Introduction

The Flin Flon Belt is the most prolific mining district in Manitoba with Cu-Zn-Au-Ag ore in 26 separate deposits totalling 183 million tonnes (combined reserves and production to 2007). The area has been the subject of geological mapping by provincial and federal surveys for over 60 years and detailed mapping and related research projects continue to the present time. In 1986, the author initiated 1: 20 000 scale geological mapping in the north part of the Flin Flon Belt, from the Manitoba-Saskatchewan boundary in the west to Naosap Lake in the east (*Figure 1*). A compilation of the results of this mapping is underway and will result in a geological report, planned for release in 2010. This report will include a 1:50 000 scale geological map of the north-central part of the Flin Flon Belt, together with descriptions of the geology and geochemistry of the various tectonostratigraphic components and a geochemical database.

Tectonostratigraphic components in the Northern Flin Flon Belt

The map area in the northern Flin Flon Belt (NFFB) contains more than 20 tectonically distinct blocks or fault slices of diverse volcanic, related intrusive and subordinate sedimentary rocks (*Figure 1*). Most of these components are akin to modern oceanic arc rocks and are part of the Flin Flon arc assemblage (Stern et al., 1995a). The arc-type rocks are structurally intercalated with mid-ocean ridge (MORB)-like volcanic rocks (*Figure 2a*), and an extensive area of rare-earth element (REE)-depleted MORB (Dismal Lake Terrane) extends along and across the northern boundary of the Flin Flon Belt, which is locally in fault contact with the Kisseynew Domain to the north. Arc-type rocks in the NFFB are assumed to be associated with subduction at a former oceanic arc, whereas MORB and depleted MORB types are interpreted to have been associated with rifting and emplacement in a back-arc basin environment. The age of these MORB rocks is not known, but analogous MORB-type formations in the southern part of the Flin Flon Belt (Elbow-Athapapuskow ocean-floor assemblage) are associated with 1.90 Ga synvolcanic intrusions that are coeval with some rocks in the tectonically juxtaposed 1.90–1.88 Ga Flin Flon arc assemblage (Stern et al., 1995b).

Arc and evolved-arc volcanic suites

Arc volcanic suites

Arc volcanic rocks consist of a wide range of massive to fragmental types and associated intrusions (*Figure 2b-2f*). Basalt and basaltic andesite are predominant and felsic types generally minor, except in the northern part of the Sourdough Bay Block where rhyolitic types constitute over half of the rock suite. Geochemically, the juvenile arc volcanic rocks are characterized by enrichment in Th and light REE but depletion of high-field-strength elements (HFSE) relative to MORB (*Figure 3a*). Compared to typical MORB-type volcanic rocks in the NFFB, the arc volcanic rocks are distinguished by elevated Th/Nb and La/Yb, and exhibit a relatively wider range of incompatible-element contents. The range of Sm-Nd isotopic ratios in NFFB arc-type rocks, with εNd values between -1.5 and +3.4 at 1.9 Ga, indicate that small amounts of recycled older crust (up to 10%) were incorporated in the mantle source of these volcanic suites (Pearce, 1983).

Evolved arc suites

Geochemically 'evolved' arc-type volcanic rocks occupy the East Mikanagan Lake Block (*Figure 1*), and analogous rocks are intercalated with 'normal' arc rocks in the Manistikwan Lake and Lac Aimée blocks. The evolved arc sequences consist largely of massive to pillowed basalt and related gabbro (±subordinate ferrobasalt, volcaniclastic and/or sedimentary rocks); they are thus less diverse lithologically compared to normal arc sequences. The evolved arc types are distinguished by higher overall incompatible-element contents relative to normal arc basalts with similar SiO_2 content (*Figure 3a, 3b*). They are variably enriched in FeO_t (7.6%–17.8%), TiO_2 (1.0%–2.2%) and Th (0.7–3.6 ppm). The Sm-Nd isotope data for evolved arc basalt and (possibly related) felsic volcanic rocks, with εNd values between -1.7 and +1.6 at 1.9 Ga, indicate that incorporation of older crustal material during magmatic evolution varied from 2% to >10% (Pearce, 1983; Stern et al.,1995a).

There appears to be a continuum of increasing overall incompatible-element contents from Lac Aimée normal arc through Lac Aimée evolved arc to East Mikanagan Lake evolved arc volcanic suites (*Figure 3a, 3b*), but these three volcanic suites have distinctive TiO_2/MgO ratios suggesting differences in their tectonic settings (*Figure 4a*). In the TiO_2 vs. MgO diagram, Lac Aimée normal arc basalt samples plot in the field of modern arc magmas and East Mikanagan Lake evolved arc rocks fall in the MORB and back-arc basin basalt (BABB) field; Lac Aimée evolved arc rocks plot between these two fields.

Evolved arc volcanic rocks in the Lac Aimée and East Mikanagan Lake blocks occur within a corridor that extends from Lac Aimée southwards into the central part of the Flin Flon Belt (*Figure 1*). Farther south in this corridor, Fe-rich tholeiite in the Scotty Lake Block is lithologically and compositionally similar to the East Mikanagan Lake evolved arc basalt. Scotty Lake basalt and evolved arc volcanic rocks in both the Lac Aimée and East Mikanagan Lake blocks could be fractionated components of a common magmatic source that evolved concomitant with the onset of arc rifting and progressive back-arc basin development. The progressive increase southward in the level of geochemically evolved composition from the Lac Aimée Block to the East Mikanagan Lake Block to the Scotty Lake Block (*Figures 3a, 3b, 4a*) may reflect a concurrent trend of increasingly more advanced rifting within this structural corridor. Subsequent tectonic reworking during 1.88–1.87 Ga assembly of the Amisk Collage (Lucas et al., 1996), associated with movement along a system of major faults, could have aligned the evolved arc volcanic suites along a structural corridor that extends from north to south across the Flin Flon Belt.

Manitoba

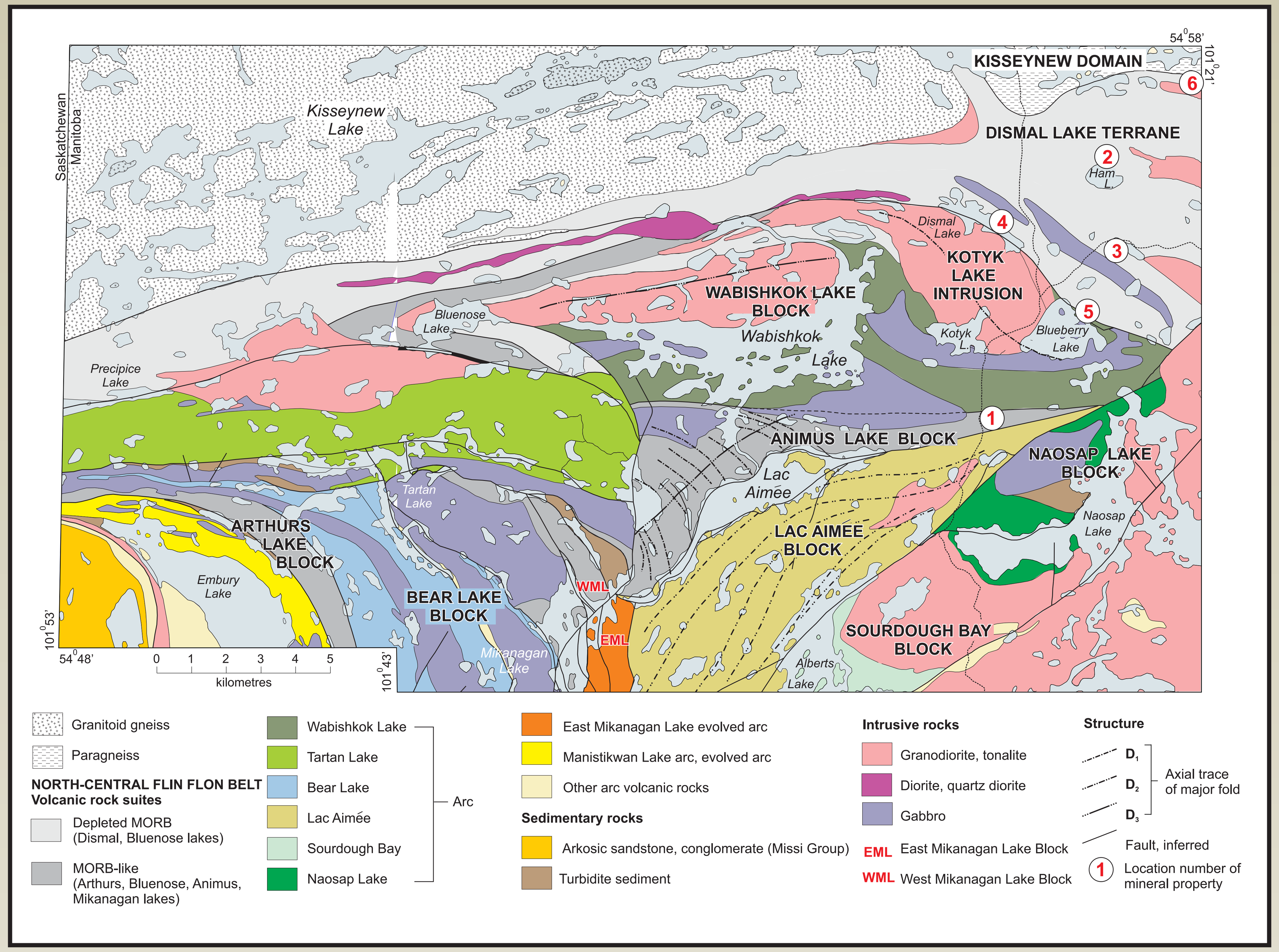

Figure 1: Geology of the north-central part of the Flin Flon Belt, showing the main tectonostratigraphic components.

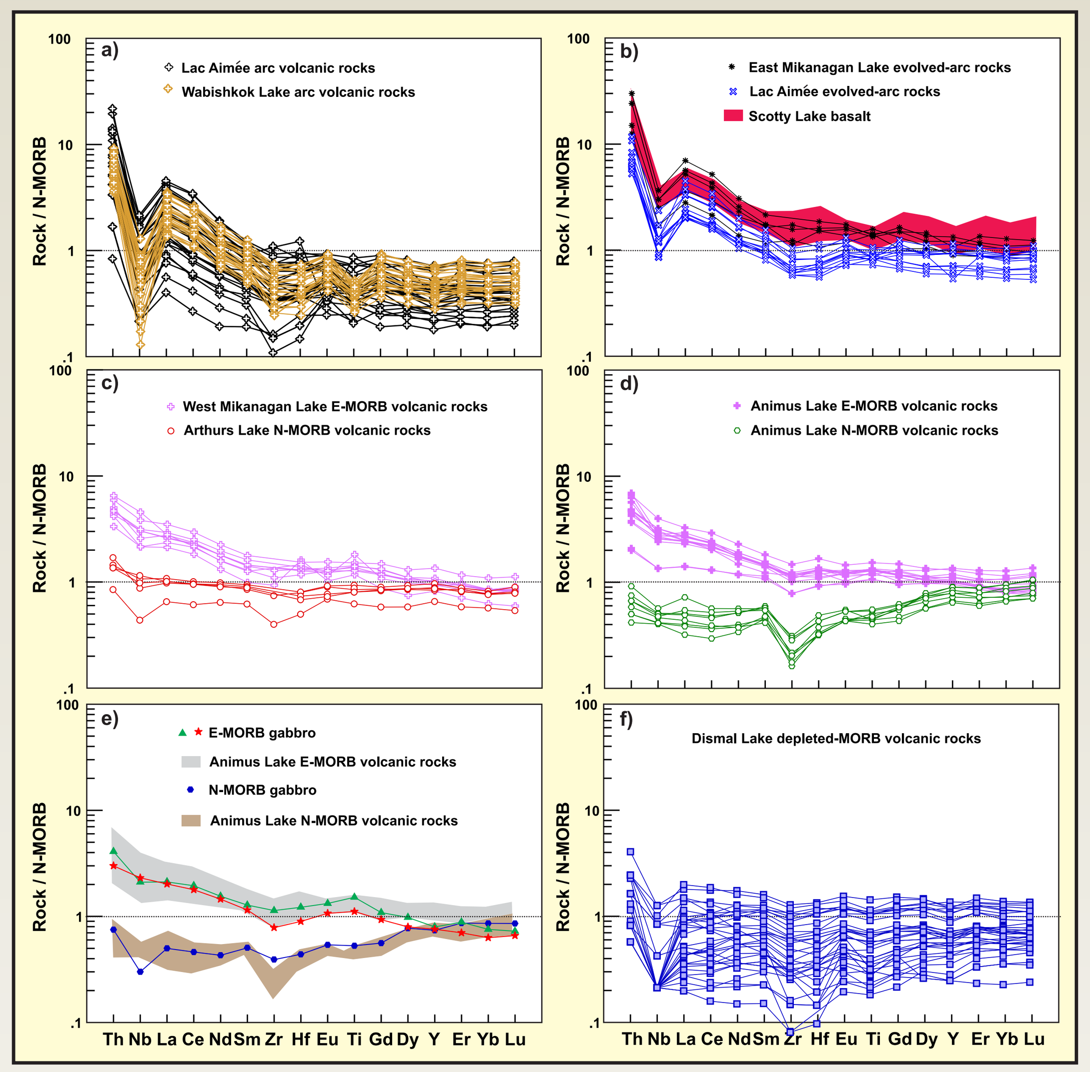

Figure 3: Incompatible-element plots of mafic to intermediate volcanic rocks in the north-central Flin Flon Belt: a) juvenile arc rocks; b) evolved arc types and Scotty Lake basalt; c) E-MORB and N-MORB types; d) Animus Lake MORB-type rocks; e) gabbro intrusions within/at the margin of the arc-type Wabishkok Lake Block, compared with Animus Lake MORB; f) Dismal Lake depleted MORB. Normalizing values after Sun and McDonough (1989).

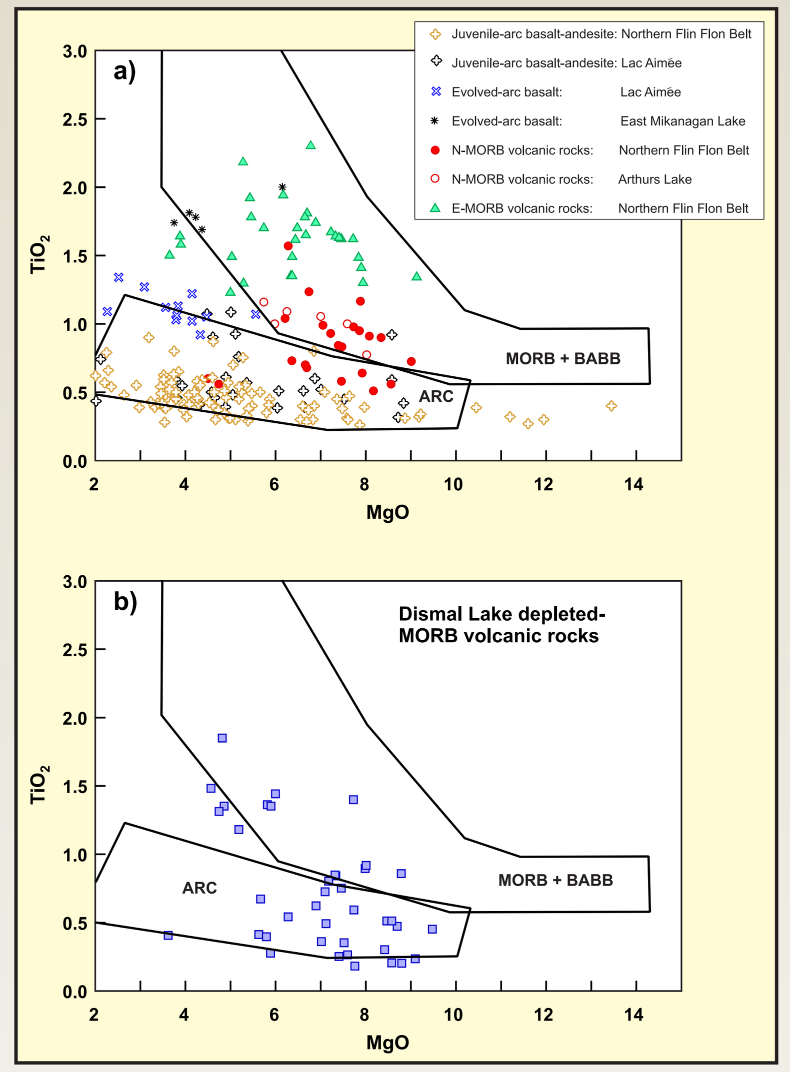

Figure 4: TiO_2 vs. MgO plot of mafic to intermediate volcanic rocks in the north-central Flin Flon Belt: a) juvenile arc, evolved arc and MORB-type rocks; b) Dismal Lake depleted-MORB types. Compositional fields of modern intra-oceanic rocks are from Stern et al. (1995b). Abbreviations: MORB, mid-ocean ridge basalt; BABB, back-arc basin basalt.

Rock suite	SiO_2	Sr	Y	Zr	Nb	Hf	Th	Zr/TiO_2	Zr/Y	$(La/Yb)_{ch}$	Rb/Sr
Tartan Lake felsic volcanic	69.4	156	21	102		2.2	1.4	197	4.8	3.3	0.3
Bear Lake felsic volcanic	75.3	132	24	101		2.2	0.7	456	4.4	1.6	0.2
Hook Lake felsic volcanic	66.8	187	34	119		3.0	1.2	170	3.3	1.3	0.2
Lac Aimee felsic volcanic	70.2	125	17	112	4.5	2.6	3.4	317	6.5	4.5	0.2
Manistikwan Lake felsic volcanic	74.0	35	33	183		4.5	6.8	415	5.8	4.7	2.8
Sourdough Bay felsic volcanic	71.6	111	26	110	6.8	3.2	3.9	335	4.2	3.6	0.1
Wabishkok Lake felsic volcanic	77.7	99	29	101	5.7	2.9	1.0	654	3.5	2.1	0.1
Lac Aimee felsic porphyry	79.5	48	76	185	17.8	6.9	5.9	1542	2.4	2.5	1.2
Cope Lake rhyolite	76.4	26	124	263	22.0	8.8	4.3	2104	2.1	1.5	1.4
Cope Lake rhyolite	78.9	19	105	246	21.0	8.0	4.0	1629	2.3	1.7	1.3

Table 1. Geochemical data for felsic volcanic rocks (averages of selected elements and element ratios).

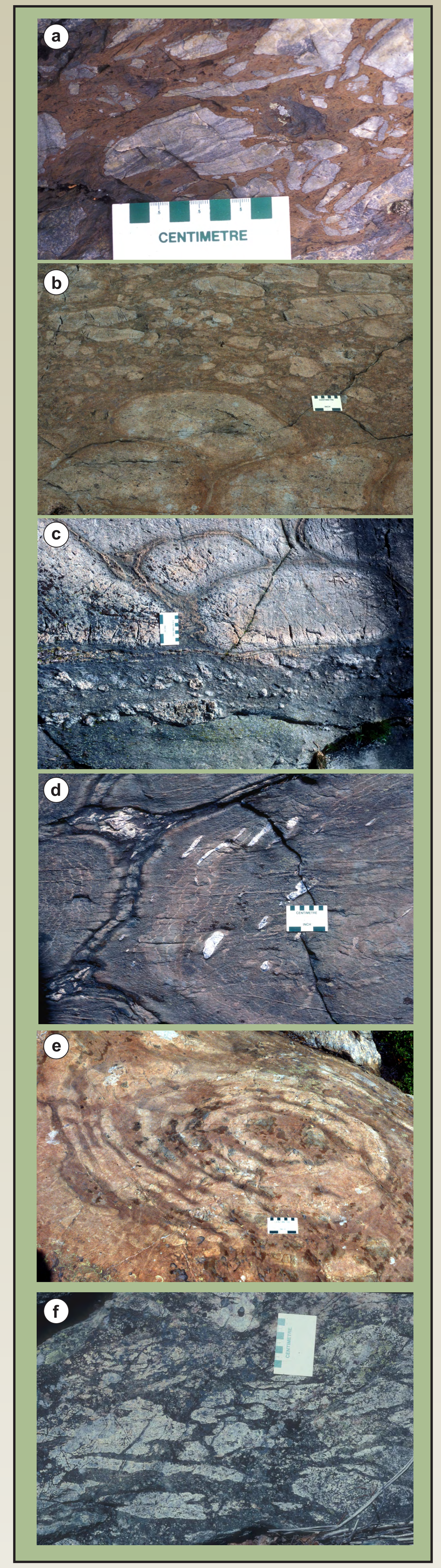

Figure 2: Outcrop photographs of massive and fragmental volcanic rocks in the northern Flin Flon Belt: a) fault breccia from a 20 m wide tectonic zone between normal mid-ocean ridge basalt (N-MORB) and arc volcanic rocks at Bluenose Lake; b) aphyric pillowed basalt and flow-top breccia within the Bear Lake arc volcanic suite; c) contact showing basal chilled margin of a Bear Lake flow overlying the flow-top breccia of the underlying unit; d) marginal zone of >2 m long pillow in Tartan Lake arc basalt flow, with quartz amygdales and thermal contraction fractures; e) lava tube in the Bear Lake arc basalt section; f) rhyolite breccia with angular to amoeboid fragments within the arc-type Sourdough Bay Block.

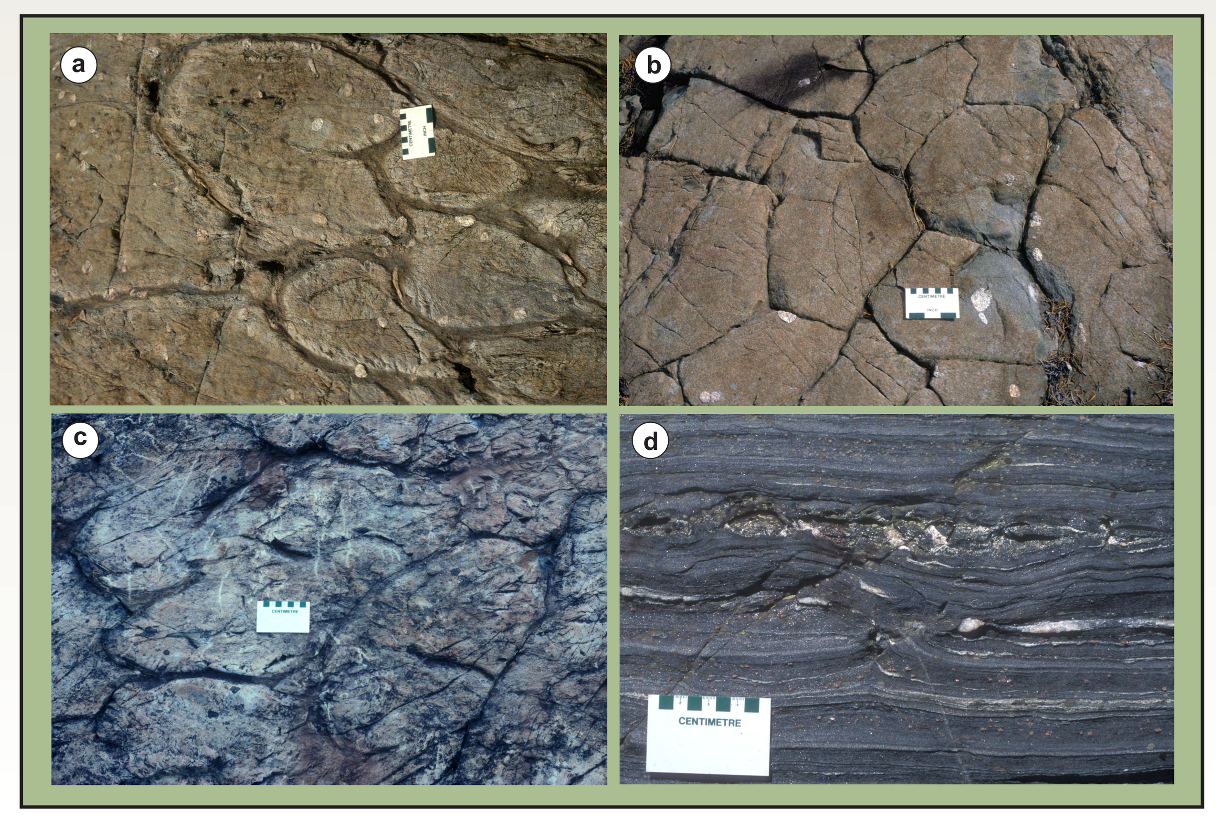

Figure 5: Outcrop photographs of volcanic and related rocks in the northern Flin Flon Belt: a) Arthurs Lake N-MORB suite - plagioclase-megaphyric pillowed basalt and b) synvolcanic gabbro; c) pillowed basalt in the Animus Lake E-MORB volcanic suite; d) laminated, garnetiferous mafic gneiss derived from Dismal Lake depleted-MORB volcanic flows.

MORB-type volcanic suites

Four tectonic enclaves of MORB-type volcanic rocks are intercalated with the numerous arc-type fault blocks within the NFFB (*Figure 1*). The MORB volcanic suites consist almost entirely of basalt and abundant related gabbro sills, which constitute up to 30% of these sequences (*Figure 5a-5c*); they are thus lithologically and compositionally much less diverse than arc volcanic suites. The MORB volcanic rocks are interpreted as back-arc rocks derived from source magmas that were largely unaffected by subduction zone influences; εNd values range from +3.3 to + 5.1 (at 1.9 Ga), consistent with a mantle source with little or no crustal recycling of older Proterozoic or Archean lithosphere. Several MORB suites contain abundant, aphyric to plagioclase ±hornblende (pyroxene)-phyric diabase dikes; geochemical data obtained from four of these minor intrusions indicate that some, at least, are associated with arc-type rather than MORB-type magmatism. On the other hand, several MORB-like gabbroic intrusions emplaced in arc-type volcanic rocks in the Wabishkok Lake Block are geochemically similar to, and possibly co-magmatic with MORB-type volcanic rocks in the contiguous Animus Lake Block (*Figure 3e*).

Two MORB volcanic types - normal (N-MORB) and enriched (E-MORB) - are recognized in the NFFB (*Figures 3c, 3d*). Whereas E-MORB volcanic rocks are relatively enriched in REE (especially light REE) compared to modern ocean-ridge basalt, N-MORB types display flat incompatible element profiles, roughly coincident with that of modern N-MORB. The TiO_2 vs. MgO diagram shows N-MORB type rocks extend into both the 'arc' and 'MORB + BABB' fields (*Figure 4a*) whereas E-MORB types are mainly confined to the 'MORB + BABB' field.

Depleted-MORB volcanic suites

Mafic volcanic rocks depleted in REE that are geochemically transitional between arc-type basalt and N-MORB extend along the north margin of the NFFB in the area north of Dismal and Dismal lakes (Dismal Lake Terrane, *Figure 1*). Dismal Lake 'depleted-MORB' is laterally continuous with geochemically similar rocks (Moody Lake basalt; Zwanzig, pers. comm. 2009) that extend along the southern margin of the Kisseynew Domain, north of the Flin Flon Belt. The Dismal Lake and Moody Lake basalts extend for more than 100 km from File Lake and Moody Lake in the east to the Bluenose Lake-Precipice Lake area in the west. The Dismal Lake depleted-MORB terrane is up to 6 km wide and consists largely of pillowed, aphyric basalt flows, derived finely laminated amphibolite and subordinate related gabbro (*Figure 5d*). Pillows at Dismal Lake indicate that the sequence is north facing, but elsewhere there is little evidence to indicate stratigraphic tops.

Geochemically, the Dismal Lake volcanic suite displays a flat to slightly positive-sloping incompatible-element profile, typical for N-MORB rocks (*Figure 3f*). On the other hand, the conspicuous negative Nb anomaly in *Figure 3f* is typical for arc-type rocks, and the average Th/Nb ratio (0.13) in Dismal Lake basalt exceeds the 'primitive' value (0.1) for MORB-type rocks (Stern et al.,1995b). In the TiO_2 vs. MgO diagram (*Figure 4b*), the depleted MORB rocks overlap the MORB + BABB and arc fields due to their wide range of TiO_2 content (0.23%–1.85%). The substantial range of overall REE contents (*Figure 3f*) is attributed primarily to fractionation, in association with mixing of different mantle types in the source magma. The generally flat REE profile and a primitive Nd isotopic composition (εNd value of +5.2 at 1.9 Ga) for the Dismal Lake depleted-MORB rocks are consistent with juvenile magmatism in a back-arc basin setting.

The combination of MORB- and arc-type features displayed by the Dismal Lake depleted-MORB rocks is interpreted as the result of mixing of depleted and enriched MORB-like mantle and subduction-modified magmatic sources, as described for several formations 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). Compositional variation in modern BABB reflects, in part, the extent of rifting, such that the magmatic source at the initiation of back-arc extension may contain more subduction-modified mantle than basalts that are erupted later in the development of the back-arc basin (Stern et al.,1990). In this model, the Dismal Lake depleted-MORB sequence may represent an earlier stage of extensional back-arc basin development, compared to N-MORB and E-MORB suites elsewhere in the NFFB.

Felsic volcanic rocks

Felsic volcanic rocks form less than 15% of the arc assemblage in the Flin Flon Belt except in the northeastern part (Alberts Lake area), where the rhyolitic Baker Patton Complex constitutes over half of the northern Sourdough Lake Block (*Figure 1*). Although rhyolitic rocks are volumetrically only a minor part of the arc assemblage, they are economically the most important component because most of the volcanogenic massive sulphide (VMS) ore deposits in the Flin Flon Belt are hosted by felsic volcanic rocks. Classification of Archean felsic volcanic rocks by Lesher et al.(1986), based on trace element content, has identified distinctive patterns of barren vs mineralized felsic volcanic types. This classification also provides a rough basis for classifying felsic volcanic rocks in the Proterozoic Flin Flon Belt, although some felsic types cannot be fitted into the scheme (Syme,1998).

Most felsic volcanic rocks in the NFFB are rhyolitic (the rhyolite:dacite ratio is 70/30) and display incompatible element plots similar to that of juvenile arc rhyolite elsewhere in the Flin Flon Belt (*Figure 6a*). These rocks are type FII in the scheme of Lesher et al.(1986), which is only rarely associated with economic mineralization in the Archean (*Figure 6b*).

Two high-silica rhyolite samples from a locality at the east margin of the Cope Lake Block are distinguished by relatively higher overall REE contents - especially HFSE - and a more pronounced Eu anomaly, compared to the majority FII-type rocks (*Table 1*). These rocks (Cope Lake rhyolite) plot in the field of 'extension-related' rocks in the Zr vs TiO_2 diagram (*Figure 6c*) and are thus identified as prospective for VMS-type mineralization (Syme, 1998). The Cope Lake rhyolite is classified as FIII type according to the scheme of Lesher et al. (1986) (*Figure 6b*), in common with rhyolite in the Flin Flon Mine sequence (Syme,1998). The FIII types are interpreted as derived from high-level, subvolcanic magma chambers, representing a heat source for hydrothermal convection systems that are directly associated with VMS-type mineralization. The Cope Lake rhyolite is also compositionally similar to ore-bearing rhyolites in the Archean Abitibi subprovince; it is classified as group 1 in the scheme of Barrie et al.(1993) - a rock type that hosts over 50% of Abitibi VMS ore deposits (*Figure 6d*). Group 1 rocks consist of high silica (>73%) rhyolite characterized by elevated REE contents, negative Eu anomalies, Zr/Y ratios <5 and Rb/Sr >1.0 (see *Table 1*).

Lac Aimée felsic porphyry 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 related to the latter, arc-type rocks. This felsic porphyry is compositionally akin to the Cope Lake rhyolite (*Figures 6a to 6d*) and thus warrants investigation for potential VMS-type mineralization. The Cope Lake rhyolite, on the other hand, is already identified as economically significant due to its proximity to the Trout Lake (Cu-Zn) ore deposit, located approximately 0.5 km east of the rhyolite. This deposit (>10 million tonnes ore reserves and production to 2007) occurs in a sequence that contains sedimentary rocks as well as felsic porphyry types that are possibly co-magmatic with the Cope Lake rhyolite. The geochemical similarity of the Cope Lake rhyolite (proximal to the Trout Lake VMS deposit) with ore-bearing rocks elsewhere, within and beyond the Flin Flon Belt, serves to show the potential of geochemical profiling as an aid for the selection of possibly fertile drill targets during mineral exploration programs.

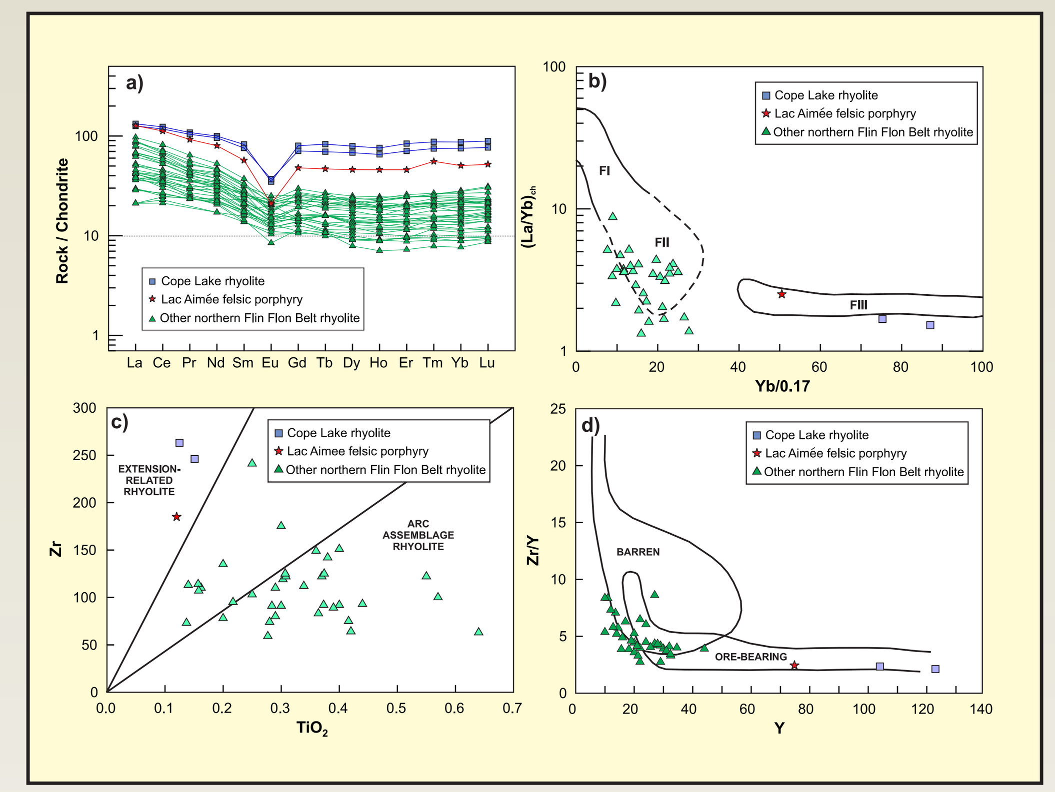

Figure 6: Geochemical plots of felsic volcanic rocks in the north-central Flin Flon Belt: a) chondrite-normalized incompatible-element plot; b)($(La/Yb)_{ch}$ vs Yb/0.17 (Lesher et al.,1986); c) Zr vs TiO_2 (Syme,1998); d) Zr/Y vs Y (Barrie et al.,1993). Normalizing values after Sun and McDonough (1989).

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