7 Ma**(3))

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

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

Intrusive rocks

MISCELLANEOUS INTRUSIONS

Gabbro, diorite, quartz-feldspar porphyry; granodiorite

(Maskwa Lake batholith II, **2725 ±6 Ma**(2); Pointe du Bois batholith, **2729 ±8.7 Ma**(2))

Metavolcanic and metasedimentary rocks

BERNIC LAKE FORMATION (**2724.6 ±1.1 Ma**(3))

Basalt, andesite, dacite and rhyolite (massive to fragmental); related intrusive rocks and heterolithic volcanic fragmental rocks

PETERSON CREEK FORMATION (**2731.1 ±1 Ma**(1))

Dacite, rhyolite (massive to fragmental); felsic tuff and heterolithic felsic volcanic fragmental rocks

DIVERSE ARC ASSEMBLAGE

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**(2))

Dunite, peridotite, picrite, anorthosite and gabbro

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

Metavolcanic and metasedimentary rocks

LAMPREY FALLS FORMATION

Basalt (aphyric to plagioclase-phyric; locally pillowed, amygdaloidal or megacrystic); related volcanic breccia; oxide-facies iron formation

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

EAGLENEST LAKE FORMATION

Greywacke-siltstone turbidite

Older intrusive rocks

Granodiorite, diorite (Maskwa Lake batholith I, **2782 ±11 Ma**, **2844 ±12 Ma**(2))

References for geochronological data:

(1) M. Duguet and D.W. Davis (pers. comm., 2006)

(2) Wang (1993)

(3) P. Kremer and D.W. Davis (pers. comm., 2006)

(4) Gilbert (2006b)

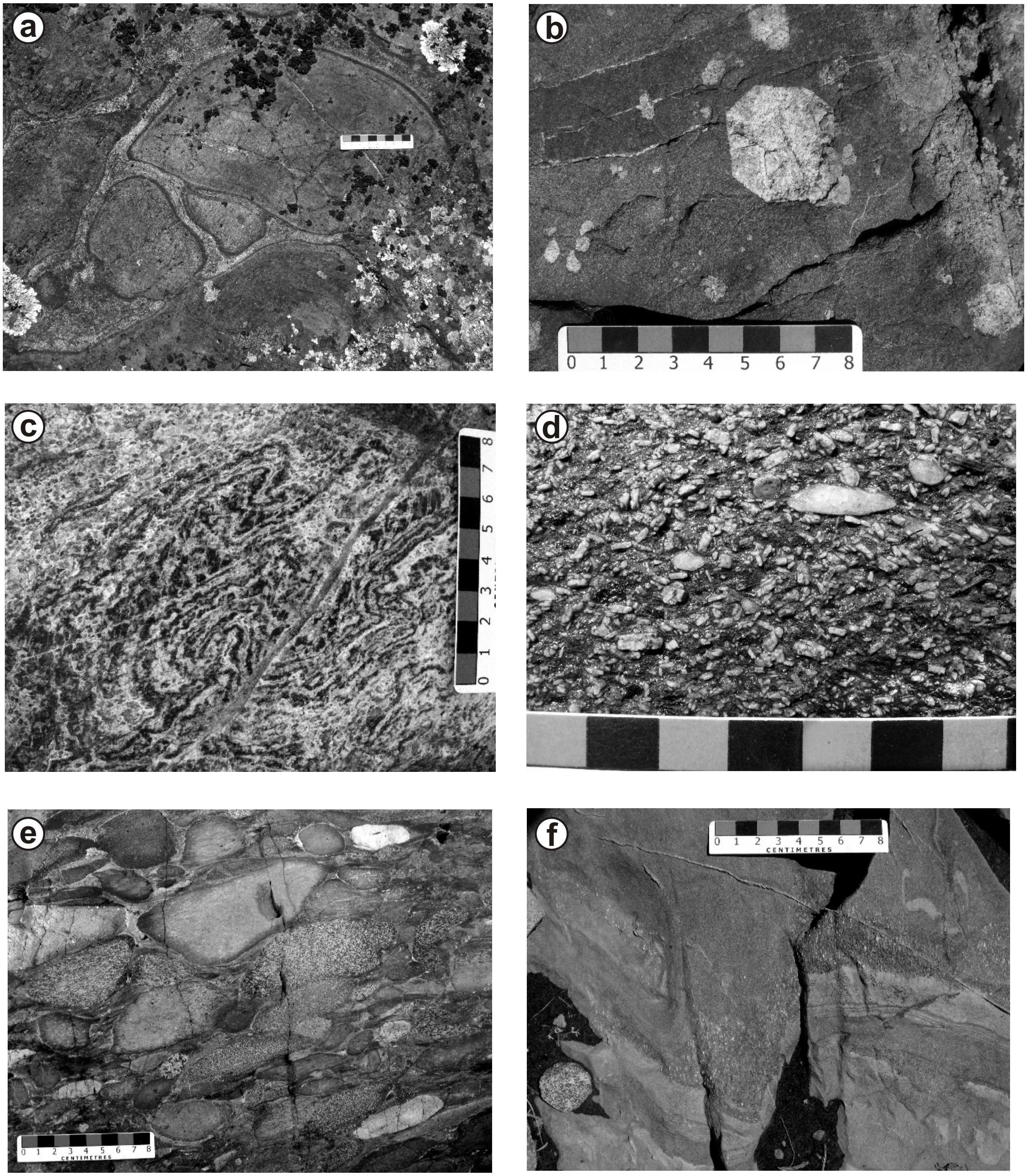

Figure GS-12-3: *Outcrop photographs of volcanic and epiclastic rocks in the north panel of the BRB:* ***a)*** *aphyric pillowed basalt with interpillow hyaloclastite, Lamprey Falls Formation (UTM 318769E, 5593392N);* ***b)*** *plagioclase-megaphyric pillowed basalt, Lamprey Falls Formation (UTM 318638E, 5593286N);* ***c)*** *spherulitic rhyolite flow with contorted flow lamination, diverse arc assemblage (UTM 319853E, 5594930N);* ***d)*** *plagioclase-hornblende–phyric basalt with quartz amygdules, diverse arc assemblage (UTM 302808E, 5586144N);* ***e)*** *polymictic conglomerate with mainly basalt and gabbro clasts, diverse arc assemblage (UTM 320494E, 5592734N);* ***f)*** *greywacke-siltstone turbidite showing graded bedding, scour and synsedimentary deformation of bedding, diverse arc assemblage, close to the axial trace of the D_1 anticline in Figure GS-12-4 (UTM 320596E, 559279N); the plane of fragment flattening (parallel to S_1) is approximately normal to bedding.*

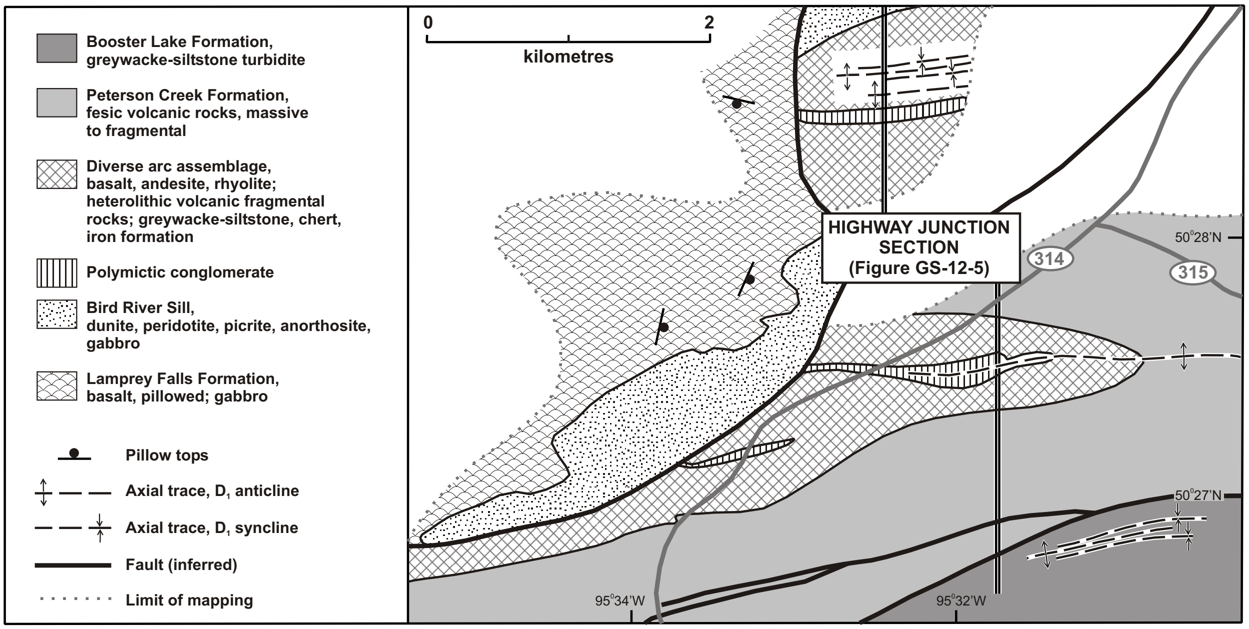

Figure GS-12-4: *Geology west of the junction of Provincial Roads 314 and 315, north panel, Bird River Belt.*

anticlinal fold occurs farther to the south. The lower part of the stratigraphic sequence consists of a wide variety of volcanic flows, associated fragmental rocks and sedimentary deposits (Figure GS-12-3c, d) that are overlain by a polymictic conglomerate unit at least 75 m thick (unit '7W' *in* Gilbert, 2006b). This stratigraphic marker unit also occurs at a locality 2 km farther south (Figure GS-12-3e), in the core of the east-trending anticline. Overlying the conglomerate, the upper part of the diverse arc assemblage consists of turbidite (Figure GS-12-3f) and volcanic fragmental rocks (Figure GS-12-6a) that are variously reworked by mass flows, as well as aphyric, quartz-amygdaloidal andesite.

Lithological units of the diverse arc assemblage are described in Gilbert (2006b, c). The following brief synopsis of the stratigraphic sequence includes data from recent (2007) mapping. The lower, 0.65 km wide part of the diverse arc assemblage contains a variety of rock types that indicate phases of rapid sedimentation (turbidites and debris flows), interspersed with relatively quiescent volcanic exhalative activity characterized by chert units and the accumulation of felsic and mafic tuffs, as well as extrusive felsic and mafic volcanic flows. The polymictic conglomerate unit that overlies the lower part of the sequence consists mainly of unsorted basalt, gabbro and subordinate rhyolite, greywacke-siltstone and chert clasts. Sporadic fragments of very coarse grained anorthositic gabbro are likely derived from the Bird River Sill (Figure GS-12-6b), whereas volcanic and sedimentary clasts are probably derived from the lower part of the diverse arc assemblage, as well as the Lamprey Falls Formation. Relative uplift of the source terrane may have been due to extensional faulting, followed by erosion and the subsequent accumulation of coarse detritus as a littoral or fluvial-fan deposit. Andesitic flows and volcanic fragmental and epiclastic rocks in the upper part of the sequence, which overlie the polymictic conglomerate, document a resumption of volcanism associated with the deposition of mass flows and turbidites (Figure GS-12-5).

Peterson Creek Formation

The Peterson Creek Formation extends the entire length of the BRB north panel, from the shore of Lac du Bonnet in the west to Bird Lake in the east, for a total strike length of approximately 40 km (Figure GS-12-2). The maximum width of the formation is 2.7 km, but the true thickness may be less because of possible structural repetition. Stratigraphic interpretation of the Peterson Creek Formation is hampered by an absence of top indicators, but the recurrence of several distinctive rock types in different parts of across-strike sections is suggestive of structural repetition, due to either folding or major faults. One such structure is an east-northeast–trending shear zone (Figure GS-12-6c) that is locally coincident with Peterson Creek in the area southwest of the junction of PR 314 and 315 (Gilbert, 2007c). The north margin of the Peterson Creek Formation appears to be conformable or disconformable with the diverse arc assemblage, whereas the south margin is sheared and mylonitized close to the faulted contact with the Booster Lake Formation (Figure GS-12-4).

Massive, dacitic and rhyolitic rocks are predominant in the Peterson Creek Formation and include both aphyric and (equally abundant) plagioclase±quartz–phyric types. Aphyric felsic volcanic flows commonly display anastomosing thermal-contraction fractures or domains of *in situ* brecciation that are gradational with autoclastic breccia.

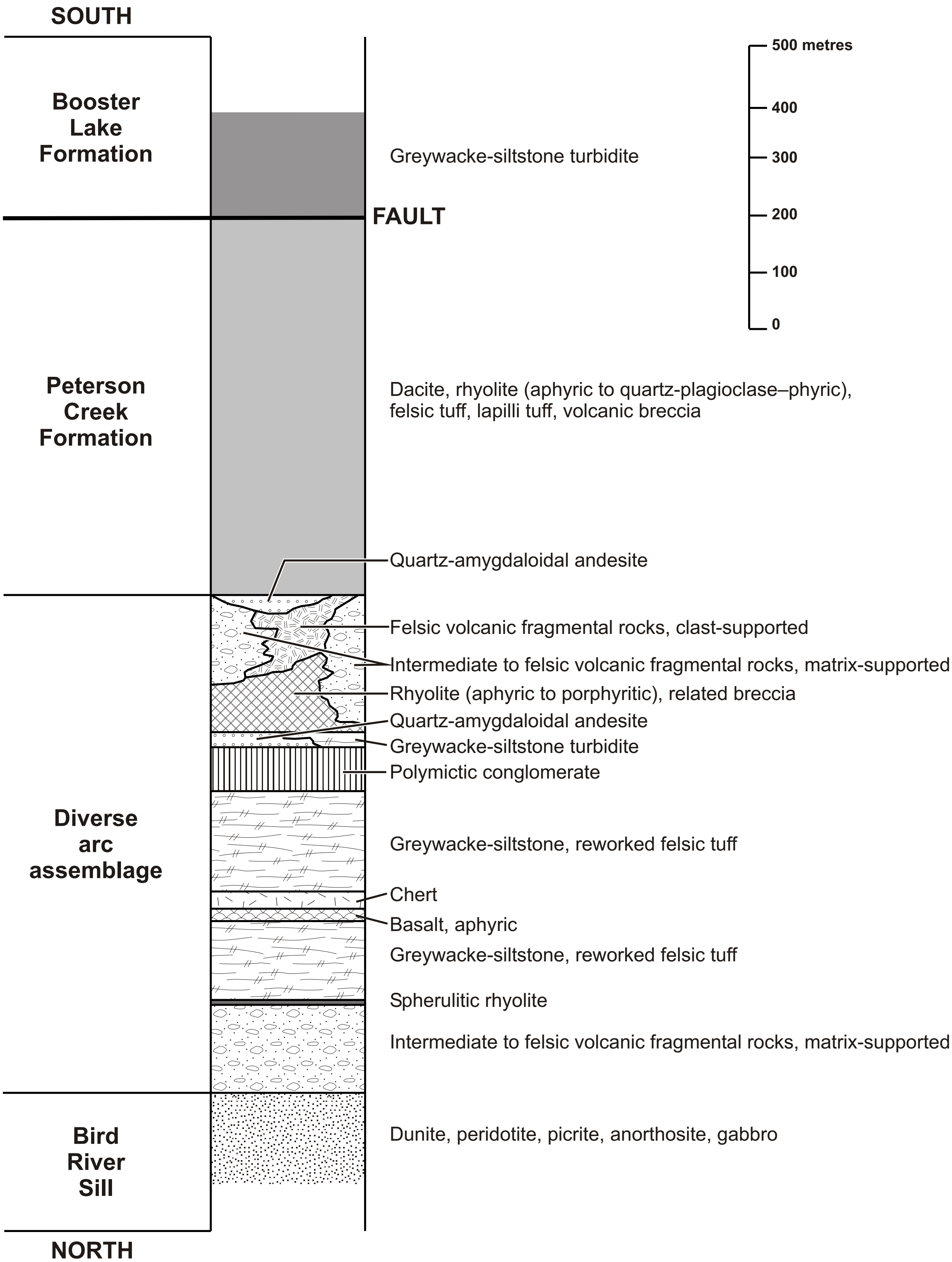

Figure GS-12-5: *Stratigraphic column of the Highway Junction section, showing lithostratigraphic details of the diverse arc assemblage, north panel, Bird River Belt.*

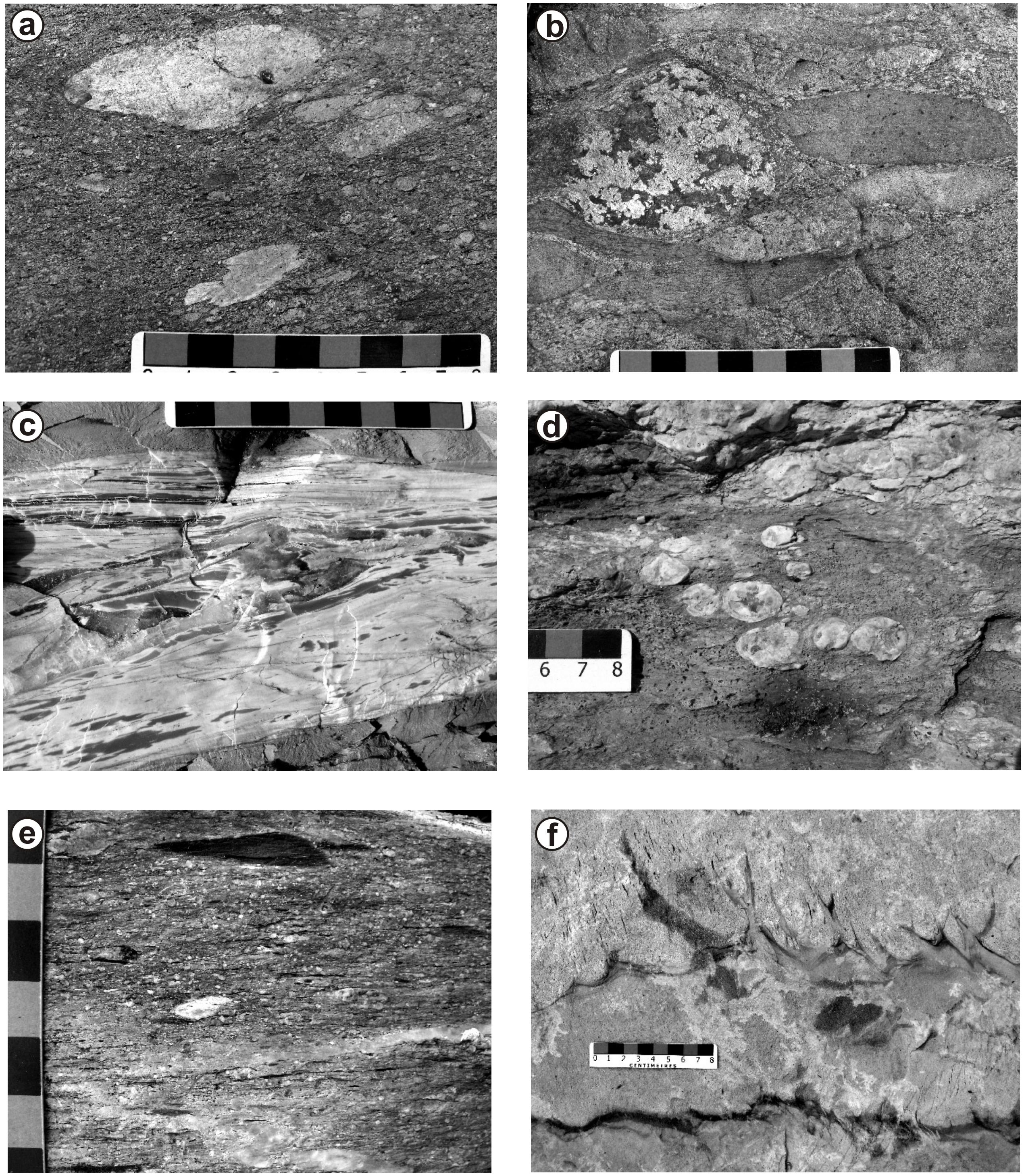

***Figure GS-12-6:** Outcrop photographs of volcanic and epiclastic rocks in the north panel of the BRB: **a)** heterolithic volcanic breccia with mainly felsic and intermediate fragments, interpreted as a reworked mass-flow deposit, diverse arc assemblage (UTM 320714E, 5592814N); **b)** polymictic conglomerate with pebble of anorthositic gabbro, probably derived from the Bird River Sill, diverse arc assemblage (UTM 320520E, 5592649N); **c)** mylonitic rhyolite with disrupted quartz veins in a shear zone coincident with Peterson Creek, Peterson Creek Formation (UTM 317457E, 5590900N); **d)** spheroidal siliceous rhyolite bodies within a felsic volcanic flow, Peterson Creek Formation (UTM 320677E, 5593348N); **e)** heterolithic lapilli crystal tuff with felsic and subordinate mafic clast types, Peterson Creek Formation (UTM 316328E, 5590768N); **f)** flame structure in turbidite from the axial zone of a D_1 fold, Booster Lake Formation (UTM 318378E, 5590432N); thickly bedded greywacke and siltstone contain thin argillitic laminae; associated rip-ups are aligned parallel to S_1, normal to the bedding.*

An unusual texture in some aphyric flows consists of two separate components: spheroidal to irregularly shaped, siliceous rhyolite bodies occur within a beige-yellow, sericitic rhyolite matrix (Figure GS-12-6d). Flows of this type occur close to both the north and south margins of the Peterson Creek Formation.

Felsic tuff and subordinate, related breccia constitute approximately 30–40% of the Peterson Creek Formation in the western part of the BRB. The most abundant fragmental rock type is a heterolithic lapilli crystal tuff that contains felsic and subordinate intermediate to mafic lapilli in a (quartz-plagioclase) crystal tuff matrix (Figure GS-12-6e). These heterolithic rocks are interpreted as reworked mass-flow deposits, in contrast to rare monolithic fragmental rocks elsewhere in the Peterson Creek Formation that may be primary pyroclastic rocks.

Bernic Lake Formation

The Bernic Lake Formation is approximately 2 km wide and extends laterally for more than 45 km, from Lac du Bonnet east to the Manitoba-Ontario provincial boundary. The formation consists of calcalkaline, felsic and mafic volcanic rocks that are roughly equal in abundance in the central part of the formation, north of Birse Lake (Figure GS-12-2; Gilbert, 2007b). Farther west at Lac du Bonnet, felsic volcanic rocks are predominant; only two units of basalt occur in that part of the formation (Gilbert, 2007c).

Reconstruction of the stratigraphic sequence of the Bernic Lake Formation is hindered by deformation and alteration, as well as by a paucity of stratigraphic facing indicators. Most pillowed flows face north, consistent with the available geochemical data that indicate an overall northward direction of younging: volcanic rocks in the north part of the Bernic Lake Formation are geochemically more evolved than those in the sequence farther to the south (*see* ‘Geochemistry’ section).

Most of the western part of the Bernic Lake Formation remains to be mapped, but parts of the north margin, as well as a lakeshore transect of the formation at Lac du Bonnet, were examined in 2007. New data from this recent mapping are summarized as follows:

- Massive dacite-rhyolite and related breccia are major stratigraphic components in the western part of the Bernic Lake Formation. Heterolithic volcanic breccia and lapilli tuff with felsic and subordinate intermediate to mafic fragments are the other principal rock types. Rare occurrences of primary volcanic features, such as *in situ* brecciation and columnar jointing in rhyolite flows, are preserved in some units, but more typically the rocks are attenuated and altered, with localized pervasive chlorite-hornblende–rich domains. Such alteration is especially conspicuous in a zone, up to several hundred metres wide, that extends intermittently along the north margin of the formation.
- A distinctive ‘iron formation’, consisting of bedded carbonate, chert, greywacke-siltstone and amphibolite at least 35 m thick, extends for more than 2 km along the south shore of the Bird River where it intersects PR 314 (Gilbert, 2007c). Contact relationships of this iron formation, which occurs close to the north margin of the Bernic Lake Formation, are not exposed. The contiguous rock unit to the south of the iron formation is a felsic volcanic flow, whereas reworked felsic crystal tuff and associated rhyolitic flows occur just a few metres to the north. Pyritic mineralization occurs locally in siltstone beds and fine-grained amphibolite layers within the iron formation.
- Silicate-facies iron formation (>5 m thick) occurs at an isolated outcrop on PR 314, approximately 120 m stratigraphically south of the carbonate-chert iron formation (Gilbert, 2007c). Alternating, 0.5–12 cm thick laminae of chert, siltstone and very fine grained amphibolite are tightly folded in a shallow, west-plunging fold.
- A 170 m wide pillowed basalt unit in the south part of the Bernic Lake Formation extends east for more than 2 km from the shore of Lac du Bonnet (Gilbert, 2007c). The basalt is aphyric and plagioclase amygdaloidal, and contains sporadic minor zones of pyritic mineralization.
- A tectonic lens of pervasively mineralized heterolithic volcanic breccia is located at the contact between the Bernic Lake and Booster Lake formations, 3.5 km west of the junction between the Tanco mine road and PR 314 (Gilbert, 2007c). This fragmental unit, more than 35 m thick and 2.5 km wide along strike, is extensively iron stained and mineralized with pyrite and pyrrhotite. The volcanic breccia contains unsorted, angular to subrounded blocks (5–25 cm) of plagioclase-phyric intermediate to felsic volcanic rocks, subordinate quartz and rare mafic fragments. The east end of the mineralized fragmental unit is structurally emplaced within the Booster Lake Formation, where the fault slice extends obliquely across its bounding fault (Gilbert, 2007c).

Booster Lake Formation

Mapping in 2007 defined the western extent of the turbiditic Booster Lake Formation, a fault-bounded structural enclave that extends from the Manitoba-Ontario boundary westward through the BRB, between the north and south panels of the greenstone belt. This formation, which wedges out approximately 1 km east of the mouth of the Bird River at Lac du Bonnet (Gilbert, 2007c), has a total strike length of approximately 44 km. The estimated, maximum true thickness of this sequence in its central part is 0.7 km, although the sequence may be 1 km or more in thickness in the area immediately west of Booster Lake (Gilbert, 2007b). The structural pattern of repeated D_1 folding established at Booster Lake persists throughout the central and western parts of the formation (Gilbert, 2007b, c). Trends of the fold-axial traces are locally oblique to the faulted margins of the formation, consistent with their early (D_1) age and thus predating tectonic emplacement of the fault-bounded enclave.

A second unit of the Booster Lake Formation occurs within the northern part of the Bernic Lake Formation, just south of the Bird River (Gilbert, 2007c). The available data indicate that this tectonic enclave contains a south-facing, monoclinal turbidite sequence over 530 m thick. It is assumed to have been emplaced at the same time as a third Booster Lake fault slice that extends through Rush Lake, close to the north margin of the Bernic Lake Formation approximately 20 km farther to the east (Gilbert, 2007b). The fault slice just south of the Bird River trends east-northeast, oblique to the easterly stratigraphic trend of the Bernic Lake Formation defined by the previously described carbonate-chert iron formation.

The eastern part of the Booster Lake Formation displays a wide variety of turbidite features characteristic of classic Bouma-type sequences (Gilbert, 2005, 2006b). The 0.1–0.5 m thick cyclic units contain abundant cordierite porphyroblasts, and these occur sporadically throughout the formation farther to the west. The depositional environment of the Booster Lake sedimentary basin is interpreted to have been at an intermediate distance from the detrital source but increasingly more proximal to the west, where the cyclic turbidite units give way to more thickly bedded (0.2–2 m scale) deposits. Two facies types are recognized in the western area:

- Intercalated coarse-grained felsic wacke and subordinate siltstone, which also occurs as local rip-ups and sporadic larger rafts within the felsic wacke: These sequences, which may represent channel deposits, are characterized by normal or reverse graded bedding, scour and localized crossbedding, and are interspersed with finer grained sedimentary rocks characteristic of more quiescent periods. The texture of the felsic wacke beds, characterized by abundant subangular to subhedral detrital quartz and plagioclase grains (1–4 mm), is similar to that of some felsic volcanic rocks in the Peterson Creek Formation, suggesting the latter may have represented a local source for the turbidite deposits.
- Fine-grained greywacke beds with minor siltstone rip-ups, interlayered with subordinate siltstone and argillite (Figure GS-12-6f): These deposits are mostly unsorted but locally graded at a scale of 0.2–1 m. A high volume of detrital supply is inferred from the relatively thick beds. The depositional environment ranges between the deeper water basin farther east at Booster Lake and the higher energy environment of the coarser grained, inferred channel deposits.

Geochemistry

The main tectonic components of the Bird River Belt (BRB) — the arc-type rocks in the north and south panels and the Lamprey Falls Formation — are lithologically and geochemically distinct, and exhibit relative age differences (Duguet et al., 2006; Gilbert, 2006b, 2007a). The contrasting geochemical signatures of these components have proven particularly useful for determining their origin, tectonic environment and potential for economic mineralization. The following discussion is restricted to rocks ranging from basalt to dacite in composition; rhyolite is excluded. Four geochemically distinct volcanic rock components are identified, from oldest to youngest, as follows:

- Lamprey Falls Formation back-arc type basalt
- BRB north panel arc-type rocks (diverse arc assemblage and Peterson Creek Formation)
- Bernic Lake Formation, south part
- Bernic Lake Formation, north part

The Lamprey Falls Formation occurs along the north and south flanks of the BRB, as well as in a narrow belt between the Bernic Lake Formation and the Birse Lake pluton (Figure GS-12-2; *see* 'Stratigraphy' section). The basaltic rocks at all three localities are remarkably similar in composition (Table GS-12-2). The aphyric pillowed basalt flows and related gabbro that constitute almost the entire Lamprey Falls Formation are characterized by nearly flat N-MORB–normalized trace-element profiles (Figure GS-12-7a) in which the light rare-earth elements (REE) are slightly elevated and Th is moderately increased. Compared to arc-type rocks throughout the rest of the BRB, Lamprey Falls basalt has lower La/Yb and Zr/Y ratios, as well as lower SiO_2 content (all samples <51% SiO_2; Table GS-12-2).

Mafic to intermediate arc-type rocks in the BRB north panel are characterized by a negatively sloping trace-element profile with a pronounced Th/Nb anomaly, as well as depleted heavy REE and TiO_2 (Figure GS-12-7b). These features are typical of modern arc-type volcanic rocks. The La/Yb and Zr/Y ratios are high and the content of SiO_2 exceeds 58% in almost all BRB north panel arc-type rocks. These rocks are also characterized by a calcalkaline affinity and thus have a significantly higher Mg# than the tholeiitic rocks of the Bernic Lake Formation in the BRB south panel (Table GS-12-2; Figure GS-12-8).

Bernic Lake Formation volcanic rocks display REE patterns typical of modern arc volcanic rocks, but overall contents of these elements are elevated compared to arc-type rocks in the BRB north panel (Figure GS-12-7c, d). Average SiO_2 content (57.3%), as well as the range of SiO_2 in Bernic Lake Formation rocks are significantly lower than in the BRB north panel arc-type rocks. Heavy REE depletion relative to light REE is progressively less pronounced from BRB north panel arc-type rocks to Bernic Lake Formation south part to Bernic Lake

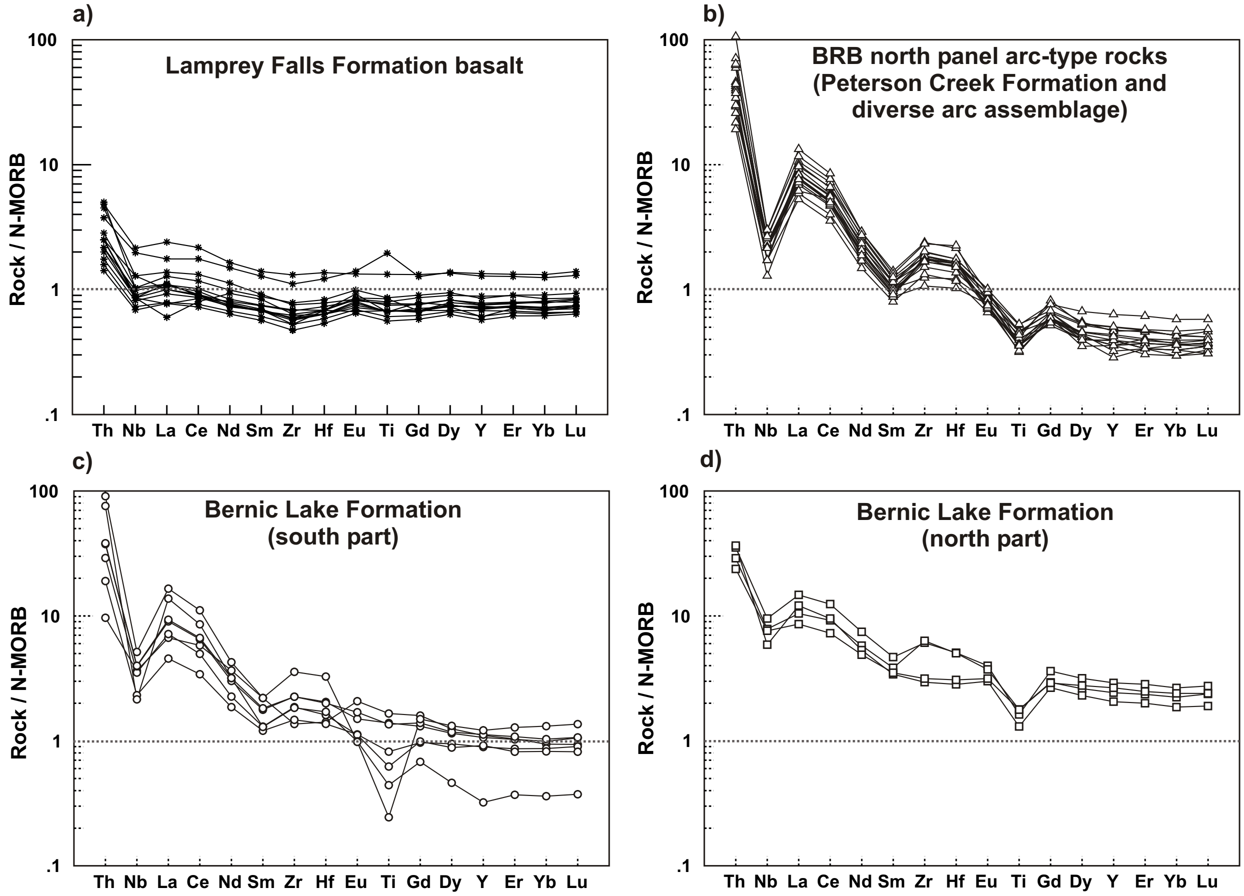

Figure GS-12-7: *Normal mid-ocean-ridge basalt (N-MORB)–normalized extended element plots of mafic to intermediate volcanic rocks in **a)** Lamprey Falls Formation back-arc type basalt; **b)** Bird River Belt north panel arc-type rocks; **c)** Bernic Lake Formation, south part; and **d)** Bernic Lake Formation, north part. Normalizing values are after Sun and McDonough (1989).*

Formation north part rocks. The REE data indicate that the north part of the Bernic Lake Formation is relatively more evolved than the south part.

The Sm/Nd isotope data for basaltic units at different localities of the Lamprey Falls Formation support the interpretation that they are part of a single N-MORB–type volcanic suite and derived from a common source magma. The ε_{Nd} values (at 2.7 Ga) for basaltic flows in the north panel, south panel and Winnipeg River locality are +1.3, +1.8 and +1.9, respectively, and thus within analytical errors. These data further indicate that the Lamprey Falls Formation was derived from a mantle source that was relatively more juvenile and less contaminated by continental crust, compared to the source of contiguous, younger arc-type rocks. The ε_{Nd} values (at 2.7 Ga) of arc-type volcanic flows in the BRB north panel are +1 to –1.1, thus suggesting slightly more crustal contamination than in the Lamprey Falls Formation basalt. In comparison, the volcanic flows in the Bernic Lake Formation yielded ε_{Nd} values (at 2.7 Ga) between +0.7 and –2.4, indicating an increase in crustal contamination and/or recycling of older crust to the south.

Economic considerations

The north panel of the Bird River greenstone belt is the focus of ongoing base-metal and PGE exploration (see 'Previous work and current exploration' section). Marathon PGM Corporation is currently prospecting the mineralized footwall ('Page zone') of the mafic–ultramafic Bird River Sill (Marathon PGM Corporation, 2007), as well as testing geophysical anomalies within the Lamprey Falls Formation northwest of the sill, where exploration targets occur within both basaltic flows (e.g., Table GS-12-3, sample 1) and synvolcanic mafic to ultramafic intrusions. Elsewhere in the Lamprey Falls Formation, mineralized oxide-facies iron formation represents an additional setting for base-metal and possible Au mineralization (Gilbert, 2006b).

Farther south in the BRB north panel, Mustang Minerals Corp. is implementing feasibility studies for a new mine at Maskwa, targeting approximately 10 million pounds of Ni concentrate per annum, as well as other metal credits (Mustang Minerals Corp., 2007). The mineralization in the former Maskwa mine occurs within the Bird River Sill along its north margin, whereas the

Table GS-12-2: Selected analytical data for mafic to intermediate volcanic rocks in the Bird River Belt.

Rock suite		Samples	SiO_2	$SiO_{2\ range}$	FeO	MgO	TiO_2	Cr	Ni
BRB north panel arc-type rocks (diverse arc assemblage + Peterson Creek Formation)		19	59.5	56.4–68.9	5.3	3.4	0.5	112	75
BRB south panel arc-type rocks (Bernic Lake Formation)		11	57.3	45.7–68.9	11.9	2.9	1.5	38	28
Lamprey Falls Formation	BRB north panel	5	49.6	46.4–49.1	13.0	7.1	0.9	214	135
	BRB south panel at Birse Lake	4	48.3	48.5–51.2	16.9	6.5	1.5	170	113
	BRB south panel at Winnipeg River	6	49.0	48.3–49.9	13.0	7.1	0.9	268	143
Lamprey Falls Formation (average)		15	49.0	48.3–49.6	14.0	6.9	1.1	213	125

Rock suite		Samples	Zr	Nb	La	Yb	Th	$La/Yb_{(ch)}$	Zr/Y	Mg#
BRB north panel arc-type rocks (diverse arc assemblage + Peterson Creek Formation)		19	135	5.7	23.7	1.2	7.0	13.9	11.1	57
BRB south panel arc-type rocks (Bernic Lake Formation)		11	223	11.8	25.7	4.3	4.6	4.3	5.2	33
Lamprey Falls Formation	BRB north panel	5	46	2.5	2.6	2.3	0.4	0.8	2.3	53
	BRB south panel at Birse Lake	4	70	3.5	4.0	3.2	0.4	0.9	2.4	44
	BRB south panel at Winnipeg River	6	44	1.9	2.3	2.2	0.2	0.7	2.3	53
Lamprey Falls Formation (average)		15	52	2.5	2.8	2.5	0.3	0.8	2.3	50

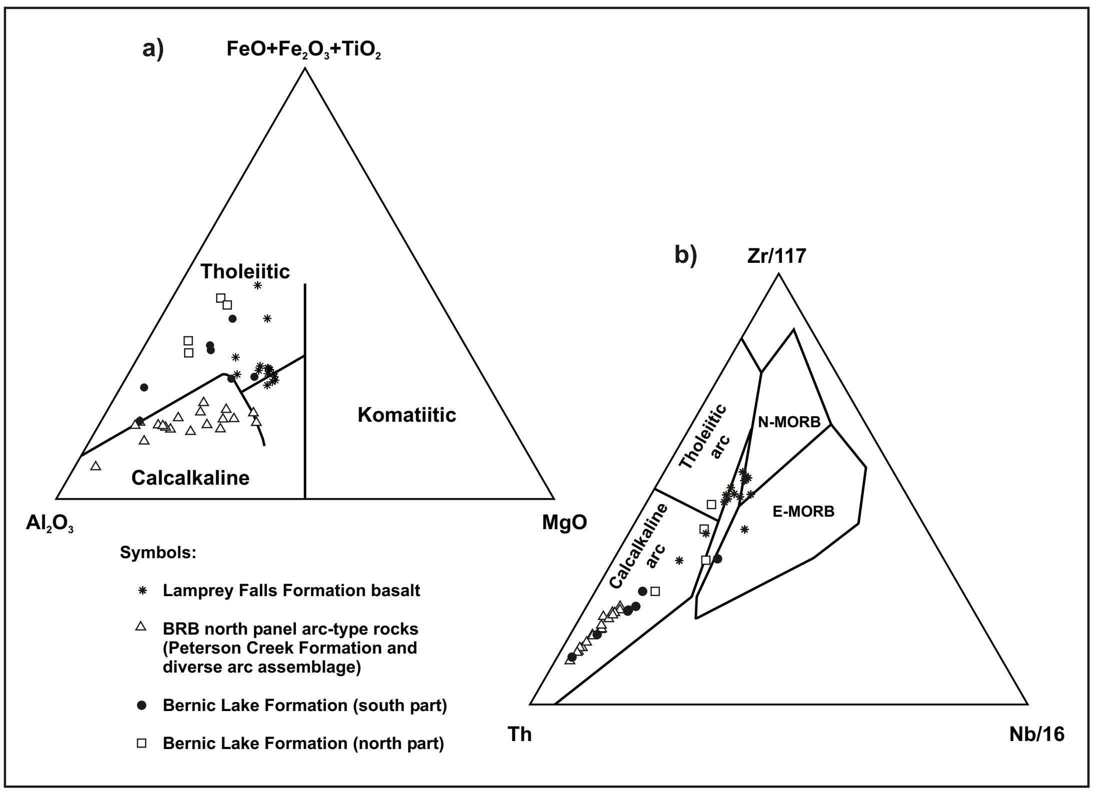

***Figure GS-12-8: a)** Jensen (1976) cation plot and **b)** Th-Zr-Nb ternary diagram (Wood, 1980) of mafic to intermediate volcanic rocks in Lamprey Falls Formation; BRB north panel arc-type rocks; Bernic Lake Formation, south part; and Bernic Lake Formation, north part.*

Table GS-12-3: Selected analytical data for mineralized rocks in the Bird River Belt.

Sample number	UTM (Zone 15U, NAD 83)	Au (ppb)	Ag (ppm)	Cu (ppm)	Zn (ppm)	Pb (ppm)	Ni (ppm)	Cr (ppm)
1	318526E, 5593305N	19	0.7	1990	53	7	26	93
2	318186E, 5590502N	-	0.3	13	22	10	8	31
3	318378E, 5590432N	-	0.7	25	51	20	9	64
4	304013E, 5585512N	-	-	153	421	148	14	12
5	303025E, 5585332N	-	-	193	154	-	24	35
6	304046E, 5585991N	-	1.1	1400	68	5	191	31
7	304721E, 5586095N	-	1	262	28	6	297	14
8	310280E, 5587794N	-	0.3	23	13	3	6	17
9	302880E, 5585188N	-	0.7	38	18	16	8	88
10	302169E, 5585219N	-	1.1	160	52	1040	24	16
11	316323E, 5589487N	-	0.9	15	32	12	6	28
12	314948E, 5589410N	-	1	17	46	11	9	29
13	314434E, 5589287N	-	1	17	39	13	13	29
Analysis method		I	M/T	T	M/T	T	M/T	I

I = instrumental neutron activation analysis

M = multi-instrumental neutron activation analysis

T = total digestion with inductively coupled plasma–mass spectrometry

contiguous Ni-Cu ore deposit at the former Dumbarton mine is associated with sulphide-facies iron formation and basalt, immediately north of the sill. Mustang Minerals is also carrying out base-metal exploration in the area east of the Maskwa property (‘Owyhee property’; Mustang Minerals Corp., 2007). The drill targets are associated with sulphide-facies iron formation within felsic volcanic flows of the Peterson Creek Formation (Gilbert, 2007b). A similar mineralized occurrence is located 1.3 km north of the junction of the Tanco mine road and PR 314, where a mineralized sulphide-facies iron formation is associated with rhyolite at the south margin of the Peterson Creek Formation, immediately north of the contact with the Booster Lake Formation (Gilbert, 2007c; Table GS-12-3, sample 2). A minor base-metal sulphide showing also occurs in cherty siltstone within the Booster Lake Formation, 200 m southeast of the latter occurrence (Table GS-12-3, sample 3).

In the BRB south panel (Bernic Lake Formation), sporadic conformable zones of mineralization occur in the Birse Lake area (Gilbert, 2006b). These showings are typically 0.5–1 m thick and hosted by both mafic and felsic volcanic rocks; the most conspicuous occurrence is more than 10 m wide and associated with pervasive alteration and a magnetic anomaly. Similar conformable mineralized zones with disseminated pyrite-pyrrhotite and sulphide stringers occur within the BRB south panel farther to the west (Gilbert, 2007c). The sulphides are commonly located at or close to the margins of the hostrock units, which include pillowed basalt (Table GS-12-3, sample 4) and felsic volcanic units (Table GS-12-3, samples 5 and 6).

A conspicuous, 5 m wide mineralized alteration zone (Table GS-12-3, sample 7) within dacite-rhyolite in the north part of the Bernic Lake Formation crops out at the junction of the Tall Timber Lodge road and PR 314. The felsic hostrock contains massive pyrite-pyrrhotite stringers within a 1.5 m wide zone containing disseminated sulphides. Silicification and pervasive chlorite-hornblende–rich domains are associated with the mineralization, which may represent a former hydrothermal alteration zone. Similar chlorite-hornblende alteration occurs sporadically along the north flank of the Bernic Lake Formation to the east (*see* ‘Bernic Lake Formation’ section), which may therefore be prospective for base-metal mineralization.

Carbonate-chert iron formation close to the north margin of the Bernic Lake Formation contains a narrow (0.5 m) pyritized zone (Table GS-12-3, sample 8; *see* ‘Bernic Lake Formation’ section) and may represent a prospective target for base-metal and/or Au exploration. A different mineralized setting occurs at the south margin of the greenstone belt, where felsic volcanic rocks in contact with the Lac du Bonnet granitic batholith to the south are pervasively iron stained due to disseminated pyrite and pyrrhotite in a zone up to 5 m wide (Table GS-12-3, samples 9 and 10; Gilbert, 2007c). In addition, a unit of heterolithic volcanic breccia at the north margin of the Bernic Lake Formation is characterized by extensive iron staining and disseminated pyrite (Table GS-12-3, samples 11, 12 and 13). These rocks are interpreted as a tectonic slice emplaced along the south margin of the Booster Lake Formation.

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