Evolution of the Paleoproterozoic Snow Lake arc assemblage and geodynamic setting for associated volcanic-hosted massive sulphide deposits, Flin Flon Belt, Manitoba, Canada

Alan H. Bailes and Alan G. Galley

Abstract: The majority of volcanogenic massive sulphide (VMS) deposits at the east end of the Paleoproterozoic Flin Flon "greenstone" belt occur in the 1.89 Ga Snow Lake arc assemblage. VMS deposits in this isotopically juvenile oceanic arc sequence are hosted within a 6 km thick monoclinal section that records in its stratigraphy and geochemistry a temporal evolution in arc development from primitive, through mature, to arc rift. VMS deposits occur in both the primitive and mature arc sequences and are interpreted to be products of arc extension and accompanying anomolously high heat flow, fracturing, and fluid circulation. Boninites, low-Ti tholeiites, and isotopically juvenile rhyolite flows, a rock association that has been attributed in both modern and Phanerozoic arcs to high-temperature hydrous melting of refractory mantle sources in an extensional and (or) proto-arc environment, forms the primitive arc. Indication that the mature arc also underwent extension includes voluminous volcaniclastic detritus (from fault scarps?), prominent synvolcanic dykes, isotopically juvenile rhyolite flows, and the fact that the mature arc is stratigraphically overlain by arc-rift basalts with MORB-like geochemistry. Interpretation of VMS deposits at Snow Lake as products of an extensional geodynamic setting suggests that the traditional Flin Flon Belt exploration model, invoking "pluton-generated" convective seawater, be augmented by the search for evidence of rifting. Economically significant rock associations at Snow Lake include geochemically primitive refractory mafic magmas (e.g., boninites), isotopically juvenile felsic magmas, bimodal basalt–rhyolite sequences, and arc-rift basalts.

Résumé : La majorité des dépôts de sulfures massifs associés à des roches volcaniques, à l'extrémité orientale de la zone de « roches vertes » de Flin Flon Paléoprotérozoïque, apparaissent dans l'assemblage de type d'arc du district de Snow Lake daté de 1,89 Ga. Ces amas de sulfures dans la séquence d'arc océanique isotopiquement juvénile sont exposés dans une coupe monoclinale d'une puissance de 6 km, et où la stratigraphie et la géochimie documentent l'évolution temporelle du développement de l'arc des stades primitif, mature, et de distension. Les dépôts de sulfures massifs associés à des roches volcaniques apparaissent dans l'une et l'autre des séquences d'arc primitive et mature; ils doivent leur origine à une extension de l'arc, accompagnée d'un flux thermique anormalement élevé, de fracturation, et d'une circulation de fluides. Les bonitites, les tholéiites pauvres en Ti et les coulées de rhyolite isotopiquement juvénile, qu'on a attribué dans les arcs actuels et du Phanérozoïque à la fusion hydratée sous haute température du manteau réfractaire dans un régime d'arc en extension et (ou) de proto-arc, forment l'arc primitif. Les volumineux dépôts de détritus volcanoclastiques (provenant d'escarpements de faille?), les dykes synvolcaniques proéminents, les coulées de rhyolite isotopiquement juvénile et le fait que l'arc mature soit stratigraphiquement recouvert par les basaltes de l'arc de distension avec une composition géochimie ressemblant aux MORB, sont tous des indices qui suggèrent que l'arc mature a lui aussi été soumis à un régime extensif. L'interprétation envisageant les dépôts de sulfures massifs associés à des roches volcaniques à Snow Lake comme produits d'une géodynamique extensive suggère qu'on élargisse le modèle traditionnel d'exploration pour la zone de Flin Flon, impliquant une convection de l'eau de mer « générée par plutonisme », en recherchant une preuve de la distension de l'arc. Les associations lithologiques offrant un potentiel économique à Snow Lake incluent les magmas mafiques réfractaires primitifs (ex. bonitites), les magmas felsiques isotopiquement juvéniles, les séquences bimodales de basalte–rhyolite et les basaltes d'arc du stade distensif.

[Traduit par la Rédaction]

Received April 21, 1998. Accepted December 1, 1998.

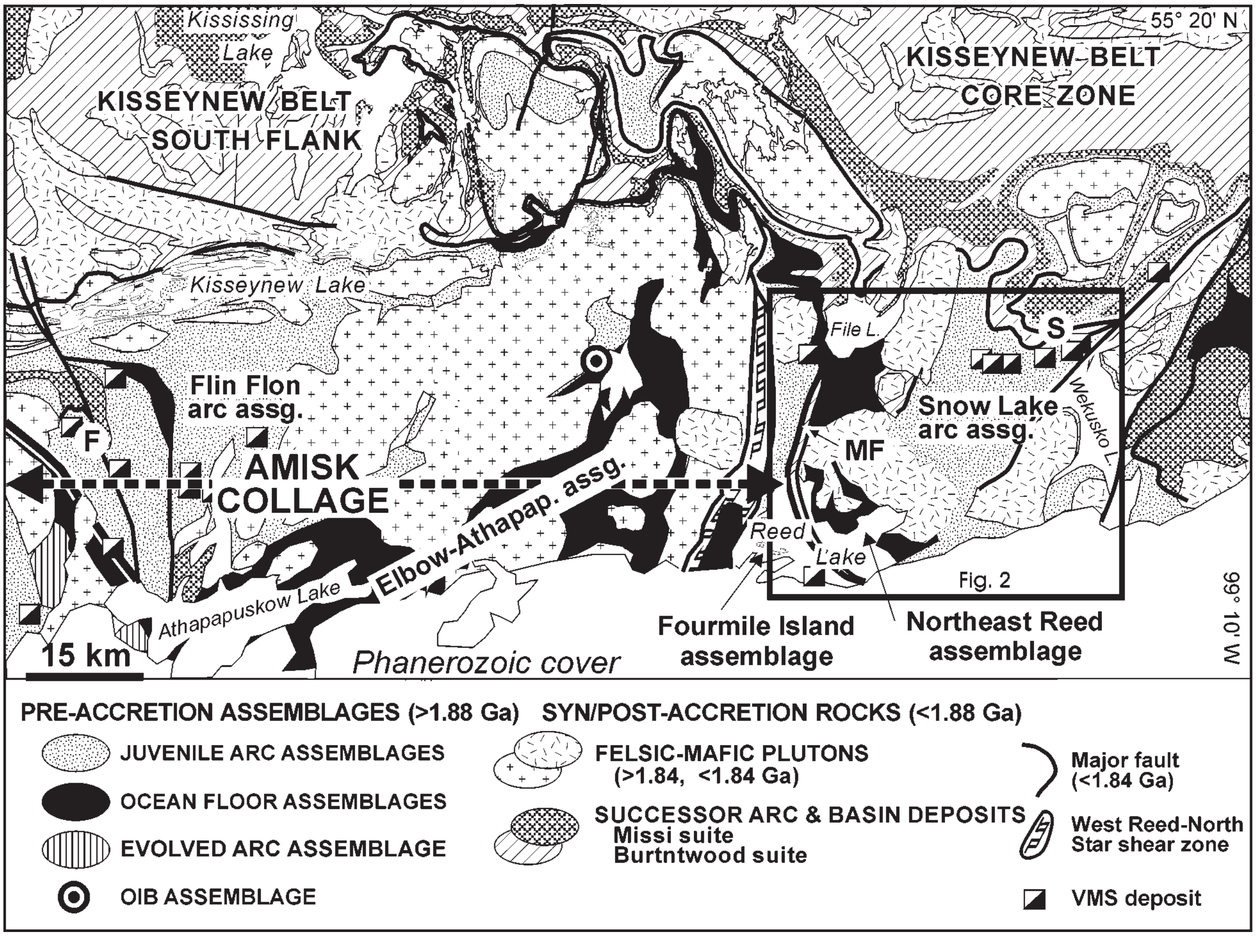
A.H. Bailes.[1] Manitoba Energy and Mines, Suite 360, 1395 Ellice Ave., Winnipeg, MB R3G 4E3, Canada.
A.G. Galley. Geological Survey of Canada, Mineral Deposits Division, 601 Booth Street, Ottawa, ON K1A 0E8, Canada.

[1]Corresponding author (e-mail: abailes@em.gov.mb.ca).

Introduction

Paleoproterozoic volcanic rocks of the Flin Flon Belt in Manitoba contain 25 past and presently producing mines with 118.7 Mt (production plus reserves) of polymetallic base metal sulphide ore, with a further 64.3 Mt contained in 43 subeconomic or pre-production deposits (Syme et al. 1999). The 1.89 Ga Snow Lake arc assemblage, at the east

Fig. 1. Simplified geology of the central and eastern portion of the Flin Flon Belt showing major tectonostratigraphic assemblages and plutons, and locations of mined VMS deposits. F, Flin Flon; S, Snow Lake; MF, Morton Lake fault zone. Rectangle shows location of Fig. 2.



end of the exposed Flin Flon Belt (Fig. 1), hosts seven of the producing and past-producing base metal mines, and accounts for production plus reserves of 20.7 Mt.

Controls on the formation of the polymetallic volcanic-hosted massive sulphide (VMS) deposits in Flin Flon Belt are of considerable interest as it contains more base and precious metals per km^2 than any other VMS mining district in Canada (J.M. Franklin, Geological Survey of Canada, personal communication 1995) and has the largest aggregate tonnage of any Paleoproterozoic VMS terrane in the world (Galley 1996). Characteristics of Flin Flon Belt VMS deposits (e.g., Sangster 1972; Sangster and Scott 1976; Walford and Franklin 1982) generally conform with the standard subvolcanic pluton-driven, convective seawater model that is widely reported in the literature (e.g., Franklin et al. 1981; Lydon 1984, 1988 and references therein). Although this model has been effective in delineating local controls on VMS mineralization in the Flin Flon Belt (particularly in the Snow Lake area), the larger scale regional controls remained obscure.

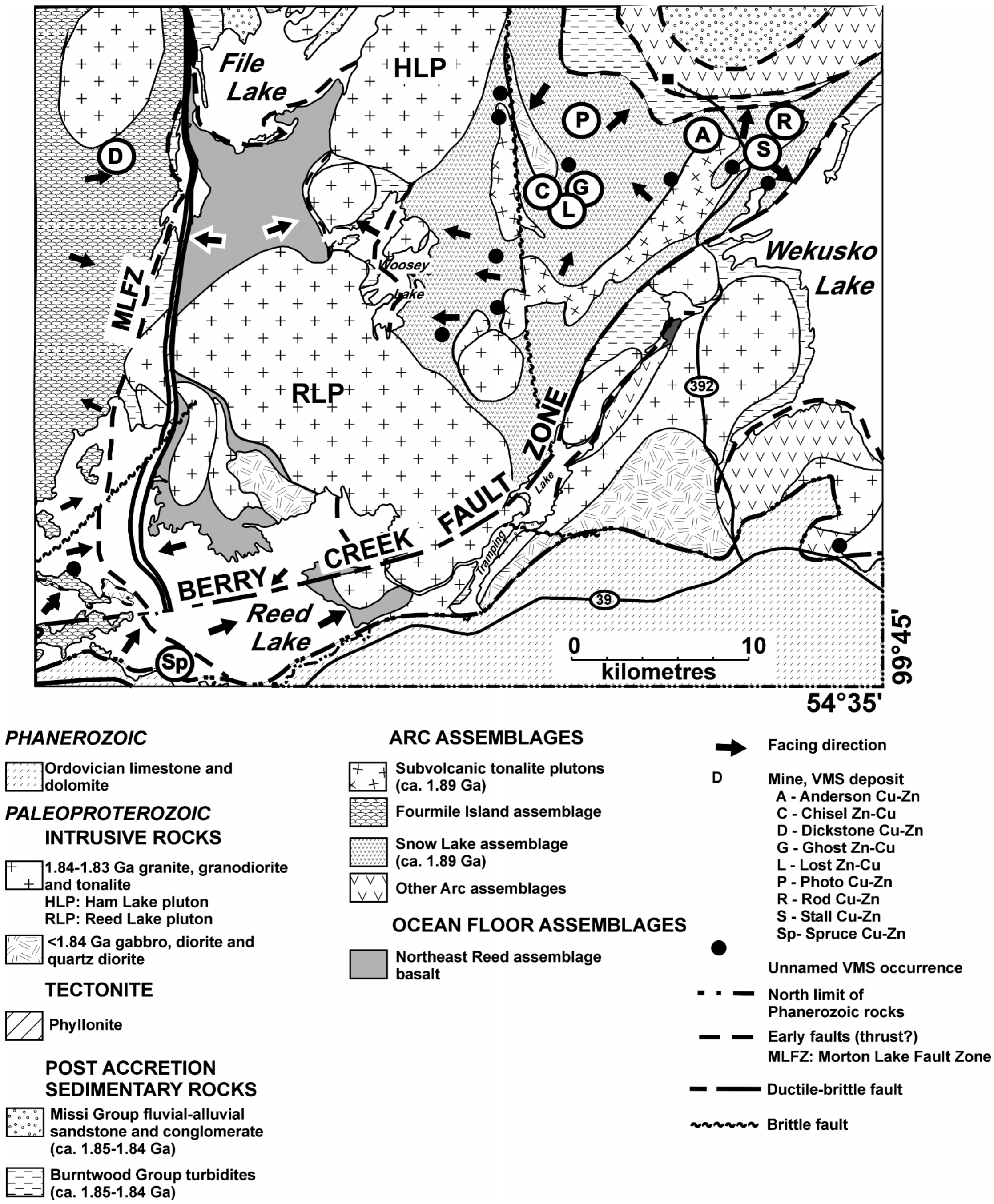
Recent mapping and geochemical studies by Manitoba Energy and Mines (Bailes and Syme 1989; Syme and Bailes 1993; Syme et al. 1996*a*, 1996*b*; Bailes and Galley 1996) and subsequent research under the GSC–Manitoba–Saskatchewan Shield Margin NATMAP program (e.g., Stern et al. 1995*a*, 1995*b*; Lucas et al. 1996) have revolutionized our understanding of the components and evolution of the Flin Flon Belt and have shown that all economic base metal deposits occur in 1.91–1.88 Ga juvenile arc tectonic assemblages, and preferentially in those that display evidence of intra-arc rifting. These findings are consistent with those of recent geological and geochemical studies in other greenstone belts and ancient volcanic terranes (Cathles 1983; Swinden 1991, 1996; Lesher et al. 1986; Barrie et al. 1993; Galley 1996), which show that throughout geological time most economic VMS deposits formed in suprasubduction arc terranes and most prolifically in those that have experienced rifting.

This paper examines the setting of Snow Lake area VMS deposits (Fig. 2) with respect to evolution of the 1.89 Ga Snow Lake arc assemblage. Our objective is to relate features in the Snow Lake arc assemblage to the geodynamic setting of volcanism and to the role this played in formation of the contained VMS deposits. This paper augments the contribution of Syme et al. (1999) that documents the tectonostratigraphic and depositional setting of VMS deposits in the central part of the Flin Flon Belt.

Regional geology

The Flin Flon Belt belongs to the juvenile (internal) zone of the Trans-Hudson Orogen, a collision zone formed during the 2.0–1.8 Ga amalgamation of several Archean micro-

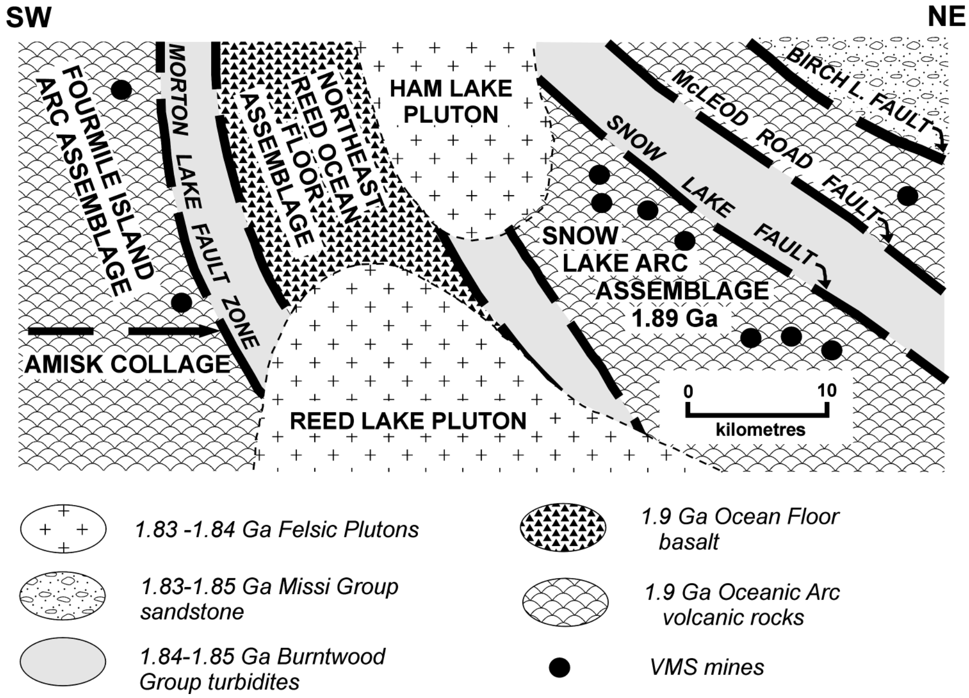
Fig. 2. Generalized geology of the Reed Lake – Snow Lake area modified from Syme et al. (1995) and Bailes et al. (1994). The Morton Lake fault zone (MLFZ) is interpreted to represent the basal thrust (Syme et al. 1995; Lucas et al. 1996) that separates the Snow Lake area from the central Flin Flon Belt (i.e., Amisk collage). The Snow Lake area is characterized by a structural style and by lithologies that are more comparable to the Kisseynew domain than those observed in the central Flin Flon Belt. The Snow Lake area consist of a series of Kisseynew-type allochthons of volcanic and sedimentary rocks.



continents into a supercontinent, Laurentia (Hoffman 1988). It forms the easten part of the Flin Flon – Glennie Lake Complex, the middle of three northeast-dipping, crustal-scale allochthons formed during collisional deformation in Trans-Hudson Orogen (Lucas et al. 1997).

The Flin Flon Belt is a collage of 1.92–1.88 Ga tectonostratigraphic assemblages juxtaposed during 1.88–1.87 Ga intra-oceanic accretion and subsequent 1.84–1.78 Ga terminal collision of the bounding Archean cratons (Lucas et al. 1996). Based on their trace element contents, volcanic rocks in the Flin Flon Belt are known to include juvenile arc (~68%), juvenile ocean floor (~20%), and minor (~12%) oceanic plateau, ocean island basalt, "evolved" plutonic arc, and undivided rocks (Syme and Bailes 1993; Stern et al. 1995*a*, 1995*b*; Syme et al. 1999). Oceanic arc assemblages include tholeiite, calc-alkaline and rare shoshonite and boninite suites (Stern et al. 1995*b*) almost identical to those forming in modern intra-oceanic arcs (e.g.,

Fig. 3. Schematic cross section showing a series of allocthons in the Reed Lake – Snow Lake area (bottom left to upper right in Fig. 2). The 1.89 Ga panels of volcanic rocks are seperated by thrust faults and panels of 1.84 Ga Burntwood Group sedimentary rocks. The allocthons of volcanic and younger sedimentary rocks are cut by late successor arc 1.84–1.83 Ga granite plutons. VMS mines are restricted to arc assemblages, with seven of the 10 mines in the Snow Lake area located in an allocthon composed of Snow Lake arc assemblage rocks.



Gill 1981). Most VMS deposits in the Flin Flon Belt occur in two ≥1.88 Ga juvenile arc segments, one near the town of Flin Flon and one at Snow Lake (Snow Lake arc assemblage) (Fig. 1). They are separated by an extensive, northeast-trending collage of 1.90 Ga (Stern et al. 1994) ocean floor mid-ocean ridge basalt (MORB-like) back-arc – ocean floor basalt flows, with associated gabbro and ultramafic rocks, that contains no known economic VMS deposits (Fig. 1).

The Snow Lake part of the Flin Flon Belt is dominated by 1.84–1.81 Ga fold–thrust style tectonics (Connors 1996; Kraus and Williams 1999) that is atypical of central and western portions of the belt. This difference in tectonic style may reflect the fact that the entire Snow Lake portion of the Flin Flon Belt is a south-verging, allochthonous, northeast-dipping imbricate that was thrust between 1.84 and 1.81 Ga (Syme et al. 1995; Lucas et al. 1996) over the previously amalgamated collage of oceanic and arc rocks (“Amisk collage”) to the west (Fig. 3). The individual allochthons of volcanic rocks in the Snow Lake area, besides being bounded by thrust faults, are also generally separated by intervening imbricates of younger, approximately 1.84 Ga sedimentary rocks (Connors 1996; David et al. 1996). The base of the thrust stack is interpreted to be the Morton Lake Fault Zone (Figs. 1–3). This thrust package has been subsequently modified by intrusion of 1.84–1.83 Ga granitic plutons, by northeast-trending and plunging open folding (Kraus and Williams 1998, 1999) and by 1.82–1.81 Ga (David et al. 1996) regional metamorphism to lower to middle almandine–amphibolite facies mineral assemblages (Froese and Moore 1980).

Snow Lake arc assemblage

Geology and main subdivisions

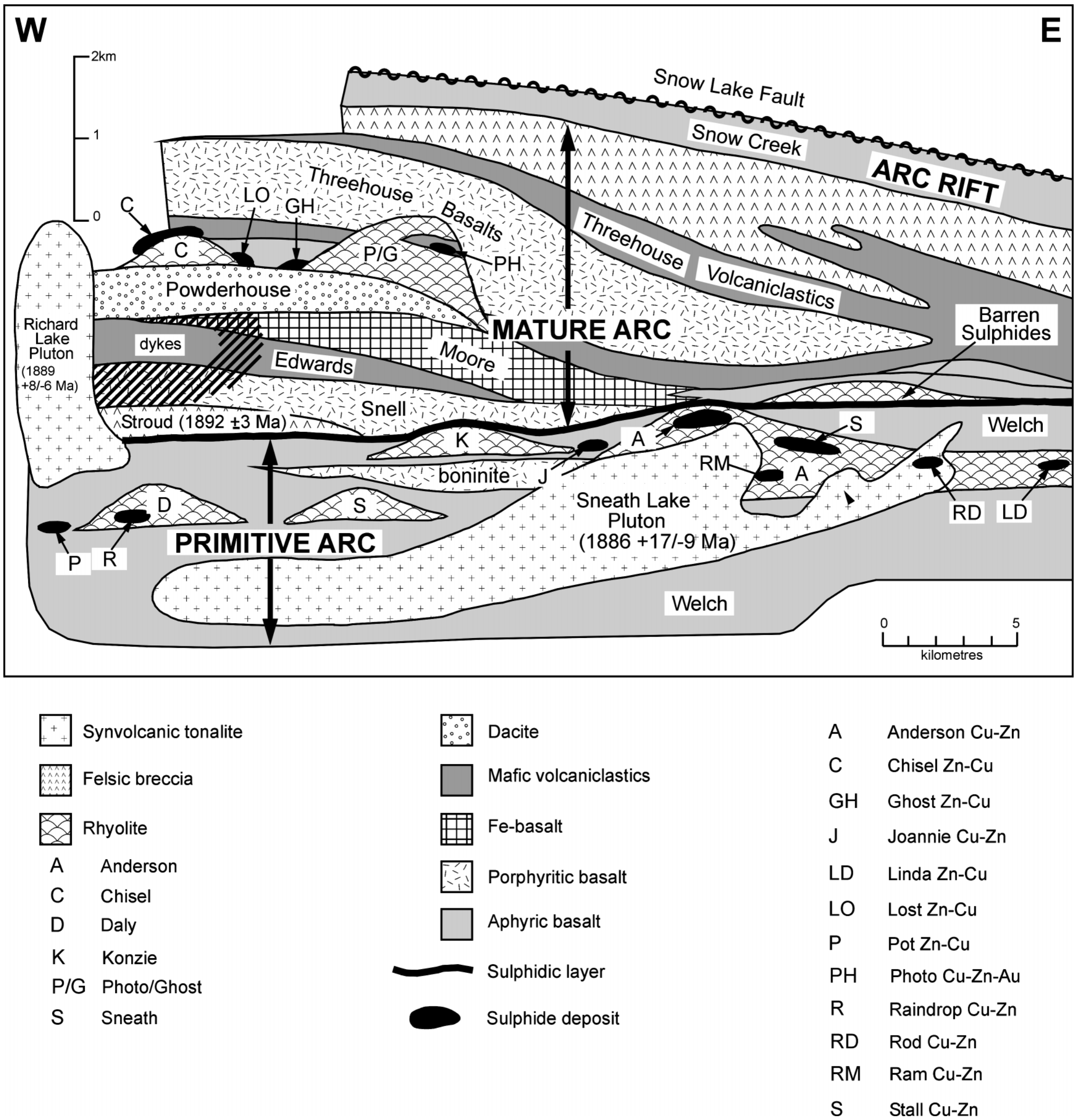
The 15 km wide Snow Lake arc assemblage (allochthon) is noteworthy as one of the most completely exposed VMS-hosting domains in the Flin Flon Belt. The seven producing and past-producing VMS mines, as well as all significant sulphide occurrences, are located within a 6 km thick, north-facing section of the allochthon, where they are spatially related to two, large, subvolcanic, multicomponent, tonalite–trondhjemite intrusive complexes (Fig. 4). The volcanic rocks, subvolcanic intrusive complexes, and associated VMS deposits in this north-facing sequence are described in detail by Bailes and Galley (1996).

Volcanic strata and associated intrusions in the 6 km thick VMS-hosting section are divided into three distinct subdivisions: a lower 2.5 km thick subdivision that consists of mafic and minor felsic flows with negligible volcaniclastic rocks; a middle 3 km thick section that comprises a lithologically diverse volcanic domain with rapid lateral facies variations and abundant volcaniclastic rocks; and an upper 0.5 km thick section that consists of pillowed basalts with no intercalated felsic rocks or volcaniclastic detritus. Geochemistry of basalts in these three subdivisions (discussed below) shows that the geological subdivisions are not only valid, but correspond to fundamental evolutionary stages in development of the Snow Lake arc assemblage.

Geochemistry of mafic and intermediate rocks

Eighty-three whole rock and trace element geochemical analyses, fifty-five rare earth element (REE) analyses, and

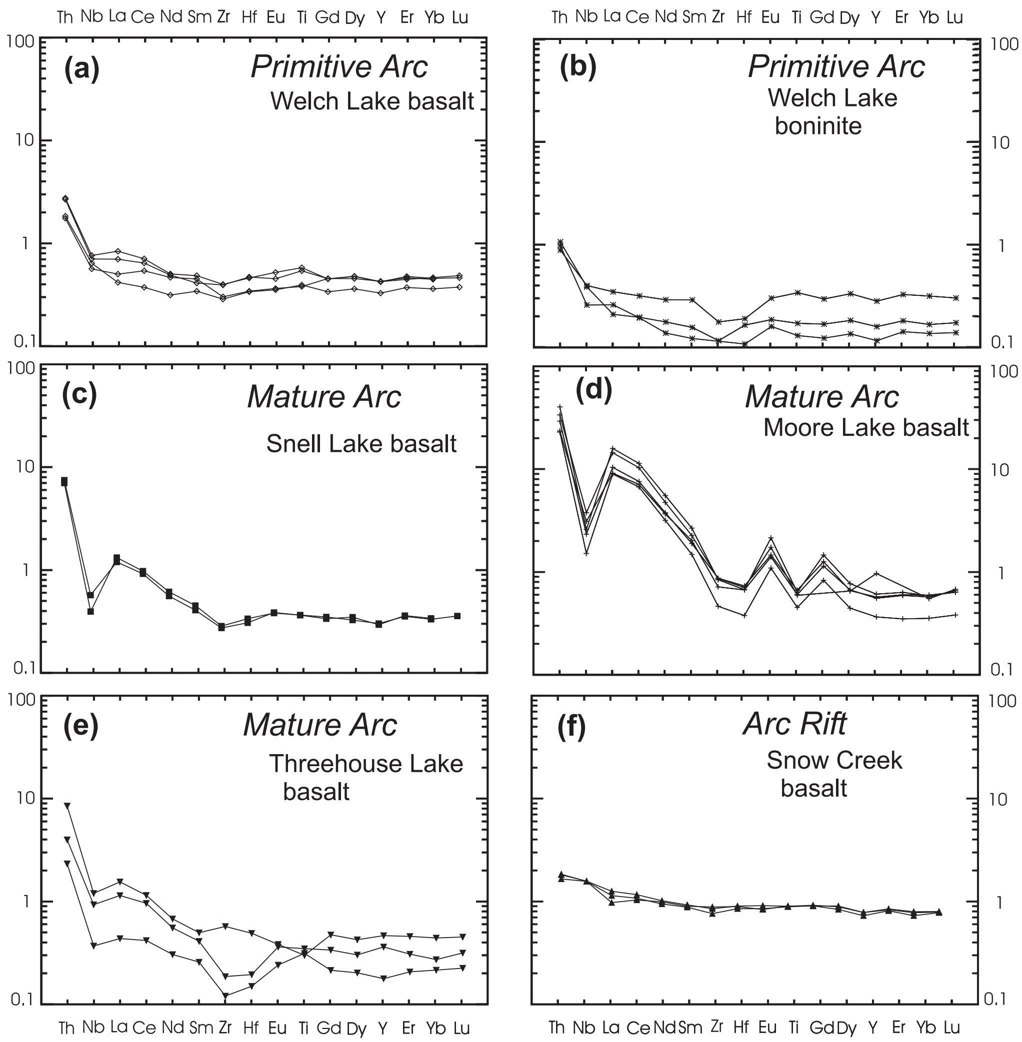
Fig. 4. Schematic stratigraphic section showing setting of base-metal rich sulphide deposits in the Snow Lake arc assemblage. Note the spatial association of sulphide deposits with rhyolite complexes (names of rhyolite complexes indicated by letters). The Sneath Lake and Richard Lake plutons are intrusive complexes that include several phases, with younger phases (not shown separately in this diagram) intruding VMS-hosting rhyolites and alteration zones. For example, a late phase of the Sneath Lake intrusive complex has intruded and enveloped the Rod VMS deposit (RD) in the Anderson rhyolite and a late phase of the Richard Lake intrusive complex cuts across volcanic rocks already altered by an earlier phase of the intrusion. The U–Pb zircon age for the Sneath Lake pluton is poorly constrained (1886^{+17}_{-9} Ma; David et al. 1996) and only indicates the subvolcanic nature of the pluton and not an actual age relative to the younger Stroud Lake felsic breccia (1892 ± 3 Ma; David et al. 1996) and subvolcanic Richard Lake pluton (1889^{+8}_{-6} Ma; Bailes et al. 1991).



fifteen Nd isotopic analyses were obtained from least-altered mafic and intermediate volcanic rocks in the Snow Lake arc assemblage (this study; Stern et al. 1992, 1995*b*). Some of these analyses have already been released (Stern et al. 1992, 1995*b*) and the remainder will be available in mid-1999 on a CD-ROM release of Shield Margin NATMAP data. The main units of mafic flows at Snow Lake each display unique geochemical attributes that serve not only to distinguish among them but also to demonstrate that they are not simply episodic extrusions of fractionated material from a single magmatic source. Geochemistry of the mafic flows indicates three stages in the evolution of the Snow Lake arc assemblage: *primitive arc* (Welch), *mature arc* (Snell, Moore, Threehouse), and *rifted arc* (Snow Creek).

The *primitive arc* Welch Lake basalts and associated high-Ca boninites are slightly to strongly depleted, respectively, in REE and high field strength elements (HFSE; e.g., Zr,Y, Ti, Hf) relative to MORB (Figs. 5*a*, 5*b*, and 6*a*). They display higher MORB-normalized contents of Th relative to Nb (Figs. 5*a* and 5*b*) and Th/Nb > 0.1 (Figs. 6*b* and 6*e*), features characteristic of subduction-related magmas formed within oceanic arc tectonic settings (Gill 1981; Tarney et al.

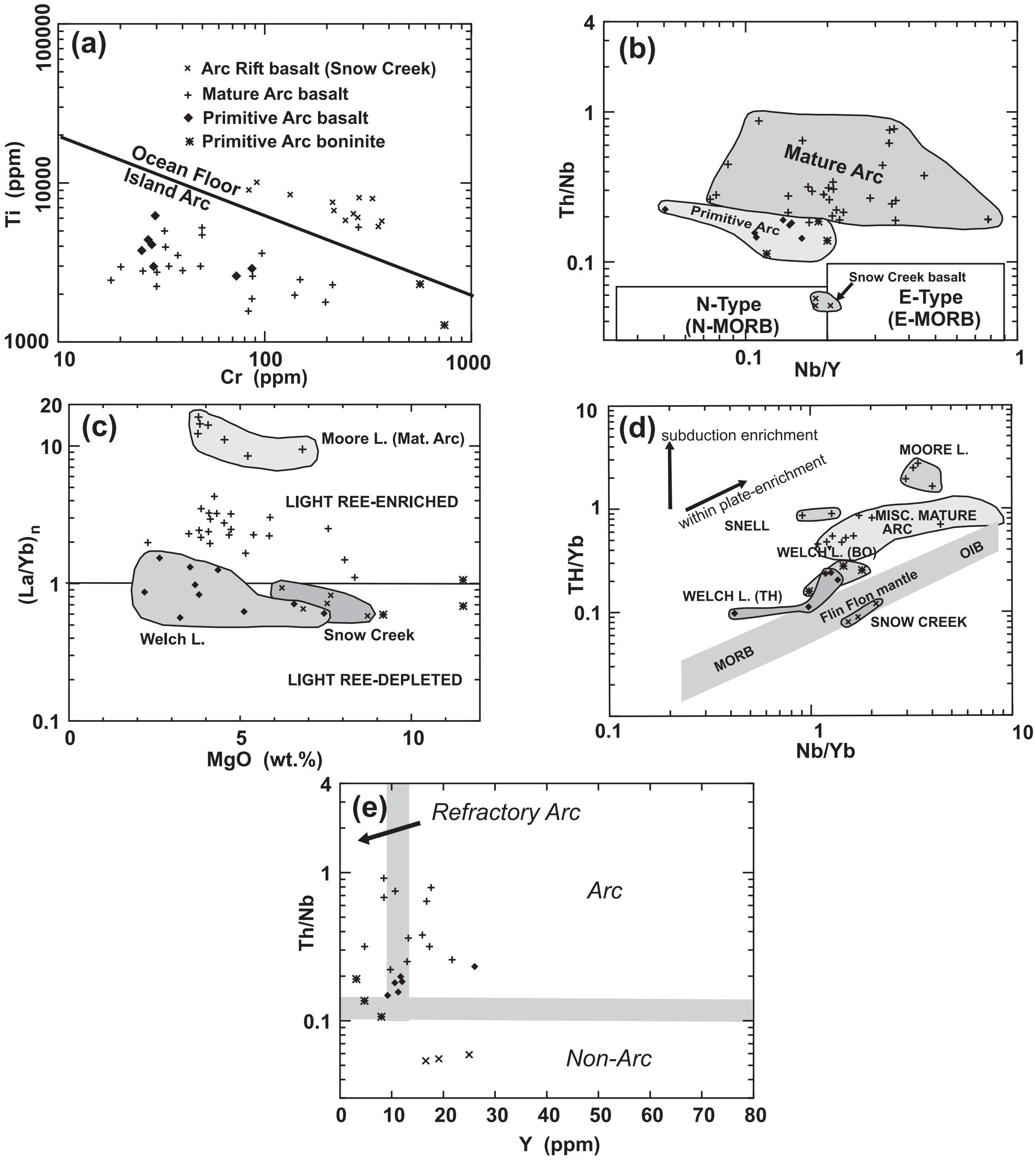
Fig. 5. MORB-normalized incompatible element diagrams, with elements arranged in order of increasing incompatibility in MORB-source mantle from left to right (after Sun and McDonough 1989; modified by Stern et al. 1995*a*).



1981). Their low $(La/Yb)_n$ and Th/Nb ratios (Figs. 6*c* and 6*e*) and low REE, Th, Ti, Zr, and Y contents (Figs. 5*a*, and 5*b*) are features that Stern et al. (1995*b*) have suggested may be due to derivation from a depleted, refractory mantle source that was residual after extraction of MORB or back-arc basin basalts. High-Ca boninites are a rock type currently found in the forearc regions of primitive Cenozoic island arcs where they have been attributed to shallow, high-temperature melting of depleted, hydrated (subducted), sub-arc refractory mantle (Crawford et al. 1989). Elevated temperatures have been attributed to subduction of either (1) young, still hot, sea-floor spreading centers (Tatsumi and Maruyama 1989) or (2) sub-arc mantle heated by MORB-source mantle diapirs (Crawford et al. 1989). In the Flin Flon Belt, high Ca-boninites are unique to the Snow Lake primitive arc sequence.

The *mature arc* mafic flows (e.g., Snell, Moore, Threehouse) display the same “decoupling” of large-ion lithophile elements (LILE) and HFSE as do primitive arc mafic flows, but they have higher, variable Th and pronounced Nb, Zr, Hf, and Ti depletion anomalies on MORB-normalized diagrams (Fig. 5*c*, 5*d*, and 5*e*), and higher Th/Nb, Th/Yb, and La/Yb (LREE-enriched) ratios compared to primitive arc Welch Lake mafic flows (Figs. 6*b*, 6*c*, and 6*d*). These features are consistent with a strong subduction signature (Fig. *6d*) and within-plate enrichment (Fig. *6d*), possibly combined with a more fertile mantle source, lower average extents of melting, and greater depths of origin (Stern et al. 1995*b*). This implies that mature arc mafic flows had a different magmatic evolution than those of the underlying primitive arc basalts, a conclusion substantiated by the generally lower ϵ_{Nd} values of 0 to +2.7 for mature arc mafic flows compared to values near +3 for primitive arc mafic flows (Stern et al. 1992; Fig. 7). Stern (1992) interprets the lower ϵ_{Nd} values of mature arc basalts to be a consequence of intracrustal contamination or, less likely, a contaminated mantle source. Intracrustal contamination during mature arc magma genesis is supported by the presence of an inherited zircon population between 2650 and 2824 Ma in the 1892 Ma mature arc Stroud Lake volcanic rocks (David et al. 1996). Initial ϵ_{Nd} values of the overlying Snell Lake basalt are among the lowest in the Flin Flon Belt and are consistent with recycling of up to 10% of older (Archean) crust. Thus, the geochemical features of mature

Fig. 6. Various basalt discrimination diagrams with Snow Lake arc assemblage samples plotted: (*a*) Ti vs. Cr (after Pearce 1975); (*b*) Th/Nb vs. Nb/Y (after Pearce 1983); (*c*) $(La/Yb)_n$ vs. MgO (after Stern et al. 1995*b*); (*d*) Th/Yb vs. Nb/Yb (after Stern et al. 1995*b*); (*e*) Th/Nb vs. Y (after Swinden 1996).



arc mafic flows relative to those in the primitive arc may reflect thicker crust and more diversified arc magma genesis as a consequence of an increasingly complex arc environment that probably included older crustal fragments and previously formed arc segments.

Arc-rift Snow Creek basalts have flat REE patterns; do not show the "decoupling" of LILE and HFSE that characterize arc magmas generated by subduction processes; have no Nb, Zr, Hf, or Ti depletion anomalies; and are indistinguishable from MORB (ocean floor – back-arc) basalts on various plots and discrimination diagrams (Fig. 5*f*, 6*a*, and 6*b*). These basalts are interpreted to be products of arc rifting as they have an unfaulted stratigraphic contact with underlying mature arc volcanic rocks (Fig. 4).

The distinctly different geochemistry of *primitive arc*, *mature arc*, and *arc-rift* basalts indicates that these rocks formed in disparate tectonic settings and suggests that either significant changes in volcanism took place in the evolving Snow Lake arc terrane or, possibly, that these volcanic rocks of diverse origin were tectonically juxtaposed along thrusts.

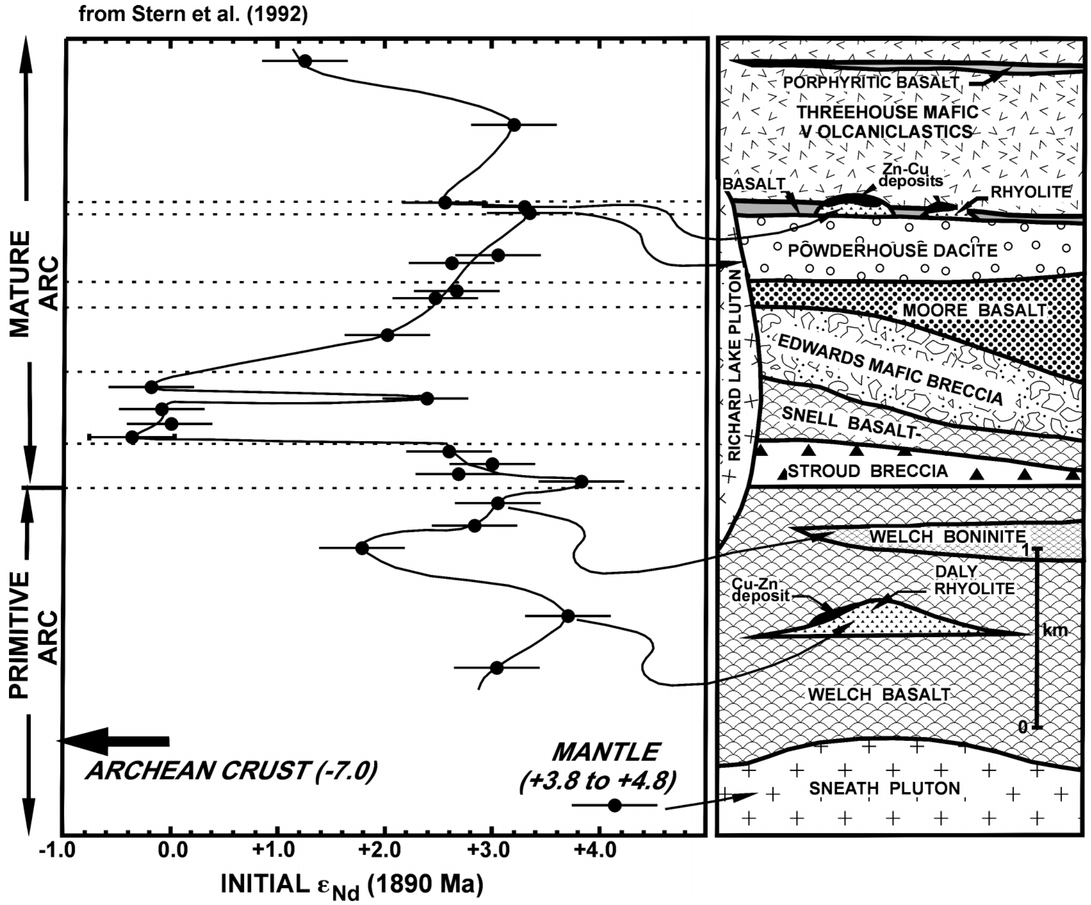


Fig. 7. Variations of ϵ_{Nd} in the primitive and mature arc sequences in the Snow Lake arc assemblage at Chisel Lake (from Stern et al. 1992).

Although 1.84–1.81 Ga thrust faults (David et al. 1996) are common structures in the Snow Lake area (Russell 1957; Froese and Moore 1980; Connors 1996; Kraus and Williams 1998, 1999), we prefer to interpret the section as structurally intact because the primitive and mature arc sections are "stitched" by the synvolcanic 1.89 Ga Richard Lake pluton (Bailes et al. 1991) and the exposed contact between mature and arc-rift volcanic rocks is unsheared and appears to be unfaulted.

Geochemistry of felsic rocks

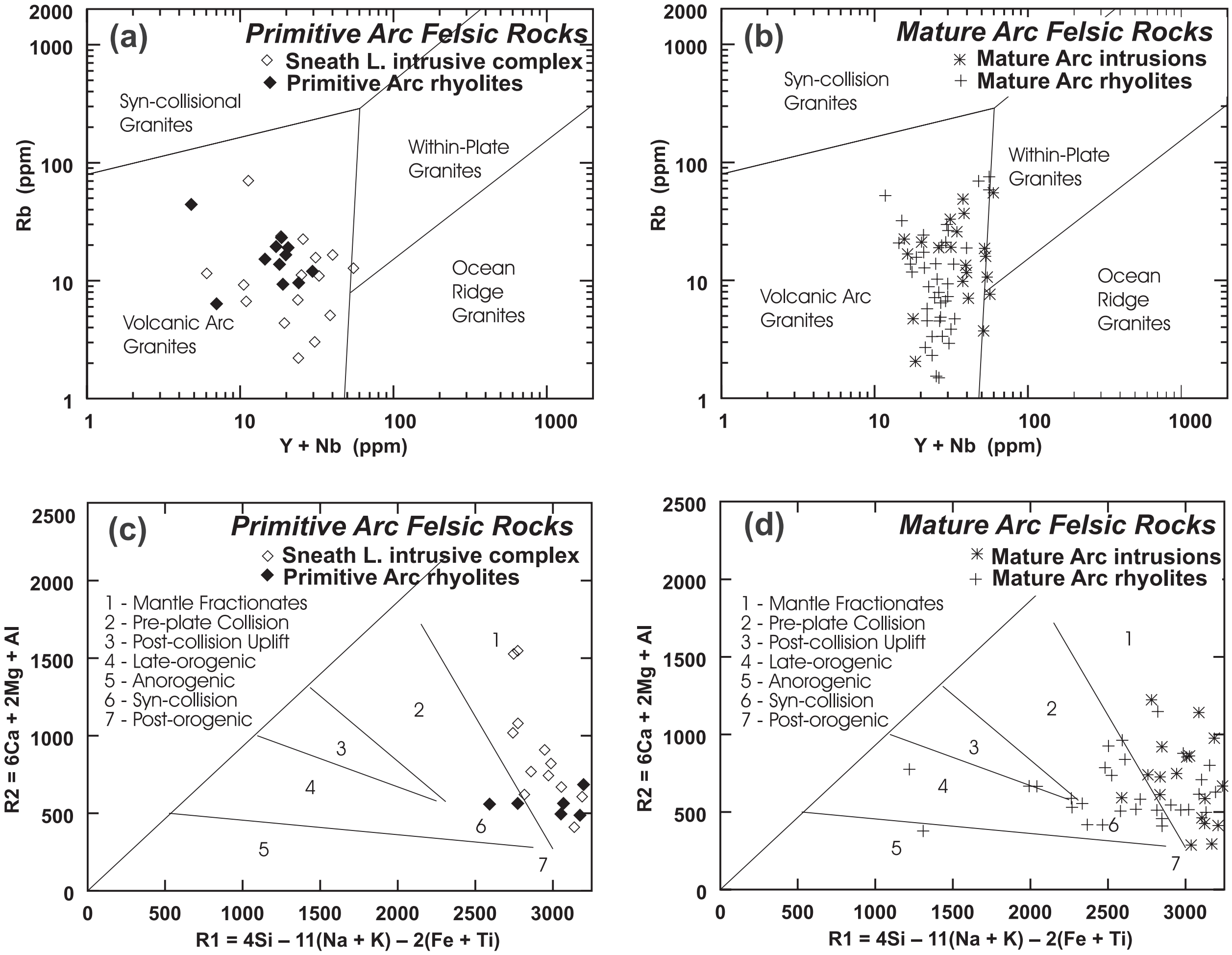
One hundred and twenty-seven whole rock and trace element geochemical analyses, sixty-seven REE analyses, and ten Nd isotopic analyses have been obtained from least-altered felsic volcanic and synvolcanic intrusive rocks in the Snow Lake arc assemblage (this study). Some of the analyses are already available (Stern et al. 1992, 1995*b*) and the remainder will be released in mid-1999 on a CD-ROM of Shield Margin NATMAP data.

Plotted on discriminant diagrams designed to identify tectonic environments of magma genesis (Fig. 8), analyses of Snow Lake area felsic extrusive and intrusive rocks show that they likely formed in a volcanic arc environment and, in addition, were probably derived from a mantle source. Geochemistry of the felsic extrusive rocks (Figs. 8 and 9), discussed below, show that the *primitive arc* (Anderson, Daly, Sneath, Konzie) and *mature arc* (Ghost, Photo, Powderhouse) felsic volcanic rocks are distinctly different, but are broadly similar, respectively, to the spatially associated Sneath and Richard–Powderhouse subvolcanic intrusions (Fig. 10). Exact geochemical correspondence between extrusive and intrusive phases is not present, nor do we expect this in our small data set, because both the Sneath Lake and Richard Lake subvolcanic intrusions are complex bodies composed of a number of phases of different age and composition.

Primitive arc felsic volcanic and intrusive rocks display flat REE to slightly light REE (LREE)-elevated profiles at approximately 10 times chondrite (Fig. 9). Although two of the rhyolite flow complexes (Anderson, Daly) contain VMS deposits, neither one includes samples with prominent negative Eu anomalies, as is typical of many VMS-hosting Archean rhyolites (Lesher et al. 1986), and two samples display positive Eu anomalies. Although the primitive arc rhyolite complexes and the underlying multicomponent Sneath Lake intrusive complex are broadly similar in age and composition, they are not necessarily coeval, as three of the four rhyolite complexes are intruded by late phases of the Sneath Lake intrusive complex.

Mature arc felsic volcanic rocks are geochemically distinct from those in the primitive arc. They have lower $(La/Yb)_n$, Zr/Y, and Th/Yb ratios than primitive arc rhyolites (Fig. 11). Both mature arc rhyolites and intrusive rocks have elevated LREE contents (Fig. 10) with HREE contents that are comparable to those displayed by primitive arc felsic magmas at 10 times chondrite. LREE contents of felsic mag-

Fig. 8. Tectonic discrimination diagrams for granitic rocks from Pearce et al. (1984) and Bachelor and Bowden (1985). Snow Lake felsic volcanic and subvolcanic intrusive complexes plot in the volcanic arc granite field (*a* and *b*) and mainly as mantle fractionates (field 1, *c* and *d*).

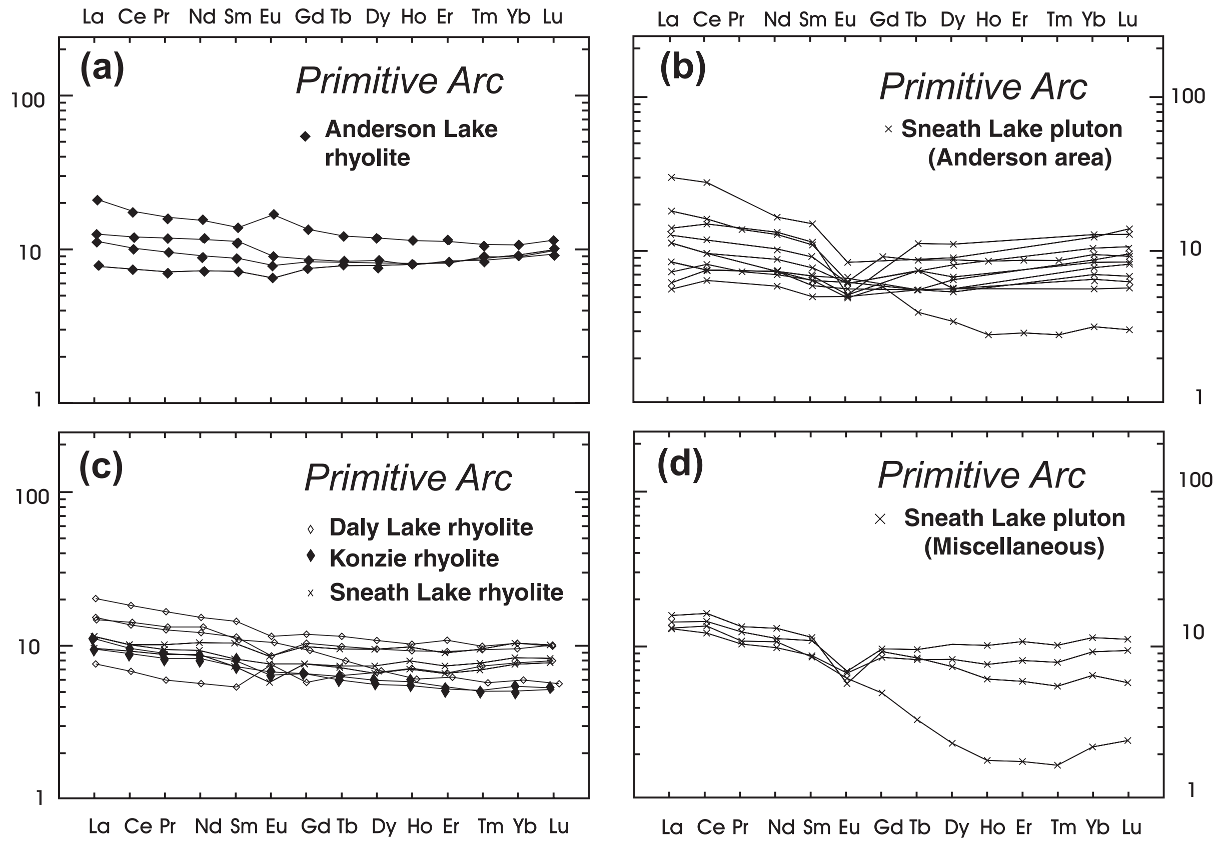


mas are up to 200 times chondrite. The Powderhouse dacite dyke swarm is clearly the intrusive equivalent of the extrusive Powderhouse dacite as both share identical REE profiles (Fig. 10*a*, 10*b*). The VMS-hosting Ghost and Photo Lake rhyolites are less clearly the extrusive equivalents of the Richard Lake pluton as the three analyzed samples of tonalite from the Richard Lake pluton are more strongly enriched in LREE. Both the Ghost and Photo Lake VMS-hosting rhyolites display negative Eu anomalies (Fig. 10*c*) as do two of the samples from the Richard Lake intrusive complex (Fig. 10*d*).

Rhyolites and subvolcanic tonalite–trondhjemite plutons from the primitive and mature arcs share similar isotopically primitive ϵ_{Nd} contents (Fig. 7; Stern et al. 1992) that are distinctly higher than associated mafic flows (e.g., Welch basalt and Daly rhyolite, Fig. 7). Higher ϵ_{Nd} values for the rhyolites suggest that the rhyolites did not form simply by fractionation in shallow magma chambers of the same magma that produced the mafic flows. This suggests that felsic and mafic magmas were generated separately, a feature consistent with the bimodal basalt–rhyolite character of Snow Lake arc assemblage magmatism and the paucity of rocks of intermediate composition. A corollary of this is that the tectonic conditions conducive for the formation of geochemically primitive and, probably, mantle-derived felsic magmas may also have been essential for the generation of the rhyolite-hosted VMS mineralization at Snow Lake area (Stern et al. 1992).

This close association between felsic volcanic rocks and VMS deposits is a fundamental characteristic of many Precambrian "greenstone belts" in Canada and has prompted interest in rhyolite geochemistry as a predictor of their potential to host ore (Campbell et al. 1982; Lesher et al. 1986; Barrie et al. 1993). Lesher et al. (1986) and Barrie et al. (1993) suggest a number of discriminants that distinguish ore-hosting from barren Archean rhyolites of the Superior Province. However, these discriminants do not appear to be directly applicable to the Paleoproterozoic rhyolites from the Snow Lake area, as ore-hosting varieties plot with barren Abitibi belt Archean rhyolites (Fig. 11). This is probably because magmas in the Flin Flon belt are depleted in REE and HFSE (Zr, Y, and Ti), elements that are used extensively in the discriminant diagrams developed by Lesher et al. (1986). Stern et al. (1995*a*, 1995*b*) suggest that this depletion is a consequence of production of magmas in the Flin Flon – Glennie Lake domain from depleted mantle that had been

Fig. 9. Chondrite-normalized REE patterns for samples from various primitive arc rhyolites and the subvolcanic Sneath Lake intrusive complex.



previously involved in extensive back-arc magmatism. This suggests that using HFSE- and REE-based rhyolite geochemistry, without regard to the overall environment of paragenesis of samples, may not necessarily provide a definitive method of identifying ore-associated rhyolites (see also Syme et al. 1999).

Tectonic setting of VMS deposits in the Snow Lake arc assemblage

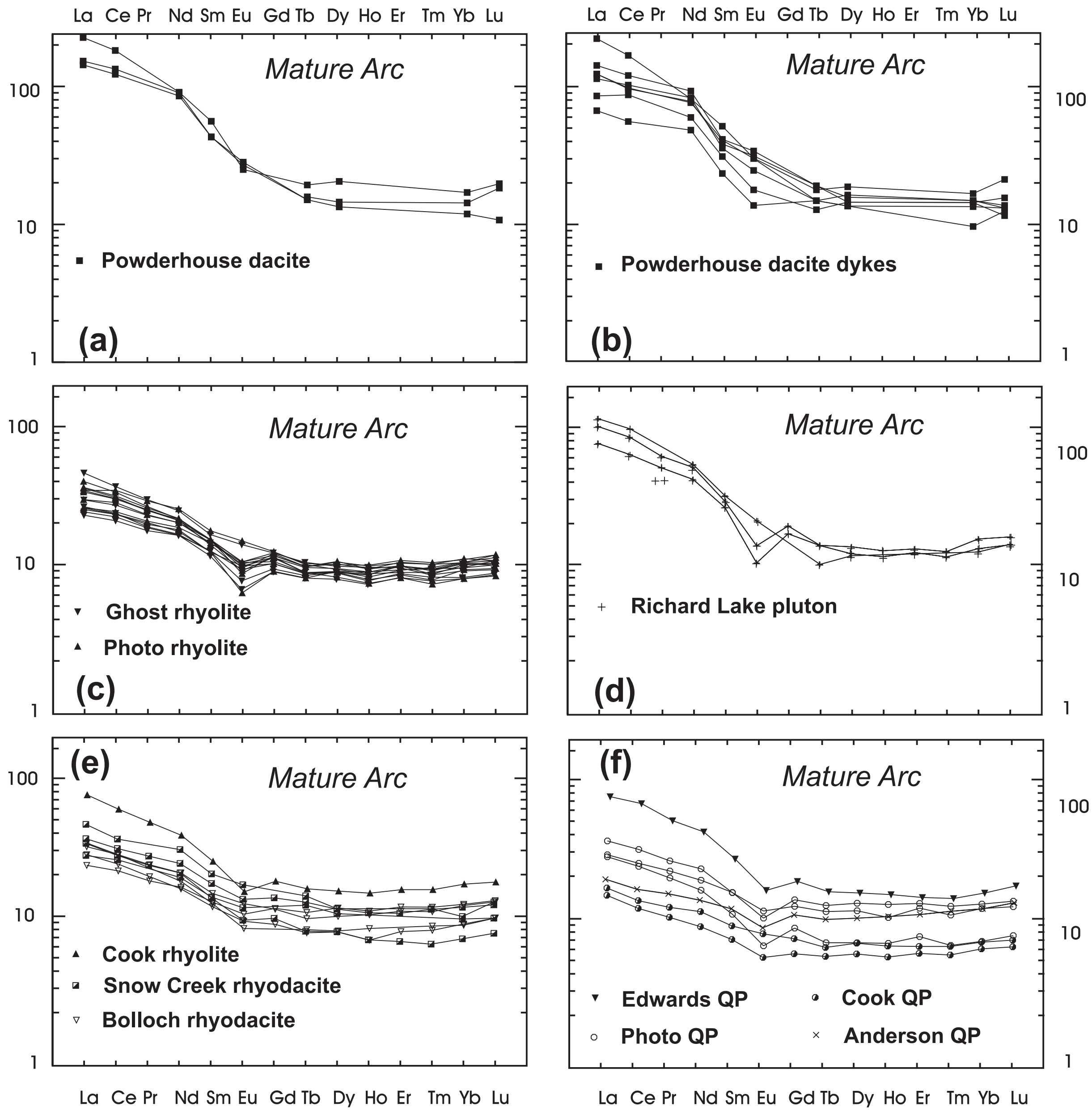
The Snow Lake arc assemblage consists of over 60% mafic flows with the VMS deposits associated with rhyolite flows. This suggests that the VMS deposits are of the bimodal-mafic type of Barrie and Hannington (1997). The stratigraphic setting of these VMS deposits is described and documented in Bailes and Galley (1996 and references therein). In summary, economically significant VMS deposits in the Snow Lake arc assemblage occur in three stratigraphic settings: (1) Cu-rich deposits (e.g., Anderson, Stall) associated with rhyolite flows in the primitive arc, (2) Zn-rich deposits (e.g., Chisel, Ghost) associated with rhyolite flows in a volcaniclastic-dominated portion of the mature arc sequence, and (3) a Cu–Zn–Au deposit (Photo) associated with a large unit of rhyolite flows also in the mature arc (Fig. 4). VMS deposits in both the primitive and mature arc sequences are spatially associated with large subvolcanic tonalite intrusive complexes (e.g., Sneath, Richard), located within rhyolite flow complexes and associated with regionally extensive semiconcordant zones of altered supracrustal rocks. Altered rocks are interpreted to be products of pluton-generated, seawater-dominated geothermal activity (Walford and Franklin 1982; Bailes and Galley 1996; Skirrow and Franklin 1994). Discordant, planar zones of highly altered rocks in the footwall to VMS deposits are interpreted to be the trace of hydrothermally modified synvolcanic faults (Walford and Franklin 1982; Bailes and Galley 1996).

The following sections outline characteristics of rocks hosting VMS deposits in the primitive and mature arcs. Our objective is to characterize the geotectonic environment of deposition of these VMS-hosting rock sequences and to identify those features that are favourable for the formation of VMS deposits.

Setting of primitive arc VMS deposits

Cu-rich VMS deposits in the *primitive arc* bimodal basalt–rhyolite sequence are spatially associated with the rhyolite flow complexes (Fig. 4). The Anderson rhyolite is host to three economic Cu-rich deposits (Anderson, Stall, and Rod) that originally contained 10.1 Mt of ore with an average grade of 4.15% Cu and 0.53% Zn. It also hosts the uneconomic 13 Mt Linda deposit, grading 0.3% Cu and 0.79% Zn, and the subeconomic, stockwork-type Ram zone. The primitive arc Daly Lake rhyolite hosts the subeconomic Cu-rich Raindrop occurrence (Hodges and Manojlovic 1993) and is in close proximity to the Pot Lake deposit. The Sneath Lake rhyolite, which lies geographically between the

Fig. 10. Chondrite-normalized REE patterns for samples from various primitive arc rhyolites and felsic subvolcanic intrusive rocks. QP, quartz porphyry.



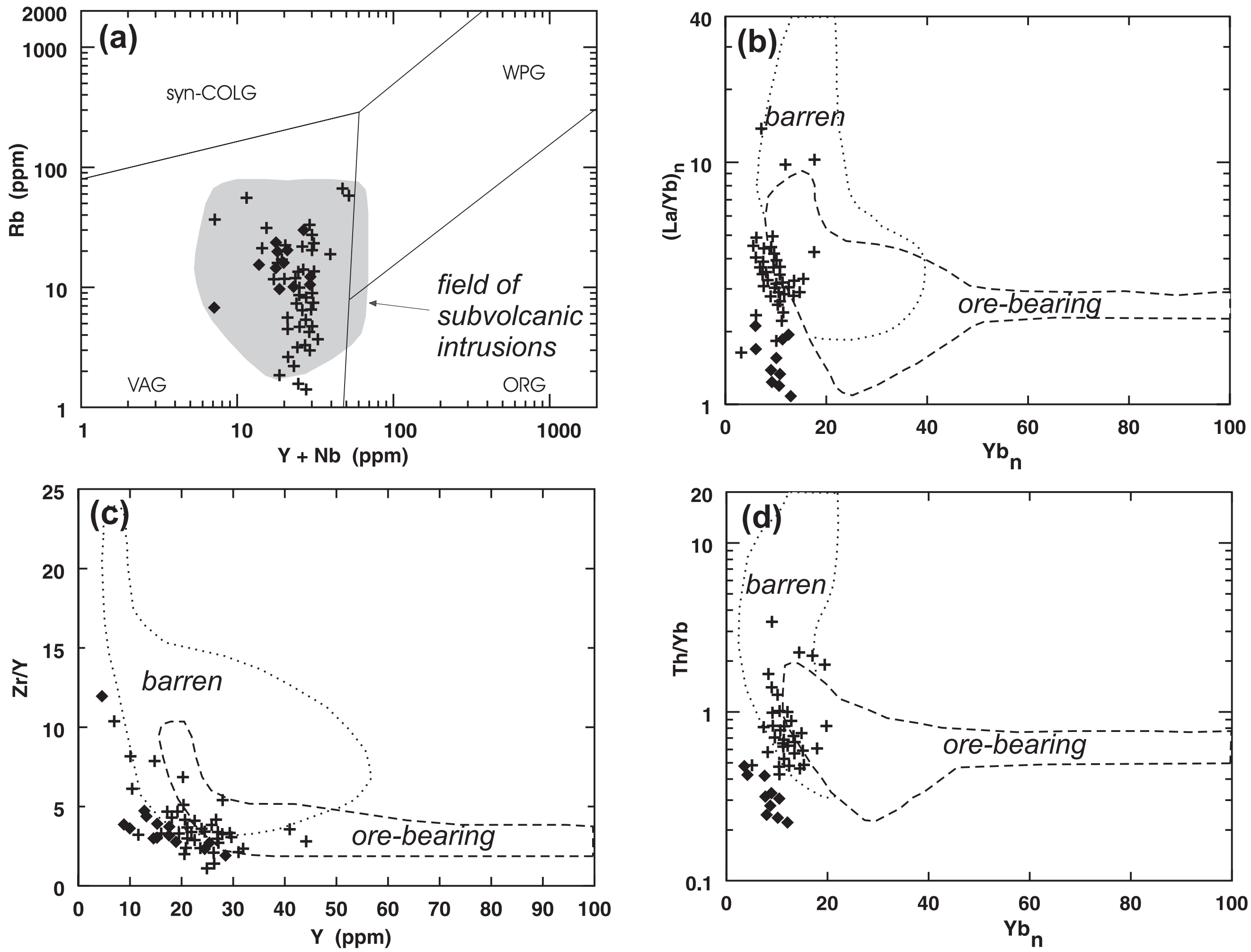
Daly and Anderson rhyolites, contains minor Cu-rich VMS-type mineralization (G. Kitzler, Hudson Bay Exploration and Development Ltd., personal communication 1995).

The *primitive arc* is a >2.5 km thick section which consists of >85% mafic flows, 10% felsic flows, and <5% mafic volcaniclastic rocks. Ubiquitous pillows in the mafic flows, abundant lobes and tongues in the felsic flows, and local graded bedding in mafic volcaniclastics suggest that this sequence was deposited in a subaqueous environment.

The supracrustal rocks are intruded by a sill-like, semiconformable 1.5 by 22 km felsic intrusive complex (Sneath Lake intrusion in Fig. 4) that displays many of the features expected of a high-level subvolcanic intrusion: absence of a metamorphic halo, multiple phases, bodies of intrusion breccia, textural variation, porphyritic character, internal alteration (including disseminated chalcopyrite), and overprinting by kinematic and metamorphic events (Bailes and Galley 1996). Fragments of the texturally distinctive quartz-megaphyric phases of the Sneath Lake tonalite in overlying primitive arc (Anderson) and mature arc (Stroud, Edwards and Threehouse) volcanogenic breccia units require uplift and erosion of the intrusion that is most logically interpreted to be due to uplift along synvolcanic fault scarps (not shown in Fig. 4). This and a U–Pb zircon age of 1886^{+17}_{-9} Ma (David et al. 1996) support an interpretation of the intrusion as synvolcanic (see also caption for Fig. 4).

The role played by the Sneath Lake intrusive complex in generating VMS deposits in the Snow Lake primitive arc has been a subject of debate since Walford and Franklin (1982) proposed it as the “heat engine” that drove subseafloor geo-

Fig. 11. Snow Lake ore-hosting rhyolites from the *primitive* (◆) and *mature* (+) arc sections are plotted on (*a*) a granite tectonic discrimination diagram from Pearce et al. (1984) and (*b–d*) diagrams developed by Barrie et al. (1993) to distinguish ore-bearing from barren rhyolites in the Abitibi Belt.



thermal activity. Certainly the apparent coeval nature of the Sneath Lake tonalite and ore-hosting rhyolite flows, the increase in intensity of alteration of the host rocks in the stratigraphic hanging wall of the pluton, and the steady increase in the Cu to Zn ratio (Cu/(Cu + Zn)) of the VMS deposits (Bailes and Galley 1996) as distance to the pluton decreases indicate a relationship between the pluton and VMS mineralization. The question is whether the pluton directly contributed to the formation of the VMS deposits (e.g., direct magmatic input, generation of subseafloor geothermal activity) or whether these associations can be explained by another mechanism.

The key to the broader geodynamic setting and associations of the Snow Lake primitive arc VMS deposits is the presence in the sequence of boninitic flows (Welch), low-Ti refractory arc tholeiites (Welch), and isotopically juvenile felsic rhyolites (e.g., Daly) and tonalites (Sneath). The association of boninites, low-Ti refractory arc tholeiites, and felsic volcanic rocks has been interpreted in both the modern (Beccaluva and Serri 1988; Crawford et al. 1981) and Phanerozoic (Swinden 1996; Lapierre et al. 1985) times to be products of high-temperature, hydrous partial melting of refractory mantle sources in proto-arc environments during arc extension. According to Crawford et al. (1989) and Tatsumi and Maruyama (1989), boninitic and refractory magmas are a reflection of zones of extremely high heat flow, because they require high heat of fusion to form. Thus, an explanation for the isotopically juvenile felsic magmas of the Sneath Lake intrusive complex and the overlying rhyolite flow complexes at Snow Lake is that they may have been produced by partial melting of primitive oceanic lithosphere in a zone of high heat flow. This interpretation allows the spatial association of VMS deposits with the Sneath Lake intrusive complex and overlying rhyolite flows to be indirect and linked through their common genetic affiliation with a zone of high heat flow, rifting, and attendant increase in fluid circulation and geothermal activity. The high temperature geothermal activity produced in this environment could produce the distinctly Cu-rich VMS deposits that characterize the Snow Lake primitive arc.

The Snow Lake primitive arc and West Shasta VMS mining district of northern California share several characteristics: low-Ti refractory basalt lavas, boninites, prominent domains of geothermally altered rock, isotopically juvenile felsic flows and tonalite plutons, and Cu-rich VMS deposits. Albers and Bain (1985) and Lapierre et al. (1985) interpret these features at West Shasta to be a product of arc rifting, with their interpretation confirmed by an overlying unit of arc-rift basalt. The numerous similar lithological and geochemical characterisitics in the two mining districts suggest that the contained VMS deposits were more likely the product of their shared geodynamic setting rather than solely the product of pluton-generated geothermal activity.

Setting of mature arc VMS deposits

The *mature arc* hosts four known Zn-rich massive sulphide deposits (Fig. 4) of which three (Chisel, Lost, and Ghost) have been mined for a total of 7.8 Mt (production plus reserves) grading 0.42% Cu and 10.06% Zn. The fourth deposit (Chisel North), which has been drill-defined but is unmined, contains 2.6 Mt grading 0.23% Cu and 8.9% Zn (Galley et al. 1993); it occurs 300 m down plunge from the Chisel deposit at a depth of 600–800 m. All four deposits occur in the same stratigraphic interval and are spatially related to rhyolite flow complexes (Chisel, Ghost). The Cu–Zn–Au-rich Photo Lake VMS deposit, 4 km north of the Chisel area deposits (Fig. 4), is hosted by the Photo Lake rhyolite which is geochemically indistinguishable from the Ghost Lake rhyolite (Fig. 10*c*; Bailes 1997). The Chisel area massive sulphide deposits are located along a linear alteration zone that is interpreted by Galley et al. (1993) to be the expression of a synvolcanic fault.

The *mature arc* is a 3 km thick section that consists of 20% mafic flows, 20% felsic flows, 10% dacite, 5% andesite, 30% mafic volcaniclastic rocks, and 15% felsic volcaniclastic rocks. Ubiquitous pillows in the mafic flows, lobe and tongue facies rhyolite flows, and graded bedding in mafic volcaniclastics indicate this to be a subaqueous sequence. However, scoria fragments and subrounded blocks in volcaniclastic units, as well as a possible unconformity at the base of the Threehouse formation (Bailes and Simms 1994), suggest that subaerial conditions did exist locally in the mature arc.

Subvolcanic intrusions are abundant in the footwall to the mature arc VMS deposits. They locally form up to 50% of the footwall sequence in volcaniclastic rocks of the Edwards Lake formation (Galley and Scoates 1990; Bailes and Galley 1996; Bailes et al. 1996) and were possibly part of a vent facies or eruptive centre. The intrusions include a small, layered mafic–ultramafic sill, quartz–plagioclase porphyritic stocks, dykes ranging in composition from peridotite through diorite to dacite, and a large tonalite intrusive complex (Richard Lake pluton). Crosscutting relationships between dyke sets suggest that their intrusion was contemporaneous from several magma sources. Many of the intrusions are geochemically identical to overlying supracrustal volcanic units. For example, a prominent synvolcanic dyke–sill swarm shown on Fig. 4 (diagonal line pattern) is composed mainly of dacite dykes that are geochemically indistinguishable from the overlying Powderhouse dacite formation. In addition, mafic dyke margins in volcaniclastic strata are commonly amoeboid, which suggests that were synvolcanic and intruded unconsolidated, water-saturated detritus.

Many of the subvolcanic intrusions were probably involved in generating and sustaining hydrothermal activity that is now recorded by altered rocks spatially associated with the intrusions (Bailes and Galley 1996). Of these, a dacite dyke–sill swarm, west of Edwards Lake and the Richard Lake intrusive complex (Fig. 4), was the most significant and the most likely to have focused hydrothermal activity in the Chisel Lake area. The Richard Lake pluton is a multiphase intrusion composed of quartz porphyritic to aphyric tonalite. Miarolitic cavities and vein–breccia systems suggest that it is an epizonal intrusion, and pyrite–chalcopyrite-enriched zones and extensive internal epidote alteration indicate interaction with hydrothermal fluids. This, in combination with the ubiquitous alteration of overlying supracrustal rocks and a synvolcanic U–Pb zircon age of 1889 Ma (Bailes et al. 1991), suggests that it was coeval with associated volcanic rocks (Bailes and Galley 1996).

The traditional interpretation of the above features is that the VMS deposits are a product of subseafloor geothermal activity initiated by the high-level subvolcanic intrusions, with the Richard Lake felsic intrusive complex playing a prominent role. Again, the issue is whether the Richard Lake felsic intrusive complex contributed directly (heat budget) to the formation of the VMS deposits or whether these associations are explicable by another mechanism, as was the case for primitive arc VMS deposits. The key to this question lies in the lithological and geochemical character of the mature arc section and the implications for the broader geodynamic setting and associations of the contained VMS deposits.

The host rocks for the mature arc VMS deposits display several features which indicate that the arc may have been undergoing extension. The feature that most strongly indicates extension is the interpretation of the stratigraphically overlying Snow Creek basalts, which exhibit a MORB-like geochemistry, as a direct product of arc rifting. Additional indirect evidence for arc extension includes voluminous volcaniclastic detritus in the mature arc, felsic magmas more isotopically juvenile than associated mafic flows, prominent synvolcanic dyke sets, and local presence of highly fractionated differentiated magma series. Volcaniclastic rocks (e.g., Stroud, Edwards, much of Threehouse), which form over 40% of the mature arc and were deposited by debris flows of local derivation (beds up to 19 m thick; Bailes and Galley 1996), indicate local topographic relief that is consistent with fault scarps and topographic depressions produced during extension. Juvenile felsic magmas that are isotopically more primitive than associated mafic magmas in a bimodal volcanic suite are also consistent with arc rifting for reasons already discussed in the above section on the primitive arc. Abundant and compositionally varied dyke sets and synvolcanic intrusions are compatible with extension and egress of magmas along channelways provided by an extensional tectonic regime. Differentiated and strongly fractionated Moore basalt and Powderhouse dacite are magma types that could be interpreted to result from low magma supply rates at a newly developed ridge site. Pearce et al. (1994 and references within) and Kerrich and Wyman (1996) have attributed rocks with this geochemical signature to be a product of low magma supply rates combined with the presence of older, colder, and thicker lithosphere resulting in magmas whose evolution is dominated by fractionation rather than re-supply from primitive melts. These conditions are typically found in modern rift tip environments.

This implies that VMS deposits in the mature arc, although spatially associated with the Richard Lake tonalite intrusive complex and overlying rhyolite flows, may be indirectly linked to these rocks through their common genetic affiliation with a zone of high heat flow, rifting, and attendant increase in fluid circulation and geothermal activity. Thus, VMS deposits could be a product of conditions inherent in their geodynamic setting rather than being directly linked to spatially associated felsic magmatism.

VMS deposits in the mature arc are distinctly Zn-rich, but do include one Cu–Zn–Au-rich deposit (Photo). The Zn-rich VMS deposits, although spatially associated with rhyolite flows, occur in volcaniclastic-dominated sequences. The Cu–Zn–Au-rich Photo Lake VMS deposit occurs in a rhyolite flow-dominated portion characterized by negligible associated volcaniclastic rocks. The high Zn content of the volcaniclastic-hosted VMS deposits may reflect inability of the mineralizing geothermal system to sustain high-temperature venting in the permeable volcaniclastic rocks. The high Cu content of the rhyolite-hosted Photo Lake deposit may reflect more focused, less diffuse discharge. The high Au content of the Photo Lake deposit compared to Cu-rich deposits in the primitive arc may indicate that it was deposited in a shallower water environment (Hannington et al. 1997 and references therein).

Discussion

One of the major contributions of the Shield Margin NATMAP project has been to provide a regional context in which to understand the setting of Flin Flon Belt VMS deposits. This has occurred both on a belt scale (e.g., arc association of VMS deposits, tectonic collage concept for the belt) and at a deposit scale (e.g., arc rifting association, isotopically juvenile rhyolite association). This has added another dimension to VMS exploration in the belt, which has up to now relied on the traditional deposit-scale VMS exploration models widely reported in the literature (e.g., Franklin et al. 1981; Lydon 1984, 1988). This study, which is based on a combination of years of careful mapping, stratigraphic analysis, modern geochemical analysis of volcanic rocks, and structural and tectonic synthesis, demonstrates that new insights into the origin and evolution of VMS deposits can be elucidated even for rocks, such as those at Snow Lake, that have undergone complex deformation and metamorphic recrystallization to lower to middle almandine–amphibolite facies mineral assemblages.

This study challenges the traditional view that the association of Snow Lake VMS deposits with two large synvolcanic tonalite intrusive complexes (Sneath, Richard), with geochemically similar rhyolite complexes (Anderson, Daly, Chisel, Photo), and with prominent zones of hydrothermally altered rocks is a direct product of pluton-generated, seawater-dominated geothermal activity (Walford and Franklin 1982; Bailes 1987; Skirrow and Franklin 1994; Bailes and Galley 1996). An alternative explanation is that arc rifting, an important element in the development of Snow Lake arc assemblage, has played a pivotal role in producing VMS deposits by generating anomalously high heat flow, fracturing, and fluid circulation. According to this interpretation, the felsic magmas, geothermal activity, and VMS deposition are indirectly related to one another and directly related to conditions set up by the geodynamic process that caused rifting. Although this idea is not new and has been proposed for other VMS-containing "greenstone" belts (e.g., Cathles 1983; Swinden 1996; Sillitoe 1982), this is the first time that it has been been applied to the Paleoproterozoic deposits of the Flin Flon greenstone belt, with the exception of Syme et al. (1999).

The implication of this reinterpretation of the traditional genetic model for formation of Snow Lake VMS deposits is that synvolcanic plutons, rhyolites, and prominent alteration systems, which have been regarded in the past as the geological signatures of highly prospective VMS terranes, may just be reflections of the larger geodynamic setting of VMS deposits. Therefore, these features are not always directly related to the VMS mineralization, and additional criteria for assessing the prospectivity of volcanic belts are required. More appropriate criteria for evaluating the base metal prospectivity of volcanic terranes may lie in examination of individual stratigraphic sections for evidence of rifting or for critical lithologic associations (Wyman 1996 and references therein). For example, the correlation of VMS deposits with particular rock associations (e.g., the low-Ti basalt, high-Ca boninite, and rhyolite association in the primitive arc at Snow Lake), geochemically primitive refractory mafic magmas (this paper; Swinden 1996; Stern et al. 1995*b*), isotopically juvenile felsic magmas in bimodal succession (this paper; Stern et al. 1995*b*; Lapierre et al. 1985), high-temperature rhyolites (Barrie 1995), arc-rift basalts (Syme et al. 1999), or some combination of these features may be more discerning criteria on which to underpin modern exploration programs.

Conclusions

This study of volcanic rocks at Snow Lake provides new insights into the stratigraphic and geodynamic setting of VMS deposits contained in the Snow Lake arc assemblage, a 15 km wide allochthon in a fold and thrust domain at the east end of the Flin Flon Belt. VMS deposits in other fault-bounded panels of volcanic rocks at Snow Lake are structurally exotic and have an indeterminate relationship to those contained in the Snow Lake arc assemblage. This emphasizes the importance of integrating studies of large-scale structures and tectonic features, such as those elucidated during Shield Margin NATMAP, with deposit-scale studies of individual VMS-rich domains.

(1) The seven producing and past-producing VMS mines in the Snow Lake arc assemblage occur in a >6 km thick section that records in its stratigraphy and geochemistry a temporal evolution in geodynamic setting from a *primitive arc*, to a *mature arc*, to a *rifted arc*. The primitive arc contained three Cu-rich VMS mines (Anderson, Stall, Rod) and the mature arc contained three Zn-rich VMS (Chisel, Lost, Ghost) and one Cu–Zn–Au (Photo) mines.

(2) The most important contribution of this study is that it provides stratigraphic and geochemical evidence that both the VMS-hosting primitive and mature arc volcanic rocks were affected by intra-arc rifting. Evidence for rifting in the

primitive arc includes the combination of boninite, low-Ti basalt, and isotopically juvenile rhyolite flows, an association of lithologies that has been attributed in both modern and Phanerozoic arcs to high-temperature hydrous melting of refractory mantle sources in an extensional and (or) proto-arc environment. Rifting of the *mature arc* is indicated by the presence of the stratigraphically overlying Snow Creek arc-rift basalts, with MORB-like geochemistry. Indirect support for rifting in the mature arc is provided by voluminous volcaniclastic detritus, prominent synvolcanic dyke sets, local presence of highly fractionated differentiated magma series, and felsic magmas that are more isotopically juvenile than associated mafic flows.

(3) Arc crust appears to have been fundamentally different during formation of the primitive and mature arcs. This is indicated by higher Th/Nb, Th/Yb, and La/Yb ratios for mature arc than primitive arc mafic flows, combined with low ϵ_{Nd} contents of the mature arc mafic flows (0 to +2.7) and presence of Archean zircon xenocrysts in the mature arc Stroud rhyolite. This suggests that mature arc magmas were affected by within-plate enrichment, by derivation from a more fertile mantle source, by lower average extents of melting at greater depths, by contamination from older crustal fragments or previously formed arc segments, or by some combination of these features. However, they both exhibit features characteristic of extension in an arc setting and were, thus, affected by an increase in heat flow, fluid circulation, and geothermal activity.

(4) Both the primitive and mature arc VMS deposits are spatially associated with isotopically juvenile rhyolite flows and related subvolcanic felsic intrusive complexes in bimodal basalt–rhyolite successions. The felsic magmas (rhyolite flows and intrusive complexes) are isotopically more juvenile than the intercalated mafic flows precluding their derivation by fractionation in a high-level magma chamber of the same parent magmas that produced the associated mafic flows. One interpretation is that the felsic magmas were produced by high-temperature partial melting of the base of the oceanic lithosphere; this explains the bimodality of the extrusive volcanic sequences and the isotopically juvenile character of the felsic magmas. One way to indirectly identify VMS-prospective terranes could be to focus on compositionally bimodal sequences (i.e., basalt–rhyolite) that contain isotopically more juvenile rhyolites.

(5) This study shows that the traditional Snow Lake VMS model, which invoked a "pluton-generated" heat source, is only partly valid. A more complete explanation of observed features of Snow Lake VMS deposits and host rocks is provided by a model that invokes an arc-rifting geodynamic setting to trigger high heat flow and increased fluid circulation. This study supports the growing body of evidence which suggests that discriminants that can identify geodynamic settings of a more global scale, such as arc rifting, may be more successful than those based solely on a deposit-scale "pluton" model for evaluating the VMS prospectivity of "greenstone belts."

Acknowledgments

This paper has drawn extensively on the work of geologists involved in two federal–provincial initiatives (EXTECH I and NATMAP Shield Margin), and we acknowledge the contributions of our many colleagues at Manitoba Energy and Mines (MEM), Geological Survey of Canada (GSC), University of New Brunswick, and GEOTOP (UQAM) who were involved in these intiatives. We are particularily indebted to Eric Syme (MEM), Richard Stern (GSC), and Steve Lucas (GSC) for data and concepts from published papers, and for discussions and ideas that have stimulated us and influenced our understanding of the Flin Flon Belt and the place of VMS mineralization in the Snow Lake arc assemblage. Eric Syme (MEM) reviewed an initial draft of the manuscript. We thank Steve Scott and Kevin Ansdell for their excellent reviews and many helpful editorial and scientific suggestions. Bonnie Lenton (MEM) supplied cartographic support.

Funding for this study was provided through the Canada–Manitoba Partnership Agreement on Mineral Development, the EXTECH I Project, the NATMAP Shield Margin Project, and the Province of Manitoba.

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