Geology and geochemistry of arc and ocean-floor volcanic rocks in the northern Flin Flon Belt, Embury–Wabishkok–Naosap lakes area, Manitoba (parts of NTS 63K13, 14)

By
H.P. Gilbert
Geoscientific Report GR2011-1

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by H.P. Gilbert
Winnipeg, 2012
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Cover illustration: The northern Flin Flon Belt in the Reindeer Zone of the Trans-Hudson Orogen includes more than 20 geochemically distinct fault blocks containing volcanic rocks of both juvenile-arc and MORB compositional type. Pillowed mafic to intermediate flows are predominant among these volcanic rocks. Major regional shear zones that locally contain tectonic breccia may have originated as crustal-scale faults associated with incipient rifting, prior to back-arc basin development. The landscape view across Wabishkok Lake is located at the northern margin of the Flin Flon arc assemblage, which is tectonically juxtaposed against back-arc basaltic rocks that extend along the southern margin of the Kisseynew Domain.
Abstract

The Paleoproterozoic Flin Flon Belt in the Reindeer Zone of the Trans-Hudson Orogen hosts many base- and precious-metal deposits and has been a focus of mineral exploration and geological investigations for over a century. Detailed mapping was initiated in 1979 by the Manitoba Geological Survey in the south-central part of the Flin Flon Belt, where most of the mineral deposits have been found. In 1986, the author initiated 1:20 000 scale geological mapping in the northern part of the Flin Flon Belt (NFFB). The map area extends from latitude 54°48′N northwards to the contact with the Kisseynew Domain, and from the Manitoba-Saskatchewan border in the west to Naosap Lake in the east. Map GR2011-1-1 (in back pocket) is a geological compilation map at 1:30 000 scale that is derived, in part, from a series of preliminary maps published by the author between 1986 and 2004.

The Flin Flon Belt is characterized by numerous allochthons that are distinguished geochemically and/or stratigraphically and are part of the Amisk Collage. This collage resulted from a 1.88–1.87 Ga collisional tectonic event that juxtaposed crustal segments of various types including juvenile arc, back-arc ocean-floor, ocean plateau, ocean-island and evolved plutonic arc. The NFFB consists of arc, arc-rift and ocean-floor (back-arc) fault blocks or slices, together with the products of subsequent 1.87–1.84 Ga successor-arc magmatism and fluvial-alluvial, as well as turbidite, sedimentation. Granitoid plutons of probable late successor-arc age locally ‘stitch’ the contacts between juvenile-arc and ocean-floor assemblages, and lensoid turbidite fault slices are locally emplaced at contacts between arc or between arc and ocean-floor volcanic rocks. Mafic intrusive sills occur within or at the margins of some fault blocks; most or all of these intrusions are interpreted as coeval with the arc/back-arc volcanism or subsequent arc-rifting.

After 1880–1870 Ma tectonic amalgamation of the oceanic-arc system, the first (D1) fold event affected juvenile-arc and back-arc rocks but predated 1870–1840 Ma successor-arc magmatism and sedimentation. The early (D1) and later (post-1840 Ma) D2 deformation events resulted in tight to isoclinal folds and locally repeated fold patterns in some fault blocks; D1 fold axial traces were locally truncated by reactivation of block-bounding faults during D2. The D3 event resulted in regional open folds, such as the east-northeast-trending Embury Lake antiform that dominates the regional structure in the western part of the NFFB. The Northeast Arm Fault is a crustal-scale structure that divides the NFFB into western and eastern parts, distinguished by northwest- to west-trending and northeast- to east-trending regional faults, respectively. The latest deformation event (D4) resulted in brittle faulting, typically at high angles to earlier structural trends.

Two north-trending panels of rift-related rock types that have been identified in the NFFB may have a potential for economic mineralization, based on the association of volcanogenic massive sulphide mineralization with arc-rifting elsewhere in the Flin Flon Belt. These two panels are spatially associated with major, crustal-scale faults that extend across the width of the Flin Flon Belt (Inlet Arm Fault, Northeast Arm Fault). Several localities of felsic volcanic rocks in the NFFB may also be prospective for base-metal and/or precious-metal mineralization, based on their geochemical signature. The location of the Trout Lake mine at the inferred contact between the Cope Lake and Embury Lake blocks suggests tectonostratigraphic contacts may, in some cases, also represent promising targets for mineral exploration.
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As outlined in the table below, GR2011-1 has digital-only components that are provided on an accompanying DVD for the print format of this publication. The DVD is also a stand-alone product of the entire publication.

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Introduction

The Flin Flon Belt is one of the largest Paleoproterozoic volcanogenic massive sulphide (VMS) districts in the world, with over 162 million tonnes of Cu-Zn-(Au) ore (combined reserves and production to 2007) in 27 past and currently active mines (Manitoba Innovation, Energy and Mines, 2010). This belt has been the subject of geological mapping by provincial and federal surveys for more than 60 years. Although reconnaissance and regional mapping has been undertaken across the entire width of the belt and beyond, detailed mapping has focused largely on the central and southern parts of the belt where the main VMS deposits have been found. The northern Flin Flon Belt (NFFB), on the other hand, had received comparatively little attention until 1986, when mapping was initiated by the author in the Embury–Wabishkok–Naosap lakes area. Detailed, 1:20 000 scale mapping was subsequently extended to the northern margin of the volcanic terrane of the Flin Flon Belt, where it is bounded by predominantly metasedimentary gneisses of the Kisseynew Domain, and eastward to the contact with an extensive granitoid terrane at Naosap Lake (Figures 1, 2 and 3). The results of this mapping have been documented in various Manitoba Geological Survey (MGS) reports, preliminary maps and one open file published between 1986 and 2004 (Gilbert, 1986a, b, 1987a, b, 1988a, b, 1989a, b, 1990a, b, 1996a, b, 1997a, b, 1998, 1999, 2001a, b, 2002a, b, 2003a, b, 2004).

Geological data gathered over the course of eleven field seasons have been compiled in Map GR2011-1-1 (in back pocket), which integrates all mapping information and interpretation of the associated geochemical data. This report contains descriptions of the various tectonostratigraphic components and a discussion of their crustal setting, inferred magmatic sources, structural history and economic geology. Analytical data on the geochemistry of 344 rock samples collected between 1986 and 2004 are provided in Appendix 1, which also includes mineralogical, petrographic and lithological notes for each sample. Appendix 2 contains a comprehensive series of field photographs as well as a less broad based collection of photomicrographs. Various map legends for the original 1:20 000 scale preliminary maps in the Embury–Wabishkok–Naosap lakes area have been integrated into a single unified legend in Map GR2011-1-1, based on lithostratigraphic as well as geochemical criteria. This map complements previous mapping in the Flin Flon–White Lake area to the south (Figure 4; Bailes and Syme, 1989) by highlighting lateral stratigraphic and geochemical differences, and similarities within various tectonic components that extend from the south-central to the northern part of the Flin Flon Belt. Map GR2011-1-1 also provides a link to geological data in the area north of the Flin Flon Belt, continuous with the latter via a regional basaltic formation that extends northwards from the NFFB and laterally for over 100 km along the southern margin of the Kisseynew Domain (Zwanzig, 2010).

**Figure 1:** Regional geology map of part of the Reindeer Zone in the southern Trans-Hudson Orogen, west-central Manitoba. The Flin Flon Domain (Flin Flon Belt) consists of volcanic, sedimentary and intrusive rocks in the Flin Flon–Snow Lake area, south of the Kisseynew Domain and north of the flat-lying Ordovician rocks that extend southwards from Athapapuskow and Reed lakes. The northern Flin Flon Belt subarea is shown in Figure 2 (inset), which corresponds approximately to the outline of Map GR2011-1-1. Figure 4 (inset) shows the lateral extent of tectonically defined components between the NFFB and the south-central part of the western Flin Flon Belt (Bailes and Syme, 1989).
Figure 2: Geology of the northern part of the western Flin Flon Belt, west-central Manitoba, showing the main tectonostratigraphic components. Numbered localities of arc rocks within the Dismal Lake assemblage are characterized by base-metal sulphide mineralization.
Figure 3: Structural geology of the northern part of the western Flin Flon Belt, west-central Manitoba, showing the main faults, shear zones and axial traces of $D_1$ to $D_3$ major folds.
Figure 4: Geology of the western part of the Flin Flon Belt, west-central Manitoba, showing the lateral extent of tectonically defined components between the northern Flin Flon Belt and south-central part of the Flin Flon Belt (Bailes and Syme, 1989). Note that Big Island Lake is known unofficially as Manistikwan lake, also used to name the fault block that contains Big Island Lake.
The following text summarizes previous work, describes the regional geology and provides an outline of the main tectonostratigraphic components with descriptions of the various volcanic rock suites in the NFFB. Five arc volcanic suites in the western and northern parts of the study area are described first (Bear Lake, Cope Lake, Hook Lake, Tartan Lake and Wabishkok Lake suites), followed by three arc/arc–rift suites (Manistikwan Lake1, East Mikanagan Lake and Lac Aimée) and two tholeiitic to calcalkaline arc suites at the eastern margin of the NFFB (Sourdough Bay and Naosap Lake). Descriptions of the arc volcanic suites and various back-arc types with mid-ocean-ridge basalt (MORB)-like and depleted-MORB compositions are followed by a discussion of their tectonic setting and magmatic origin. A short section on the structural history of the NFFB is also provided, followed by a final section on the economic geology of the area.

Map GR2011-1-1 (in back pocket) and this report with associated figures are presented in both print form and on DVD (also in back pocket). Additional components that are provided only on the DVD are as follows:

1) Appendix 1: geochemical data and notes (include mineralogical, petrographic and lithological data for analyzed rock samples)

2) Appendix 2: field photographs and photomicrographs

3) Map GR2011-1-2: an interactive GIS map with locations of geochemically analyzed rock samples (listed in Appendix 1) as well as field photographs and photomicrographs (listed in Appendix 2)

Analytical data and photographic images for specific map units may be readily accessed either in the appendices (where the data is referenced and grouped according to the map units), or directly on the GIS map. In addition, geochemical data are compiled into averages for individual volcanic rock suites, and Sm-Nd isotopic data are presented in separate tables within the text below.

Previous work

The NFFB was mapped previously at a scale of 1 inch to 1 mile (1:63 360) by Tanton (1941) and Bateman and Harrison (1945). Detailed mapping at a scale of 1:5000 was carried out by Peloquin and Gale (1985) in the Tartan Lake area. Compilations of mineral deposit data (Gale and Eccles, 1988a, b, c; Gale and Norquay, 1996), mineral deposit studies (Gale, 2001) and detailed mapping (Gale and Dabek, 2002) were carried out in the NFFB concurrent with mapping by the author.

In 1979, a detailed geological mapping program was initiated by the MGS in the Flin Flon–White Lake area (Bailes and Syme, 1989), just south of the area covered by Map GR2011-1-1. Numerous geological investigations and targeted research projects have subsequently been carried out in the central and southern portions of the Flin Flon Belt, both during and after completion of mapping in the NFFB by the author, of which only a selection are cited here (Stern et al., 1995a, b, 1999; Lucas et al., 1996; NATMAP Shield Margin Project Working Group, 1998; Syme, 1998; Syme et al., 1999; Ames et al., 2002; Devine et al., 2002; Jonasson et al., 2002; Mitchinson et al., 2002; Gibson et al., 2003a, b, 2005, 2009; Kremer and Simard, 2007; MacLachlan and Devine, 2007; Simard and Creaser, 2007; DeWolfe, 2008, 2009, 2010; DeWolfe et al., 2009a, b, 2010; Ordóñez-Calderón et al., 2009, 2011; Simard and MacLachlan, 2009; Babechuk and Kamber, 2010; Rayner, 2010).

Regional geology

The Paleoproterozoic Flin Flon Belt is part of the internal Reindeer Zone within the Trans-Hudson Orogen and consists largely of juvenile (mantle-derived) crust (Lewry, 1981; Stauffer, 1984; Syme, 1990; Thom et al., 1990; Stern et al., 1995a). The belt contains a series of tectonostratigraphic assemblages that are thought to represent components of an island-arc ocean-floor volcanic system (i.e., juvenile arc, back-arc ocean-floor, ocean plateau, ocean-island basalt and evolved plutonic arc)—similar, in some respects, to present-day analogues in the western Pacific Ocean (Stern et al., 1990; Martínez and Taylor, 2003). These assemblages, which range in age from 1.87 to 1.91 Ga (Stern et al., 1999), were amalgamated ca. 1.88–1.87 Ga into an accretionary tectonic complex (Amisk Collage, Lucas et al., 1996). The accretionary complex was subsequently ‘stitched’ together by calcalkaline plutons related to 1.87–1.84 Ga successor-arc magmatism penecontemporaneous with ≤1.87 Ga marine to subaerial volcanism and sedimentation (‘Schist-Wekusko assemblage’ of NATMAP Shield Margin Project Working Group, 1998; ‘Schist-Wekusko suite’ of Stern et al., 1999). Uplift during the waning stage of successor-arc magmatism resulted in unroofing of the Amisk Collage, leading to turbidite sedimentation (ca. 1.86–1.84 Ga Burntwood Group, Machado et al., 1999) in marine basins, and the development of a paleosol and sedimentation in continental alluvial-fluvial environments (ca. 1.846–1.842 Ga Missi Group; Ansdell et al., 1992, 1993, 1999; Heaman et al., 1992; Syme et al., 1993). Intracontinental tectonic activity ca. 1.84–1.78 Ga associated with convergence of bounding Archean cratons resulted in segmentation of the Flin Flon Belt into a series of strike-slip fault blocks of volcanic and sedimentary rocks (Lucas et al., 1996). Geochemically distinct volcanic rock suites of contrasting tectonic affinity (e.g., arc, back-arc ocean-floor) are now juxtaposed or locally separated by intervening tectonic slices of younger, sedimentary rocks (Missi and Burntwood groups) of successor-arc age (Lucas et al., 1996). The various allochthons were locally intruded by 1.83–1.84 Ga late successor-arc granitic plutons, further deformed and variably metamorphosed during the final, ca. 1.77 Ga stage of the Trans-Hudson orogeny.

The Flin Flon arc assemblage consists mainly of tholeiitic basalt and basaltic andesite, with subordinate heterolithic breccia, felsic volcanic rocks and epilastic rock types. All of the VMS deposits mined to date in the western Flin Flon Belt

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1 Manistikwan lake is an unofficial name for Big Island Lake. In this report, the geological terms Manistikwan Lake Block (Bailes and Syme, 1989) and Manistikwan Lake suite are used for the tectonostratigraphic feature and its associated volcanic rocks, respectively, whereas ‘Big Island Lake’ is used for the geographical feature.
are hosted by this juvenile-arc assemblage (Syme and Bailes, 1993). The rocks of the Flin Flon arc assemblage range in age from 1881 to 1889 Ma (Lucas et al., 1996; Stern et al., 1999; Rayner, 2010). The Flin Flon mine rhyolite within the Flin Flon Block is the oldest part of this assemblage; it yielded an age of 1903 ±7/–5 Ma (Stern et al., 1999), which has subsequently been constrained to 1887 ±2 Ma (Rayner, 2010).

In contrast to the Flin Flon arc assemblage, the compositionally MORB-like ocean-floor assemblage consists of back-arc basalt that is lithologically simple and virtually devoid of mineralization. It consists almost exclusively of subaqueous basalt flows intercalated with synvolcanic gabbro and ultramafic intrusions. Most of these rocks occur in a broad, northeast-trending collage (1.90 Ga Elbow-Athapapuskow ocean-floor assemblage, Stern et al., 1994, 1995b) that extends along the southern and eastern margins of the Flin Flon arc assemblage in the western Flin Flon Belt (NATMAP Shield Margin Project Working Group, 1998, Figure 1b; Figure 1). Compositionally similar rocks occur as tectonic enclaves intercalated with fault blocks of arc rocks in the NFFB, and similar but geochemically more depleted MORB-like rocks extend along the northern margin of the western Flin Flon Belt.

Postaccretion, successor-arc sedimentary rocks of the Missi Group occur 1) in a large structural basin in the western Flin Flon Belt, in the vicinity of the city of Flin Flon; 2) in several fault-bounded enclaves farther to the east; and 3) at Athapapuskow Lake to the south (Gilbert, 1986a, 1987a, 1990a, 2002a; NATMAP Shield Margin Project Working Group, 1998, sheet 2; Bailes and Syme, 1989). A series of turbiditic fault slices in the NFFB are of uncertain age, but at least one turbidite deposit is interpreted as part of the (successor-arc) Burntwood Group. Missi Group rocks were not examined in detail by the author; for more information on these rocks the reader is referred to the earliest description by Bruce (1918), and subsequent publications including those of Mukherjee (1971), Stauffer and Mukherjee (1971), Bailes and Syme (1989), Stauffer (1990) and Gale et al. (1999). Burntwood Group turbidites were the main focus of detailed mapping that resulted in a comprehensive description of the rocks by Bailes (1980).

**Geology of the northern Flin Flon Belt**

Map GR2011-1-1 covers an area that is approximately 20 km by 33 km in size and is underlain by more than 20 stratigraphically and tectonically distinct blocks or fault slices that contain volcanic and/or sedimentary successions. Most of these fault blocks are dominated by volcanic rocks, which are grouped into three main compositional types: 1) juvenile arc and arc-rift (unit J); 2) normal mid-ocean-ridge basalt (N-MORB); and 3) depleted MORB (unit T; Tables 1 and 2). The rocks with various MORB-like compositions are interpreted as products of back-arc magmatism as opposed to volcanism in a mid-ocean-ridge setting.²

² The terms MORB, ‘MORB-like’ and ‘MORB-type’ in this report denote only compositional equivalence or similarity to MORB; they do not imply a mid-ocean-ridge setting.
### Table 1: Geological formations, northern Flin Flon Belt, west-central Manitoba.

**Paleoproterozoic**

<table>
<thead>
<tr>
<th>Group</th>
<th>Description</th>
<th>Rocks and Mineralogy</th>
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<td><strong>SUCCESSOR-ARC AND YOUNGER ROCKS (1.84–1.88 Ga)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>Late intrusive rocks (may be &lt;1.84 Ga)</td>
<td>Quartz-feldspar porphyry, felsite</td>
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<tr>
<td>P</td>
<td>Granitoid intrusive rocks (may include rocks older than 1.88 Ga)</td>
<td>PISTOL LAKE, KOTYK LAKE, NAOSAP LAKE PLUTONS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Granodiorite, granite, tonalite, quartz diorite, quartz-feldspar porphyry, related gneiss</td>
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<tr>
<td>X</td>
<td>Mafic to ultramafic intrusive rocks (age uncertain, may be &gt;1.88 Ga)</td>
<td>TARTAN LAKE COMPLEX, WABISHKOK LAKE SILL, KOTYK LAKE SILL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gabbro, quartz gabbro, leucogabbro, anorthositic gabbro, diorite, pyroxenite, hornblendite, diabase</td>
</tr>
<tr>
<td>M</td>
<td>Missi Group (1.84–1.85 Ga)</td>
<td>Polymictic conglomerate, sandstone, pebbly sandstone, related gneiss, meta-arenite, metarhyolite</td>
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</tbody>
</table>

### VOLCANIC, INTRUSIVE AND SEDIMENTARY ROCKS (1.88–1.90 Ga)

<table>
<thead>
<tr>
<th>Group</th>
<th>Description</th>
<th>Rocks and Mineralogy</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>Sedimentary rocks of uncertain age (includes some rocks probably ≤1.86 Ga in age)</td>
<td>BARTLEY LAKE, SMOOK LAKE, TARTAN LAKE, NAOSAP LAKE, SWORDFISH LAKE, EMBURY LAKE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Feldspathic greywacke, siltstone, argillite, schist, conglomerate, chert</td>
</tr>
<tr>
<td>J</td>
<td>Juvenile arc and arc-rift rocks</td>
<td>CLIFF LAKE PLUTONIC SUITE (1886 ±1 Ma, Stern et al., 1999; 1888 ±1 Ma, Rayner 2010)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tonalite, quartz diorite</td>
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<tr>
<td></td>
<td></td>
<td>Mafic to ultramafic intrusive rocks (compositionally layered sills)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BATTERS LAKE SILL, TARTAN LAKE SILL, MIKANAGAN LAKE SILL (1881 +3/-2 Ma, Stern et al., 1999)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Gabbro, gabbronorite, quartz gabbro, diorite, hornblendite, quartz-eye tonalite, ferrotonalite</td>
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<td></td>
<td></td>
<td>Felsic volcanic rocks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BAKER PATTON COMPLEX, COPE LAKE, LAC AIMÉE, BARTLEY LAKE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Rhyolite, dacite flow/sill, related fragmental rhyolite, felsic volcanic breccia, tuff, plagioclase±quartz porphyry</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mafic to intermediate volcanic rocks</td>
</tr>
<tr>
<td></td>
<td></td>
<td>BEAR LAKE (1885 ±3 Ma, Stern et al., 1993), COPE LAKE, HOOK LAKE (1882 ±1 Ma, Rayner, 2010), TARTAN LAKE, WABISHKOK LAKE, MANISTIKWAN LAKE¹, EAST MIKANAGAN LAKE, LAC AIMÉE, SOURDOUGH BAY, NAOSAP LAKE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basalt, basaltic andesite, andesite, autoctonic breccia, heterolithic volcanic breccia, tuff</td>
</tr>
<tr>
<td>T</td>
<td>Depleted-MORB mafic volcanic rocks</td>
<td>DISMAL LAKE, BLUENOSE LAKE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basalt, basaltic andesite</td>
</tr>
<tr>
<td>F</td>
<td>MORB-type mafic volcanic rocks</td>
<td>ANIMUS LAKE, WEST MIKANAGAN LAKE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basalt</td>
</tr>
<tr>
<td></td>
<td></td>
<td>N-MORB</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ARTHURS LAKE, BLUENOSE LAKE, ANIMUS LAKE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Basalt, plagioclase-megaphyric basalt, related gabbro</td>
</tr>
<tr>
<td>U</td>
<td>Undivided mafic volcanic rocks</td>
<td>Basalt, andesite</td>
</tr>
</tbody>
</table>

¹ Manistikwan lake is an unofficial name for Big Island Lake.
Table 2: Tectonic setting, geochemical affinity and rock types of volcanic suites in the northern Flin Flon Belt, west-central Manitoba.

<table>
<thead>
<tr>
<th>Volcanic rock suite</th>
<th>Tectonic setting</th>
<th>Map units</th>
<th>Tholeiitic/calcalkaline type</th>
<th>Rock types (in order of abundance)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Juvenile arc and arc-rift volcanic suites (J)</strong></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Naosap Lake</td>
<td>arc</td>
<td>J10a, J10b</td>
<td>calcalkaline</td>
<td>Andesite to dacite flow, autocratic breccia, heterolithic volcanic breccia, related porphyroblastic gneiss</td>
</tr>
<tr>
<td>Sourdough Bay</td>
<td>arc</td>
<td>J12, J9</td>
<td>tholeiitic to calcalkaline</td>
<td>Felsic volcanic flow, related breccia and intrusive rocks; basalt to andesite flow, autocratic breccia, heterolithic volcanic breccia</td>
</tr>
<tr>
<td>Lac Aimée</td>
<td>arc, arc-rift</td>
<td>J8a, J8b, J11, J14</td>
<td>tholeiitic</td>
<td>Basalt to andesite flow, autocratic breccia, heterolithic volcanic breccia, tuff, felsic volcanic flow, related breccia and intrusive rocks</td>
</tr>
<tr>
<td>East Mikanagan Lake</td>
<td>arc-rift</td>
<td>J7</td>
<td>tholeiitic</td>
<td>Basalt, autocratic breccia</td>
</tr>
<tr>
<td>Manistikwan Lake¹</td>
<td>arc, arc-rift</td>
<td>J6, J11</td>
<td>tholeiitic to calcalkaline</td>
<td></td>
</tr>
<tr>
<td>Wabishkok Lake</td>
<td>arc</td>
<td>J5, J11</td>
<td>tholeiitic</td>
<td></td>
</tr>
<tr>
<td>Tartan Lake</td>
<td>arc</td>
<td>J4, J11</td>
<td>tholeiitic to calcalkaline</td>
<td></td>
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<tr>
<td>Hook Lake (rhyolite, south of the area covered by Map GR2011-1-1, yields 1882 ±1 Ma)²</td>
<td>arc</td>
<td>J3, J11</td>
<td>tholeiitic</td>
<td></td>
</tr>
<tr>
<td>Cope Lake (possibly coeval rocks at Trout Lake mine yield 1878 ±1.1 Ma)³</td>
<td>arc</td>
<td>J2, J11, J13</td>
<td>calcalkaline</td>
<td></td>
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<tr>
<td>Bear Lake (tuff, south of the area covered by Map GR2011-1-1, yields 1885 ±3 Ma)⁴</td>
<td>arc</td>
<td>J1, J11, J15</td>
<td>calcalkaline</td>
<td></td>
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<td><strong>Depleted-MORB volcanic suites (T)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Bluenose Lake</td>
<td>back-arc/ ocean floor</td>
<td>T2</td>
<td>tholeiitic</td>
<td>Basalt, basaltic andesite</td>
</tr>
<tr>
<td>Dismal Lake</td>
<td>back-arc/ ocean floor</td>
<td>T1</td>
<td>tholeiitic</td>
<td>Basalt, basaltic andesite</td>
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<tr>
<td><strong>MORB-type volcanic suites (F)</strong></td>
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<tr>
<td>(synvolcanic gabbro in compositionally equivalent Elbow-Athapapuskow ocean-floor assemblage in the southeast part of the Flin Flon Belt yields ages of 1901–1904 Ma)⁵</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>West Mikanagan Lake (E-MORB)</td>
<td>back-arc/ ocean floor</td>
<td>F5</td>
<td>tholeiitic</td>
<td>Basalt</td>
</tr>
<tr>
<td>Animus Lake (N-MORB, E-MORB)</td>
<td>back-arc/ ocean floor</td>
<td>F3, F4</td>
<td>tholeiitic</td>
<td>Basalt</td>
</tr>
<tr>
<td>Blu enose Lake (N-MORB)</td>
<td>back-arc/ ocean floor</td>
<td>F2</td>
<td>tholeiitic</td>
<td>Basalt</td>
</tr>
<tr>
<td>Arthurs Lake (N-MORB)</td>
<td>back-arc/ ocean floor</td>
<td>F1</td>
<td>tholeiitic</td>
<td>Basalt, plagioclase-megaphyric basalt, related gabbro</td>
</tr>
</tbody>
</table>

¹ Manistikwan lake is an unofficial name for Big Island Lake; ²³ N. Rayner, 2010; ⁴ Stern et al., 1993; ⁵ Stern at al., 1995b

Gabbroic intrusions (units X1 to X6), emplaced both within arc and MORB-type sequences, may also be synvolcanic in age (e.g., Wabishkok Lake and Kotyk Lake sills and intrusions in the Dismal Lake assemblage, Figure 2). The tectonic affinity and age of the heterogeneous Tartan Lake complex (unit X2; Gilbert, 1990a) are, however, unknown.

**Juvenile arc and arc-rift volcanic suites (units J1 to J15)**

Subaqueous mafic volcanic and related intrusive rocks of juvenile-arc affinity are the main components of the NFFB, where 10 tectonically distinct arc volcanic suites are structurally juxtaposed with MORB-like volcanic rocks and sedimentary fault slices (Figure 2). The arc volcanic rocks consist of a wide range of massive to fragmental types and associated intrusions. These volcanic suites are typically bimodal, consisting mainly of basalt or basaltic andesite and dacite-rhyolite¹. Based on the FeO/MgO ratios (Mg#) and the discriminant diagrams of Jensen (1976) and Irvine and Baragar (1971), the arc volcanic suites are classified as follows: 1) tholeiitic—Hook, Wabishkok and Lac Aimée suites; 2) transitional (calcalkaline to tholeiitic)—Tartan Lake and Sourdough Bay suites; and 3) calcalkaline—Bear Lake, Cope Lake and Naosap Lake suites (Figure 5a to 5f).

¹ Terminology of volcanic rock types, according to SiO₂ content, is as follows: basalt 46–53%, basaltic andesite 53–57%, andesite 57–62%, dacite 62–70%, rhyolite >70%. Geochemical samples were obtained from localities without visible alteration or veining.
Figure 5: Ternary diagrams ($\text{Al}_2\text{O}_3$–$\text{FeO}^T$–$\text{MgO}$) after Jensen (1976) and ($\text{Na}_2\text{O}+\text{K}_2\text{O}$–$\text{FeO}^T$–$\text{MgO}$) after Irvine and Baragar (1971), for mafic to felsic arc volcanic rocks in the northern Flin Flon Belt, west-central Manitoba: a) and b) tholeiitic—plots of Manistikwan Lake suite rocks from Bailes and Syme, 1989; c) and d) transitional (tholeiitic to calcalkaline); and e) and f) calcalkaline volcanic suites. Abbreviations: $\text{FeO}^T = \text{FeO} + (0.8998 \times \text{Fe}_2\text{O}_3)$. 

[Diagram descriptions and labels as per figure 5]
Basalt, basaltic andesite and related fragmental rocks are the predominant rock types; felsic volcanic rocks (units J11 to J15) are generally minor components, except in the southeastern part of the study area where rhyolitic types form approximately 15% of the Lac Aimée Block and >50% of the northern part of the Sourdough Bay Block (Figure 2).

Geochemically distinctive volcanic rocks, interpreted as products of early arc-rifting, occupy the East Mikanagan Lake Block (unit J7), and similar rocks are intercalated with arc types in the Lac Aimée and Manistikwan Lake blocks (units J8 and J6). Contacts between arc and arc-rift rocks are commonly faulted, but locally these rock types appear to be stratigraphically and compositionally gradational.

**Bear Lake suite (unit J1, calcalkaline arc)**

The Bear Lake suite occupies a lensoid tectonic block that extends laterally for over 30 km from the central part of the Flin Flon Belt, north and northwest to the Manitoba-Saskatchewan boundary (Figure 2). The Bear Lake suite is thickest in the central Flin Flon Belt where it forms a monocline, east to northeast-facing calcalkaline sequence of basaltic andesite flows and fragmental rocks up to 3.3 km thick, capped by thin (25 m) pelagic sedimentary rocks and overlain by an upper calcalkaline section of volcaniclastic rocks up to 900 m thick (Vick Lake andesitic tuff, Bailes and Syme, 1989). A mafic-felsic bimodal sequence—Two Portage Lake ferrobasalt and rhyolite tuff (1885 ±2 Ma, Gordon et al., 1990)—occurs between the basaltic calcalkaline sequence and overlying Vick Lake tuff (1885 ±3 Ma, Stern et al., 1993). The upper, volcaniclastic section wedges out northwards in the vicinity of southern (1.885 ±3 Ma, Stern et al., 1993). The upper, volcaniclastic section wedges out northwards in the vicinity of southern Mikanagan Lake, where small remnants of the tuff persist at the southwestern shoreline. Up to 1.5 km of subsidence is estimated to have occurred after the initial Bear Lake mafic volcanism, mainly during deposition of the upper volcaniclastic sequence (Bailes and Syme, 1989).

The Bear Lake suite in the NFFB consists of a 3 km wide sequence of massive to fragmental volcanic rocks that diminishes in thickness progressively northwards toward the Manitoba provincial boundary, where the width is less than 150 m. This sequence, which is stratigraphically equivalent to the lower, calcalkaline part of the Bear Lake suite in the central part of the Flin Flon Belt, contains aphyric to plagioclase-hornblende+pyroxene–phyric basaltic flows, related flow breccia and synvolcanic intrusions. The majority of flows are characterized by ovoid to bun-shaped pillows, typically 0.5–2.0 m in diameter. Size variation of individual pillows reflects their stratigraphic level within the flow; large ‘mega-pillows’ (up to 5 by 13 m) occur in the lowermost parts of some flow units, whereas small amoeboid pillows are typical of upper zones. Several features reflect rapid cooling of the volcanic rocks at shallow to intermediate water depth, such as widespread vesicularity and amygdaloidal texture, as well as concentric zoning and cooling fractures within pillows. Flow brecciation and interpillow hyaloclastic tuff are also characteristic of the Bear Lake suite. Subordinate, heterolithic fragmental deposits up to 350 m thick are interpreted as debris flows (Gilbert, 1986a). Homogeneous gabbro lenses up to 300 m wide, abundant synvolcanic mafic dikes and sills, and occasional lava tubes are intercalated with the flows. The dikes and sills, typically 1–5 m thick, are locally amygdaloidal and, in some cases, display banded margins attributed to chilling of separate intrusive pulses.

The two-fold geochemical subdivision of the Bear Lake suite (lower calcalkaline and upper alkalic, shoshonitic section) is unique among arc volcanic suites in the Flin Flon Belt, most of which are uniformly tholeiitic or of transitional, tholeiitic to calcalkaline affinity (Stern et al., 1995a). In the NFFB, the lower part of the Bear Lake succession is predominantly basaltic (13 flows, average of 51.1% SiO₂, average Mg# of 0.60, Table 3, back pocket), whereas stratigraphically equivalent, least altered rocks in the central Flin Flon Belt consist mainly of basaltic andesite (9 flows, average of 53.08% SiO₂, average Mg# of 0.55, based on analytical data [including volatiles] in Bailes and Syme, 1989). One interpretation of this variation in SiO₂ content and Mg# is that the lensoid volcanic edifice is diachronous; the relatively distal, basaltic part of the volcanic sequence in the NFFB was likely erupted prior to the slightly more fractionated, basaltic andesite part farther southeast, closer to the source of the volcanic rocks. The Bear Lake suite has been interpreted as erupted from a single volcanic centre during an interval of steadily decreasing water depth, with the upper section (Vick Lake tuff) rapidly deposited by turbidity currents in a subsiding basin (Bailes and Syme, 1989).

The TiO₂ versus MgO plot (Figure 6a) shows Bear Lake mafic to intermediate volcanic rocks occur in a calcalkaline subfield (Syme et al., 1999) within the field of NFFB arc volcanic rocks. Compared to tholeiitic and transitional tholeiitic to calcalkaline arc suites in the NFFB, Bear Lake basalt has a higher average Mg number (Mg# of 0.60 versus 0.40–0.52), and lower FeOT (9.8% versus 10.7–12.1%) and TiO₂ (0.40% versus 0.44–0.64%; Table 3, back pocket). Bear Lake basalt Ni (67 ppm) and Cr (305 ppm) contents are over twice the combined average values of all other NFFB arc basalts. In incompatible-element plots, however, Bear Lake calcalkaline volcanic rocks are not readily distinguished from tholeiitic or transitional suites (Figure 7a to 7h). Bear Lake rocks display an arc-type, rare earth element (REE) profile with pronounced negative Nb and Ti anomalies, elevated Th and light rare-earth elements (LREE), and depleted middle to heavy rare-earth elements (HREE), relative to modern N-MORB. The Th/Nb ratios are significantly higher in arc rocks compared to N-MORB and E-MORB rock types, which are clearly distinguished in the Th/ Nb versus Nb/Y diagram (Figure 8a). The εNd isotopic ratio for Bear Lake basalt to basaltic andesite (average +4.1, range from +3.8 to +4.8 at 1.90–1.86 Ga, Stern et al., 1995a) is in the range estimated for depleted mantle of the same age (from +3.0 to +5.5, Lucas et al., 1996) and indicates the source magma for the Bear Lake suite was juvenile (Figure 9).

**Cope Lake suite (unit J2, calcalkaline arc)**

Massive to fragmental arc volcanic rocks occupy the elongate Cope Lake Block, up to 1.4 km wide and extending

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FeOT = FeO + (0.8998 x Fe₂O₃)
Figure 6: Plots of \( \text{TiO}_2 \) versus MgO for mafic to intermediate volcanic rocks in the northern Flin Flon Belt (NFFB), west-central Manitoba: a) field of all NFFB arc volcanic rocks (gray field in all four diagrams) and plots of selected arc types—Bear Lake suite and southern part of Manistikwan Lake suite (plots of Manistikwan Lake suite rocks from Bailes and Syme, 1989); field of arc volcanic rocks in the calcalkaline section of the south-central Bear Lake Block after Syme et al. (1999); b) arc and ‘arc-rift’ types (Lac Aimée and East Mikanagan Lake suites); c) N-MORB and E-MORB suites, and plots of Grassy Narrows basalt (from Bailes and Syme, 1989); d) depleted-MORB types. MORB and BABB compositional field of modern intra-oceanic rocks from Stern et al. (1995b). Abbreviations: BABB, back-arc basin basalt; MORB, mid-ocean-ridge basalt; E-MORB, enriched mid-ocean-ridge basalt; N-MORB, normal mid-ocean-ridge basalt.

Figure 7: Plots of N-MORB normalized incompatible-elements for mafic to intermediate rocks in arc volcanic suites in the northern Flin Flon Belt, west-central Manitoba: a) Bear Lake, b) Cope Lake. Normalizing values from Sun and McDonough (1989). Abbreviation: N-MORB, normal mid-ocean-ridge basalt.
Figure 8: Plots of Th/Nb versus Nb/Y for mafic to intermediate arc volcanic rocks in the northern Flin Flon Belt, west-central Manitoba: a) arc, N-MORB and E-MORB types, b) arc, arc-rift and depleted-MORB types, and Scotty Lake basalt (after Syme et al., 1999). Most depleted-MORB rocks do not appear because their Nb content is below the analytical detection limit (applies to 21 out of the 27 Dismal Lake rocks and 6 out of 8 Bluenose Lake rocks, see Appendix 1). Field of Elbow-Athapapuskow ocean-floor assemblage after Stern et al. (1995b). Compositional fields are from Stern et al. (1995b), based on data in Saunders et al. (1988) and Sun and McDonough (1989). Abbreviations: MORB, mid-ocean-ridge basalt; N-MORB, normal mid-ocean-ridge basalt; E-MORB, enriched mid-ocean-ridge basalt; NFFB, northern Flin Flon Belt.
Figure 9: Plot of $\varepsilon_{\text{Nd}}$ versus Nb/Yb for mafic to felsic volcanic rocks in the northern Flin Flon Belt (NFFB), west-central Manitoba, showing the calculated percentage of older crustal Nd (methodology after Stern et al., 1995a) in various volcanic rock suites in the NFFB, except for Bear Lake basalt (Stern et al., 1995a) and Scotty Lake basalt (Syme et al., 1999), where data are from the south-central part of the Flin Flon Belt. Manistikwan Lake arc-rift rhyolite samples ($\varepsilon_{\text{Nd}}$ 0.7 and –1.7 at 1.90 Ga) would plot close to the line of 10% crustal assimilation (these samples are not plotted due to the lack of Nb analytical data). Abbreviations: MORB, mid-ocean-ridge basalt; N-MORB, normal mid-ocean-ridge basalt; E-MORB, enriched mid-ocean-ridge basalt; Depleted-MORB, depleted mid-ocean-ridge basalt.
laterally for approximately 14 km along the western side of Embury Lake and farther south to Big Island Lake (unofficially known as Manistikwan lake). The Cope Lake suite consists of predominantly mafic volcanic rocks that are lithologically and geochemically similar to the lower part of the Bear Lake arc sequence. The aphyric to porphyritic flows contain up to 30% plagioclase-hornblende (after pyroxene) phenocrysts, typically 1–5 mm in size. Vesicles, amygdules and localized gas cavities are common in the massive flows, which are intercalated with hyaloclastic tuff and related autoclastic breccia. The Cope Lake suite has been subdivided, on the basis of porphyritic texture, into six stratigraphic units that are folded in a major northwest-trending syncline (Bailes and Syme, 1989) and a complementary anticline farther north (Figure 3). The axial trace of the syncline is truncated by the block-bounding fault at the western margin of the Cope Lake Block, where it is juxtaposed against the Hook Lake Block. At the eastern margin of the Cope Lake Block, sporadic lensoid greywacke units up to 50 m thick, which occur along the shoreline of Embury Lake, are interpreted as fault slices derived from the contiguous Embury Lake Block to the east.

The calcalkaline affinity of the Cope Lake suite is indicated by ternary discriminant diagrams (Figure 5e, 5f) that reflect higher Mg# and lower FeO and TiO₂ contents, compared to arc tholeiitic rocks in the NFFB (Table 3, back pocket). The Al₂O₃ content of Cope Lake basalt is relatively higher than in the tholeiitic volcanic suites, probably due to the widespread occurrence of plagioclase phenocrysts (stoichiometric Al₂O₃ in plagioclase feldspar is approximately 35%, roughly twice the average Al₂O₃ content of Cope Lake basalt).

A lensoid, high-silica rhyolite unit within the Cope Lake Block at the shoreline of Embury Lake (unit J13; ‘Cope Lake rhyolite’) is compositionally similar to rhyolite that hosts the Trout Lake mine Cu-Zn ore deposit (Ordóñez-Calderón et al., 2009), located offshore 0.5 km farther to the east (Figure 4; Map GR2011-1-1). The Cope Lake rhyolite plots in the field of ‘extension-related’ rocks in the Zr versus TiO₂ diagram (Figure 10) and is thus identified as prospective for VMS-type mineralization (see ‘Felsic volcanic rocks’ below). The age of a felsic porphyry intrusion (inferred as synvolcanic) at Trout Lake mine (1878 ±1.1 Ma, N. Rayner, 2010) suggests that the diverse volcano-sedimentary mine sequence (Ordóñez-Calderón et al., 2009) is part of the Flin Flon arc assemblage (Stern et al., 1995a) and may represent a dismembered part of the Cope Lake Block (or possibly the Hook Lake Block farther to the west—see next paragraph). Graphitic greywacke and argillite (over 0.3 km thick) in the hanging wall, immediately east of the diverse volcano-sedimentary rocks in the mine sequence, is considered part of the turbiditic Embury Lake Block and has a successor-arc depositional age (<1843 ±9 Ma, age of youngest detrital zircon, Ordóñez-Calderón et al., 2011). The faulted contact between the Cope Lake and Embury Lake blocks is thus apparently located within, or immediately east of, the Trout Lake mine succession.

Hook Lake suite (unit J3, tholeiitic arc)

The Hook Lake Block, located between the Cope Lake Block to the east and Missi sedimentary basin to the west (Figure 2), extends laterally for over 30 km from Annabel Creek at the Manitoba-Saskatchewan provincial boundary, southeast to the area south of Schist Lake. In the south-central part of the Flin Flon Belt, the Hook Lake Block has been subdivided by major faults into five sub-blocks that together have a maximum stratigraphic thickness of 7.5 km (Bailes and Syme, 1989). More recently, a two-fold subdivision has been established for the
Hook Lake Block (‘western’ and ‘eastern’ sequences, Simard et al., 2010). Geochronological data by Rayner (2010) show that the older western sequence, which is intruded by a 1888 ±1 Ma quartz diorite phase of the Cliff Lake plutonic suite, is likely coeval with ca. 1889 Ma VMS-hosting rocks of the Flin Flon Block to the west (Simard et al., 2010); whereas the relatively younger eastern Hook Lake sequence (1882 ±1 Ma) is similar in age to the 1878 ±1.1 Ma Trout Lake mine sequence to the east. Conspicuous similarities between part of the eastern Hook Lake sequence and the Trout Lake mine sequence are consistent with their possible stratigraphic equivalence and structural repetition between these two sections (P.D. Kremer, pers. comm., 2009).

In the south-central Flin Flon Belt, the Hook Lake volcanic suite consists mainly of aphyric to porphyritic or cumulophytic mafic flows, related flow breccia and subordinate scoriaceous tuff and breccia (Bailes and Syme, 1989). These rocks apparently accumulated in a consistently shallow-water (possibly locally subaerial) environment, probably with associated subsidence. This theory is supported by the presence of environmental indicators for shallow-water conditions, such as coarse vesicularity, throughout the sequence. A proximal environment for this part of the fault block is indicated by such features as the common thick interbedding of volcanic strata (10s to 100s of metres) and the occurrence of sporadic ballistic features, as well as coeval with ca. 1889 Ma VMS-hosting rocks of the Flin Flon Block to the west (Simard et al., 2010); whereas the relatively younger eastern Hook Lake sequence (1882 ±1 Ma) is similar in age to the 1878 ±1.1 Ma Trout Lake mine sequence to the east. Conspicuous similarities between part of the eastern Hook Lake sequence and the Trout Lake mine sequence are consistent with their possible stratigraphic equivalence and structural repetition between these two sections (P.D. Kremer, pers. comm., 2009).

Within the NFFB, the northern part of the Hook Lake Block, like the more proximal south-central part, is dominated by aphyric to porphyritic basalt and abundant, typically amygdaloidal autoclastic breccia (Gilbert, 1989a). Subordinate stratigraphic members include massive to fragmental dacite and rhyolite (up to 65 m thick), as well as conglomerate (30 m thick) containing volcanic and fine-grained, sedimentary clast types. The synvolcanic Cliff Lake plutonic suite in the central part of the Hook Lake Block (1886 ±1 Ma, Stern et al., 1999; 1888 ±1 Ma, Rayner, 2010) extends north and northwestward, between the western and eastern Hook Lake sequences. A major northwest-trending anticlinal fold occurs within the volcanic rocks, close and parallel to the western margin of the Cliff Lake pluton (Figures 2 and 3).

In the south-central part of the Flin Flon Belt, the diverse mafic to intermediate Hook Lake volcanic sequence contains rocks of tholeiitic to calcalkaline affinity that were probably derived from more than one volcanic centre (Bailes and Syme, 1989). Basalt in the more distal, northern part of the Hook Lake Block is charactetized by relatively higher FeOT and TiO₂ contents and lower Mg# compared to calcalkaline volcanic types (Table 3, back pocket) and displays tholeiitic to transitional trends in ternary discriminant diagrams (Figure 5a, 5b). Elevated Al₂O₃ (18.3%) in Hook Lake basalt, relative to the average Al₂O₃ content for all NFFB arc volcanic suites (15.0%), probably reflects the local abundance of plagioclase phenocrysts, as in the case of Cope Lake basalt. The average εNd isotopic ratio for Hook Lake basalt is +3.9 at 1.9 Ga, consistent with a juvenile magmatic source (Stern et al., 1995a).

Tartan Lake suite (unit J4, tholeiitic to calcalkaline arc)

The Tartan Lake suite is a south-facing, monoclinal basin that extends for over 17 km from Animus Lake in the east to the area beyond the Manitoba-Saskatchewan boundary in the west. It is structurally juxtaposed against MORB-type basalt to the north (unit F2), east (units F3 and F4) and southeast (unit F5). Mafic and felsic intrusions up to 100 m thick within the basaltic sequence are assumed to be synvolcanic: felsic intrusions are confined to the west, whereas gabbro and hornblende intrusions are most prominent in the eastern part of the fault block. At the northern margin of the Tartan Lake Block, a fault sliver of arc rocks is emplaced within part of the N-MORB Bluenose Lake Block to the north (Figure 2).

The majority of Tartan Lake mafic flows are pillowed and, based on top indicators preserved in the central and eastern parts of the fault block, almost universally south-facing. Sporadic pillow tops in the area north of the Tartan Lake gold mine delineate the approximate positions of axial traces of west-trending folds close to the southern margin of the fault block (Figures 3 and 4). The mafic volcanic rocks are less well preserved in the western part of the fault block, where pillows are more attenuated and partly epidotized. Tectonic strain in that area is typically localized in discrete, intensely sheared 1–3 m wide zones, which occur within the otherwise relatively undeformed basaltic sequence.

The Tartan Lake arc volcanic suite is of transitional, tholeiitic to calcalkaline affinity (Figure 5c, 5d). Incompatible-element contents are similar to those of other NFFB arc volcanic rocks (Table 3, back pocket); the N-MORB-normalized plot (Figure 7d) displays elevated LREE, negative Nb and Ti anomalies and depleted high-field-strength elements (HFSE), as described previously for the calcalkaline Bear Lake volcanic suite. The εNd isotopic ratios for two Tartan Lake basalt flows are +2.3 and +2.8 at 1.9 Ga (Table 4), indicating a small amount (1–2%) of recycled older crust was incorporated in the source magma' (Stern et al., 1995a; Pearce et al., 1983). Stern et al. (1995a) noted that Flin Flon Belt arc volcanic rocks locally provide evidence for intracrystal recycling of older (e.g., Archean) crust and speculated that rifted, older crustal remnants in the basement under the arc volcanic rocks may be implicated in such a process. The presence of 2.52 Ga, late Neoarchean basement slivers of tonalite (David and Syme, 1994) within the Northeast Arm Fault (Figures 3 and 4; ‘Northeast Arm shear zone’ of Lucas, 1993; Syme, 1995) suggest such rocks could have contaminated the source magma for the arc volcanic rocks—see ‘Discussion’ below.

Wabishkok Lake suite (unit J5, tholeiitic arc)

Arc volcanic rocks of the Wabishkok Lake suite occupy an ovoid fault block that extends for approximately 18 km from Wabishkok Lake to Blueberry Lake (Figure 2). The predominantly mafic volcanic rocks are intruded by several granitoid and gabbroic intrusions that constitute over half the

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5 Modelled on rare Archean slivers in the Flin Flon Belt (Stern et al., 1995a).
Table 4: The $\varepsilon_{\text{Nd}}$ isotopic values for selected volcanic rock suites in the northern Flin Flon Belt, west-central Manitoba. Geochemical and petrographic data as well as UTM locations for all rock samples are given in Appendix 1.

<table>
<thead>
<tr>
<th>Sample number</th>
<th>SiO$_2$ (%)</th>
<th>Volcanic rock suite</th>
<th>Tectonic affinity</th>
<th>$\varepsilon_{\text{Nd}}$ (at 1.9 Ga)</th>
<th>Sm (ppm)</th>
<th>Nd (ppm)</th>
<th>$^{147}$Sm/$^{144}$Nd</th>
<th>$^{143}$Nd/$^{144}$Nd</th>
<th>± 2δ absolute</th>
<th>$T_{\text{ch}}$ (Ga)</th>
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<tr>
<td>32-90-4820-1</td>
<td>50.4</td>
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<td>5.32</td>
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</table>

1 Estimated SiO$_2$ content. Note that this sample and sample 32-01-0261-1 (listed in Appendix 1) are from the same location.
2 Estimated error is better than 0.5%.
3 Crustal residence Nd model ages ($T_{\text{cr}}$) calculated according to the model of Goldstein et al. (1984) for samples with $^{147}$Sm/$^{144}$Nd <0.14.
4 Manistikwan lake is an unofficial name for Big Island Lake.

Note: analyses were performed at the University of Alberta Radiogenic Isotope Facility in Edmonton, Alberta, Canada.

Details on the Sm-Nd analytical methods are in Creaser et al. (1997).

bedrock exposure of the fault block (Pistol Lake and Kotyk Lake plutons, Kotyk Lake and Wabishkok Lake sills). Emplacement of the granitoid plutons and subsequent deformation, probably due to lateral movement along the contact between the Flin Flon Belt and the Kisseynew Domain to the north (see ‘Structural Geology’ below), resulted in the irregular, three-branched configuration of volcanic rocks in the Wabishkok Lake Block.

The volcanic sequence at Wabishkok Lake is up to 2 km wide and provisionally interpreted as a south-facing monoclinal. Pillow structures are less well preserved than in the contiguous Tartan Lake Block and top directions were obtained at only two localities. Pillows at Blueberry Lake face west-southwest, whereas at the southern shore of Wabishkok Lake (UTM 334699E, 6084541N) pillows are south-facing.

The volcanic arc volcanic suite consist exclusively of basaltic to andesitic flows and related gabbro that are largely aphyric; sporadic plagioclase-phyric flows constitute less than 10% of the sequence. In contrast, the eastern branch that extends through southern Kotyk Lake to Blueberry Lake is lithologically more varied, and the rocks appear to have potential for VMS-type mineralization (see below; Gilbert 2003a). A 160 m wide inlier of massive to fragmental rhyolite occurs within the Kotyk Lake sill (Figure 2; Gilbert, 2001b) and felsic volcanic rocks also occur east of Blueberry Lake, where they are intercalated with basalt and andesite flows that are locally silicified. Hornblende (pyroxene)-phyric pillows basalt and heterolithic mafic volcanic breccia occur at islands in the middle of Blueberry Lake, which is the only known locality of these rock types within the Wabishkok Lake Block. Numerous electromagnetic (EM) anomalies are associated with base-metal (+gold) mineralization at basal-gabbro contacts south of Kotyk Lake and in rhyolite flows close to the east shore of Blueberry Lake (Gilbert, 2001a, b, 2003a, b).

Geochemically, the Wabishkok Lake suite displays a tholeiitic trend in the ternary discriminant plot (Figure 5a, 5b) and is characterized by lower average Mg#, and Ni and Cr contents, compared to calcalkaline suites in the NFFB (Table 3, back pocket). Average SiO$_2$ for Wabishkok Lake volcanic rocks (57%) exceeds the combined average of all other NFFB mafic to intermediate arc rocks (53%). The incompatible-element plot is correlative with other arc volcanic types, with elevated LREE, intermediate arc rocks (53%). The incompatible-element plot is correlative with other arc volcanic types, with elevated LREE, high Th/Nb and La/Yb ratios, negative Nb and Ti anomalies and depleted HREE (Figure 7e). Variable $\varepsilon_{\text{Nd}}$ values (calculated at 1.9 Ga) for Wabishkok Lake basalt (+3.4), rhyolite (+3.0) and andesite (+1.7) suggest minor amounts of recycled older crust.
were incorporated in the source magma (Stern et al., 1995a; Table 4).

Manistikwan Lake arc, arc-rift (unit J6, tholeiitic to calcalkaline) and N-MORB–type volcanic suites

The Manistikwan Lake Block is up to 3 km wide and extends laterally for over 20 km from northern Embury Lake to the southern end of Big Island Lake. The west to southwest-facing, lithologically diverse volcano-sedimentary sequence within this fault block contains three geochemically distinct volcanic types. Internal faulting (Gilbert, 1989a, b; Bailes and Syme, 1989) has resulted in the juxtaposition of contrasting arc, arc-rift and N-MORB geochemical types within the Manistikwan Lake Block.

Basalt and subordinate flow breccia are predominant in the northern part of the fault block. The grey-green weathering flows are locally pillowed, amygdaloidal, and amygdaloidal weathering plagioclase-phyric. Subordinate rock types within this sequence include heterolithic volcanic breccia, felsic tuff, conglomerate, siltstone and argillitic siltstone. Abundant felsic porphyry and quartz-eye tonalite intrusions, and a 160 m thick extrusive/intrusive rhyolitic unit occur in the northern part of the Manistikwan Lake Block. Gabbro constitutes approximately 10% of the northern part of the Manistikwan Lake Block, which also contains at least three fault-bounded ultramafic lenses. A series of fine-grained sedimentary lenses along the southwestern margin of the fault block are interpreted as structurally detached parts of the turbiditic Embury Lake Block.

The central and southern parts of the Manistikwan Lake Block are dominated by a 600 m thick sequence of basaltic pillow-fragment breccia with minor interlayered flows of aphric basalt (Bailes and Syme, 1989). Many of these rocks are characterized by conspicuous vesicularity, suggesting a relatively shallow-water (<700 m) depositional environment (Jones, 1969; Moore and Schilling, 1973); however, highly vesicular lava has locally been reported at deeper levels in modern oceans (e.g., >1150 m, Staudigel and Schmincke, 1984). Other rock types include buff-brown weathering porphyritic basalt (600 m), rhyolite and abundant intrusive rocks such as felsic porphyry, quartz diorite and diorite. Subordinate deposits include pyritic mudstone (140 m) and well-bedded, coarse-grained sandstone and conglomerate (350 m) that are interpreted to represent a subaerial depositional environment (Bailes and Syme, 1989).

Mafic volcanic flows in the south-central part of the Manistikwan Lake Block are characterized by low TiO₂, Zr and Y contents (Bailes and Syme, 1989), within the range of arc basalt compositions, and plot within the field of NFFB arc volcanic rocks (Figure 6a). These basalts, together with rhyolitic extrusive/intrusive rocks in the south-central part of the Manistikwan Lake Block, are characterized by a tholeiitic trend of magmatic evolution (Figure 5a, 5b).

In the northern part of the Manistikwan Lake Block, pillow-fragment breccia and porphyritic, amygdaloidal basalt comparable to the predominant arc volcanic rock types in the southern part of the block are apparently absent. Instead, massive basalt sequences with 1) arc-rift and 2) N-MORB–type compositions were identified at two separate localities in the northern part of the fault block. North of Embury Lake, arc-rift mafic flows occur in a >275 m wide section in the inferred lower to middle part of the stratigraphic sequence. At a different locality 6 km to the southeast, N-MORB–type basalt occurs in a >320 m wide section within the inferred middle to upper part of the sequence. Whereas these two types are geochemically distinctive, they are lithologically quite similar, that is, massive to pillowowed, grey-green weathering, aphric and locally sparsely amygdaloidal.

Compared to the arc volcanic rocks in the south-central part of the Manistikwan Lake Block, arc-rift basalt in the northern part of the fault block is characterized by variably elevated FeO²⁺ (7.6–16.4%) and TiO₂ (1.2–2.2%) contents, similar to the compositional range of arc-rift basalt and ferrobasalt in the Lac Aimée and East Mikanagan Lake blocks (11.69–17.8% FeO²⁺, 0.9–2.0% TiO₂, Appendix 1). The profiles of incompatible-element plots in all three of these arc-rift rock suites are similar to those of NFFB arc rocks, but overall contents of incompatible elements are relatively higher, especially Nb and Ti (Figure 7i, 7j). This pattern may reflect a lower degree of partial melting in the magmatic source compared to arc volcanic types and/or incorporation of a more fertile mantle component in the source magma (see ‘Discussion’ below). High average Th content (1.23 ppm, Table 3, back pocket) of Manistikwan Lake arc-rift rocks, together with evolved Nd isotopic compositions (εNd ratio of +1.6 for basalt, +0.7 to –1.7 for rhyolite at 1.9 Ga, Table 4), suggest greater amounts of older crustal lithosphere (up to 10%, Figure 9; Stern et al., 1995a) were incorporated in the source magma, compared to arc volcanic rocks in contiguous fault blocks in the northwestern part of the Flin Flon Belt (e.g., εNd values of +2.3, +2.8 at 1.9 Ga for Tartan Lake basalt).

Manistikwan Lake N-MORB is distinguished from the previously described arc-rift basalt by flat incompatible-element profiles and moderate depletion (relative to modern N-MORB) of all elements, except Th. Manistikwan Lake N-MORB is compositionally very similar to Arthur’s Lake and Bluenose Lake N-MORB (Table 3, back pocket), which are interpreted to represent a back-arc basin (BAB) setting (see ‘Discussion’ below). The association of compositionally distinct volcanic rocks characteristic of different tectonic settings (arc, arc-rift and BAB) within the Manistikwan Lake Block is likely a result of intrablock faulting during tectonic assembly of the Amisk Collage, during which fault slices of contrasting geochemical type were tectonically juxtaposed.

East Mikanagan Lake arc-rift suite (unit J7, tholeiitic)

The East Mikanagan Lake Block consists largely of arc-rift basalt and related gabbro that occur in a >1 km thick, southwest-facing monocline sequence east of Mikanagan Lake. These rocks are separated from E-MORB–type basalt in the West Mikanagan Lake Block by the northern part of the Northeast Arm Fault, which bifurcates farther to the north (Figures 2 and 3). The East Mikanagan Lake Block is shown in Figure 4 as on strike with rocks in the Whitefish Lake–Mikanagan Lake Block (Bailes and Syme, 1989), but the sequences in these two fault blocks differ both geochemically and lithologically, and they are therefore assumed to be separated by faults. The
arc-type Whitefish Lake–Mikanagan Lake Block consists of a wide variety of massive and fragmental volcanic and epiclastic rocks (Bailes and Syme, 1989), in contrast to the simpler arc-rift, basalt-gabbro sequence in the East Mikanagan Lake Block. The arc-rift–type Scotty Lake Block farther to the south (Figure 4), on the other hand, is compositionally similar and may be stratigraphically equivalent to the East Mikanagan Lake Block (see ‘Structural Geology’ below).

The volcanic sequence at East Mikanagan Lake contains massive to pillowed, aphyric basalt that is devoid of subordinate autoclastic breccia zones and displays minimal seafloor-type alteration, in contrast to arc sequences found in the contiguous Lac Aimée Block to the northeast. Hornblende (after pyroxene) ±plagioclase porphyritic mafic dikes of arc composition that occur sporadically within the arc-rift sequence indicate a relative age between the arc and arc-rift types. The arc-type mafic dikes are thus enigmatic if the arc and arc-rift rocks are related within an evolving magmatic sequence.

The arc-rift basalt weathers grey-green and is grey or locally blue-grey on fresh surfaces. Sporadic amygdules are typically sparse and small (1–3 mm) but locally attain 1 cm in size; polygonal cooling joints are locally preserved. Some fine-grained flows contain coarser-grained gabbroic cores; discrete interflow gabbro sills up to 50 m thick form approximately 10% of the section. Two variolitic pillowed flows (20 m and 35 m wide respectively) within the basaltic section contain pale-weathering varioles (2–20 mm in diameter), which locally increase in size and abundance (10–90%) and are coalescent toward the cores of pillows (Gilbert, 1990a). These flows are sparsely quartz-amygdaloidal and exhibit quench textures in thin section, characterized by skeletal, branched filaments of very fine-grained amphibole, epidote, as well as elongate amphibole prisms (probably clinopyroxene-derived), oriented in subparallel, pinnate or partly radiating patterns. Variolitic textures elsewhere have been interpreted variously as due to liquid immiscibility or spherulitic crystallization during or after solidification, possibly associated with devitrification of original volcanic glass (Gélinas et al., 1977; Hughes, 1977; Fowler et al., 1987; Arndt and Fowler, 2004).

Similar spherulitic and clinopyroxene-quench textures occur in pillowed basalt approximately 10 km along strike to the south (Bailes and Syme, 1989) in the possibly related Scotty Lake basalt (see ‘Geochemistry of arc and arc-rift rocks in Lac Aimée, East Mikanagan Lake and Scotty Lake blocks’ below). East Mikanagan Lake arc-rift basalt is also akin to some volcanic rocks in the Manistikwan Lake and Lac Aimée blocks; these arc-rift types are geochemically distinguished by higher overall incompatible-element contents compared to more primitive, juvenile-arc rocks (Figure 7a to 7h, 7i, 7j). Whereas Th/Nb and Th/Yb ratios in East Mikanagan Lake basalt are comparable to those of some arc rocks, HFSE contents are relatively higher, in particular Th (average of 2.54 ppm), which exceeds that of rocks in all other NFFB mafic to intermediate volcanic suites (Table 3, back pocket).

A rhyolite lens in the southeastern part of the fault block consists mainly of felsic volcanic breccia intercalated with massive felsic volcanic rock. This rhyolite lens, approximately 0.3 km wide and over 0.6 km long, is provisionally interpreted as conformable with the arc-rift basalt but could alternatively be an allochthonous fault slice. Several north-trending faults within the East Mikanagan Lake Block, at or close to the eastern shore of Mikanagan Lake, are associated with base-metal sulphide mineralization and hydrothermal alteration (silicification and carbonatization). The north-trending fault along the eastern margin of the fault block is also locally altered and mineralized over a 3.5 m wide zone; assays yielded up to 3.4% Cu, 4 ppm Au and 12 ppm Ag.

Lac Aimée arc and arc-rift suites (unit J8, tholeitic)

The Lac Aimée Block, located between the MORB-type Animus Lake Block to the northwest and arc-type Sourdough Bay Block to the southeast (Figure 2), is one of the most lithologically and compositionally diverse blocks in the NFFB. The Lac Aimée volcanic suite consists mainly of massive and fragmental mafic extrusive rocks that have been locally redeposited as heterolithic mass flows; these are intercalated or laterally gradational with fine-grained turbidite deposits (unit S1) that range from 1 to >400 m in thickness. The turbidites, volcaniclastic mass-flow deposits and sporadic thin (0.5–1 m) chert beds represent ephemeral breaks in the extrusive magmatic activity. Interpillow chert and silicic-alteration zones within basalt flows are interpreted as products of seafloor volcanic hydrothermal activity. Mafic and felsic synvolcanic intrusions range from minor dikes and sills (1 m thick) to larger bodies up to 400 m wide.

Two geochemically distinct volcanic types are recognized: 1) arc and 2) arc-rift. The contact between the arc and arc-rift rocks has not been observed and the stratigraphic relationship between these two types is thus unknown. Geochemical data suggest that the arc-rift types may be fractionated Fe-rich flows derived from the same magmatic source that produced the arc rocks (Figures 6b, 7f, 7i). Lac Aimée arc mafic flows (unit J8a) are typically aphyric, less commonly plagioclase-phryic and/or hornblende (pyroxene)-phyric. Quartz-amygdules are widespread; densely amygdaloidal basalt flows typically contain zones of autoclastic breccia. Quartz amygdules form up to 65% of pillowed basalt flows and flow breccia in a 900 m wide zone extending northeast through the northern part of Alberts Lake. Some units display very coarse amygdaloidal texture, with large spheroids of quartz up to 4 cm across. The arc flows are commonly pillowed, grey-green to beige-grey weathering, and locally display concentric thermal contraction fractures and polygonal cooling joints. Mafic tuff and heterolithic volcanic breccia (unit J8b) are subordinate to the mafic flows; the breccia is unsorted and contains both mafic and felsic clasts as well as sporadic blocks of mafic tuff. The mixed composition, lack of sorting and subangular to angular fragment shapes are consistent with a mass-flow mode of emplacement. Diffuse to well-defined layering and graded bedding of tuffaceous interlayers in the breccia are attributed to reworking by ephemeral turbidity currents.

* See discussion of terminology in Arndt and Fowler (2004).
Arc-raft basalt, ferrobasalt and basaltic andesite extend through the central part of the Lac Aimée Block in a zone up to 0.75 km wide and over 9 km along strike. The green-brown or khaki-coloured ferrobasalt is typically massive, aphyric and devoid of pillows; polygonal cooling fractures are locally characteristic. Finely disseminated magnetite grains constitute approximately 5% of the flows. Plagioclase-phryic mafic rocks associated with the ferrobasalt are interpreted as synvolcanic intrusions. Arc flows with up to 14% FeO\textsuperscript{2} occur in close proximity to the ferrobasalt and probably represent part of an evolving magmatic series from arc basalt (average of 11.9% FeO) to arc-raft ferrobasalt (average of 14.0% FeO, Table 3, back pocket).

Felsic volcanic rocks constitute approximately 15% of the Lac Aimée arc volcanic suite and are thus relatively more abundant than in other NFFB arc volcanic suites, except for the Sourhadow Bay suite. The felsic rocks are predominantly rhyolitic and typically plagioclase-quartz–phyric; in many cases these rocks are homogeneous and their origin (extrusive/intrusive) cannot be reliably determined. Sporadic, monolithic autoclastic breccia zones and rare flow-laminated lobes within massive felsic volcanic units suggest an extrusive environment of emplacement. A lensoid, 400 m thick plagioclase-quartz porphyry sill in the southwestern part of the Lac Aimée Block is coarsely porphyritic, with quartz and plagioclase phenocrysts up to 1 cm in size (20–30% of the rock) and scattered pyritohedra (up to 5%); polygonal cooling fractures are locally preserved.

The volcano-sedimentary sequence is deformed by a series of folds that form a southwest-plunging synclinorial structure (Figure 3). Gale and Dabek (2002) identified several faults parallel or subparallel with the stratigraphy in the southern part of the Lac Aimée Block. The relative age relationships between the various lithologically defined components in the fault block are uncertain as a result of this folding and faulting.

**Geochemistry of arc and arc-raft rocks in Lac Aimée, East Mikanagan Lake and Scotty Lake blocks**

Lac Aimée arc basalt and basaltic andesite display incompatible-element profiles characterized by a wider compositional range than any other NFFB arc volcanic suite (Figure 7a to 7h). Lac Aimée arc rocks have REE profiles that are similar to those of arc-raft rocks in both Lac Aimée and contiguous East Mikanagan Lake blocks, but the arc-raft rocks are characterized by higher overall incompatible-element contents, especially Th (0.88 ppm, 2.54 ppm, respectively), and lower Th/Nb ratios (0.32, 0.38; Table 3, back pocket), resulting in somewhat less conspicuous negative Nb anomalies (Figure 7i). The arc-raft volcanic rocks also contain more TiO\textsubscript{2} but less Ni and Cr than Lac Aimée arc rocks. There is a continuum of increasing, overall incompatible-element content from Lac Aimée arc, through Lac Aimée arc-raft, to East Mikanagan Lake arc-raft volcanic suites (Figure 7f, 7i). In the TiO\textsubscript{2} versus MgO diagram, however, these three volcanic suites plot in separate fields with distinctive TiO\textsubscript{2}/MgO ratios, suggesting differences in their tectonic settings (Figure 6b).

Lac Aimée arc basalt plots in the field of NFFB arc volcanic rocks (grey shaded field in Figure 6a to 6d), which corresponds approximately with that of modern arc magmas (Stern et al., 1995b); East Mikanagan Lake arc-raft rocks fall in the ‘MORB + back-arc basin basalt (BABB)’ field, whereas Lac Aimée arc-raft rocks plot in-between these two fields.

Arc-raft volcanic rocks in the Lac Aimée and East Mikanagan Lake blocks occur within a corridor that extends from Lac Aimée southwards to the Whitefish Lake–Mikanagan Lake and Scotty Lake blocks in the central part of the Flin Flon Belt (Figures 2 and 4). The Fe-rich tholeiite in the Scotty Lake Block is lithologically and compositionally very similar to the East Mikanagan Lake arc-raft basalt 7 (Table 3, back pocket; Figure 7i). Both types occur as relatively homogeneous, massive to pillowed sequences with relatively low vesicularity and localized quench texture, as well as abundant mafic intrusions. The ε\textsubscript{Nd} isotopic ratios for Scotty Lake basalt (–0.88 to +1.93 at 1.9 Ga, Syme et al. 1999) and Lac Aimée arc rhyolite (–1.5 at 1.9 Ga, Table 4) are similar and among the lowest of all values for Flin Flon Belt volcanic rocks, suggesting that up to 12% of older continental crust was recycled during the evolution of the source magmas (Figure 9; Stern et al., 1995a).

Scotty Lake basalt and arc-raft volcanic rocks in both Lac Aimée and East Mikanagan Lake blocks could be fractionated components of a common magmatic source that evolved concomitant with the onset of rifting and development of an intra-arc basin. Mixing of primitive, fertile mantle magma with a depleted arc volcanic source may have contributed to higher overall incompatible-element contents in the arc-raft rocks, compared to arc rocks (see ‘Discussion, tectonic setting of NFFB arc and MORB-type volcanic rocks’ below). The progressive gradation southward of arc to arc-raft compositions (from the Lac Aimée Block to the East Mikanagan Lake Block to the Scotty Lake Block; Figures 7f, 7i) may reflect a concurrent trend of increasingly more advanced rifting within this structural corridor. This model implies northward propagation of the rift axis and widening of an intra-arc basin to the south. However, this geometry may not correspond to the original orientation of the intra-arc basin, because the present configuration is assumed to be a result of tectonic reworking during and after 1.87 Ga assembly of the Amisk Collage (Lucas et al., 1996). Tectonic movement along the Sourhadow Bay and Northeast Arm faults and related fault splays (Figures 2, 3 and 4) was likely a major control that resulted in the alignment of the arc-raft volcanic suites along a north-northeast-trending structural corridor across the Flin Flon Belt (see ‘Structural geology discussion’ below).

**Sourdough Bay suite (unit J9, tholeiitic to calcalkaline arc)**

The Sourdough Bay fault block (Figure 2), one of the largest supracrustal components in the Flin Flon Belt, extends from the north-northeast to the south-southwest across the belt for approximately 25 km (Bailes and Syme, 1989). The northern part of the fault block at Alberts Lake consists largely of felsic

\(^7\) Scotty Lake basalt, average content of FeO\textsuperscript{2} (11.0%), TiO\textsubscript{2} (1.3%), Th (2.9 ppm) and La/Yb\textsubscript{sub} ratio (3.0) (Bailes and Syme, 1989).
volcanic rocks with subordinate basalt, volcanic fragmental rocks and rare chert. The southern part of the block at northern Athapapuskow Lake contains parts of two contrasting volcanic sequences: 1) felsic, massive to fragmental rocks and associated intrusions, and 2) mafic flows and breccia, layered with volcanlastic and turbiditic sedimentary deposits (Bailes and Syme, 1989). Structural data indicate that the stratigraphic sequence in the Sourdough Bay Block is a west- to northwest-facing monocline. Felsic volcanic rocks (unit J12), which are the predominant type in the northern part of the Sourdough Bay Block, form the felsic ‘Baker Patton Complex’ (Gale, 2001), which is over 3 km wide and, with an area of approximately 50 km², is the largest felsic volcanic terrane in the Flin Flon Belt. The Baker Patton Complex displays evidence of having undergone intense hydrothermal alteration and is endowed with one known gold and at least five massive sulphide–type deposits, as well as over 20 primarily base-metal mineral occurrences (Gale and Eccles, 1988a; Gale and Dabek, 2002). Substantial VMS mineralization has, however, yet to be found in the Baker Patton Complex; the largest known deposit is at Pine Bay and was reported by the Cerro Mining Company of Canada to contain 1 340 000 tonnes at an average grade of 1.5% Cu (Gale and Eccles, 1988a). Two massive Cu-Zn sulphide deposits that occur farther south in the Sourdough Bay fault block (Centennial, Sourdough Bay) are hosted by mudstone and felsic volcaniclastic rocks within a mafic volcanic flow sequence.

The felsic volcanic rocks at Alberts Lake represent the northern part of the Baker Patton Complex; they are separated from the main part of this complex by major gabbro and granodiorite intrusions immediately south of Alberts Lake (Map CR2011-1-1). Massive rhyolite and related autoclastic breccia at Alberts Lake appear to be in gradational contact with the fine-grained, marginal phase of the granitoid Naosap Lake pluton (unit P4) to the northeast, suggesting that this part of the pluton, at least, may be synvolcanic in age. The massive to fragmental felsic volcanic rocks are typically plagioclase (+ quartz)-phyric; autoclastic breccia contains an unsorted assemblage of rhyolite fragments that constitute up to 70% of the rock. Small, angular to irregular or amoeboid fragments (0.5–10 cm) and subordinate blocks up to 70 cm across are characteristic of the autoclastic breccia. Sporadic, flow-laminated rhyolite lobes (up to 2 by 3 m) and elongate tongues in the breccia are locally flow folded and probably represent extrusions of massive rhyolite within unconsolidated autoclastic deposits. The majority of the clasts display fine flow laminae (1–3 mm scale) that are commonly warped due to contemporaneous flow during emplacement of the breccia. Massive rhyolite flows, subordinate to the breccia, also exhibit flow lamination, are locally spherulitic, and contain pyritohedra and hornblende porphyroblasts.

The felsic volcanic rocks at Alberts Lake are stratigraphically (and locally tectonically) intercalated with subordinate basaltic flows and related breccia. These mafic flows are lithologically similar to arc volcanic rocks in the Lac Aimée Block. Pillows are typically 1–2 m long, but megapillows (up to 5 by 1.7 m) occur at several localities in the southeastern part of Alberts Lake. The mafic flows are aphyric to locally plagioclase-phyric and quartz-amygdaoid; amygdules are typically smaller and less abundant than in the Lac Aimée arc basalt. Epidote alteration affects both mafic and felsic flows in the Sourdough Bay Block but is more pervasive in basaltic rocks, which locally contain epidosite pods up to 0.5 m across that form up to one third of some flows. Plagioclase-phyric diabase dikes interpreted as synvolcanic are abundant in the northeastern part of Alberts Lake, where they constitute up to 20% of the basaltic section.

In the southeastern part of Alberts Lake, minor components of the arc volcanic section include heterolithic volcanic breccia, mafic tuff and chert. Heterolithic breccia contains aphyric basalt and rhyolite fragments (1–10 cm), and sporadic blocks up to 0.5 by 1 m. The clasts are subangular to angular and the breccia is unsorted, typical of debris-flow deposits. Sporadic, 1–3 m thick mafic tuff layers within the felsic volcanic sequence contain thin (1–4 cm) laminated chert layers. The chert laminae are locally disrupted and rafted into the mafic tuff due to synsedimentary deformation. In addition, a thin (0.25 m) chert deposit occurs at the contact between two basaltic flows near the southeastern end of Alberts Lake; elsewhere, sporadic white chert rafts up to 80 cm long within a mafic flow are assumed to represent reworked interflow chert deposits. These occurrences of chert are locally magnetiferous and/or mineralized with up to 7% pyrite-chalcopyrite and associated malachite.

Geochemically, Sourdough Bay mafic to intermediate volcanic rocks are very similar to the arc volcanic rocks in the Lac Aimée Block, except for a relatively narrower compositional range. The Mg# and other diagnostic element ratios for the Sourdough Bay volcanic rocks are similar to average values for other NFFB arc volcanic rocks (Table 3, back pocket). The εNd isotopic ratios for Sourdough Bay basaltic andesite, dacite and rhyolite (−0.8, +0.1 and −0.5 at 1.9 Ga, respectively; Table 4) suggest up to 9% of older continental crust was incorporated in the evolving source magma prior to eruption (Stern et al., 1995a; Figure 9).

Naosap Lake suite (unit J10, calcalkaline arc)

The Naosap Lake calcalkaline suite at the eastern margin of the NFFB is separated from Lac Aimée arc volcanic rocks to the west by the northeast-trending Sourdough Bay Fault (Figures 2, 3); to the east and south, the Naosap Lake Block is flanked by younger intrusive rocks at the western margin of an extensive granodiorite terrane that extends eastward for over 30 km to the Elbow Lake area (NATMAP Shield Margin Project Working Group, 1998, sheet 2). The stratigraphy and geochemistry of rocks in the Naosap Lake Block are distinctive and suggest it does not represent a northern extension of the Sourdough Bay Block to the southeast, as previously inferred (Gilbert, 2002a). The theoleitic to calcalkaline Sourdough Bay suite is dominated by felsic volcanic rocks, whereas the Naosap Lake suite is calcalkaline and consists mainly of andesite to dacite, with only minor rhyolite.

Mafic to intermediate flow and fragmental rocks (unit J10a) are the predominant rock types in the Naosap Lake Block. These rocks are mainly aphyric and locally contain densely quartz-amygdaoidal zones, probably coincident with flow tops. Intercalated flow breccia units contain mafic fragments that are variously aphyric, plagioclase-phyric and/or amygdaoidal. Epidosite pods and irregular masses (+ densely packed, quartzofeldspathic amygdules) are locally conspicuous. Pillows
are rarely preserved due to pervasive tectonic attenuation. The section also contains sporadic units of heterolithic volcanic breccia that are interpreted as mass-flow deposits; the breccia clasts are moderately to strongly attenuated and include both mafic and subordinate, plagioclase-phyrhic felsic rock types.

A unique occurrence of monolithic volcanic breccia (>20 m wide) at the northwestern shore of Naosap Lake consists of unsorted, angular quartz-phyrhic rhyolite fragments (1–8 cm) within a very dark grey, mafic tuff matrix. Subordinate thin beds of diffusely laminated and graded mafic tuff are interleaved with the breccia. This fragmental deposit may be the result of an explosive volcanic event in which felsic volcanic ‘cap rocks’ were shattered by rising magma and subsequently incorporated as fragments within the mafic tuff matrix.

The predominantly intermediate compositional range of volcanic rocks distinguishes the Naosap Lake suite from other arc volcanic suites in the NFFB, which are bimodal basalt and rhyolite sequences. Relative to other NFFB arc rocks, Naosap Lake volcanic rocks have higher average light to medium REE contents, higher contents of HFSE (Nb, Zr and Hf), as well as higher La/Yb and Th/Yb ratios (Table 3, back pocket). Average Th content in the Naosap Lake suite (2.4 ppm) exceeds that of almost all other NFFB mafic to intermediate volcanic suites and is three times the combined average of other NFFB arc rocks. These trace element patterns are consistent with the calcalkaline affiliation of Naosap Lake volcanic rocks, as indicated by the lack of an iron enrichment trend, and lower average FeO\(^{\text{avg}}\) content, compared with tholeiitic or transitional calcalkaline-tholeiitic NFFB arc rocks (Figure 5a to 5f; Table 3, back pocket).

The mainly intermediate composition of the Naosap Lake volcanic suite may be due to modification of the source magma by either 1) assimilation of contemporaneous (volcanic-derived) sedimentary detritus in the subduction zone and/or older continental crust, or 2) the addition of (or metasomatism by) subduction-related mantle. Involvement of older crust in the evolution of the Naosap Lake magma is indicated by the evolved Nd isotopic composition (\(E_{\text{ND}}\) of −0.5 at 1.9 Ga; Table 4), which is consistent with a moderate amount of crustal recycling (Figure 9; Stern et al., 1995a). Incorporation of sialic lithosphere by assimilation is consistent with the conspicuous enrichment in Th and overall incompatible-element patterns, which are characterized by variable amounts of slope (Figure 7h) due to variation in LREE, Th and Nb contents.

Porphyroblastic, cordierite-bearing gneiss (unit J10b) is characteristic of a 400 m wide section of metamorphosed rocks that underlie an island very close to the south shore of Naosap Lake, at the southeastern margin of the Naosap Lake Block (Map GR2011-1-1). The porphyroblastic gneiss and associated amphibolite are interpreted as derived from metasomatized volcanic rocks, but a sedimentary precursor cannot be ruled out.

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8 An alternative explanation for this metamorphic contrast is to interpret the high-grade gneiss as a fault-bounded remnant of a former granulite terrane that may have been significantly older than the Naosap Lake arc volcanic rocks. The gneiss is possibly coeval with late Neoarchean (2.52 Ga) fault slivers that have been identified within the Northeast Arm Fault (David and Syme, 1994) and granulite facies rocks of similar age that have been identified at several other localities in the Reindeer Zone of the Trans-Hudson Orogen, for example, in Sask craton, west of the Flin Flon Domain (Ashton et al., 1999) and at Southern Indian Lake, north of the Flin Flon Domain (Corrigan et al., 2001). High-grade gneiss of similar age could also exist at deep crustal levels elsewhere within the southeastern part of the Trans-Hudson Orogen, in the vicinity of the Flin Flon Belt. Fault slivers of such rocks could have been tectonically intercalated with the Paleoproterozoic volcanic rocks during late collisional tectonism (D\(_4\) of Lucas et al., 1996).
however, does not support this model. The composition of a >1.2 m wide, probably intrusive dacitic layer (sample 32-97-1550-1, Appendix 1) within the high-grade gneiss sequence is very similar to the average composition of rocks of the Naosap Lake arc volcanic suite (Figure 11), suggesting it could be associated with Naosap Lake magmatism. These data suggest that the section containing the porphyroblastic gneiss is not allochthonous but is derived from the Naosap Lake volcanic suite, as implied by the original field interpretation. The implications for this model are as follows:

1) The volcanic and/or sedimentary rocks from which the gneiss was derived were subjected to pervasive (possibly synvolcanic) alteration and magnesian metasomatism.

2) High-grade metamorphism that affected the metasomatized rocks was likely associated with ca. 1830–1800 Ma peak metamorphism in the Flin Flon Belt (Lucas et al., 1996).

3) The orthopyroxene-bearing, high-grade gneiss to the north and relatively lower grade volcanic rocks to the south were tectonically juxtaposed by faulting, possibly during terminal collision of the Reindeer Zone (Trans-Hudson Orogen) with Archean cratons, following peak metamorphism (Lucas et al., 1996; see ‘Structural geology discussion’ below).

4) Amphibolite-facies contact metamorphism overprinted the high-grade mineral assemblage in the porphyroblastic gneiss. If this assemblage is a product of the ca. 1830–1800 Ma peak metamorphism, the contact metamorphism thus postdated both the high-grade metamorphism and earlier emplacement of 1838–1876 Ma successor-arc plutons (Stern et al., 1999).

**Felsic volcanic rocks (units J11–15)**

Felsic rocks are subordinate (<10%) among all arc rocks in the NFFB, except in the eastern part (Alberts Lake area), where the Baker Patton Complex (unit J12) constitutes over half of the northern Sourdough Bay Block (Figure 2). Although felsic volcanic rocks are volumetrically only a minor part of the Flin Flon arc assemblage, they are economically the most important component because of the close association between felsic volcanic rocks and VMS ore deposits, both in the Flin Flon Belt (Syme, 1998) and elsewhere (Franklin, 1996). Incompatible-element plots of the NFFB rocks are similar to those of juvenile-arc rhyolite types elsewhere in the Flin Flon Belt (Syme, 1998; Figure 12a, 12b). Most of these rocks are FII type in the scheme of Lesher et al. (1986) for the classification of Archean volcanic rocks (Figure 13)—a system that has been shown to be, in part, applicable to (Paleoproterozoic) Flin Flon Belt rocks (Syme, 1998, Bailes and Galley, 1999). The FII-type felsic volcanic rocks are only rarely associated with economic mineralization.

The lensoid Cope Lake rhyolite (unit J13), at least 140 m wide and 0.5 km along strike, is located at the northeastern margin of the Cope Lake Block, 0.5 km southwest of the Trout Lake (Cu-Zn) ore deposit (Figure 4, Map GR2011-1-1). The stratigraphic and structural setting of this rhyolite suggest that it may have potential for base-metal mineralization, being situated close to the tectonic contact between the Cope Lake and Embury Lake blocks as well as the Trout Lake ore deposit, which is hosted by similar felsic volcanic rocks (Ordóñez-Calderón et al., 2009). This VMS-type ore deposit, which is one of the largest in the Flin Flon area, occurs within a sequence of felsic volcanic rocks and related porphyry, basalt, gabbro and argillite (Ordóñez-Calderón et al., 2009). The geochemical signature of the Cope Lake rhyolite identifies it as different from most other NFFB felsic volcanic rocks and is consistent with a possible genetic link to the ore-bearing rhyolite in the Trout Lake mine sequence.

Compared with most other NFFB felsic volcanic rocks, the high-silica Cope Lake rhyolite is distinguished by relatively high REE and HFSE contents, and a more pronounced Eu anomaly.
The extended element plot shows Cope Lake rhyolite has a relatively flat profile and incompatible-element contents that exceed those of all other Flin Flon Belt rhyolites (Syme, 1998). Cope Lake rhyolite is classified as FIII type (of Lesher et al., 1986; Figure 13) indicating it may be prospective for VMS mineralization. Such rocks, which also include FIII rhyolite in the Flin Flon mine sequence (Syme, 1998), are interpreted as derived from high-level, subvolcanic magma chambers, representing a heat source for hydrothermal convection systems that are directly associated with VMS mineralization (Lesher et al., 1986).

The Cope Lake rhyolite is also compositionally similar to ore-bearing rhyolites in the Archean Abitibi Subprovince and is classified as group I in the scheme of Barrie et al. (1993)—a rock type that hosts over 50% of Abitibi VMS ore deposits. Group I rocks consist of high-silica rhyolite (SiO₂ >73%) characterized by elevated incompatible-element contents, negative Eu anomalies, Zr/Y ratios <5 and Rb/Sr ratios >1.0 (Figure 14; compare with data in Table 3, back pocket and Appendix 1).

Lac Aimée felsic porphyry (sample 32-97-1149-1, unit J14; Appendix 1 and Map GR2011-I-1) is a massive, >10 m wide unit located in the faulted contact zone between the MORB-type Animus Lake Block and arc-type Lac Aimée Block. It is interpreted as an intrusive/extrusive formation associated with...
Lac Aimée arc volcanic rocks. This FIII-type quartz-plagioclase porphyry is more REE-enriched (especially Y) than other NFFB felsic rocks and is compositionally similar to the Cope Lake rhyolite (Figures 12, 13 and 14; Table 3, back pocket). The distinctive geochemical profile suggests that the Lac Aimée porphyry and/or similar felsic lenses along strike to the northeast (Map GR2011-1-1) represent potential exploration targets for base-metal mineralization.

MORB-type volcanic suites (unit F)

Four tectonic enclaves of various MORB-type volcanic rocks (Arthurs Lake, Bluenose Lake, Animus Lake and West Mikanagan Lake blocks) are tectonically intercalated with the numerous arc fault blocks within the NFFB. The MORB volcanic suites consist almost entirely of basalt and abundant related gabbro sills that constitute up to 30% of these sequences; they are thus lithologically and compositionally much less...
diverse than the arc volcanic suites. The MORB volcanic suites are interpreted as back-arc rocks derived from source magmas that were largely unaffected by subduction zone influences; $^{\varepsilon_{\text{Nd}}}$ values range from +3.3 to +5.1 at 1.9 Ga (Table 4), consistent with a mantle source with little or no crustal recycling of older lithosphere. Several MORB suites contain aphyric to plagioclase–hornblende (pyroxene)–phyric diabase dikes that are compositionally akin to arc rather than MORB-type magmatism.

Two MORB volcanic types—normal (N-MORB) and enriched (E-MORB)—are recognized in the NFFB. These two types are geochemically similar to analogous varieties of MORB in the Elbow-Athapapuskow ocean-floor assemblage (Stern et al., 1995b) that is located in the southern and eastern parts of the Flin Flon Belt (Figure 1). Geochemical variation between the various formations within the ocean-floor assemblage has been attributed to mixing of depleted MORB and enriched mantle together with, in some cases, a subduction-modified mantle source, but without any crustal assimilation (Stern et al., 1995b; see ‘Discussion’ below).

**Arthurs Lake N-MORB suite (unit F1)**

Arthurs Lake N-MORB and abundant related gabbro intrusions (unit F1) occupy a crescent-shaped tectonic slice (Arthurs Lake Block) between the Manistikwan Lake and Bear Lake fault blocks (Figure 4). The southwestern margin of this tectonic slice is bound by the Inlet Arm Fault (Bailes and Syme, 1989), whereas the northeastern margin consists of a splay of this same fault that originates in the northeastern part of Big Island Lake. To the south and along strike from the Arthurs Lake Block, a heterogeneous assemblage of structurally intercalated volcanic and subordinate epiclastic rocks occurs within the Grassy Narrows Zone, between the Manistikwan Lake and Bear Lake blocks (Bailes and Syme, 1989). To the northwest, the Arthurs Lake N-MORB rocks extend around the northern part of Embury Lake and are assumed to wedged out farther west, beyond the Manitoba-Saskatchewan boundary.

The Arthurs Lake sequence, up to 800 m thick and over 10 km along strike, contains two major folds with axial planes that trend south to south-southeast and are overturned to the southwest (Figures 2 and 3). These structural trends are, in part, discordant to the block-bounding faults, suggesting the folds predate tectonic emplacement of the N-MORB fault block. The margins of the Arthurs Lake Block are characterized by cataclasis and alteration, as well as localized base-metal mineralization along the contact with the Bear Lake Block between Arthurs and Krasny lakes (Map GR2011-1-1). Along this same contact, fine-grained greywacke-siltstone deposits (unit S1) up to 60 m wide are interpreted as fault-bounded lenses of volcanic-derived detritus that is assumed to be either contemporaneous with volcanic activity in the contiguous Bear Lake Block or younger, of successor-arc age.

The Arthurs Lake N-MORB suite consists mainly of aphyric and plagioclase-megaphyric basaltic flows; associated gabbro intrusions within the flows form approximately one third of the fault block. Synvolcanic diabase dikes were not observed within this section, unlike in arc volcanic suites where such intrusions are common. The N-MORB rocks are characterized by pseudohexagonal plagioclase megacrysts that occur in approximately half of the flows, as well as in related gabbro sills. The megacrysts are, within the NFFB, unique to the Arthurs Lake volcanic suite and are most common in the area west of Arthurs and Krasny lakes; they have not been observed within the stratigraphically and compositionally similar Grassy Narrows basalt to the south (Figure 4; Bailes and Syme, 1989). The euhedral to ovoid plagioclase crystals are typically 1–6 cm in size and constitute 5–15% of the hostrock. The megacrysts are distributed in irregular zones, in trails of single crystals or, rarely, in diffuse ‘strata’ within gabbroic intrusions—probably due to sorting by convection currents during emplacement of the gabbro. The megacrysts are also present in rare autoclastic breccia zones up to 5 m wide, within pillowed flows or between massive and pillowed flows. Pillow flows are widespread but rarely exceed 1.5 m in length, in contrast to those in arc volcanic sequences that locally exceed 5 m. Amygdules (quartz±plagioclase) occur in a minority of flows and are typically sparse (1–5%); variolitic texture was identified in one basaltic flow at the southern extremity of Ruby Lake. Polygonal cooling fractures are well preserved at several localities within both the mafic volcanic and related gabbroic rocks.

Basaltic flows and synvolcanic gabbro sills are intimately intercalated and their mutual contacts are variously sharp or gradational. Contacts are locally very irregular, suggesting the gabbro permeated the volcanic flows as laccolith-type intrusions, penecontemporaneous with the volcanism. The gabbros are compositionally akin to the flows but less fractionated; they are typically mesocratic to melanocratic (hornblende content of 35–70%), but leucocratic varieties are also present. These rocks contain subhedral hornblende pseudomorphs after pyroxene (2–8 mm across) within a medium- to coarse-grained matrix. Plagioclase megacrysts are widely developed but generally sparse, rarely exceeding 15% of the gabbroic hostrock. At a few localities the feldspars are abundant and result in anorthositic compositions (e.g., 20–50% over 30 m; 70–90% over 6 m).

The Arthurs Lake volcanic suite is compositionally very similar to modern N-MORB; incompatible-element contents are equivalent to or slightly less than those of N-MORB (Figure 15a), except for Th, which shows slight relative enrichment. One of the synvolcanic gabbro sills was found to be slightly REE-depleted relative to associated basalt flows, with moderate negative Nb and Zr anomalies in the incompatible-element plot. In the TiO₂ versus MgO diagram (Figure 6c), Arthurs Lake N-MORB (as well as Grassy Narrows basalt, along strike to the south) plot within the ‘MORB + BABB’ field. The $+3.3^{\varepsilon_{\text{Nd}}}$ value (at 1.9 Ga) for Arthurs Lake N-MORB (Table 4) is equivalent to the projected value for depleted mantle of that age (DePaolo, 1981), indicating a juvenile origin for the source magma with little or no crustal contamination. The lithological and compositional uniformity of the N-MORB sequence and lack of evidence for subduction zone influences is consistent with a BAB setting for the Arthurs Lake suite.

**Bluenose Lake N-MORB suite (unit F2)**

A 1.5 km thick sequence of N-MORB–type volcanic rocks occurs in the vicinity of Bluenose Lake, where it occupies the
Figure 15: Plots of N-MORB normalized incompatible-elements for MORB-type mafic volcanic suites in the northern Flin Flon Belt, west-central Manitoba: a) Arthurs Lake, b) Bluenose Lake, c) Animus Lake, d) West Mikanagan Lake; depleted-MORB suites: e) Dismal Lake and f) Bluenose Lake; g) gabbro phases within Wabishkok Lake and Kotyk Lake sills, compared with Animus Lake N-MORB and E-MORB rocks; and h) arc-type porphyritic diabase dikes within E-MORB hostrocks (West Mikanagan Lake and Animus Lake volcanic suites). Note that in Figures 15e and 15f, a notional value of 0.2 ppm Nb has been used for those rocks where Nb is below the analytical detection limit (applies to 21 out of the 27 Dismal Lake rocks and 6 out of 8 Bluenose Lake rocks, see Appendix 1). Abbreviations: MORB, mid-ocean-ridge basalt; E-MORB, enriched mid-ocean-ridge basalt; N-MORB, normal mid-ocean-ridge basalt. Normalizing values from Sun and McDonough (1989).
axial zone of a major, east-plunging synclinal fold (Figures 2 and 3; see ‘Structural Geology’ below). Formerly described as the ‘Wabishkok Lake antiform’ (Gilbert, 2001a, b), this fold is re-interpreted as synclinal, based on the limited structural data available. The Bluenose Lake N-MORB volcanic suite consists largely of aphric, massive to pillowied flows; related gabbro intrusions form less than 10% of the section. Quartzofeldspathic amygdules and/or plagioclase phenocrysts occur in only a few flows and are sparsely distributed (2–10% of the rock). Pillows are mostly obliterated due to tectonism, and the rocks are variously altered to massive or finely laminated amphibolite, locally with minor epidote alteration. Garnet porphyroblasts and medium-grained recrystallized zones of mafic gneiss occur sporadically in the amphibolite.

Conspicuous mineralization occurs within the N-MORB sequence in the southwestern part of Bluenose Lake; assays yielded Cu, Zn and traces of Au, hosted by sulphide stringers and lenses within amphibolite hostrocks. The mineralization occurs within a 0.5 km wide zone of west-trending EM anomalies that extend laterally within the N-MORB volcanic suite for at least 1.5 km (Gilbert, 2004). The EM anomalies, which are roughly conformable with the basaltic flows in which they occur, may be related to stratatound mineralization or alternatively represent tectonic zones of faulting and mineralization, postdating the N-MORB volcanism.

A 120 m wide fault slice of arc rocks derived from the Tartan Lake Block is emplaced within the N-MORB volcanic suite in the southern bay of Bluenose Lake, approximately 350 m south of the mineralized zone described above (Figures 2 and 3). This fault slice occurs within a splay of a west-trending fault that separates arc- and MORB-type volcanic rocks and is continuous southward as the Northeast Arm Fault, which extends for over 35 km across the Flin Flon Belt (Figures 2, 3 and 4). At the northern margin of the fault slice, a >17 m wide zone of fault/ intrusion breccia contains angular to tabular, siliceous blocks within an altered ultramafic matrix containing remnants of clinopyroxene and disseminated pyrrhotite. The fine-grained quartzitic fragments contain dark laminae, possibly derived from bedding in a sedimentary precursor. The laminae are partly disrupted due to folding that preceded the deformation episode when they were incorporated into the breccia.

Geochemically, Bluenose Lake N-MORB is very similar to Arthurs Lake N-MORB but differs from the relatively more REE-depleted Animus Lake N-MORB (see below). The compositional range of incompatible elements in Bluenose and Arthurs Lake N-MORB rocks is virtually the same (Figure 15a, 15b), as are their respective fields in the TiO₂ versus MgO discriminant diagram that distinguishes these rock suites from more TiO₂-depleted arc volcanic types (Figure 6c). Slight Th and LREE enrichment is characteristic of some flows, but otherwise incompatible elements are moderately depleted compared to modern N-MORB.

The +4.0 Euⁿ⁺ value for Bluenose Lake N-MORB (at 1.9 Ga, Table 4) indicates the source magma was juvenile and lacked crustal contamination. Incompatible-element data show this compositionally uniform N-MORB suite was virtually unaffected by subduction zone influences, consistent with a BAB tectonic setting. Stratigraphic and/or structural breaks within the volcanic sequence, inferred from EM anomalies at southern Bluenose Lake, may be due to rifting associated with the development of an intra-arc basin.

**Animus Lake N-MORB and E-MORB suites (units F3 and F4)**

Compositionally distinct, N-MORB and E-MORB volcanic and related gabbroic rocks occupy the triangular-shaped Animus Lake Block, immediately south of Wabishkok Lake. The fault block is a highly deformed tectonic wedge located at a major structural divide in the NFFB, between northeast-trending rocks to the east (at Lac Aimée) and northwest-trending formations to the west (Embury–Tartan–Mikanagan lakes area). The Animus Lake rocks are juxtaposed against several geochemically contrasting fault blocks that include arc, arc-rift and E-MORB types (Figure 2).

Gabbro sills up to 300 m thick constitute approximately 20% of the Animus Lake Block. Subordinate rock types (less than 2% of the sequence) include: 1) greywacke-siltstone, volcanic breccia and rhyolite, which occur in several thin (<20 m) enclaves interpreted as fault slivers within the MORB rocks (Gale and Norquay, 1996; Gilbert, 1997a, 2002b); and 2) felsic volcanic rocks that contain massive pyrite layers up to 2 m wide, identified in drillcore 1 km east of Animus Lake (Gale and Eccles, 1988a). Minor flow-top breccia occurs locally between basaltic units. The mafic volcanic rocks are mostly nonvesicular and aphric, although sparse plagioclase phenocrysts (0.5–2 mm) and amphibole pseudomorphs after pyroxene occur in a few flows. Animus Lake E-MORB is typically medium- to dark-green weathering, in contrast to generally paler-weathering N-MORB rocks. Pillows are virtually ubiquitous and provide top determinations that indicate a complex structural pattern.

The volcanic sequence is characterized by repeated folding, with at least 11 anticline-syncline fold pairs with northwest-trending axial planes, interpreted as D₁, in age. These early folds were subsequently deformed by a regional northeast-trending D₂ fold (see ‘Structural Geology’ below). The structural pattern suggests the sequence may originally have consisted of a lower E-MORB section overlain by N-MORB–type basalts (Gilbert, 1998, 1999). The contact relationships between N-MORB and E-MORB are uncertain; although there is little evidence in the field that the contacts are faulted, a conformable stratigraphic relationship appears unlikely in view of the absence of any compositional gradation between these geochemically distinctive types. Within the tectonically similar Elbow-Athapuskow ocean-floor assemblage (Figure 1), intercalated E-MORB and N-MORB formations are structurally juxtaposed by faulting (Stern et al., 1995b), and it appears likely that the contacts between the two MORB types in the Animus Lake Block are also faulted.

The Animus Lake E-MORB and N-MORB suites are geochemically distinct, suggesting they are derived from separate, unrelated magma sources. Relative to modern N-MORB, Animus Lake N-MORB rocks are conspicuously depleted in both REE and HFSE. The incompatible-element plot of Animus N-MORB displays a flat to positive-sloping profile, in contrast to the negative-sloping pattern for Animus
E-MORB, with no overlap between the two types (Figure 15c). Animus Lake N-MORB has characteristically low Th content (0.08 ppm, Table 3, back pocket); such extreme Th depletion is rare elsewhere in the Flin Flon Belt, matched only by the N-MORB–type Moen Bay formation within the Elbow-Athapapuskow assemblage (Table 3, Stern et al., 1995b). Virtually all other Flin Flon Belt volcanic rocks display slight to pronounced Th enrichment relative to modern N-MORB. Animus Lake N-MORB is also characterized by conspicuous Zr and TiO₂ depletion, resulting in these rocks plotting outside the fields of typical N-MORB rocks in some discriminant plots (e.g., TiO₂ versus MgO, Figure 6c).

Compared to modern N-MORB, incompatible-element contents are equivalent or somewhat higher in Animus Lake E-MORB (Figure 15c). The Nb/Y ratios in the Animus Lake E-MORB suite (average of 0.21) contrast with much lower E-MORB (Figure 15c). The Nb/Y ratios in the Animus Lake contents are equivalent or somewhat higher in Animus Lake Athapapuskow ocean-floor assemblage (εNd at 1.9 Ga in Table 4) and within the range of MORB types of the Elbow-Athapapuskow assemblage. Animus Lake rocks (Figure 15g). The two mafic sills may be compositionally akin, respectively, to N-MORB and E-MORB.

The Nd isotope ratios in Animus Lake volcanic rocks are primitive (εNd at 1.9 Ga: +5.1 in N-MORB, +3.9 in E-MORB, Table 4) and within the range of MORB types of the Elbow-Athapapuskow ocean-floor assemblage (εNd at 1.9 Ga in N-MORB is +3.3 to +5.4, and in E-MORB is +3.1 to +4.5; Stern et al., 1995b). The isotope data for Animus Lake MORB-type rocks are consistent with a BAB setting in which crustal contamination was insignificant or absent.

The composition and the structural setting of the Animus Lake Block, among other geochemically contrasting types, suggests that this fault block is an allochthonous component of the NFFB that represents part of a back-arc ocean-floor assemblage. Animus Lake MORB-type rocks may have been intercalated with arc components in the Amisk Collage during tectonic accretion ca. 1.88–1.87 Ga (Lucas et al., 1996), but final emplacement of the fault block likely occurred after D₃ (see 'Structural Geology' below). The most likely source for the Animus Lake rocks appears to be the back-arc assemblage at the northern side of the Flin Flon Belt (units T1 and T2), in which sporadic occurrences of N-MORB occur at the northernmost margin and at Bluenoshe Lake (Map GR2011-1; Figure 2). Alternatively, the Animus Lake rocks may represent a dismembered part of the Elbow-Athapapuskow ocean-floor assemblage in the southern and eastern parts of the Flin Flon Belt (Figure 1; Stern et al., 1995b; NATMAP Shield Margin Project Working Group, 1998, sheet 2).

Gabbroic phases within the Wabishkok Lake and Kotyk Lake sills, in the central and southern parts of the Wabishkok Lake Block, include two different types that are compositionally akin, respectively, to N-MORB and E-MORB. Animus Lake rocks (Figure 15g). The two mafic sills may be syngeneic and derived locally from magmatic sources that were also the sources for the Animus Lake MORB-type rocks. This interpretation implies that the allochthonous Animus Lake MORB-type rocks were locally derived and possibly related to back-arc magmatism at the northern side of the Flin Flon Belt, rather than representing a dismembered part of the more distant Elbow-Athapapuskow ocean-floor assemblage.

**West Mikanagan Lake E-MORB suite (unit F5)**

The West Mikanagan Lake E-MORB–type volcanic suite occupies a fault block flanked by gabbroic rocks to the west and the East Mikanagan Lake arc-raft suite to the east. The western margin is, in part, intruded by gabbroic rocks of the Tartan Lake complex (Gilbert, 1986a); elsewhere the fault block is bounded by splays of the Northeast Arm Fault (Figures 2 and 3). South of Mikanagan Lake, the West Mikanagan Lake volcanic suite is juxtaposed by the same fault against the arc-type Whitefish Lake–Mikanagan Lake Block (Figure 4).

The West Mikanagan Lake E-MORB suite consists of a uniform, southwest-facing monoclinal sequence of massive to pillowed basaltic flows and abundant related gabbro; fragmental rocks are confined to minor (<1 m) interflow breccia units. In contrast to typical arc volcanic sequences, alteration is not widespread in the West Mikanagan Lake section and pyroclastic/epiclastic detritus is absent. The E-MORB is typically aphyric, green-grey or blue-grey on fresh surfaces, and locally sparsely vesicular. Some flows contain minor quartz or quartzofeldspathic amygdules (typically <5%) and/or minor plagioclase phenocrysts (~5%); rare polygonal cooling fractures are locally preserved. Syngeneic gabbro sills (commonly 2–25 m, rarely up to 100 m thick) are geochemically similar to the pillowed flows but have slightly lower incompatible-element contents. Porphyritic diabase dikes with up to 30% hornblende (after pyroxene) phenocrysts are widely distributed; in contrast to the interflow gabbros, several of these dikes (and a similar porphyritic dike within Animus Lake E-MORB hostrock) were found to have an arc-type composition and are thus not related to the host, E-MORB–type basalt (Figure 15h).

A northwest-trending zone of variolitic quenched basalt, up to 165 m thick and extending over 1 km along strike, intersects the northwestern tip of Swordfish Lake; it occurs approximately in the centre of the monoclinal West Mikanagan Lake E-MORB–type sequence (Gilbert, 1987a). The flows contain ovoid, 0.5–1 cm saussuritic varioles that vary in abundance from 10 to 75% of the rock. These rocks are also typically vesicular and contain 3–25% quartz or quartzofeldspathic amygdules. Textures derived from quenched clinopyroxene crystals are defined by delicate trails/filaments/chains of very fine grained amphibole and/or epidote. The amphibole/epidote texture is characterized by a wide variety of branched/pinnate/feather-like patterns that occur within quartzofeldspathic domains. The varioles appear to have ‘overprinted’ the clinopyroxene quench texture and are interpreted as products of spherulitic crystallization that occurred during or after consolidation of the volcanic flow.

The localized clinopyroxene quench texture in variolitic basalt within West Mikanagan Lake E-MORB (and East Mikanagan Lake arc-raft rocks) is interpreted as due to
rapid cooling of basalt in a quiescent, back-arc/ocean-floor environment. The controlling factors for this textural feature may include locally elevated volatile content in the magma, because basalt with quench texture is invariably quartz amygdaloidal, especially northwest of Swordfish Lake, where quartz amygdules are locally more abundant than they are anywhere else within the E-MORB–type sequence. Clinopyroxene quench texture is of very limited extent in the NFFB and appears to be confined to arc-rift or MORB-type settings. It was encountered elsewhere at only two other localities: 1) within Arthurs Lake N-MORB (unit F1) at the southern end of Ruby Lake, and 2) in a silicified diabase dike (unit X1) hosted by Animus Lake N-MORB (unit F3).

West Mikanagan Lake E-MORB–type rocks are high-TiO₂ tholeiites that display smooth, negative-sloping profiles in plots of incompatible elements, characterized by moderately elevated Th and LREE but lacking HFSE depletion relative to N-MORB (Figure 15d). The E-MORB plots show no negative Nb anomalies, unlike those of both arc and arc-rift volcanic rocks in the NFFB (Figures 7a to 7j). West Mikanagan Lake basalt, as well as compositionally similar E-MORB volcanic suites elsewhere in the Flin Flon Belt, is more similar to modern transitional or plume-related MORB types than to the depleted mantle source of N-MORB volcanic suites (Stern et al., 1995b). Both the TiO₂ versus MgO plot (Figures 6a to 6c) and the Th/Nb versus Nb/Y discriminant diagram (Figure 8a) clearly demonstrate the compositional distinction of West Mikanagan Lake E-MORB, compared to N-MORB types and arc volcanic rocks in the NFFB. The +3.5 εNd value for West Mikanagan Lake E-MORB at 1.9 Ga (Table 4) is within the +3.1 to +4.5 range for Flin Flon Belt E-MORB volcanic rocks (Table 3, back pocket). The low average Th content of depleted-MORB rocks; alternatively, they may be conformable with the depleted MORB and represent periodic changes in the composition of a heterogeneous mantle source.

Dismal Lake basalt is typically aphyric and pillowed, with sparsely distributed quartz–plagioclase amygdules. Pillows are locally well preserved and ovoid (up to 1.5 m long), but more typically they are deformed and strongly flattened. Rare autoclastic breccia zones occur sporadically within the massive flows. Epidote alteration is common but of generally minor extent (<10% of individual rock outcrops). Gabbro sills (1–20 m thick) form over 10% of the depleted-MORB assemblage, but syngenic diabase dikes are virtually absent. Plagioclase–phyric pillow basalt at the northern shore of Dismal Lake, and along strike farther to the west, contains plagioclase phenocrysts (1–4 mm, 5–20% of the rock) as well as quartzfeldspathic amygdules.

Thinly laminated amphibolite and mafic gneiss are lithologically gradational and intercalated with pillowed to massive basalt and gabbro at a scale of 1–20 m. They represent highly strained, incompetent zones within the volcanic sequence. Epidote hornblende chlorite–rich laminae, typically 1–25 mm thick, are interpreted as structurally transposed features such as pillow selvages, autoclastic fragments and epidote domains. Boudinage and minor folding of the lamination are characteristic. Both massive and laminated parts of the depleted-MORB sequence contain widespread porphyroblastic garnet (1–4 mm) and hornblende (2–5 mm), and display localized silicic alteration (+garnet+pyrite).

GEOCHEMICALLY, the Dismal Lake volcano suite is characterized by a flat to slightly positive-sloping incompatible-element profile, typical for N-MORB rocks (Figure 15e). However, in contrast to both N-MORB and E-MORB types, the depleted MORB has a conspicuous negative Nb anomaly (Nb is below the detection limit in most analyzed rocks) and the average Th/Nb ratio (0.22 ppm) is more than twice that of MORB-type basalts (Table 3, back pocket). The low average Th content of
Nd isotopic composition of the Dismal Lake depleted-MORB (see ‘Discussion, tectonic setting of depleted-MORB types in the NFFB’ below). The generally flat REE profile and primitive (0.23–1.44%). Incompatible-element contents in Dismal Lake basalt, which exhibit a wide range of values (Figure 15e), are controlled mainly by the amount of partial melting in the mantle source (Gribble et al., 1998), with the extent of depletion being directly proportional to the degree of melting basalt, which are arc-volcanic rocks, along a mineralized horizon that extends laterally for at least 8 km (Gale and Norquay, 1996).

These four arc volcanic enclaves contain variously altered mafic to felsic volcanic rocks (+ sulphide-facies iron formation and fine-grained sedimentary rocks) and derived gneiss, in which EM conductors have been delineated. Zones of base-metal (+Au) mineralization are characterized by pervasive silicic, chloritic and epidote alteration, as well as conspicuous garnet (+hornblende+anthophyllite) blastesis. The mineralized zones are typically strongly deformed and intruded by one or more granitoid, gabbroic and/or minor ultramafic igneous phases. Contact relationships of the arc volcanic enclaves are unknown; they may be structural outliers within the depleted-MORB rocks that represent remnants of the Flin Flon arc assemblage, or a relatively older oceanic arc. Alternatively, they may be due to ephemeral changes in the composition of the magmatic source for Dismal Lake rocks that reflect the heterogeneous nature of the mantle source.

Bluenose Lake depleted-MORB suite (unit T2)

A fault-bounded enclave of depleted-MORB–type basalt, compositionally akin to flows in the Dismal Lake assemblage, extends for over 12 km between northern Wabishkok Lake and Bluenose Lake (Figure 2). At Bluenose Lake, this tectonic enclave is folded by a major, east-plunging synclinal fold (Figure 3; see ‘Structural Geology’ below). The southern limb of the fold is a north-facing, apparently monoclinal sequence up to 1.2 km thick that consists of massive to pillow-domed aphyric basalt, derived gneiss and mafic intrusive rocks, intercalated at a scale of 2–50 m. A conspicuous 300 m wide altered zone, at the northern (upper) margin of the southern limb, is characterized by pervasive silicification and epidotization, and contains felsic porphyry intrusions and sporadic base-metal mineralization. One 65 m thick plagioclase-porphyry sill is geochemically very similar to the Kotyk Lake rhyolite (unit J1) in the contiguous Wabishkok Lake arc volcanic block, suggesting the felsic
porphyry intrusions, as well as the alteration and mineralization, may be associated with arc magmatism postdating the depleted-MORB suite.

Bluenose Lake basalt flows contain ovoid pillows that are typically 0.5–1.5 m long, but mega-pillows up to 3.5 by 0.8 m occur in several flows. The pillows are commonly quartz-amphibole, with up to 15% spheroidal or pipe amygdules, locally concentrated in upper vesicular zones; rare flat-based vugs occur sporadically in larger pillows. Garnetiferous gneiss and laminated amphibolite intercalations within the mafic volcanic flows are similar to basalt-derived metamorphic rocks in the previously described Dismal Lake assemblage.

Geochemical plots of incompatible elements (Figure 15f) show Bluenose Lake depleted MORB has a flat to slightly positive-sloping profile, similar to that of Dismal Lake basalt, but with lower average LREE and HFSE contents (Table 3, back pocket). Conspicuous negative Nb and slight negative Ti anomalies—features that are typical of modern arc magmas—suggest a subduction zone influence in the evolution of the source magma. The depleted-MORB composition with anomalously low Nb and TiO₂ contents is consistent with a BAB setting for the Bluenose Lake volcanic suite, as suggested previously for the Dismal Lake depleted-MORB rocks.

Sedimentary rocks of uncertain age (unit S)

Turbiditic rocks of uncertain age are intercalated with arc and MORB-type volcanic rocks in the area between Embury Lake and Naosap Lake (Figure 2). These sedimentary enclaves (units S1–S7) are typically devoid of volcanic interlayers and, in most cases, appear to be fault bounded; in these respects they are distinguished from sporadic units of lithologically similar, fine-grained sedimentary rocks that are interpreted as conformable with juvenile-arc volcanic rocks. The fault-bounded sedimentary enclaves consist largely of greywacke, siltstone and subordinate argillaceous mudstone and pebble conglomerate. These rocks locally display graded bedding, cyclic sequences with Bouma divisions and less commonly, crossbedding, flame structures, rip-ups and rare sedimentary folds.

The age of these turbiditic rocks (unit S) is unknown except in two cases. Greywacke within the westernmost sedimentary enclave (unit S7, Embury Lake Block) has a maximum depositional age of 1843 ±9 Ma (age of the youngest detrital zircon, Ordóñez-Calderón et al., 2011). The same greywacke also contains zircons derived from older, juvenile-arc rocks (ca. 1881–1889 Ma) but Archean zircons are apparently absent; the statistical centre of the detrital zircon population is 1860 ±10 Ma (ca. 1881–1889 Ma) but Archean zircons are apparently absent; the statistical centre of the detrital zircon population is 1860 Ma (N. Rayner, pers. comm. 2009; see ‘Cope Lake suite’ above). The Embury Lake greywacke apparently represents a successor-arc sedimentary deposit, whereas turbiditic rocks at Bartley Lake (unit S2) are likely part of the 1885 ±3 Ma Vick Lake tuff (Stern et al., 1993)—a shoshonitic formation that occupies the upper part of the Bear Lake arc volcanic sequence in the area south of Mikanagan Lake (Bailes and Syme, 1989). The Bartley Lake sedimentary rocks are associated with volcaniclastic deposits (Gilbert, 1990a) and are interpreted as stratigraphically equivalent to the Vick Lake tuff. Fault-bounded turbidite deposits elsewhere in the NFFB (units S1, S3 to S6) may be affiliated with either successor-arc rocks (i.e., Burntwood Group age, deposited between 1860 and 1840 Ma, Machado et al., 1999) or older epiclastic sequences penecontemporaneous with juvenile-arc volcanism (1889–1881 Ma, Rayner, 2010).

Successor-arc sedimentary rocks

Missi Group rocks (unit M)

Fluvial-alluvial conglomerate and crossbedded sandstone of the Missi Group are among the youngest known supracrustal rocks in the Flin Flon Belt. These sedimentary rocks have yielded detrital zircon ages indicating both Neoarchean and Proterozoic detrital sources, the youngest of which are approximately 1847–1851 Ma in age (Ansdell et al., 1992; Ansdell, 1993). Missi Group sedimentary and associated volcanic rocks are unconf ormable or in fault contact with volcanic rocks of the Flin Flon arc assemblage; more recent data indicate that deposition occurred between 1846 and 1842 Ma (Stern et al., 1999).

Missi Group conglomerate and arkosic sandstone occupy a large (approximately 12 by 6 km) structural basin at the western end of the Flin Flon Belt (Figure 4). These rocks, which were mapped and described in detail by Bailes and Syme (1989), extend farther west for over 30 km beyond the boundary between Manitoba and Saskatchewan (NATMAP Shield Margin Project Working Group, 1998, Figure 1b). Missi Group rocks also occur in the northern part of Mikanagan Lake, where a thin fault sliver of conglomerate contains a wide variety of volcanic, sedimentary and granitoid clasts (Gilbert, 1990a, b). The clasts range up to boulder-size (80 by 40 cm) and include some types that display spheroidal hematitic veining, interpreted as evidence for subaerial exposure and weathering prior to deposition. The >40 m wide conglomerate is part of a series of structural enclaves of Missi Group rocks that extend from Athapapuskow Lake, northwards through Whitefish Lake to Mikanagan Lake (NATMAP Shield Margin Project Working Group, 1998, sheet 2).

Intrusive rocks (units P, X and J)

Granitoid plutons (unit P) extend along the boundary between arc volcanic and depleted-MORB rocks, parallel to the northern margin of the Flin Flon Belt (Figure 2). These predominantly tonalitic to granodioritic rocks intrude their volcanic hostrocks and are typically massive to slightly foliated. A weakly defined foliation in the Pistol Lake pluton (unit P2) is deformed by a late (D₃) east-northeast-trending fold that also deforms the Kotyk Lake pluton (see ‘Structural Geology’ below). These granitoid plutons thus stitch contacts between contrasting volcanic terrains but predate subsequent deformation related to intracontinental tectonics post-1840 Ma (Lucas et al., 1996; Gale et al., 1999). In contrast, tonalitic intrusions within the Flin Flon arc assemblage (e.g., unit P1 in Lac Aimée Block)

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* Felsic sill (sample 32-01-0391-4) and Kotyk Lake rhyolite (sample 32-01-0261-1) in Appendix 1. Incompatible-element contents of these two rocks vary by an average of only 5%, resulting in virtually identical chondrite-normalized plots.
may be synvolcanic and penecontemporaneous with the 1888 ±1 Ma Cliff Lake plutonic suite (unit J19; Rayner, 2010). The southwestern part of the Naosap Lake pluton (unit P4), which appears to be in gradational contact with the Baker Patton Complex (unit J12), may also be of juvenile-arc age (see ‘Sourdough Bay suite’ above).

Mafic intrusions, which occupy at least 15% of the area of the NFFB, are subdivided into 1) compositionally layered sills, and 2) mafic to ultramafic rocks of uncertain age (units J and X respectively, Table 1). Batters Lake sill (unit J16) and Tartan Lake sill (unit J17) are lithostratigraphically similar to the 1881 +3/-2 Ma Mikanagan Lake Sill (unit J18; Stern et al., 1999), which has been interpreted as rift-related and coeval with the youngest products of juvenile-arc volcanism (Zwanzig et al., 2001). Some gabbroic intrusions of unit X, emplaced either within arc or MORB-type sequences, may also be synvolcanic in age; geochemical data are locally consistent with such a genetic relationship (e.g., Wabishkok Lake sill (unit X5) and Kotyk Lake sill (unit X4) contain phases that are compositionally similar to Animus Lake MORB-type rocks; see Figure 15g). The Tartan Lake complex (unit X2) is a multiphase heterogeneous gabbroic intrusion that is intruded by younger granitoid rocks (Peloquin, 1985; Gilbert, 1990a); its tectonic affinity and age are unknown.

Discussion

The NFFB consists of two main assemblage types—arc and MORB—that have been mapped in detail and subdivided primarily on the basis of geochemical affinity. Arc volcanic suites are tholeiitic, calcalkaline or of transitional (tholeiitic-calcalkaline) composition, and are typically bimodal. An additional subdivision is based on isotopic data that indicate arc volcanic rocks in the three fault blocks in the eastern part of the NFFB (Lac Aimée, Naosap Lake and Sourdough Bay suites; Figure 2) are distinguished by lower values of εNd (−1.5 to +0.1), indicating up to 12% assimilation of older crust by their source magmas, compared to other NFFB arc volcanic rocks that have higher εNd values (−1.7 to +3.4), indicating relatively less (<3%) crustal assimilation (Table 4; Figure 9). This pattern of more conspicuous crustal assimilation in the three eastern arc-type fault blocks suggests that they may all have originated in the same part of the original oceanic arc, where the amount of lithospheric contamination in the mantle source was greater than elsewhere in the arc system. Similar contamination of the source for arc volcanic rocks elsewhere in the Flin Flon Belt has been attributed to Archean crustal remnants (Stern et al., 1995b). Such rocks have locally been identified as fault slivers within the Northeast Arm Fault (David and Syme, 1994), and Archean crust has also been inferred within the basement underlying arc volcanic rocks in the eastern part of the Flin Flon Belt at Snow Lake (Stern et al., 1995a).

Arc-rift rock suites that are interspersed with the mainly juvenile-arc types in the northern and central parts of the Flin Flon Belt occur in two separate zones. The majority of the (predominantly basaltic) arc-rift volcanic rocks occur within the Lac Aimée and East Mikanagan Lake blocks, which are interpreted as part of a structural corridor that also contains the (arc-rift) Scotty Lake basalt farther to the south (Figures 2, 3 and 4). This corridor extends southwards across the Flin Flon Belt for over 30 km (NATMAP Shield Margin Project Working Group, 1998, sheet 2). Arc-rift basalt also occurs in the northern part of the lithologically diverse Manistikewan Lake Block, which includes rhyolite, volcaniclastic and sedimentary deposits, N-MORB extrusive types and abundant ultramafic to felsic intrusive rocks; the central and southern parts of the fault block contain arc volcanic formations (Bailes and Syme, 1989). The Manistikewan Lake Block, together with the MORB-type rocks in the contiguous Arthurs Lake Block and Grassy Narrows Zone farther to the south (Figure 4; Bailes and Syme, 1989), are interpreted as a second structural corridor, bounded to the east by the Inlet Arm Fault, a major structural feature with approximately 11 km of dextral displacement (Bailes and Syme, 1989). The two structural corridors (associated with the Northeast Arm and Inlet Arm faults respectively) are interpreted as accretion-related tectonic zones that may, in part, be coincident with former zones of rifting within the original oceanic arc. Subsequent deformation along these corridors resulted in the development of anastomosing, steeply dipping faults and the juxtaposition of various fault slices of contrasting tectonic affinity.

The MORB-type volcanic rocks in the NFFB consist almost entirely of tholeiitic basalt and related gabbro and include three geochemically distinctive types: 1) N-MORB and 2) E-MORB volcanic rocks in the Arthurs Lake, West Mikanagan Lake and Animus Lake blocks are tectonically interleaved with arc-type fault blocks, whereas 3) depleted MORB of the Dismal Lake assemblage extends along the northern margin of the Flin Flon arc assemblage. The distinctive REE patterns of the N-MORB and E-MORB suites in the NFFB are comparable to those of similar formations in the Elbow-Athapapuskow ocean-floor assemblage (Stern et al., 1995b). The N-MORB rocks in the ocean-floor assemblage are assumed to be derived from depleted mantle in an ocean-ridge environment, whereas the source of the E-MORB formations is interpreted as enriched mantle, similar to that of plume-related ocean-island basalt.

The combination of MORB- and arc-type compositional features displayed by both the Dismal Lake and Bluenose Lake depleted-MORB rocks is interpreted as the result of mixing of depleted and enriched MORB-like mantle, as well as subduction-modified magmatic sources, as described for some rock types in the Elbow-Athapapuskow ocean-floor assemblage (‘MORB types with arc signature’; Stern et al., 1995b). Variations in the ratio of these different mantle components could account for the compositional range between the several NFFB volcanic suites that are interpreted to have been erupted in back-arc settings (N-MORB, E-MORB and depleted-MORB types). Similar compositional variation within modern BABB has been attributed to differences in the depth and amount of partial melting in the mantle source; the amount of partial melting would be least in E-MORB, greater in depleted MORB and most conspicuous in subduction-modified mantle components (Fryer et al., 1990). In addition, such compositional variation in modern BABB may reflect the extent of back-arc extension, such that the magmatic source at the initiation of rifting may contain more subduction-modified mantle than basalts that are erupted later in the development of the BAB (Stern et al., 1990). According to this model, the Dismal Lake and Bluenose
Lake depleted-MORB sequences may represent an earlier stage of extensional BAB development, compared to N-MORB and E-MORB suites elsewhere in the NFFB.

**Tectonic setting of NFFB arc and MORB-type volcanic rocks**

Comparison of the various arc and MORB geochemical types in the NFFB with modern analogues in the southwestern Pacific Ocean is the basis for the following discussion of their tectonic setting.10 Juvenile-arc volcanic suites and associated epiclastic deposits in the NFFB are stratigraphically and compositionally similar to modern oceanic-arc successions. In addition, geochemically diverse modern BAB such as the Lau basin and Mariana Trench contain rock types that can be equated with the various MORB types in the NFFB (Stern et al., 1990; Martinez and Taylor, 2003). Tectonism, including early deformation in the Flin Flon Belt (1886 ±3 Ma; Zwanzig et al., 2001) and subsequent collisional tectonism, resulted in a collage of the various crustal components (Amisk Collage, Lucas et al., 1996). Fault blocks of contrasting geochemical types have been juxtaposed, and the block-bounding faults are commonly discordant to the truncated axial traces of their internal folds; thus the stratigraphic and age relationships between the various volcanic suites are, in many cases, largely conjectural. In spite of these constraints, instances of continuity such as the occurrence of arc-rift volcanic rocks in the structural corridor containing Lac Aimée and the Scotty Lake blocks suggest that the associated regional faults/shear zones may, in part, be conformable with the trend of the original island arc. Furthermore, interpretation of the tectonic setting of NFFB volcanic rocks by comparison with widely documented modern analogues in western Pacific oceanic arcs indicates how the arc, arc-rift and back-arc types in the NFFB may be related by progressive evolution of an arc system, from initial subduction to subsequent juvenile-arc magmatism, arc-rifting and the establishment of a mature BAB (Figure 17).

**Arc-rift propagation, development of intra-arc and back-arc basins and the potential for VMS mineralization**

The association of extensional tectonic regimes with occurrences of VMS mineralization, which has long been discussed in both ancient and modern arc volcanic terranes (e.g., Sillitoe, 1982), has been well documented in the Flin Flon Belt (Syme et al., 1996, 1999; Bailes and Galley, 1999, 2007; Gibson et al., 2009). The presence of arc-rift volcanic rocks in the NFFB is thus of particular interest, in view of their potential economic importance. Stratigraphic details within the Bear Lake arc succession south of the NFFB map area (Syme et al., 1999) show that two ore deposits (Cuprus and White Lake) were emplaced at an early stage of arc-rifting, which was initiated after deposition of the lower, calcalkaline part of the succession. Uranium-lead zircon dating indicates rifting in the Flin Flon Belt occurred in the 1886–1881 Ma interval (Zwanzig et al., 2001); within the Bear Lake Block, the latter extent of melting (e.g., 28 ±8% in Mariana Arc; Gribble et al., 1998) and thus the degree of depletion of REE and especially HFSE; and 3) convey selected elements (large-ion lithophile elements, alkalis, Al) directly (or indirectly via metasomatism) to the site of melt generation. Flux melting results in characteristic arc magmatic signatures, best shown in plots of incompatible elements (Figure 7a to 7j). In contrast, melts in mature BAB have a different magmatic path and reach the rift axis in a stream of upwelling mantle governed by decompression melting, rising directly beneath the spreading axis. The amounts of melting are relatively less (e.g., 13 ±5% in Mariana Trough; Gribble et al., 1998) and thus depletion of incompatible elements is much reduced, compared to a subduction zone setting. The BAB continues to widen in a process similar to that which generates new lithosphere at mid-ocean ridges. Based on investigations in the Mariana arc system, the interval between initiation of rifting and onset of spreading is 1–4 m.y., and the spatial extent of rifting is 100–150 km, which is the distance between the volcanic front of the arc and the rift axis when spreading would typically be initiated (Gribble et al., 1998). Once the mature BAB has reached a width of approximately 400 km, the supply of magma may be exclusively derived from upwelling mantle via decompression melting—the spreading ridge is then analogous to a mid-ocean-ridge and has a similar magmatic source, with no subduction zone influence. Earlier stages of BAB development are characterized by a wide variety of magmatic types that include arc, arc-rift and various MORB types. Factors that determine the particular composition of the erupted magma include 1) crustal depth, amount of hydrous fluid available from the subducted slab and rate of subduction, which control the temperature, degree of partial melting and the amount of incompatible-element depletion (inversely proportional to crustal depth); 2) composition of the mantle source (i.e., REE-depleted versus fertile, more primitive mantle); strongly depleted mantle melts are generated by incorporation of magmatic sources partially depleted by a prior melt cycle or by several cycles; and 3) extent of mixing of subduction-modified mantle, depleted mantle and undepleted, fertile magma. The interaction between these various factors in the source magma results in a gradation, temporally and spatially, between two BABB types (Gribble et al., 1998)—‘Rift BABB’ (early, at subduction zones) and ‘Spread BABB’ (those in mature BAB that exhibit little, if any, subduction zone influence).

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10 The following synopsis of modern island-arc development (based largely on Stern et al., 1990; Gribble et al., 1998; Martinez and Taylor, 2003; Sinton et al., 2003) serves as a base for further discussion of the relationship between arc and MORB-type volcanic terranes in the NFFB. Arc-rifting of oceanic lithosphere and intra-arc extension are characteristic features of modern island-arc development that have been attributed to ‘slab roll back’ (Hamilton, 1995). This occurs when the angle of the subducting lithospheric slab increases, resulting in a change from a compressive to an extensional tectonic regime in the BAB. After an extensional regime has been established in the oceanic lithosphere at a subduction zone, a rift parallel to the arc axis may be initiated anywhere across the breadth of the arc from the ‘front’ (trench) side to the back-arc area (Figure 17). The rift will propagate actively, parallel to the elongation of the arc, and an intra-arc basin will develop behind it, widening progressively on either side of a central rift. The magmatic regime at the subduction zone continues uninterrupted during this process, but the site of volcanic eruption is diverted away from the arc axis to the nearby rift axis (extension axis). Thus initial magmas at inception of arc-rifting may be indistinguishable from the arc types to which they are related, but subsequent arc-rift magmas incorporate a component of more primitive, fertile ambient mantle that results in higher overall incompatible-element contents. The intra-arc basin may not develop into a large BAB if rifting does not persist. Alternatively, rifting may continue to propagate parallel to the arc, the rift axis at the same time migrating steadily away from the arc. Eventually a point is reached where this axis becomes a ‘spreading axis’ and a BAB is established, which may proceed to become more extensive (e.g., Mariana Trough is over 400 km wide and part of the Izu-Bonin-Mariana arc, initiated at 43 Ma, which extends laterally to 2800 km; Gribble et al., 1998; Stern et al., 2006). During BAB development, the extension axis becomes steadily more remote from the arc and there is a change in the way in which the supply of magma (erupted at the axis) is generated. The mantle melt at the subduction zone is derived by a combination of decompression melting in rising diapirs and ‘flux melting’ (Pearce and Peate, 1995) in an open system that is largely controlled by the influence of hydrous fluids rising from the subducted slab. These fluids 1) lower the melting point of the mantle source; 2) increase the
Figure 17: Sequence of events leading to rifting and BAB development in modern oceanic arcs (based largely on Martinez and Taylor, 2003; Sinton et al., 2003): a) Subduction zone magmatism: partial melting in the mantle wedge (MW) is increased due to hydrous fluids derived from the subducted slab. The amount of fluid and degree of associated (‘flux’) melting are greatest at shallow depth. Viscous coupling results in ‘corner flow’ as mantle convection streams down, parallel to the subducting slab, against the direction of rising mantle diapirs (red lines). Arc volcanism is associated with progressive depletion in the magma of HFSE and HREE due to partial melting of the mantle source and melt extraction, resulting in a wide compositional range. Fractional crystallization and the addition of slab-derived components (H$_2$O, LILE, Al and alkalis) increase the diversity of the arc-type rocks; b) Onset of rifting, development of intra-arc basin and generation of arc-rift basalt: slab rollback (shown by yellow arrow) steepens the subduction angle and initiates an extensional tectonic regime (white arrows) and the onset of rifting. The rift propagates parallel to the plate boundary, at the same time migrating progressively away from the volcanic front (VF). Initially, arc-type magmas are redirected to the site of rifting. Mantle convection adjusts to the new extensional axis, resulting in advection of depleted mantle back to the rift axis, where it may mix with ambient, more fertile mantle to produce arc-rift basalt; and c) Mature BAB and MORB-type magmatism: the extensional axis (EA) is now remote from the subduction zone and beyond the influence of the subducting slab. The N-MORB and E-MORB magma types are generated at the spreading centre by decompression melting in upwelling mantle. During transition from stage (b) to (c), various ‘MORB types with arc signature’ (including ‘depleted-MORB’ types) may be generated by mixing of different mantle types, and reflect the waning influence of the subducting slab. A new arc may develop due to ongoing magmatism, as long as subduction continues at the plate boundary. Abbreviations: BAB, back-arc basin; HFSE, high-field-strength element; HREE, heavy rare-earth element; LILE, large-ion lithophile element; MORB, mid-ocean-ridge basalt; E-MORB, enriched mid-ocean-ridge basalt; N-MORB, normal mid-ocean-ridge basalt.
part of rifting was accompanied by deposition of the Vick Lake shoshonitic tuff (1885 ±3 Ma, Stern et al., 1993) within an actively subsiding rift basin. Economic mineralization is thought to have been localized at the site of rifting due to a combination of high heat-flow and abundant hydrothermal fluids, facilitating the development of high-temperature zones of alteration and mineralization (Syme et al., 1999). The rifting is manifested both geochemically (MORB-like ferrobasalt and associated rhyolite) and structurally (faulting, unconformities and rift-basins with shoshonitic turbidite).

In the case of the two structural corridors in the NFFB associated with the Northeast Arm and Inlet Arm faults, respectively (see previous ‘Discussion’), arc-rifting is inferred largely from geochemical considerations (see descriptions of units J6, J7 and J8 above). In both cases, the presence of arc-rift basalt and juxtaposed arc volcanic rocks (± MORB-type rocks, ± volcaniclastic/epiclastic deposits) suggests that the structural corridors may coincide, in part, with rifted parts of the original island arc. Additional support for this model is provided by the Mikanagan Lake Sill (1881 ±3/–2 Ma; Stern et al., 1999) that extends along the western side of the Northeast Arm Fault and has been interpreted to be associated with rifting at the end of juvenile-arc volcanism (Zwanzig et al., 2001). In spite of numerous exploration programs for base- and precious-metal mineralization since the early 1950s, no economic mineralization has been identified, so far, in either the Lac Aimée–Mikanagan Lake–Scotty Lake corridor or the Manistikwan Lake–Arthurs Lake–Grassy Narrows Zone corridor.

The presence of the Baker Patton Complex immediately south of Lac Aimée Block may also be related to rifting of the Proterozoic arc system. This felsic complex, which represents by far the largest felsic volcanic terrane in the Flin Flon Belt, contains one gold and at least five VMS-type mineral deposits (Gale and Eccles, 1988a). The location of the felsic complex at the margin of the Lac Aimée–Scotty Lake Zone of rifting is noteworthy, in light of the association of felsic volcanic rocks with arc-rifting elsewhere, such as 1) rhyolite and rhyolite-related volcanics at Bartley Lake (units J15 and S2, respectively); 2) elsewhere within the Flin Flon Belt (e.g., Grassy Narrows rhyolite and basalt, Two Portage Lake rhyolite crystal tuff and ferrobasalt, Syme et al., 1999); and 3) some sites of active rift propagation within modern oceanic arcs (Gribble at al., 1998; Stern et al., 2006).

Tectonic setting and ages of N-MORB and E-MORB types in the NFFB

The Elbow-Athapapuskow ocean-floor assemblage (Figure 1) has been interpreted as a back-arc component of the Paleoproterozoic arc represented by the Flin Flon arc assemblage (Stern et al., 1995b; NATMAP Shield Margin Project Working Group, 1998). The ages of several synvolcanic intrusions within the ocean-floor assemblage (1901–1904 Ma, Stern at al., 1995b) indicates it is slightly older than the oldest part of the Flin Flon arc assemblage (1889 Ma, Rayner, 2010) and thus predates both the juvenile-arc magmatism and the previously quoted 1886–1881 Ma interval of rifting within the Paleoproterozoic arc. It is noteworthy that the BAB represented by the Elbow-Athapapuskow ocean-floor assemblage consists of N-MORB and E-MORB types that show little or no evidence for admixed subduction-modified mantle, and thus likely represent a mature stage of BAB development (see ‘Tectonic setting of NFFB arc and MORB-type volcanic rocks’ above). If this BAB is analogous to those in the present-day western Pacific island arcs, associated arc volcanic rocks of similar or greater age (i.e., ≥1904 Ma) might be expected to occur in abundance in the Flin Flon Belt. However, rocks of that age that might represent the onset of juvenile-arc magmatism have not been documented. It thus seems likely that most of the oceanic arc within which the ‘Elbow-Athapapuskow BAB’ presumably began as a rift-basin is not represented in the stratigraphic record, due to recycling by erosion and/or subduction.

The original site in the Flin Flon Belt from which the disparate N-MORB and E-MORB components of the NFFB (Arthurs, Bluenose, Animus and West Mikanagan lakes) were derived is uncertain. The relative consistency of their geochemical composition (Figure 15a to 15d) and their stratigraphic simplicity (basalt and gabbro) suggest that they may be parts of a mature BAB similar to the Elbow-Athapapuskow BAB, and represent allochthonous fault slices tectonically emplaced within the Amisk Collage. If they represent dismembered parts of a BAB flanking the arc rocks, they may well be derived from the MORB-type assemblage at the (current) northern side of the Flin Flon Belt, at or possibly close to the present site of the Bluenose Lake N-MORB suite (see discussion in ‘Animus Lake N-MORB and E-MORB suites’ above).

Tectonic setting of depleted-MORB types in the NFFB

In contrast to N-MORB and E-MORB types, depleted MORB in the Dismal Lake assemblage and at Bluenose Lake is characterized by a wide compositional range and distinctly different pattern in plots of incompatible elements (Figure 15e, 15f). Although the depleted-MORB sequence is, like other MORB types, stratigraphically simple (predominantly basalt and gabbro), the incompatible-element abundances and ratios indicate the evolution of the magmatic source was more complex. The incompatible-element pattern suggests that the source magma was subjected to a substantial amount of partial melting, based on the petrogenetic principle that incompatible-element contents are controlled by the amount of melting in the mantle source of basaltic magmas (Gribble et al., 1998). In closed systems, the contents of these elements are inversely proportional to the degree of partial melting; thus the most strongly depleted-MORB types are likely associated with the greatest amounts of partial melting.

The least depleted rocks in the Dismal Lake suite display flat to slightly positive-sloping patterns (Figure 15e), with equal or slightly increased contents of some incompatible elements relative to N-MORB, suggesting partial melting was not significant in the MORB-type source magma. At the other extreme, the most depleted types are, in this respect, unequalled by any other basaltic rocks in the Flin Flon Belt. Theoretical considerations suggest it is unlikely such extreme depletion could simply be the result of a single episode of partial melting, and may be better explained as a result of multiple melting episodes; in other words, a mantle source that was already
depleted was subjected to additional partial melting prior to extrusion (Sinton et al., 2003). The site of greatest partial melting in modern oceanic-arc systems is at shallow crustal levels within subduction zones, where hydrous (slab-derived) fluids are most abundant and exert the most influence to facilitate melting of rising mantle diapirs. Some of the resulting partial melts may, via ‘corner flow’ within the mantle convection system, be reintroduced to the rift axis in the developing intra-arc basin after mixing with ambient mantle at this site (Figure 17). The BABB that is generated is thus a mixture of a partly depleted melt (‘subduction-modified mantle’) and a MORB-like mantle source (Martinez and Taylor, 2003; Sinton et al., 2003). The subduction-modified mantle, being derived in part from the descending crustal slab, is also somewhat enriched in LILE, alkalis and Al. The modest Th enrichment and elevated Th/Nb values of some Dismal Lake depleted MORB (Figure 15e; Appendix 1) may be explained as a result of the incorporation of (or metasomatism by) such partly depleted, subduction-modified mantle melts in the magmatic source. The depleted-MORB types are clearly distinguished from N-MORB and E-MORB by higher Th/Nb ratios but have lower Nb contents than E-MORB (Figure 15a to 15f; Table 3, back pocket) and as a result, plot in or close to the fields of arc rocks (Figure 16). In contrast to arc rocks, however, $\varepsilon_{Nd}$ isotope data for Dismal Lake basalt (+5.2) show the depleted-MORB magmatic source did not incorporate any older continental crust (Table 4).

Apart from partly depleted, subduction-modified mantle, the other main component in the mantle source for Dismal Lake volcanic rocks is assumed to be N-MORB and/or possibly a primitive, moderately fertile mantle type. The wide compositional range of Dismal Lake basalts likely reflects different ratios of these various mantle components, which may be a result of the progressive movement of the spreading centre away from the volcanic front during BAB evolution.

In this model, the youngest and least depleted rocks are compositionally similar to modern N-MORB with a slight arc signature. Moderately depleted types, some of which occur very close to the southern margin of the Dismal Lake assemblage, are similar to the most primitive basalts in the present-day Manus Basin (‘M1’ type in Sinton et al., 2003). The incompatible-element plot of one flow located at the Manus spreading centre (‘Manus Basin basalt’ in Figure 18) compares very closely with moderately depleted basalt 50–100 m from the southern margin of the Dismal Lake assemblage. The most depleted basalts in the Dismal Lake assemblage are assumed to be the earliest products, associated with the onset of spreading in the BAB; these have no systematic distribution geographically.

In addition to depleted MORB, sporadic occurrences of arc and N-MORB volcanic types are present within the Dismal Lake assemblage. Contact relationships between these contrasting rock types are not known, but localized disruption suggests some arc enclaves may be fault-bounded. In other cases the contrasting rock types may be conformable with the depleted-MORB hostrock—a similar relationship is evident in modern BAB such as Mariana Trough (Stern et al., 1990; Martinez and Taylor, 2003), where the presence of a wide variety of MORB- and arc-type rocks reflects the heterogeneous mantle and ephemeral changes in the magmatic source during BAB evolution.

The regional distribution of BAB rock types relative to the arc volcanic rocks in the Flin Flon Belt (Figures 1 and 2)—that is, on the northern side (Dismal Lake depleted MORB) and the eastern and southern sides (Elbow-Athapapuskow ocean-floor assemblage)—may reflect a formerly less disrupted combination of two distinct basins within one back-arc terrane. Geochemically distinct and apparently unrelated, these two BABB assemblages may, however, have been erupted contemporaneously, but in different parts of the back-arc basin.

**Figure 18**: Plot of N-MORB normalized incompatible-elements for two depleted-MORB flows at the southern margin of the Dismal Lake assemblage (spaced 10 km apart along strike), compared with a modern MORB-type flow from the Manus Spreading Centre, Manus Basin (M1 type, sample 32-5 in Sinton et al., 2003). Normalizing values from Sun and McDonough (1989). Abbreviations: N-MORB, normal mid-ocean-ridge basalt.
Structural geology

Structural studies in the Flin Flon Belt were initiated over 70 years ago (Ambrose, 1936; Stockwell, 1960; Byers at al., 1965; Stauffer and Mukherjee, 1971) and mostly focused on the western part of the belt, where good to excellent preservation and outcrop exposure facilitated investigation of the tectonic history in both the juvenile-arc and later successor-arc rocks. Interpretations of the deformation history vary among these and more recent studies (Bailes and Syme, 1989; Thomas, 1992, 1994; Fedorowich et al., 1995; Gale et al., 1999; Lafrance et al., 2007), but the latter group of authors all concur that after 1880–1870 Ma tectonic amalgamation of the oceanic-arc system, an early deformation event (D$_1$) in this study) occurred prior to deposition of successor-arc sedimentary rocks; all other events affected both the juvenile-arc and successor-arc rocks, and thus were post-1840 Ma (Table 5). After D$_1$ deformation and the subsequent deposition of successor-arc sediments of the Burntwood and Missi groups (1860–1842 Ma), the sedimentary rocks were tectonically intercalated with the juvenile-arc rocks during a renewed collisional event (D$_2$ and D$_{2a}$ of Lucas et al., 1996; D$_3$ and D$_3a$ in this study) that was characterized by thrusting and tectonic displacement. The D$_3$ event in the NFFB is identified where major F$_3$ folds deform an older regional foliation (S$_2$), as in the Lac Aimée Block (Figure 3). These folds are typically tight to isoclinal and have moderately to steeply plunging axes. Axial traces of F$_3$ folds are roughly parallel to the trend of the fault blocks in which they occur, but they are locally truncated by block-bounding faults.

Open, east-northeast-trending folds characterize D$_3$, such as the Embury Lake antiform that dominates the regional structure in the western part of the NFFB. This antiform has a moderate easterly plunge, estimated as 30$^\circ$ with azimuth 096$^\circ$ by Stauffer and Mukherjee (1971). A northeast-trending open D$_1$ fold deforms the internal fabric of the Animus Lake Block, which is characterized by a series of curvilinear D$_1$ fold pairs that outline the D$_3$ structure. Open, east-northeast-trending folds, also interpreted as D$_3$ in age, deform volcanic and intrusive rocks east of Wabishkok Lake, as well as the foliation in the Pistol Lake pluton (unit P2; Figures 2 and 3). These folds have a moderate easterly plunge, estimated as 17$^\circ$ with azimuth 080$^\circ$ (Gilbert, 2001a, b), and are associated with a shallow, east-plunging lineation. The D$_3$ deformation event has been attributed to sinistral movement at the contact between the Flin Flon Belt and Kisseynew Domain (Wilcox, 1990; Ashton, 1993).

North-northeast to north-northeast trending, high-angle faults are products of a final episode of deformation (D$_4$). Within the NFFB, these late faults are most abundant in the area between Embury Lake and Tartan Lake, where they are locally truncated by block-bounding faults, indicating renewed displacement occurred along some of the older faults. Fault breccia within the block-bounding faults may be products of this late reactivation. At one locality along the Sourdough Bay Fault, close to the western end of Naosap Lake (Figure 3), a 45 m wide zone of heterolithic tectonic breccia contains a chaotic assemblage of massive to foliated blocks of volcanic, sedimentary and gneissic rocks up to 1 m long. Fault breccia that occupies a >17 m wide zone within the block-bounding fault at southern Bluenose Lake is characterized by an ultramafic (altered pyroxenite) matrix.

Structural geology discussion

Recognition of most of the major fold blocks in the NFFB is based on stratigraphic-facing indicators and the attitudes of primary layering, which identify the fold type, style and orientation. The age of deformation is interpreted from these data, but such an age is provisional unless constrained by evidence such as the deformation of an earlier tectonic fabric, or the relationship with younger, successor-arc rocks. Recognition of the Cope Lake anticline as a first generation structure (Figure 3) is based on the interpretation of a D$_2$ age for the complementary syncline immediately to the south (Bailes and Syme, 1989). Major folds in other fault blocks could be contemporaneous with either the D$_2$ Cope Lake folds or the significantly younger, (post–successor arc) D$_3$, Lac Aimée synclinorium (Gilbert, 2002a). Most folds have been provisionally designated as D$_2$ in age. The numerous subparallel folds in the Animus Lake Block are, like the Cope Lake fold pair, northwest-trending, discordant to the block-bounding faults, and deformed by a later (D$_3$) fold; they are interpreted as products of early (D$_3$) deformation, even though they do not appear to be overprinted by a later foliation—unlike the Cope Lake syncline (Bailes and Syme, 1989).

It is unlikely that Animus Lake and Lac Aimée blocks were contiguous during D$_2$ because there is no evidence (i.e., northwest-trending structures) for the early deformation event in the Lac Aimée rocks. Both fault blocks, however, contain sporadic southwest-plunging minor folds and lineations that are attributed to D$_3$ deformation, suggesting that they had been juxtaposed by tectonic transport during D$_{2a}$, prior to D$_3$ (Table 5). These two fault blocks are separated by the Lac Aimée Fault Zone (Figure 3; Gilbert, 1997a)—a northeast-trending branch of the Northeast Arm Fault that represents a major structural break within the Flin Flon Belt.

The Northeast Arm Fault is a regional structure that extends from the southern part of the Flin Flon Belt northward for over 35 km (Figures 2, 3 and 4). The fault bifurcates at southwestern Mikanagan Lake and again at the rapids between Lac Aimée and Mikanagan Lake; a north-trending branch extends through Animus Lake, from where several fault splays continue northwestwards through Bluenose Lake and beyond. The crustal scale of the Northeast Arm Fault is indicated by the fact that 1) it corresponds to a discontinuity in the pattern of reflectors in a regional seismic survey (LITHOPROBE section line 7A, Lucas et al., 1994; Gilbert, 1997a); 2) late Neoarchean, 2.52 Ga tonalitic slivers within the shear zone are interpreted as derived from a basement underlying the Flin Flon Belt (David and Syme, 1994); 3) it juxtaposes a variety of tectonically contrasting fault blocks in both the NFFB (Figures 2 and 4) and the south-central part of the Flin Flon Belt (Bailes and Syme, 1989); and 4) it divides the NFFB into two structurally distinct subareas: west of the Northeast Arm Fault, major faults and folds trend mainly northwest, whereas east of the fault the main structural trends are northeast or east. The Northeast Arm Fault has a long history of repeated movement (Syme, 1986; David and Syme, 1994; Lucas et al., 1996) and was probably initiated
Table 5: Deformation history of the northern Flin Flon Belt, west-central Manitoba, compared with interpretations of the sequence of events in the Flin Flon Belt by Bailes and Syme (1989), Lucas et al. (1996) and Gale et al. (1999).

<table>
<thead>
<tr>
<th>Stage</th>
<th>Bailes and Syme (1989), Flin Flon–White Lake area</th>
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<tr>
<td>D₃</td>
<td>Steeply dipping shear zones, north-trending folds and associated foliation. Terminal collision with Superior Province (ca. 1800–1770 Ma).</td>
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<td></td>
<td>Open, east-northeast-trending faults are defined 1) in Animus Lake Block, by deformation of F₁ fold axial traces; 2) in western part of NFFB, by deformation of fault blocks in Cliff Lake–Tartan Lake area (Embry Lake antiform, Stauffer and Mukherjee, 1971); and 3) in eastern part of NFFB, by deformation of Kotyk Lake pluton and hostrocks. Subsequent major fault displacement. Reactivation of block-bounding faults; truncation of intrablock fold axial-traces. Brittle deformation (e.g., fault breccia in Sourdough Bay Fault, Northeast Arm Fault).</td>
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<tr>
<td>D₃a</td>
<td>Magmatism and thrusting of Kisseynew Domain (Burntwood Group) southward over the Amisk Collage; collision of Reindeer Zone with Sask craton (1840–1830 Ma).</td>
<td>Intrusion of plutons (1860–1840 Ma); north-trending folds with associated foliation, shear zones.</td>
<td>North-northeast-verging folds; rare cleavage (S₁); imbrication and thrusting of volcanic basement rocks over cover sedimentary rocks; age bracket 1842–1820 Ma (1840–1835 Ma, Connors, 1996).</td>
<td>Major, tight to isoclinal folds roughly concordant with trend of fault blocks deform S₁ foliation (e.g., synclinal structure in Lac Aimée Block with moderate to steep, southwest plunge). Tight, synclinal fold with east-northeast plunge deformed the Bluenose Lake Block. Minor southeast-plunging folds in both Lac Aimée and Animus Lake blocks. Regional foliation (S₂).</td>
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<tr>
<td>D₃b</td>
<td>Southward thrusting of Reindeer Zone over the Sask craton; peak metamorphism (1830–1800 Ma), S₂ foliation.</td>
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<td>Reactivation of Northeast Arm Fault; juxtaposition of Lac Aimée and Animus Lake fault blocks.</td>
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<tr>
<td>P₃</td>
<td>North-trending moderately open folds in Missi Group. Foliation in Missi Group but rare in Flin Flon arc assemblage. Peak metamorphism.</td>
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<tr>
<td>P₄</td>
<td>North- to northeast-trending open to tight folds in Flin Flon arc assemblage. Foliation well developed.</td>
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<tr>
<td>P₅</td>
<td>East- to east-southeast trending open to tight folds in Missi Group. No foliation.</td>
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Boundary intrusion ca. 1842 Ma

Missi Group sedimentation ca. 1845–1835 Ma

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<td>P₅</td>
<td>North- to northwest-trending tight isoclinal folds (Burley Lake, Cope Lake synclines) predate Mikanagan Lake Sill type (1.81 Ga) intrusions. No foliation.</td>
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<td>D₃</td>
<td>Tectonic accretion and regional shear zones resulting in Amisk Collage (1880–1870 Ma).</td>
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as a major thrust during tectonic accretion (Table 5), when the late Neoarchean basement slivers may have been incorporated (Lucas, 1993; Lucas et al., 1993). In the south-central part of the Flin Flon Belt, the sense of movement of the fault is not known but the amount of displacement was probably several kilometres, based on the truncation of the Bear Lake Block stratigraphy (Bailes and Syme, 1989).

The north-trending branch of the Northeast Arm Fault at Animus Lake is interpreted to have been associated with approximately 3 km of sinistral displacement, based on stratigraphic offset by the fault. Restoration of the pattern of fault blocks to the pre-faulting configuration would align juvenile-arc rock types in the Tartan Lake and Wabishkok Lake blocks, MORB-type volcanic rocks in the Animus Lake and West Mikanagan Lake fault blocks, as well as the large (1 km thick) gabbroic intrusions that extend along the northern margins of these two MORB-type blocks (Batters Lake sill; Figures 2, 3, 4 and 19). Farther south on the Northeast Arm Fault, restoration based on several kilometres of sinistral offset would move arc-rift basalt in Scotty Lake and East Mikanagan Lake blocks closer together but not into alignment, possibly due to additional offset along the Lac Aimée Fault Zone during emplacement of the Whitefish Lake–Mikanagan Lake Block (Figures 4 and 19). Much of the lateral displacement on the Northeast Arm Fault may have occurred during D2a, possibly corresponding to the interval when Lac Aimée and Animus Lake blocks were presumably juxtaposed along the Lac Aimée Fault Zone. Continued deformation (D3) is assumed to have resulted in folding in Lac Aimée Block as well as various other fault blocks (e.g., Hook Lake, Arthurs Lake, Tartan Lake).

**Economic geology**

The potential for particular rock suites in the NFFB to host base-metal and/or precious-metal ore deposits can be assessed by investigation of the distribution and setting of known mineral occurrences in rocks 1) within the NFFB and 2) within correlative stratigraphic units in the southern and central parts of the Flin Flon Belt (Gale and Eccles, 1988a, b, c; Syme and Bailes, 1993; Gale and Norquay, 1996; Syme, 1998; Bailes and Galley, 1999; Syme et al., 1999; Gale 2001; Gale and Dabek, 2002). Volcanogenic massive sulphide (VMS)-related mineralization in the southern and central parts of the Flin Flon Belt is associated with juvenile-arc and MORB-type volcanic rocks along the Northeast Arm Fault (Figure 19).

**Figure 19:** Northeast Arm Fault, northern Flin Flon Belt, west-central Manitoba: restoration of fault blocks on opposite sides of the fault prior to the inferred last major movement (possibly during D2a), based on an estimated 3 km of sinistral displacement.
Belt is typically associated with one or more of the following features: 1) rifting of arc sequences; 2) felsic magmatism in arc sequences; and 3) faulted contacts between contrasting stratigraphic components or distinctive fault blocks. These three parameters serve as the most obvious guides for assessing the mineralization potential of localities within the NFFB that have not so far been targeted for exploration.

Two panels extending across the Flin Flon Belt may have potential for base- or precious-metal mineralization, based on the interpretation of an arc-rift tectonic setting for some of their components (see ‘Arc-rift propagation, development of intra-arc and back-arc basins and the potential for VMS mineralization’ above). The two rift-related panels correspond, respectively, to 1) Manistikwan Lake Block–Arthurs Lake Block–Grassy Narrows Zone, and 2) Lac Aimée–East Mikanagan Lake–Scotty Lake blocks. In spite of ca. 1.88–1.78 Ga tectonic amalgamation that resulted in the juxtaposition of contrasting components of the original oceanic-arc system, it is suggested that these panels are structural corridors that correspond, in part, to zones of rifting in the original arc.

Mineral exploration has been carried out, beginning in the 1950s, at numerous localities in the northern part of the Manistikwan Lake Block, within the first rift-related panel (locations 44, 45 and 126 to 130 in Gale and Eccles, 1988b). Similar investigations have been carried out at mineralized localities farther to the south, at the margins of the Grassy Narrows Zone (locations 108 and 123 in Gale and Eccles, 1988a). The second rift-related panel also has a long history of exploration. Precious- and base-metal mineralization has been prospected in the northern part of Lac Aimée Block and at stratigraphic/structural contacts immediately to the north by Esso Minerals, between 1988 and 1992 (Assessment Files 71615, 71818). At the southeastern margin of Lac Aimée Block, base-metal mineralization was discovered 90 years ago at the faulted contact between the arc volcanic rocks and arc-rift volcanic rocks of the East Mikanagan Lake Block (‘KD zone’, identified in 1921, Gilbert, 1996a); base-metal mineralization also occurs in north-trending faults within arc-rift rocks at northeast Mikanagan Lake (see ‘East Mikanagan Lake arc-rift suite’ above). In summary, both of the rift-related panels contain numerous prospects that have been explored periodically for over five decades and appear to have potential for VMS-associated mineralization.

Rhyolite-hosted base-metal mineralization at Trout Lake mine (Figure 4), a Cu-Zn ore deposit of over 20 million tonnes (Ordóñez-Calderón et al., 2009), occurs at the faulted contact between a volcano-sedimentary sequence (to the west) and a greywacke-argillite sequence (to the east), probably corresponding to the contact between the Cope Lake and Embury Lake blocks (Gilbert, 1988a, 1990b). This Cu-Zn deposit, which is the subject of ongoing study (Ordóñez-Calderón et al., 2009), is hosted by 1878 ±1.1 Ma rocks (Rayner, 2010) and has a somewhat different stratigraphic setting compared to the relatively older Flin Flon–777–Callinan VMS deposits farther southwest, within the Flin Flon Block; the Flin Flon deposits are hosted by the 1887 Ma mine rhyolite that is part of the ca. 1889 Ma Flin Flon formation (Rayner, 2010).

Within the NFFB, rhyolite-associated VMS-type mineralization occurs

1) in arc volcanic rocks close to Kotyk Lake and at north-eastern Blueberry Lake, less than 100 m from the contact between arc volcanic and depleted-MORB (back-arc) rocks of the Dismal Lake assemblage (Gilbert, 2003b; Assessment Files 93337, 90400, 90401); 2) in felsic volcanic rocks within the Baker Patton Complex (Sourdough Bay Block); and 3) in arc rocks that occur as enclaves within, or at the margins of the Dismal Lake assemblage.

These rocks have been targets of mineral exploration for over 50 years, most recently between 1997 and 2002 (Assessment Files 73994, 73546, 73348; see ‘arc volcanic enclaves within the Dismal Lake depleted-MORB assemblage’ above). The Cu-Zn and precious-metal mineralization in these enclaves is typically hosted by felsic volcanic rocks and is associated with alteration, metasomatism and pervasive deformation.

In many of the occurrences of VMS-type mineralization cited above, structural controls have played an important role in localizing the deposits. Such controls are particularly important in the Tartan Lake gold mine (Figure 4), an approximately 600 000 tonne orebody (Peloquin and Gale, 1985) that is currently under redevelopment by St. Eugene Mining Corporation Ltd. (St. Eugene Mining Corporation Ltd., 2010). The gold mineralization, which is associated with quartz veining and carbonate alteration, is located in shear at the margin of the gabbroic Tartan Lake complex (Figure 2; Peloquin and Gale, 1985).

Detailed mapping has revealed a hitherto unknown complexity of structure in the NFFB, and geochemical investigations have attempted to relate the diverse tectonostratigraphic components as belonging to various tectonic types that have been defined in modern oceanic arcs. As a result, several areas favourable for base-metal and/or gold exploration have been identified, in addition to areas likely not to be prospective for such mineralization. This new information, together with the fact that the Flin Flon district has an established infrastructure for mineral exploration and development, may provide a significant incentive for renewed exploration in the area.

Conclusions

Map GR2011-1-1 represents a substantial upgrade to the previous geological maps of the NFFB published in the 1940s. This new map serves as a link between detailed maps recently published in the area to the north (southern Kisseynew Domain, Zwanzig, 2010) and the Flin-Flon–White Lake area map immediately to the south (Bailes and Syme, 1989). Geochemical investigations that have accompanied mapping of the NFFB have been key for distinguishing the various allochthons that make up this part of the belt, as well as for identifying localities that may represent prospective targets for VMS-associated mineralization. Trace element, REE and selective Sm-Nd isotopic data from approximately 300 analyzed volcanic rock samples in the NFFB has resulted in the recognition of:

• various crustal types (juvenile arc, arc-rift and back-arc
ocean-floor) juxtaposed by block-bounding faults;

- continuity, discontinuity or lateral gradation of map units between the south-central and northern parts of the Flin Flon Belt;

- two structural corridors with evidence for arc-rifting, bounded in part by the Inlet Arm and Northeast Arm faults, which may contain promising targets for VMS-associated mineralization; and

- felsic volcanic rock map units that may be prospective for VMS-associated mineralization, based on their geochemical similarity to ore-bearing rhyolites both in the Flin Flon area and in older (Archean) successions elsewhere.

The most promising scenarios for base-metal or precious-metal mineralization in the NFFB appear to be stratigraphic and/or structural discontinuities, rift-related successions and felsic volcanic hostrocks. The fact that the NFFB has, in general, received less intensive mineral exploration activity than areas closer to the various ore deposits in the vicinity of Flin Flon may be argued in favour of renewed exploration initiatives in the NFFB. The results of detailed mapping and the associated geological investigations reported here have indicated several localities that may profitably be targeted in future exploration programs. This work has also provided a basis for new programs of more detailed or focused mapping and associated geological investigation.

Acknowledgments

Numerous student assistants were employed during the course of field mapping and their contribution to the project is gratefully acknowledged here, as well as in the annual MGS ‘Report of Activities’ that have summarized the results of mapping at the end of each field season. Logistical support for field operations was provided by N. Brandson, and staff at MGS Rock Preparation Lab under G. Benger (and formerly D. Berk) processed rock samples. Preparation of the map by digital cartography was by M.E. McFarlane, GIS processing was by L.E. Chackowsky and B.K. Lenton drafted the figures. These marginal notes benefited from fruitful discussion with H.V. Zwanzig and A.H. Bailes, as well as C.O. Böhm and R.-L. Simard, both of whom also edited the first drafts of this manuscript and the accompanying map. The contribution of these colleagues at MGS, as well as the meticulous editing of T. Sifrer is gratefully acknowledged.

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