Setting of Paleoproterozoic volcanic-hosted massive base metal sulphide deposits, Snow Lake

A.H. Bailes[1] and A.G. Galley[2]

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Abstract: Two discrete volcanic-hosted massive sulphide (VHMS) mineralizing events, one Cu-rich and the other Zn-rich, are recognized in the oceanic arc sequence at Snow Lake, Manitoba. Cu-rich deposits occur in volcanic rocks accumulated in a primitive, possibly forearc or protoarc, arc tectonic setting. Zn-rich deposits exist in a stratigraphically higher sequence formed in an evolved, more mature arc tectonic setting. Rhyolite flow complexes and geochemically similar subvolcanic tonalite plutons are spatially associated with both Cu- and Zn-rich deposits at Snow Lake. A separate genesis for the felsic and mafic parental magmas is likely as rhyolite flows and subvolcanic tonalite intrusions share similar ε_{Nd} values that are distinctly higher than those of associated mafic flows.

Volcanic-hosted massive sulphide deposits typically occur stratigraphically above the subvolcanic tonalite plutons within rhyolite flow complexes and associated regionally extensive semiconcordant zones of altered supracrustal rocks. Altered rocks are interpreted to be a product of pluton generated, seawater-dominated hydrothermal activity. Discordant, planar zones of highly altered rocks in the footwall to volcanic-hosted massive-sulphide deposits are interpreted to be the trace of hydrothermally modified synvolcanic faults.

Our work indicates that exploration activity at Snow Lake could be targeted into the most prospective terrains by: 1) choosing volcanic rocks with arc geochemical signature, 2) picking areas with known subvolcanic intrusions, 3) emphasizing terranes with large zones of hydrothermally altered rocks, 4) concentrating on rhyolite flow complexes, and 5) targeting of crosscutting alteration zones.

Résumé : Dans la séquence d'arc océanique de la région de Snow Lake, au Manitoba, on distingue deux épisodes de minéralisation en sulfures massifs volcanogènes, l'un cuprifère et l'autre zincifère. Les gisements cuprifères sont encaissés dans des volcanites accumulées dans un milieu tectonique à un stade d'évolution précoce, probablement d'avant-arc ou de proto-arc. Les gisements zincifères s'observent dans une séquence stratigraphiquement plus haute, formée dans un milieu tectonique à un stade d'évolution plus avancé, donc d'arc plus mature. Les complexes de coulée rhyolitique et les plutons hypovolcaniques de tonalite géochimiquement semblables sont spatialement associés aux gisements tant cuprifères que zincifères de la région de Snow Lake. Il semble que les magmas parentaux felsiques et mafiques aient une origine distincte, étant donné que les coulées de rhyolite et les intrusions hypovolcaniques de tonalite ont des valeurs de ε_{Nd} semblables qui sont nettement plus élevées que celles des coulées mafiques associées.

[1] Manitoba Energy and Mines, Suite 360, 1395 Ellice Ave., Winnipeg, Manitoba R3G 3P2
[2] Geological Survey of Canada, 601 Booth St., Ottawa, Ontario K1A 0E8

Dans la stratigraphie, les gisements de sulfures massifs volcanogènes sont typiquement situés au-dessus des plutons hypovolcaniques de tonalite. Ils s'observent au sein des complexes de coulée rhyolitique et des zones semi-concordantes associées, qui sont d'étendue régionale et composées de roches supracrustales altérées. Les roches altérées sont interprétées comme le produit d'une activité hydrothermale d'origine plutonique où domine l'eau de mer. Les zones planaires discordantes de roches très altérées dans l'éponte inférieure des gisements de sulfures massifs volcanogènes sont interprétées comme le témoignage de failles synvolcaniques modifiées par l'activité hydrothermale.

Les présents travaux indiquent que l'exploration dans la région de Snow Lake pourrait être orientée vers les terrains les plus prometteurs en ciblant 1) les volcanites dont la signature géochimique est celle d'un milieu d'arc, 2) les secteurs où il y a des intrusions hypovolcaniques, 3) les terrains caractérisés par de vastes zones de roches altérées par des fluides hydrothermaux, 4) les complexes de coulée rhyolitique et 5) les endroits où les zones d'altération se recoupent.

INTRODUCTION

The Snow Lake area contains 11 producing and past-producing base metal mines, and accounts for production plus reserves of 25.4 Mt (Table 1). It is located at the east end of the Paleoproterozoic Flin Flon metavolcanic belt in northern Manitoba and Saskatchewan (Fig. 1 and 2). At 109.5 Mt of contained base metal sulphide ore, the Flin Flon Belt is one of the most productive base metal regions in Canada (Syme and Bailes, 1993), and the most productive Paleoproterozoic greenstone belt in the world (Franklin et al., 1995).

Snow Lake area polymetallic base metal massive sulphide deposits are noteworthy in that their host volcanic rocks are well exposed in cross-section, from a series of underlying subvolcanic intrusions, through hydrothermally altered volcanic rocks to the overlying massive sulphide deposits. This represents a unique opportunity to investigate factors that

Table 1. Metal grades in volcanic-hosted massive sulphide.

Deposit	District	Status	Cu %	Zn %	Cu:Zn	Au g/t	Ag g/t	Au:Ag	Prod.+Res. (tonnes)
Flin Flon	Flin	CL	2.19	4.2	0.52	2.6	41.5	0.06	62 446 734
Trout Lake	Flin	OP	2.11	4.79	0.44	1.41	15.43	0.09	10 180 608
Chisel Lake	Snow	CL	0.6	10.94	0.05				7 299 816
Stall Lake	Snow	CL	4.39	0.5	8.78				7 000 000
Osborne Lake	Snow	CL	3.14	1.52	2.07				3 380 061
Anderson Lake	Snow	CL	3.41	0.10	34.10				3 189 601
Callinan	Flin	OP	1.43	3.7	0.39	1.68	20.57	0.08	2 800 000
Spruce Point	Snow	CL	2.36	2.8	0.84	2.0	25.0	0.08	1 931 000
Schist Lake	Flin	CL	4.21	7.00	0.60	1.4	37.0	0.04	1 877 813
Centennial	Flin	CL	1.41	2.48	0.57	0.05	0.59	0.08	1 624 550
Westarm	Flin	CL	3.34	1.25	2.67				1 579 403
Coronation	Sask	CL	4.25	0.30	14.17	1.87	4.68	0.40	1 282 088
Dickstone	Snow	CL	2.47	3.13	0.79				1 083 590
Chisel pit	Snow	CL	0.23	10	0.03	2.74	54.86	0.05	1 140 000
White Lake	Flin	CL	1.97	4.63	0.43				849 598
Rod No. 2	Snow	CL	6.63	2.9	2.30				810 440
Photo Lake	Snow	OP	5.6	6.2	0.9	5.1	20	0.26	660 000
Ghost Lake/Lost Lake	Snow	CL	1.34	8.87	0.15				605 690
Cuprus	Flin	CL	3.24	6.42	0.50	1.37	28.69	0.05	462 002
Flexar	Sask	CL	3.75	0.47	7.98				305 940
Birch	Sask	CL	6.15						278 825
North Star	Flin	CL	6.11						241 643
Mandy	Flin	CL	5.63	13.95	0.40				123 116
Don Jon	Flin	CL	3.07						79 313
Rod No. 1	Snow	CL	5.00	4.5	1.11				22 675

District: Flin = Flin Flon; Snow = Snow Lake; Sask = Amisk Lake, Saskatchewan
Status: OP = present producer; CL = past producer
Grades quoted are production grades
Deposit size includes production plus reserves
Sources of grade and tonnage information: Bamburak, 1990; Thomas, 1990; Hudson Bay Exploration and Development data, 1995

control massive sulphide deposition. In this paper we describe and discuss the setting of and controls on the Snow Lake volcanic-hosted massive sulphide deposits.

Regional geology

The Paleoproterozoic Flin Flon belt is a collage of 1.92-1.88 Ga tectonostratigraphic assemblages juxtaposed during a period of 1.88-1.87 Ga intra-oceanic accretion and subsequent 1.84-1.78 Ga terminal collision of bounding Archean cratons (Lucas et al., in press). The volcanic rocks include oceanic arc, ocean floor-back arc, oceanic island, oceanic plateau, and older crustal assemblages (Syme and Bailes, 1993, Stern et al., 1995, in press). Oceanic arc assemblages include tholeiite, calc-alkaline, and rare shoshonite and boninite suites (Stern et al., 1995), almost identical to those forming in modern intra-oceanic arcs (e.g. Gill, 1981).

Volcanic-hosted base metal massive sulphide deposits in the Flin Flon Belt occur preferentially in oceanic island arc rocks that were extruded between 1.91 and 1.88 Ga (Machado and David, 1992; Syme and Bailes, 1993; David et al., 1993; Stern et al., 1993, 1995). Two volcanic-hosted massive sulphide-hosting oceanic island arc segments, one near the town of Flin Flon and one at Snow Lake, occur in the Manitoba portion of the Flin Flon Belt (Fig. 2). They are separated by an extensive, northeast-trending collage of 1904 Ma (Stern et al., 1994) ocean floor (MORB-like) back arc basalt flows and associated gabbro and ultramafic rocks (Stern et al., in press), with no associated volcanic-hosted massive sulphide deposits (Fig. 2). Lithological, geochemical, and isotopic criteria, for example the higher overall ε_{Nd} of mafic flows in the Snow Lake segment relative to those at Flin Flon (Stern et al., 1993), suggest that these oceanic island arc segments may represent unrelated, structurally juxtaposed terranes (Stern et al., 1995; Lucas et al., in press).

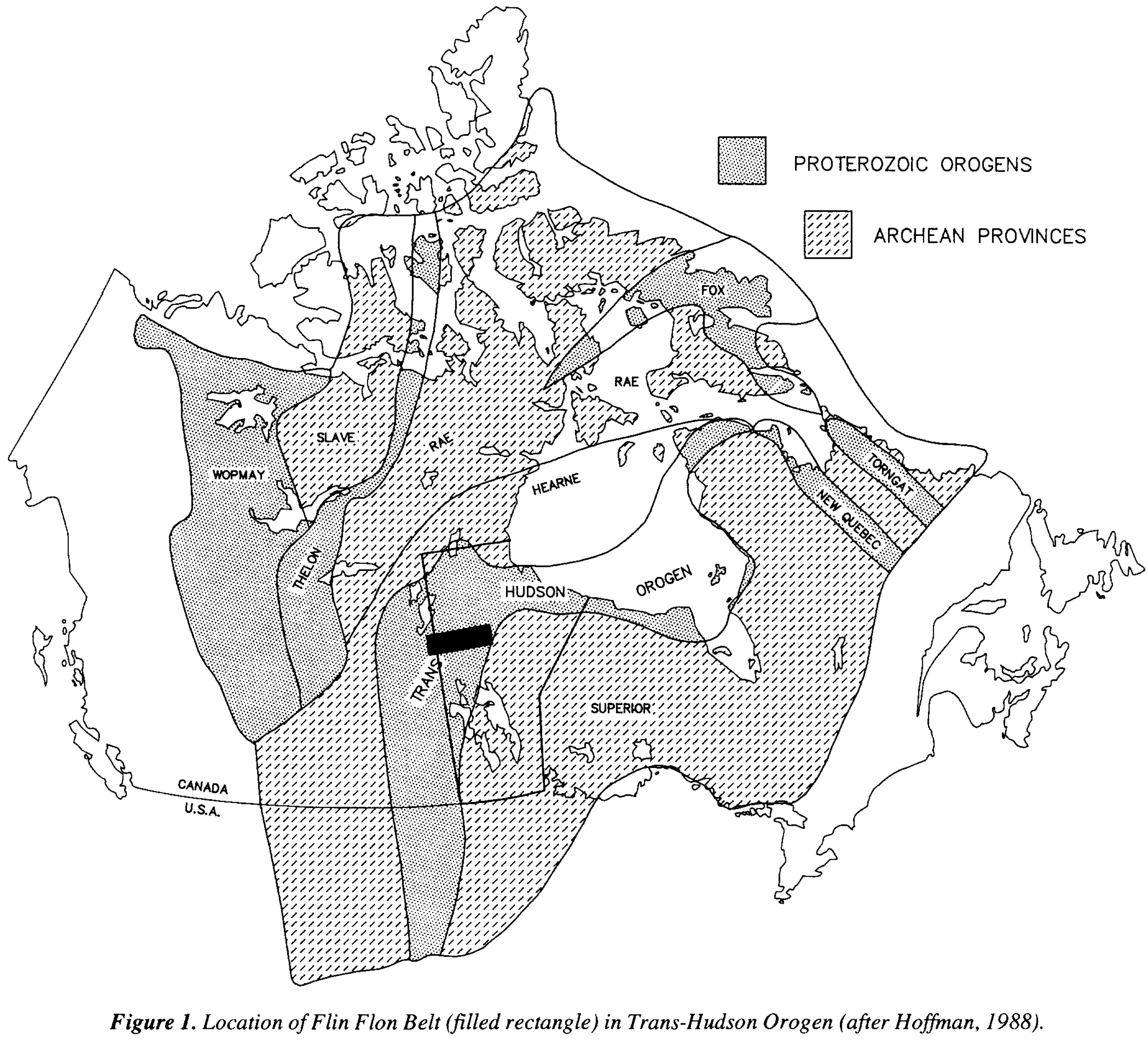

Figure 1. Location of Flin Flon Belt (filled rectangle) in Trans-Hudson Orogen (after Hoffman, 1988).

Accretion of intra-oceanic volcanic rocks (1.88-1.87 Ga) is followed by 1.87-1.83 Ga intrusion of isotopically juvenile calc-alkaline plutons, and eruption of volcanic equivalents (only rarely preserved). Lucas et al. (1994) and Stern et al. (1994) interpret these rocks to be successor arc(s) and basins developed on the older, accreted, oceanic volcanic rocks. The Snow Lake area is dominated by ca. 1.84-1.83 Ga fold-thrust style tectonics (Connors and Ansdell, 1994) that is atypical of central and western portions of the Flin Flon Belt. This difference in tectonic style may reflect the fact that the entire Snow Lake segment is a south-verging, allocthonous, imbricate zone that was thrust ca. 1.84 Ga (Lucas et al., 1993; Syme et al., 1995; Lucas et al., in press) over the previously amalgamated collage of oceanic and arc rocks to the west (Fig. 2).

Setting of Snow Lake area volcanic-hosted massive sulphide deposits

An 84 km^2 area directly south of the town of Snow Lake (shown in Fig. 3) contains eight of the area's eleven producing and past-producing base metal mines, plus numerous subeconomic base metal occurrences. Host rocks for Snow Lake massive sulphide deposits (Fig. 3 and 4) comprise a ca. 1.89 Ga bimodal mafic-felsic volcanic sequence intruded by two large, subvolcanic tonalite intrusive complexes (Bailes et al., 1991; David et al., 1993). We divide the volcanic rocks into five depositional phases, based on groupings of strata that display either distinct geochemical signatures or geological attributes, or a combination of both (Fig. 4b).

Mafic volcanic rocks consist mainly of basalt (45-53 wt.% SiO_2) and basaltic andesite (53-57 wt.% SiO_2) flows and related breccias (Fig. 4b). Those belonging to phases 2 to 4 include significantly more volcaniclastic rocks than either phases 1 or 5. Mafic flows and volcaniclastic rocks of phases 1 to 4 display classic oceanic arc tholeiite geochemical characteristics whereas phase 5 mafic flows show ocean floor-back arc affinities (Stern et al., 1995). Geochemical signatures of phase 1 mafic flows are typical of magmas formed in a primitive forearc tectonic setting whereas those of phases 2-4 are similar to mafic magmas formed in an evolved arc setting (Stern et al., 1995).

Dacite (62-70 wt.% SiO_2) and rhyolite (70-80 wt.% SiO_2) are volumetrically less extensive than mafic flows and volcaniclastic rocks but are important as most of the significant volcanic-hosted massive sulphide deposits at Snow Lake are hosted by felsic extrusive complexes. Cu-rich deposits are associated with phase 1 rhyolite complexes in the primitive arc (e.g., Stall Lake, Anderson Lake, Rod) and Zn-rich deposits are affiliated with phase 3 dacite volcaniclastic rocks

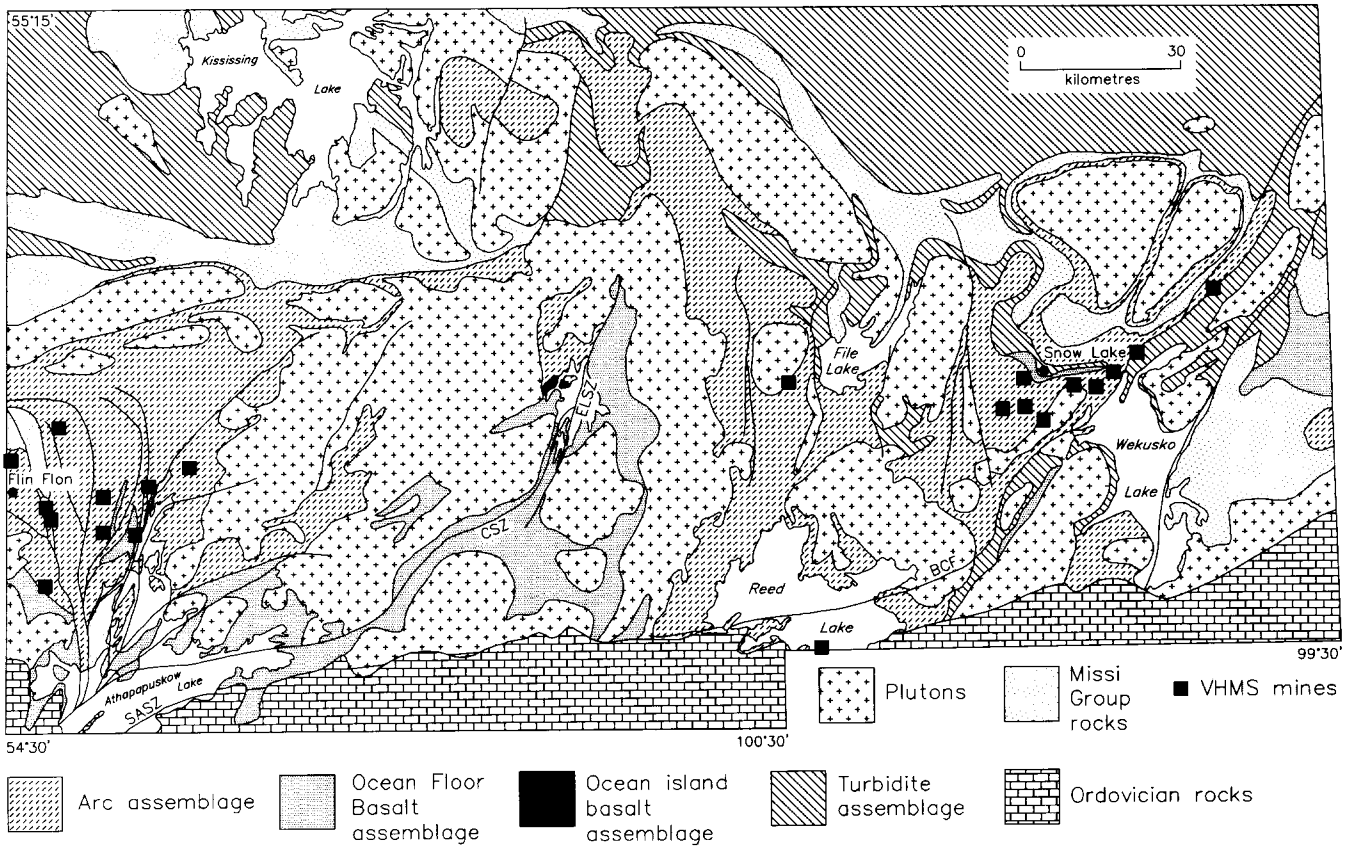

Figure 2. *Simplified geological map of Flin Flon Belt. Base metal mines (past and current producers), shown by bold squares, occur in arc volcanic rocks near towns of Flin Flon and Snow Lake. SASZ – South Athapapaskow shear zone; CSZ – Cranberry shear zone; ELSZ – Elbow Lake shear zone; BCF –Berry Creek Fault.*

and rhyolite flows in the evolved arc (e.g., Chisel Lake, Ghost Lake, Lost Lake) (Fig. 3 and 4). The recently discovered Photo Lake Cu-rich deposit is contained wholly within rhyolite flows (Fig. 3).

Thick accumulations of heterolithological mafic breccia are not directly related to volcanic-hosted massive sulphide deposits at Snow Lake, but we speculate that these highly permeable units may have played an important role in the hydrology of hydrothermal systems integral to the genesis of Zn-rich deposits at Chisel Lake. The heterolithological mafic breccias include minor amounts of felsic volcanic debris.

Most of the volcanic rocks in the Snow Lake area were deposited in a shallow to moderately deep marine environment. Some of the pyroclastic rocks may have been erupted subaerially and then deposited under water. Blocks of subvolcanic tonalite in mafic heterolithological breccias indicate the presence of primary topographic relief sufficient for portions

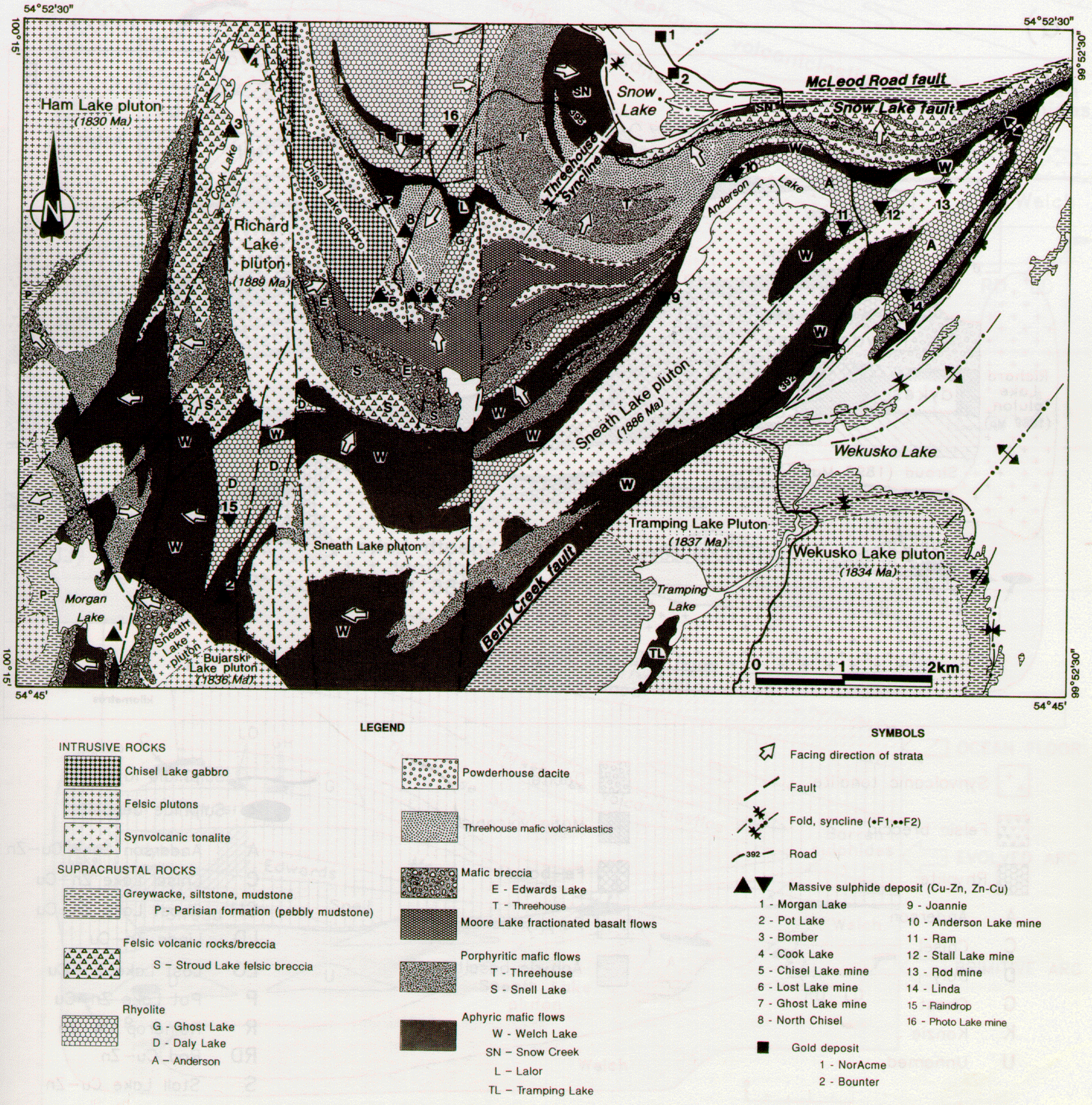

Figure 3. Simplified geology of Snow Lake area. Bold triangles mark location of massive sulphide deposits.

of the subvolcanic intrusions to be unroofed and eroded. An angular unconformity at the base of phase 4 (Bailes and Simms, 1994) attests to topographic relief and local subaerial erosion during deposition of the volcanic succession at Snow Lake.

Megascopically altered rocks (Fig. 5a and 5b), occur in broad, semiconformable zones, and affect up to 25% of the rocks at Snow Lake. These zones are evidence that large portions of the volcanic succession at Snow Lake were affected by circulatory hydrothermal fluid flow. This geothermal activity is most logically interpreted to have been caused by emplacement of two large subvolcanic tonalite intrusions (Bailes et al., 1991). Base metal deposits at Snow Lake are generally considered to be products of this geothermal activity and, thus, to be genetically related to the subvolcanic tonalite bodies (Walford and Franklin, 1982; Bailes, 1987b; Galley et al., 1990).

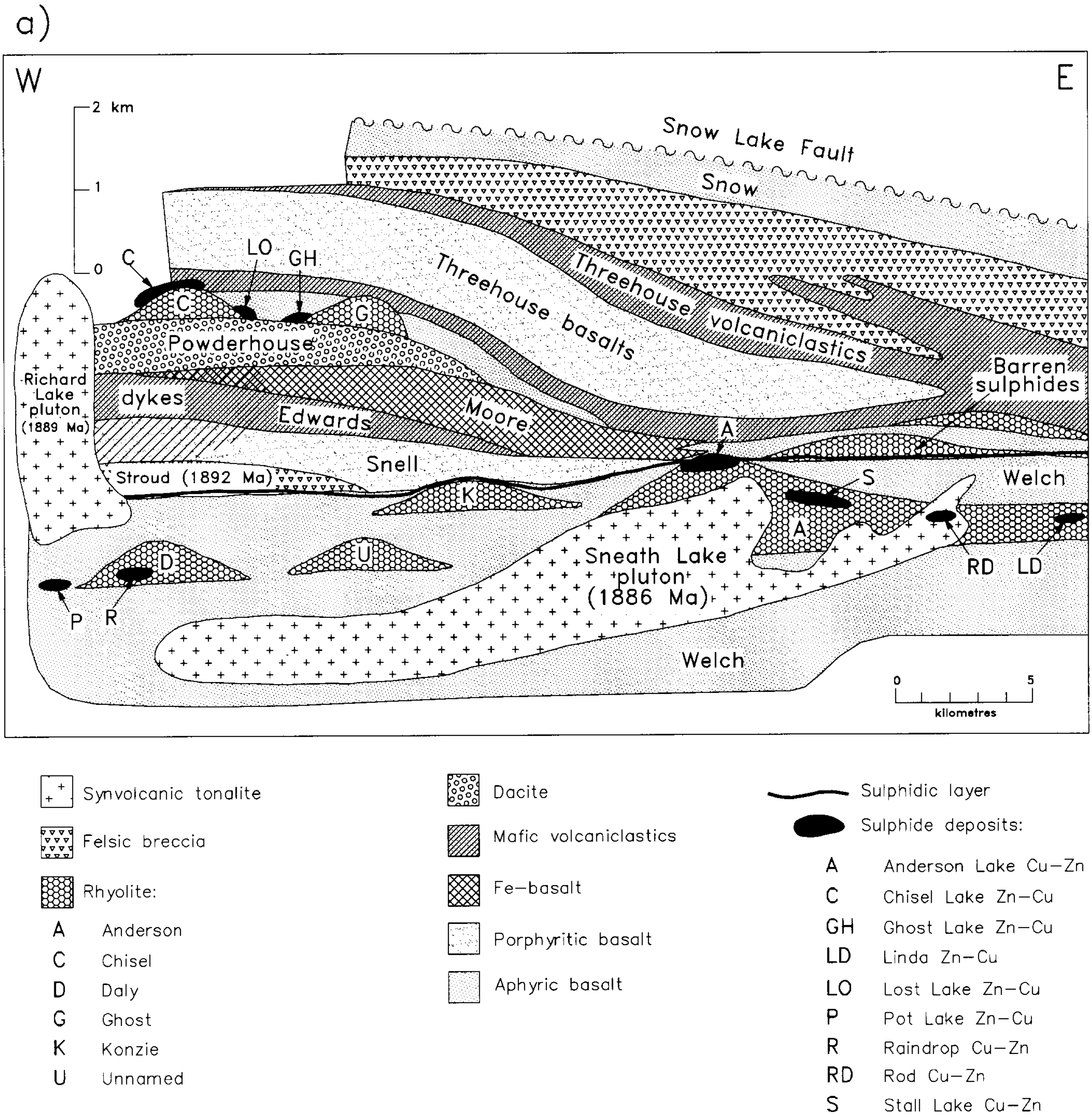

***Figure 4. a)** Schematic geological cross-section showing massive sulphide-hosting volcanic rocks at Snow Lake, **b)** five "phases" of volcanism, and **c)** tectonic setting in which volcanic rocks were extruded.*

b)

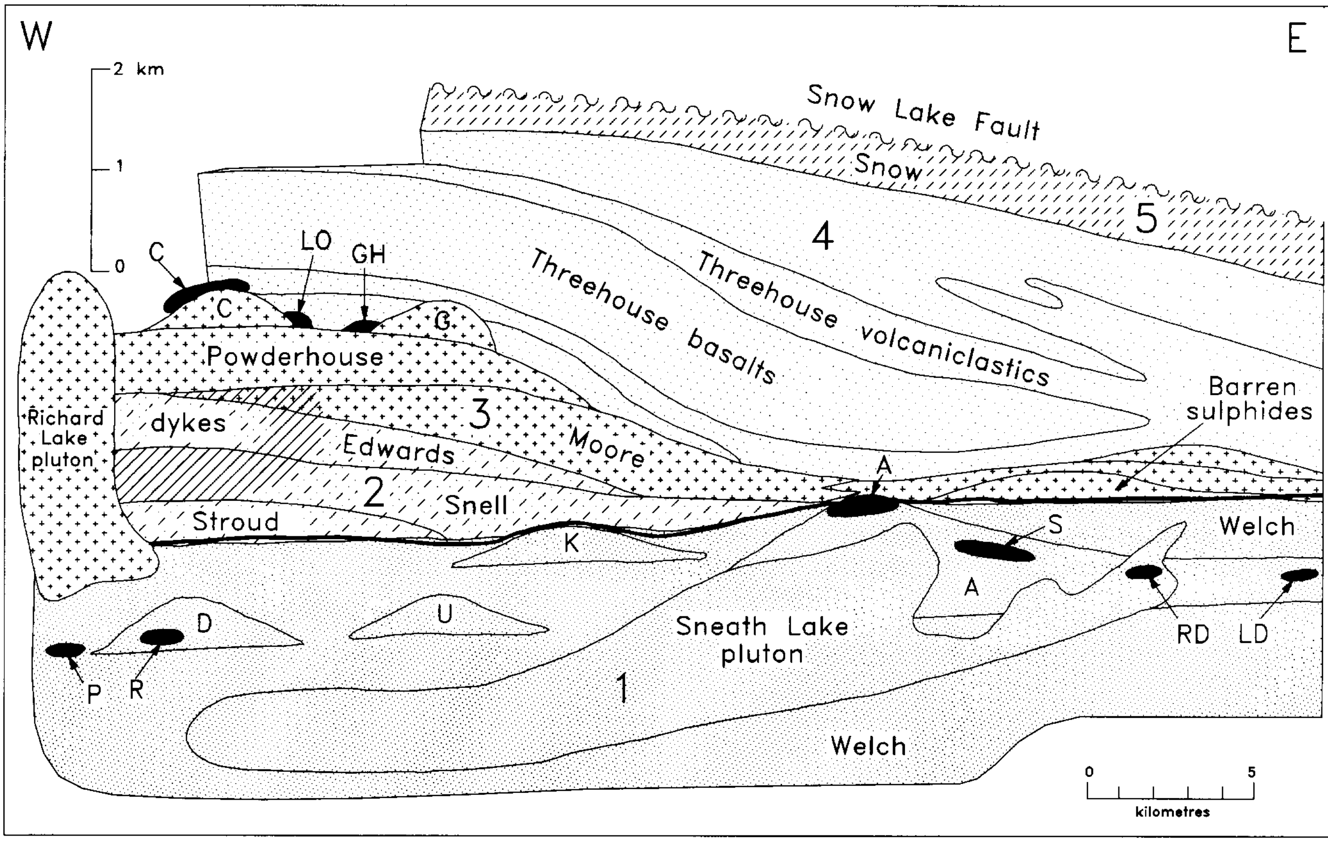

Figure 4b.

c)

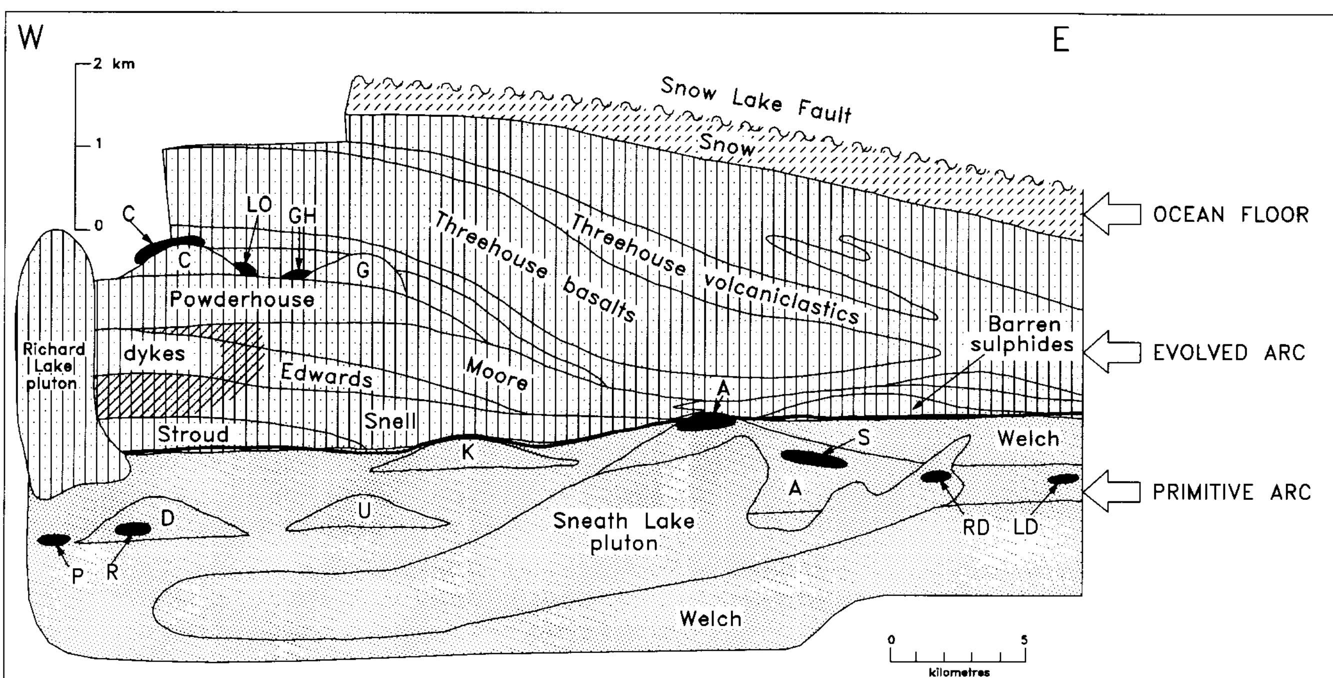

Figure 4c.

Four folding events and a peak regional metamorphic event coincident with the second folding episode are recognized in the Snow Lake area rocks (Kraus and Williams, 1993; Connors and Ansdell, 1994). A titanite age from a sample in the Anderson felsic complex dates the peak regional metamorphism at 1810 Ma (Machado and David, 1992), and indicates that this metamorphism postdated volcanism and hydrothermal activity by 80 million years. Mineral assemblages, formed during peak regional metamorphism, grade south to north from greenschist to middle almandine-amphibolite facies. Most massive sulphide deposits and associated hydrothermally altered rocks are coarsely recrystallized to lower to middle amandine amphibolite facies mineral assemblages. This recrystallization enhances ability to recognize altered rocks, because even weakly altered lithologies are characterized by distinctive metamorphic mineral assemblages.

Two major episodes of deposition of base metal-rich massive sulphides are recognized at Snow Lake: 1) Cu-rich deposits within the phase 1 Anderson and Daly rhyolite complexes in the primitive arc succession, and 2) Zn-rich deposits at the top of phase 3 associated with evolved arc rhyolite flows (Fig. 4). Each sulphide mineralizing event is clearly related to a distinct episode of hydrothermal alteration. The interplay between massive sulphide deposition and hydrothermal activity is described in the following sections. Other volcanic-hosted massive sulphide deposits shown on Figure 3 (Morgan Lake, Bomber, North Cook, Photo Lake) are of uncertain stratigraphic affinity to the main mineralizing episodes. The Morgan Lake Zn-rich deposit is most similar in setting and composition with the Chisel Lake area Zn-rich deposits at the top of phase 3. The Bomber, North Cook, and Photo Lake deposits are tentatively interpreted to be associated with a third mineralizing event (Bailes and Simms, 1994) that is not discussed in this paper. A base metal-poor episode of sulphide deposition, the Foot-Mud unit, is briefly discussed in the section dealing with hanging wall alteration to the Anderson Lake area Cu-rich deposits.

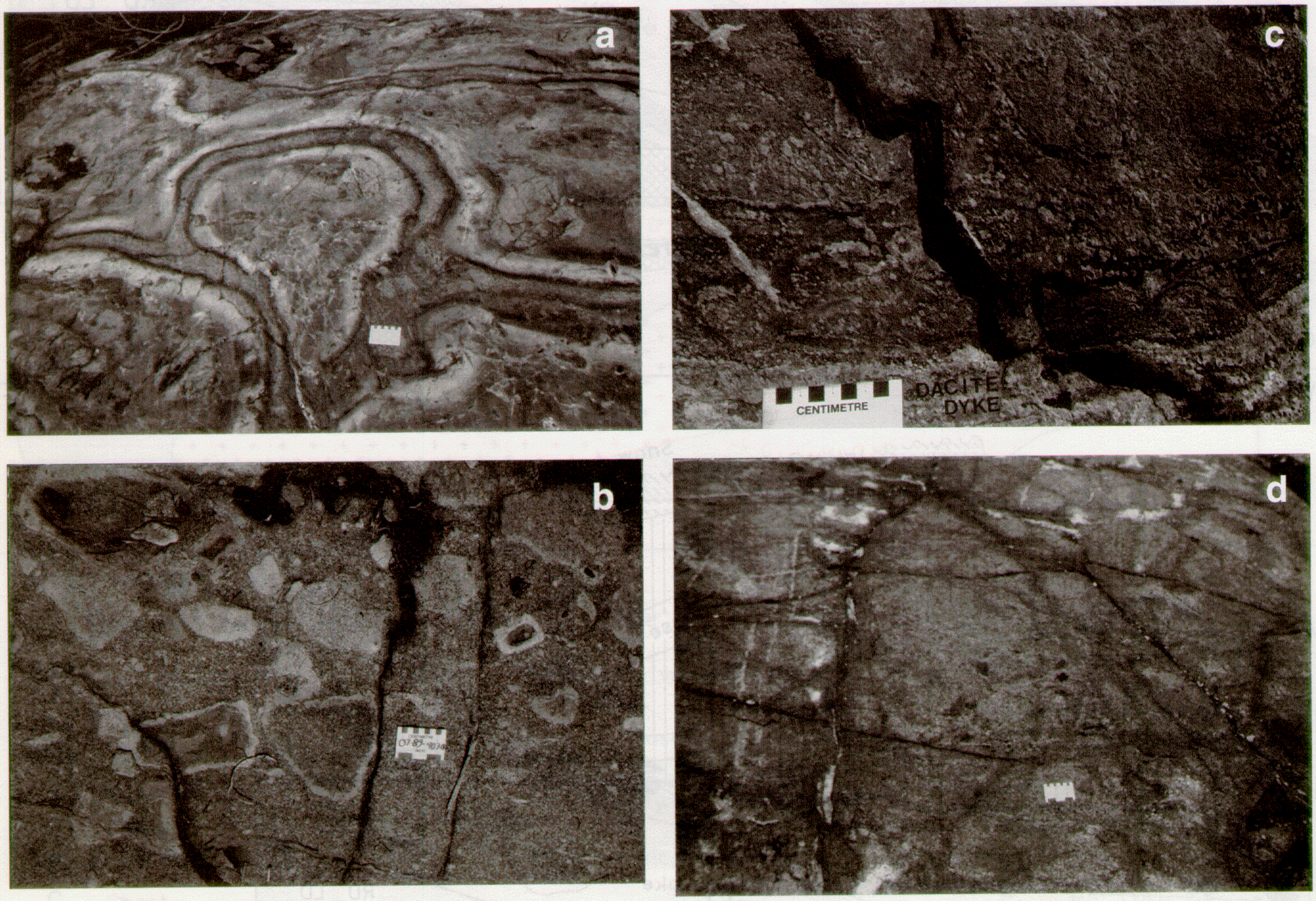

*Figure 5. Hydrothermally altered rocks typical of Snow Lake area: **a)** silicified pillow margins, Welch formation basalt, **b)** silicified rims on fragments in Edwards formation mafic breccia, **c)** mottled silicification in Edwards formation mafic wacke adjacent to synvolcanic dacite dyke, and **d)** chlorite- and staurolite-rich altered fractures in Sneath Lake tonalite.*

PRIMITIVE ARC-HOSTED Cu-RICH DEPOSITS

Introduction

Cu-rich volcanic-hosted massive sulphide deposits in the primitive arc bimodal basalt-rhyolite sequence are spatially associated with the rhyolite flow complexes (Fig. 3 and 4). The Anderson rhyolite is host to three economic Cu-rich deposits (Anderson Lake, Stall Lake, and Rod) that originally contained 10.1 Mt 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 two subeconomic, stockwork-type zones (Joannie and Ram). The primitive arc Daly Lake rhyolite hosts the subeconomic Cu-rich Raindrop occurrence and is in close proximity to the Pot Lake deposit. The Unamed rhyolite, which lies geographically between the Daly and Anderson rhyolites, contains minor Cu-rich volcanic-hosted massive sulphide-type mineralization (G. Kitsler, Hudson Bay Exploration and Development, pers. comm., 1995).

In this section we describe the geological setting of the Anderson rhyolite-hosted deposits (Anderson Lake, Stall Lake, Rod, and Linda) as an example of the nature of primitive arc-hosted mineralization at Snow Lake. The Anderson Lake, Stall Lake, and Rod deposits occur on the north limb of a major east-northeast-trending fold, the Anderson Bay anticline, and the Linda deposit occurs on the south limb (Fig. 6). Deformation has structurally thinned host units and elongated individual sulphide deposits into prolate lenses that plunge parallel to regional stretching lineations.

Stratigraphic footwall

Phase 1 volcanic rocks

Welch basalt

Aphyric to minor porphyritic subaqueous Welch basalt flows are present both in the footwall and hanging wall to the massive sulphide deposits at Anderson Lake. Footwall portions of the Welch basalt are poorly preserved to the south of Anderson Lake, due to intrusion by the Sneath Lake pluton (Fig. 6), but to the west form an up to 3000 m thick unit (Fig. 7) truncated to the south by the Berry Creek fault and capped to the north by the Foot-Mud sulphidic sediments. Welch mafic flows are primitive arc tholeiites (Stern et al., 1995) that display a crude upward change from basalt to andesite, and are intercalated with minor lenses of pillow fragment breccia, heterolithological mafic breccia, and porphyritic high-Mg flows. The high-Mg porphyritic flows geochemically resemble Ca-boninites (Stern et al., 1995*)* that occur in forearc, or protoarc settings in modern arcs (Crawford et al., 1987).

Anderson rhyolite

This 1 x 12 km rhyolite body is the largest of several felsic extrusive complexes that occur in the upper 1 km of the Welch basalts (Fig. 6 and 7). Near the Stall Lake deposit, the basal 750 m of the Anderson rhyolite is aphyric and massive, and is overlain to the north by 100 m of quartz-phyric and 150 m of quartz megacrystic varieties. The original character of the Anderson rhyolite is obscured by intrusion of the Sneath Lake pluton, by large areas of hydrothermal alteration, by tight folding about the Anderson Bay anticline (Fig. 6), and by recrystallization to lower almandine-amphibolite facies mineral assemblages during regional metamorphism. Recrystallized lithologies are composed of fine grained granoblastic mosaics of quartz, feldspar, and biotite, with varying amounts of amphibole, garnet, sericite, chlorite, staurolite, and kyanite that increase in amount with degree of hydrothermal alteration.

Primitive arc phase 1 rhyolites, including that at Anderson Lake, have similar rare-earth element and ε_{Nd} values as do the underlying Sneath Lake tonalite complex and are, for this reason, interpreted as an extrusive equivalent. Primitive arc rhyolites and tonalites display higher ε_{Nd} values (+3.7) than the Welch basalt (+3.0) indicating that they are not directly related to the Welch basalt by fractionation of the same parent magma (Stern et al., 1992).

Sneath Lake pluton

This sill-like, semiconformable 1.5 x 22 km complex 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. A synvolcanic age is supported by a U-Pb zircon age of 1886 +17/-9 Ma for the quartz megacrystic tonalite (Bailes et al., 1991) and 1892 ± 4 Ma for overlying phase 2 Stroud felsic breccia (Machado and David, 1992). Fragments of the distinctive Sneath Lake quartz megacrystic tonalite in overlying phase 1 and 2 volcanogenic breccia units is conclusive evidence that the intrusion is synvolcanic.

The Sneath Lake pluton is composed of at least seven texturally distinct tonalite bodies separated by intrusive contacts. The largest individual body, located south of Anderson Lake, is 1.5 x 5 km, semiconformable, and composed of quartz megacrystic tonalite (Fig. 3 and 6). From west to east this body cuts up section, at a shallow angle, through approximately 1 km of phase 1 volcanic stratigraphy, rising to within 0.3 km of the top of phase 1 volcanic rocks at its eastern end (Fig. 7). A quartz-feldspar porphyry phase of the Sneath Lake tonalite, previously interpreted to be extrusive (Coats et al., 1970; Studer, 1982; Walford and Franklin, 1982; Zaleski, 1989), completely envelops the Rod volcanic-hosted massive sulphide deposit, and intrudes hanging wall portions of the Welch basalt. This suggests a range in age of the different phases of the Sneath Lake tonalite, with some postdating massive sulphide deposition.

Footwall alteration zone

Various types and intensities of alteration affect almost all of the Anderson rhyolite, portions of the underlying Welch basalt, as well as the upper portion of the underlying Sneath

Lake tonalite. Many of the more highly altered rocks are soft, preferentially eroded, and poorly exposed. Diamond drilling by Hudson Bay Exploration and Development Co. Ltd. (HBED) has demonstrated that the shape of Anderson Lake is largely due to an extensive domain of highly altered lithologies under the lake (Walford and Franklin, 1982; Hudson Bay Exploration and Development, pers. comm., 1992). The Anderson Lake alteration system has three main components: a broad zone of weak alteration that affects most of the Anderson rhyolite; a large, semiconformable zone of moderate to strong alteration centered in the top of the Sneath Lake pluton and in directly overlying strata; and discordant zones of strongly altered rocks.

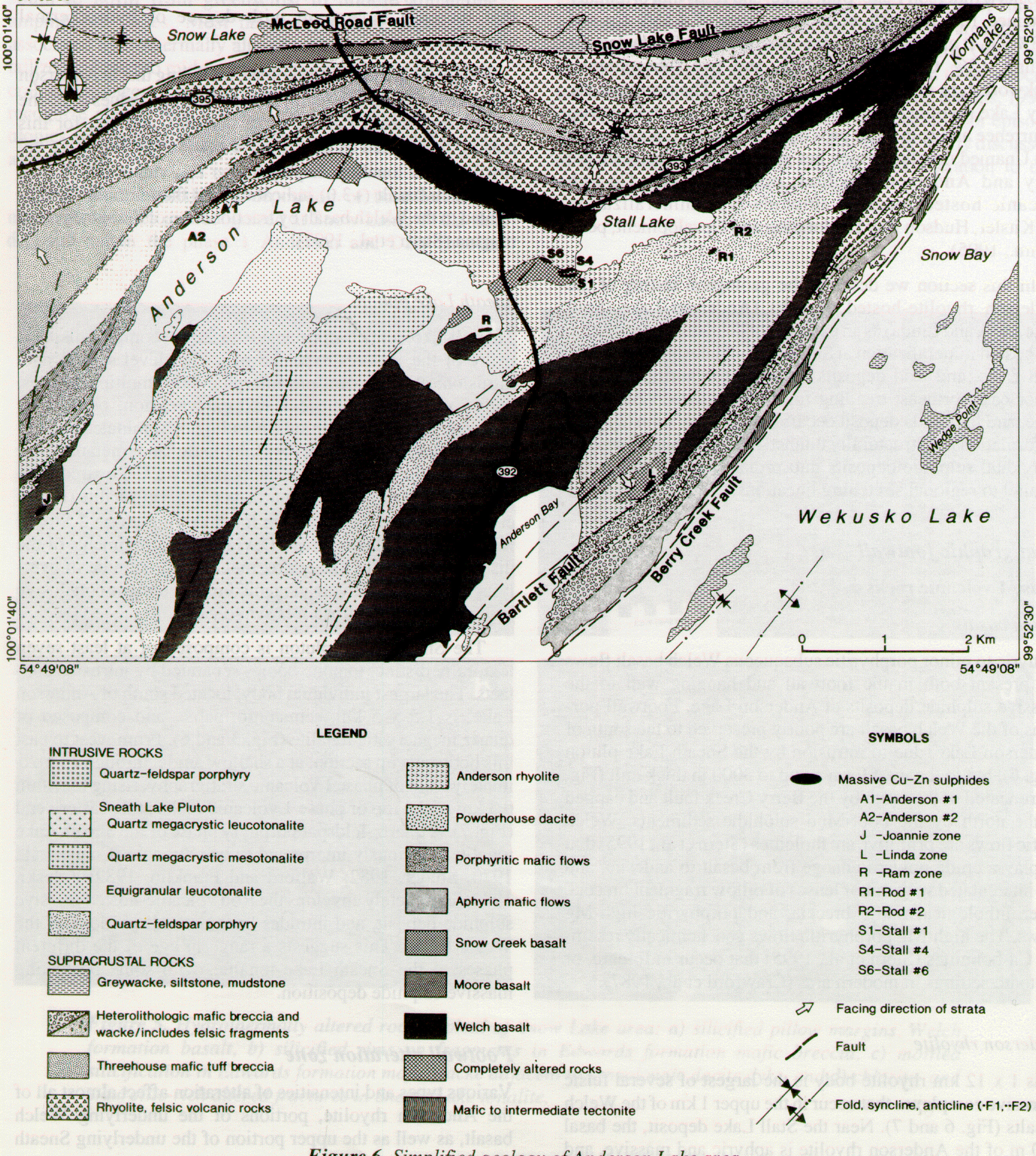

Figure 6. Simplified geology of Anderson Lake area.

The broad domain of weak, pervasive alteration that affects virtually all of the Anderson rhyolite complex is characterized by quartz-biotite-staurolite-garnet metamorphic mineral assemblages. The altered rocks contain distinctive 1-5% staurolite porphyroblasts and patchy, 1-5 cm bleached domains overgrown by actinolite porphyroblasts. The amount and size of staurolite porphyroblasts gradually increases towards discordant alteration zones. The altered rhyolites display a patchy depletion in Na (Walford and Franklin, 1982) that, according to studies by Mottl and Holland (1978) and Riverin and Hodgson (1980) , can be interpreted as a product of interaction of the rhyolite with a Na-depleted hydrothermal fluid at high fluid/rock ratios.

The large semiconformable zone of moderately to strongly altered rocks under Anderson Lake is 150-700 m in width and approximately 5 km long. It is generally widest and most intense stratigraphically above the mesotonalite phase of the Sneath Lake pluton, between the Anderson Lake and Stall Lake mine sites, but has been identified in drill core and in surface exposures from the Joannie zone in the west to Stall Lake in the east (Fig. 6). Although the semiconformable alteration mainly affected the Anderson rhyolite, it has also affected the upper 300 m of the Sneath Lake pluton and parts of the Welch basalt southeast of the Anderson Lake mine. The semiconformable alteration consists of a broad zone of chlorite-rich rocks containing varying amounts of coarse grained biotite, staurolite, amphibole, garnet, magnetite, and kyanite. Down section the semiconformable zone displays increasing chlorite and staurolite contents. Chlorite-rich alteration also affects the upper part of much of the Sneath Lake pluton, with remnant, 2 cm quartz megacrysts the only evidence of the tonalite precursor. Chlorite-rich altered rocks in the semiconformable zone are generally characterized by abundant porphyroblasts of biotite, staurolite, and kyanite.

A more areally restricted zone of semiconformable alteration is present in the footwall stratigraphy to the Linda deposit (Zaleski, 1989; Zaleski et al., 1991). This 150 m thick and over 450 m long "distal zone" occurs 150-200 m below the massive sulphide body, and consists of a core of Na-Ca depletion composed of staurolite-rich gneiss surrounded by an envelope of calc-silicate alteration characterized by abundant plagioclase, epidote and amphibole.

Discordant zones of completely altered rocks, referred to colloquially as "pipes" by Sangster (1972), transect the Anderson rhyolite in the immediate footwall to the Anderson Lake, Stall Lake, and Linda deposits. These zones are characterized by chlorite- and sericite-rich rocks containing varying concentrations of staurolite, garnet, biotite, magnetite, and kyanite. A general observation for the Anderson Lake and Stall Lake discordant zones is that their lower parts and cores are chlorite-rich, with sericite-rich envelopes surrounding their upper margins. At Anderson Lake the discordant zone has a core of chlorite-biotite-kyanite schist and an irregular margin of muscovite-kyanite schist (Walford and Franklin, 1982). At Stall Lake it is composed largely of chlorite-staurolite schist with subordinate sericite-kyanite schist (Fig. 8; Studer, 1982). At the Linda deposit the discordant alteration zone is more diffuse than at either Anderson Lake or Stall Lake and is dominated by sericite, typically with a core of muscovite-staurolite-gahnite and a periphery of muscovite-garnet-staurolite (Zaleski et al., 1991). The Anderson Lake and Stall Lake discordant zones contain disseminated blebs, veinlets, and stockworks of sulphide minerals, mainly pyrite, within 10 to 20 m of the main sulphide lenses, as well as local areas of anhydrite-, carbonate- and anthophyllite- rich domains in proximity to the ore bodies.

The Anderson Lake discordant alteration zone is over 2 km long and 300 m wide and the Stall Lake zone is 1 km by 100 m; both originate near the mesotonalite phase of the Sneath Lake pluton (Fig. 6 and 7b). At both Anderson Lake and Stall Lake the discordant zones terminate up-section at the massive sulphide deposits, with only minor, metres-wide zones of intensely altered rocks immediately above the sulphide lenses. The planar morphology of both the Anderson Lake and Stall Lake discordant alteration zones suggests that they may have been fault- or fracture-controlled channelways for discharging hydrothermal fluids involved in formation of the sulphide lenses. The acute angle of the footwall alteration zone to primary layering at Anderson Lake and Stall Lake has been attributed by Walford and Franklin (1982) to tectonic flattening. However, because this does not explain the similar shallow angle to primary layering of the footwall alteration zone beneath the much less deformed Raindrop deposit in the Daly rhyolite (Hodges and Manojlovic, 1993), we suggest that the shallow orientation to primary layering may be as much a product of primary orientation as it is of subsequent tectonic flattening.

The Rod deposit only has a small zone of intensely altered, chlorite- and staurolite-rich rocks directly adjacent to the ore lens. We interpret these rocks to be the remnants of an originally much larger footwall alteration zone that has been largely obliterated by intrusion of a late phase of the Sneath Lake tonalite (see description of the Rod deposit below). The Joannie and Ram sulphide occurrences are postulated to be discordant stockwork zones defining proximal, discordant alteration zones (Fedikow et al., 1989; this study).

The Stall Lake and Linda deposits both display stacked massive sulphide ore lenses, attached by disconformable alteration zones (Studer, 1982; Zaleski et al., 1991). This stacking of massive sulphide lenses is a characteristic of "Noranda" type deposits where it has been interpreted by Knuckey et al. (1982) as evidence for long-lived hydrothermal activity coeval with continued plutonism and extrusion of felsic flows, an interpretation that we embrace for phase 1 volcanic-hosted massive sulphide deposits at Anderson Lake.

Massive sulphide deposits

Stall Lake deposit

The Stall Lake deposit, discovered in 1963 and mining discontinued in 1994, is the largest Cu-rich orebody in the Snow Lake area at 7 Mt, grading 4.39% Cu and 0.5% Zn (Table 1). It is described in considerable detail by Studer (1982) and a summary of his observations follow.

The Stall Lake orebody consists of four large and a number of smaller massive sulphide lenses. The main massive sulphide lenses consist of coarse grained pyrrhotite with lesser pyrite and chalcopyrite. They commonly contain massive magnetite and anhydrite along footwall contacts. Hanging wall contacts of the ore are sharp but footwall contacts are generally gradational. Disseminated stockwork and vein breccia ore were prominent only at the west end of the No. 4 orebody, where it was associated with a discordant chlorite-rich alteration zone. The deposit has an average Cu-Zn ratio (Cu/Cu+Zn) of 90, with sections of the No. 1 and No. 4 lenses consistently containing in excess of 10% Cu. The west sides of ore lenses grade higher in Cu. For example, portions of the ore zone in contact with the footwall sulphide stockwork on the west side of the No. 4 lens are richer in Cu by a factor of two. Such Cu-rich zones are also Au-rich, with some intersections of massive sulphide and vein stockwork from No. 4 lens grading up to 32 g/t Au (Studer, 1982).

Main ore lenses at Stall Lake occur at the contact between the lower aphyric and middle quartz phyric members of the Anderson rhyolite, whereas smaller lenses lie

a)

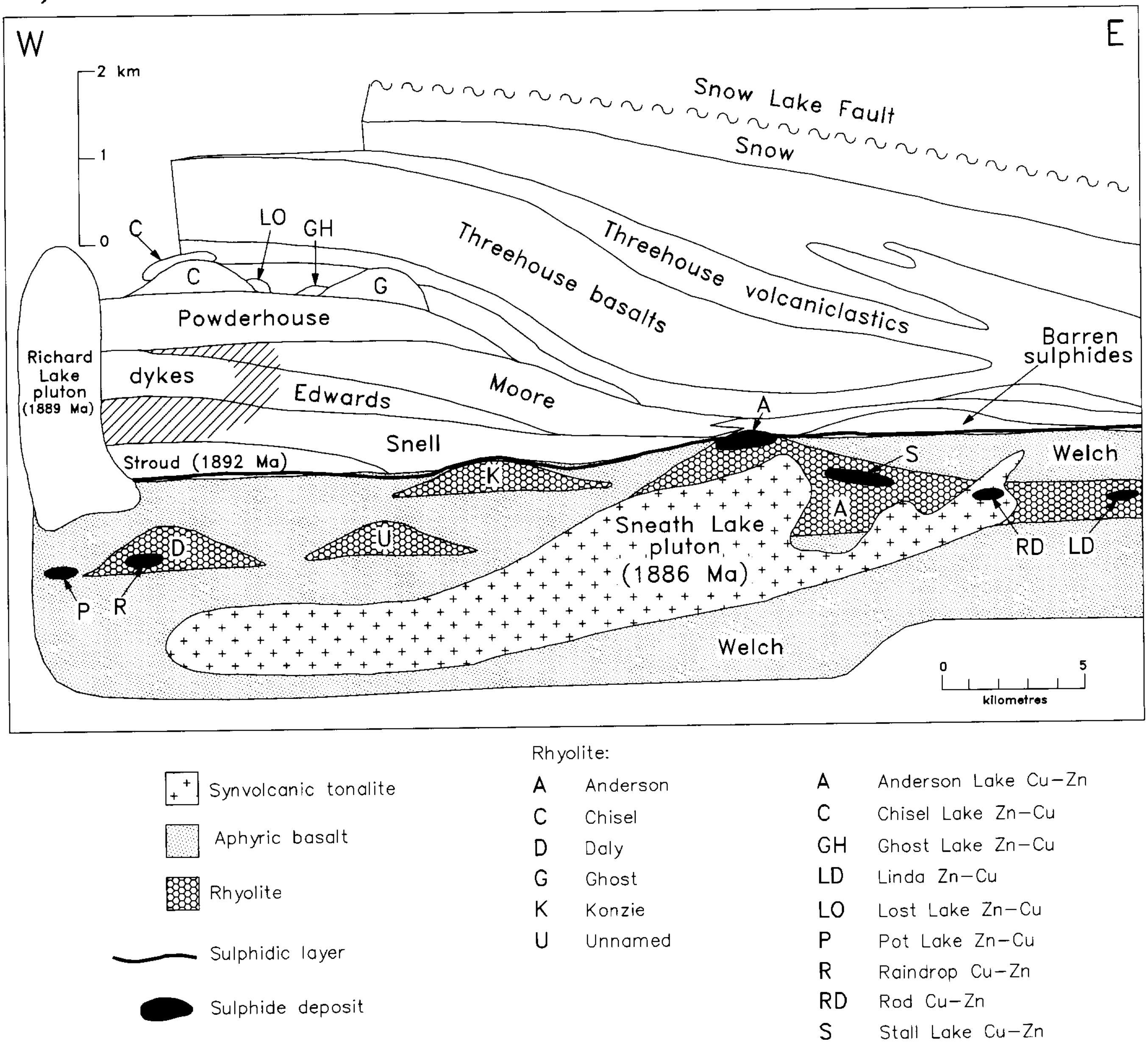

***Figure 7.** Schematic geological cross-section of phase 1 (primitive arc) volcanic rocks with location of associated Cu-rich massive sulphide deposits: **a)** geological units, **b)** distribution of hydrothermally altered rocks.*

stratigraphically within the overlying quartz-phyric flow unit. The ore lenses strike 105° and dip 45°N, and together extend from surface to about 1450 m along a plunge of 45° at an azimuth of 015°. The largest individual sulphide lens, the No. 4 ore zone, has a down-plunge length of 950 m, with an average strike length of 91 m and a width up to 40 m. The sulphide lenses define a series of connected synclines and anticlines with long axes of individual lenses parallel to the north- northeast-trending elongation lineations.

Anderson Lake deposit

The Anderson Lake deposit, discovered in 1963 and mined out in 1988, consists of two sulphide lenses (Fig. 6), 350 m apart. Only the eastern body was mined and it contained 3.2 Mt grading 3.41% Cu and 0.10% Zn (Table 1). This deposit, with as average Cu-Zn ratio (Cu/Cu+Zn) of 97, is the most Cu-rich of the Anderson Lake area deposits. It is conformable with the volcanic host rocks, strikes 065° and dips 60°N, and plunges 65°NE. It has a strike length of 150 m, a maximum width of 10 m, and a down-plunge length of 1220 m (Fig. 9). It is composed largely of pyrite, chalcopyrite, and pyrrhotite, with minor sphalerite. The Cu grade of the sulphide zone decreases from stratigraphic footwall to hanging wall.

The stratigraphic/structural hanging wall to the sulphide lens consists of 4 m of muscovite schist, 5 m of muscovite-bearing partly altered quartz phyric felsic rocks, and a 1-3 m cap of barren sulphidic sediments ("Foot-Mud horizon"). The footwall consists of up to 50 m of sparsely quartz-phyric altered rhyolite followed down section by 300 m of aphyric rhyolite. This suggests that the Anderson Lake sulphide body occurs at a slightly higher stratigraphic position than the main sulphide bodies at the Stall Lake mine as they occur along the contact between aphyric and quartz-phyric rhyolite.

Rod deposit

The Rod deposit consists of two elongate, strongly deformed sulphide lenses (Fig. 6 and 10). The small Rod No. 1 lens was discovered in 1957 whereas the somewhat larger Rod No. 2 lens was located down-plunge in 1969 (Table 1). The Rod deposits are described in detail by Coats et al. (1970) and portions of their description are summarized in this section.

The Rod No. 1 orebody contained 22 675 t averaging 5% Cu and 4.5% Zn, and was mined between 1962 and 1964. This prolate sulphide lens has an aspect ratio of 24:14:1 and varies from 0.5 to 8 m in thickness, with a strike length up to 68 m, and a down-plunge length of 120 m. It strikes west-southwest and dips 40 to 45°NW, and plunges 32° at an azimuth of 28°.

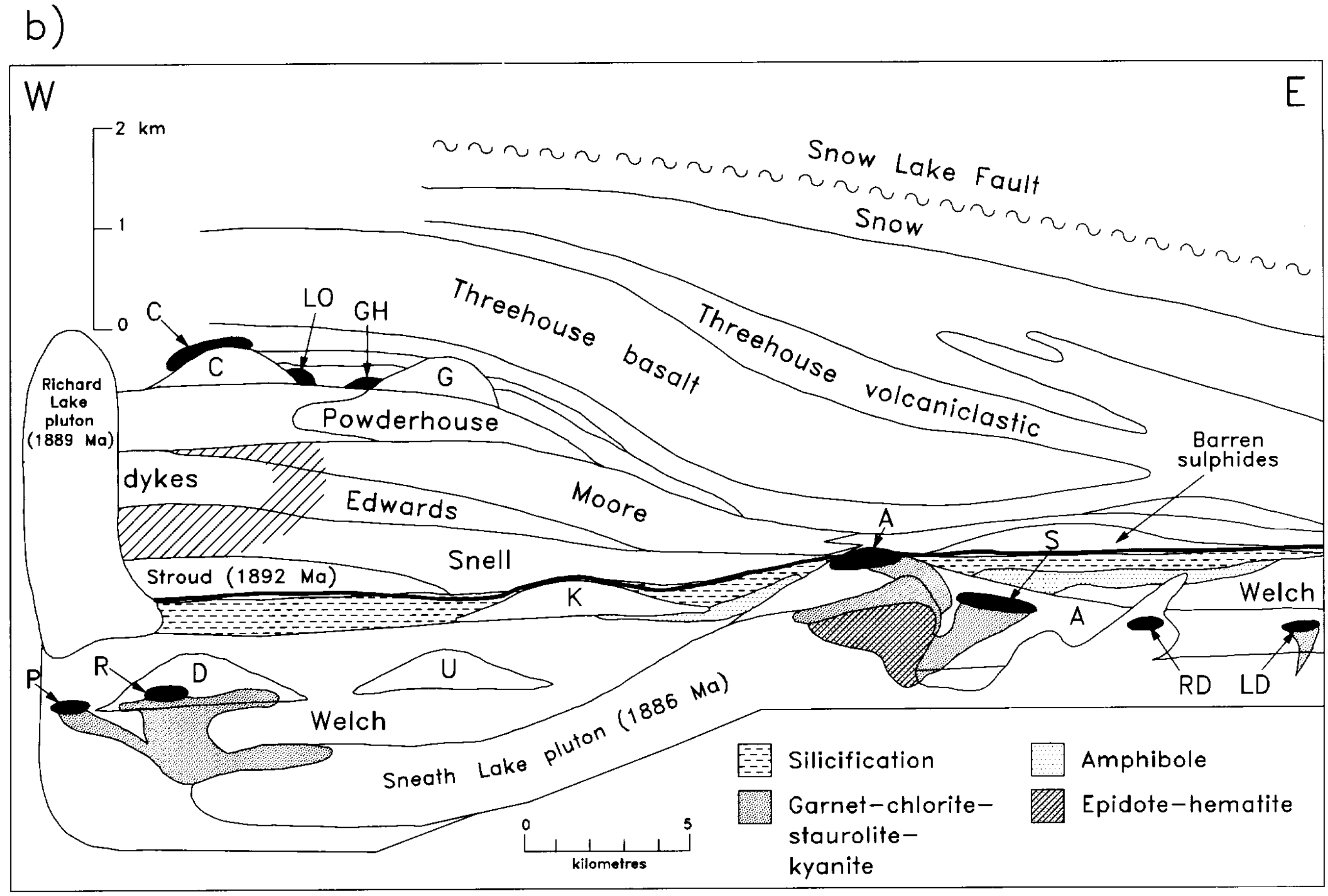

Figure 7b.

The ore has knife-edge hanging wall and footwall contacts. It contains wall rock fragments, including quartz porphyritic Sneath Lake tonalite, that are believed to have been incorporated during deformation of the sulphide lens.

The Rod No. 2 ore body, mined from 1984 to 1991, contained 810 440 t grading 6.63% Cu and 2.9% Zn (G. Kitzler, Hudson Bay Exploration and Development, pers. comm., 1993) with the combined No. 1 and 2 orebodies having a composite Cu-Zn ratio (Cu/Cu+Zn) of 69. The Rod No. 2 ore body has an aspect ratio of 180:14:1 and averages 3.5 m in thickness, 50 m in strike length, and 625 m in down-plunge length. It strikes west-southwest, dips 55°NW, and plunges 25° to 35° at azimuth 45° (shallowing at depth). The ore is tectonically banded, full of foliated wall rock fragments, and consists of coarsely recrystallized chalcopyrite and pyrrhotite locally containing abundant 5 to 10 mm porphyroblasts of arsenopyrite. Many ore zone contacts are faults and the ore itself is complexly deformed and tectonically remobilized (Hudson Bay Exploration and Development staff, pers. comm., 1991). The presence of tectonic breccias, strong tectonic banding and local interfolial folding of the massive sulphides, and extreme rodding of the sulphide lenses indicates a higher degree of deformation than is displayed by the Anderson Lake and Stall Lake deposits to the west. This is probably due to proximity of the deposit to the axial trace of the east-northeast-trending Anderson Bay anticline (Fig. 3).

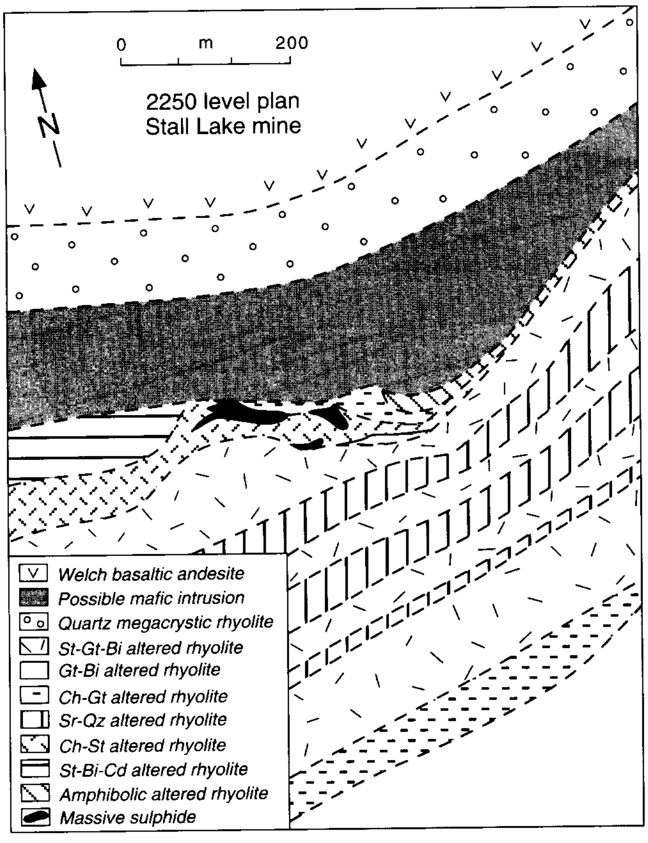

Figure 8. 2250 Level plan, Stall Lake mine (modified from Studer, 1982) St – staurolite; Gt – garnet; Bi – biotite; Ch – chlorite, Cd – cordierite; Qz – quartz.

The host rock for both of the Rod deposit ore lenses is a fine grained felsic rock with 5 mm quartz phenocrysts. Although Coats et al. (1970) consider this to be a pyroclastic rock, recent mapping by Bailes and Galley (1994) demonstrates that it is more likely a younger and crosscutting quartz porphyry phase of the subvolcanic Sneath Lake pluton (Fig. 6). Narrow, 1 to 2 m zones of staurolite-sericite schist, that locally occur adjacent to the sulphide ore body, are interpreted to be remnants of altered host supracrustal rocks that were left adjacent to the ore zone after intrusion of the Sneath Lake pluton. Coats et al. (1970) suggested that fracture-controlled carbonate, which is abundant in the vicinity of the Rod deposit, was produced by synvolcanic alteration but we interpret this as a late feature associated with subsequent deformation.

Linda deposit

The 13 Mt Linda massive sulphide deposit is the largest in the Snow Lake area. It is pyrite-rich with 0.30% Cu, 0.79% Zn, and an unusual Cu-Zn ratio (Cu/Cu+Zn) of 27 for a phase 1-hosted primitive arc deposit. The Linda deposit and host rocks are described in detail by Zaleski (1989) and Zaleski et al. (1991), and most of the following information is excerpted from these sources.

The Linda deposit occurs on the south limb of the Anderson Bay antiform (Fig. 3 and 6) within the quartz-megacrystic upper unit of the Anderson felsic extrusive complex. Footwall alteration associated with the Linda deposit lies northwest of the deposit, in the structural hanging wall, a configuration that requires stratigraphy to face down and to the southeast (Fig. 11). The host felsic rocks are in possible fault contact with heterolithological mafic breccias to the southeast (Bailes and Galley, 1994).

The Linda deposit consists of a series of stacked massive sulphide lenses, one large and three small, with the largest lens stratigraphically highest in the sequence. It consists of granular pyrite (60-90%) and granoblastic calcite (10-40%), with disseminated magnetite and pyrrhotite, and minor sphalerite and chalcopyrite. Minor barren enclaves and veins of calcite cut the pyrite-rich ore.

The main sulphide lens is elongate, with an aspect ratio of at least 30:2:1, plunging 30°at an azimuth of 030°. Elongation of clasts, mineral lineations, and mineral aggregates in host volcanic rocks are indistinguishable from the orientation of the sulphide lens. The lineations are considered by Zaleski (1989) to be related to the same deformation event that produced the Anderson Bay antiform.

Stratigraphic hanging wall

At Stall Lake, the massive sulphide-hosting Anderson rhyolite is overlain by up to 300 m of phase 1 Welch basalt. This basalt thins to the west, disappearing from the section 300 m before the Anderson Lake sulphide deposit. The Welch mafic flows are capped by 2 to 3 m of sulphidic sediments, locally termed the "Foot-Mud horizon". The sulphidic sediments, which contain disseminated pyrite and pyrrhotite, have been traced by drilling and geophysics for over 20 km. Although low in base metal content, they represent a significant episode of sulphide deposition in the Snow Lake region. The Foot-Mud unit is overlain to the north by up to 1 km of intermixed, coarse mafic and felsic volcaniclastics, with some contained mafic flows.

Hanging wall semiconformable alteration

Welch basalt and related mafic flows in the hanging wall to the Anderson rhyolite complex contain two zones of semiconformable alteration (Fig. 7b). One is an over 7 km long zone that is characterized by amphibole blastesis and the other is an over 20 km long zone of albitization/silicification that is prominent in the upper 0.5 km of the Welch basalt.

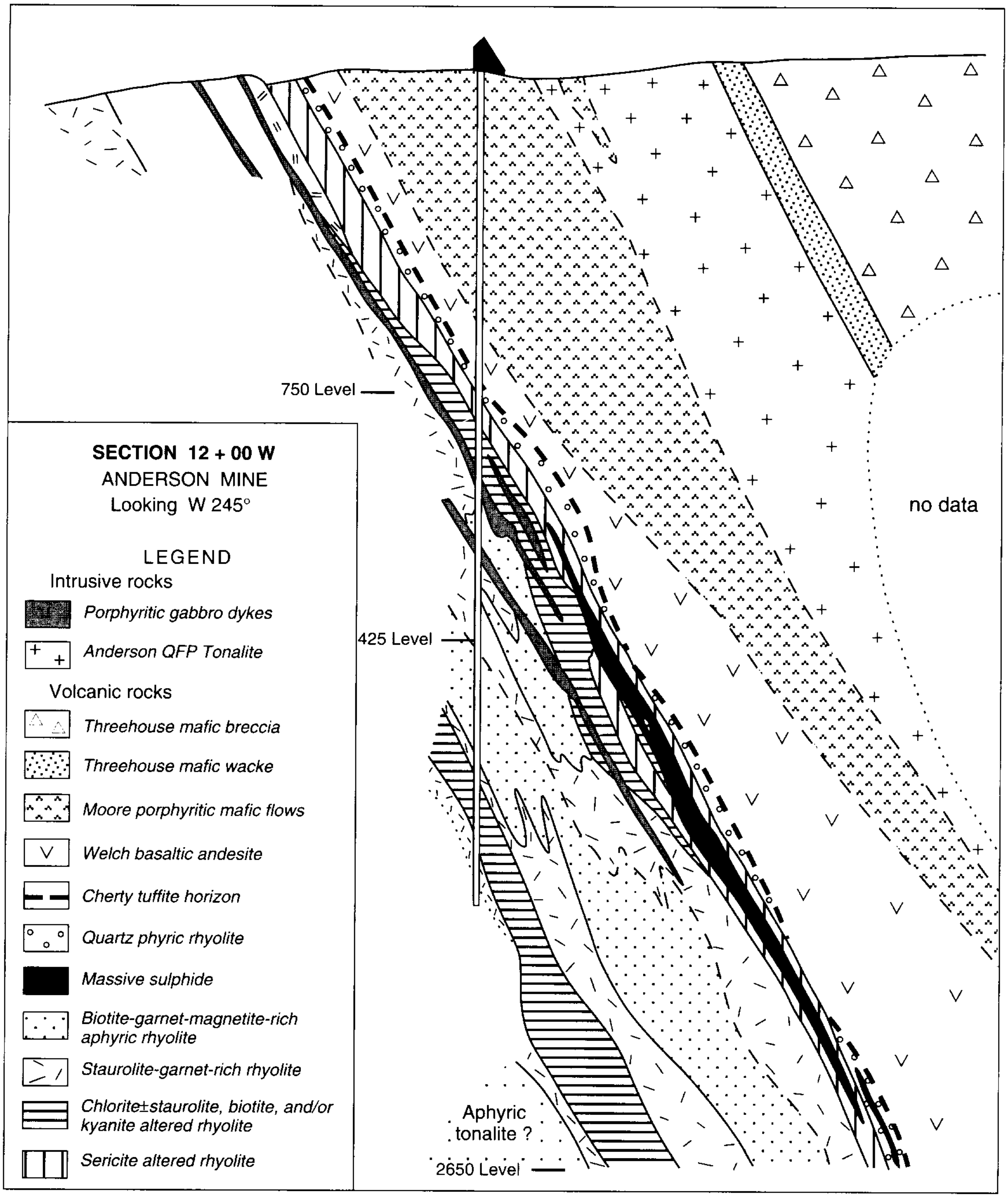

Figure 9. Cross-section (12+00W), Anderson Lake mine, looking west (modified from Walford and Franklin, 1982).

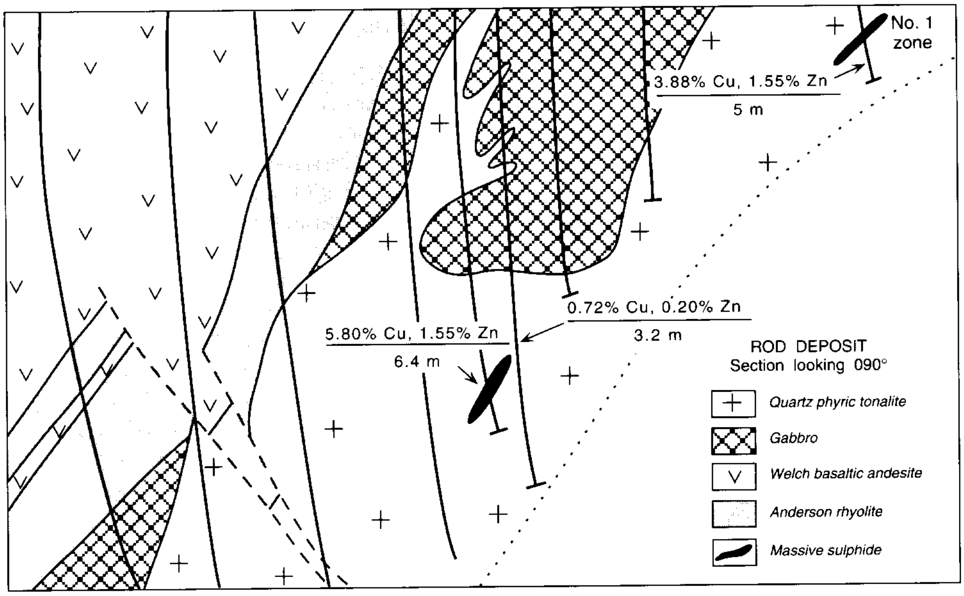

***Figure 10.** Longtitudinal section of Rod deposit, looking south (modified from Coats et al., 1970).*

The zone of amphibole blastesis occurs consists of up to 70% coarse grained amphibole with associated intermittent concentrations of Fe-carbonate and disseminated pyrrhotite and chalcopyrite. The alteration overlies the Joannie occurrence in the west and extends for 7 km with varying intensity to the stratigraphic hanging wall of the Linda deposit. This unusual alteration type does not display large net mass gains or losses of major elements relative to less altered equivalents. Its spatial association with a discontinuous zone of mylonite along the northwest shore of Anderson Lake has raised the possibility that it may represent an altered and metamorphosed syn-F_1 fault zone.

The 0.5 by over 20 km semiconformable albitization/silicification zone at the top of the Welch basalt directly underlies the Foot-Mud sulphidic sediments (Fig. 7b). The albitization/silicification is not related to the prominent footwall alteration associated with phase 1 Cu-rich volcanic-hosted massive sulphide deposits. Rather it overlies these deposits and represents either a separate hydrothermal event or a waning stage of the mineralizing hydrothermal activity. The alteration involved a gain in Si and Na and losses in Mg, Fe, Mn, and Zn (Skirrow, 1987). The close temporal and spatial relationship between this semiconformable alteration zone and the directly overlying Foot-Mud unit suggests that geothermal activity responsible for the alteration zone also produced the barren sulphidic sediments. Skirrow and Franklin (1994) interpret the albitization/silicification as a product of interaction of diffuse, near-seafloor hydrothermal discharge with hot lava flows. Gibson (1989) suggested a similar genesis for the silicified Upper Amulet Formation and overlying C contact tuff of the Cental Volcanic Complex at Noranda, Quebec. Gibson (1989) has postulated that the Amulet silicification zone played a major role in forming volcanic-hosted massive sulphide deposits at Noranda by self sealing the hydrothermal system leading to production of evolved base metal-rich fluids. The apparent absence of any economically significant base metal mineralization in the Foot-Mud sulphidic sediments suggests that the underlying semiconformable albitization/silicification zone did not self-seal a hot hydrothermal system and generate evolved base metal rich fluids.

Summary

Volcanic-hosted massive sulphide deposits in the primitive arc sequence are comparable in a number of respects to the "Noranda-type" deposits of Morton and Franklin (1987). They are Cu-rich (Cu/Cu+Zn ratios range from 27 to 98), occur in a bimodal basalt-rhyolite package, are hosted within isolated subaqueous rhyolite flow complexes, consist of multiple (stacked) lenses with extensive discordant chlorite-rich discordant alteration zones, and are underlain by a large felsic subvolcanic intrusive complex.

The integral role played by the subvolcanic Flavrian pluton in generating Noranda volcanic-hosted massive sulphide deposits is paralleled at Anderson Lake by the Sneath Lake intrusive complex. This is apparent from the coeval nature of the Sneath Lake tonalite and ore-hosting rhyolite flows, the increase in intensity of alteration of the host rocks with proximity to the pluton, and the steady increase in the Cu-Zn ratio (Cu/Cu+Zn) of the volcanic-hosted massive sulphide deposits from 27 at Linda to 97 at Anderson Lake as distance to the pluton decreases. We interpret this increase in Cu-Zn ratio of the sulphide deposits as a product of high Cu values coincident with higher temperature, pluton-proximal portions of the regional synvolcanic hydrothermal system. The presence of molybdenum and high Cu-Au values at Anderson Lake may also indicate a stronger magmatic component to the hydrothermal fluid responsible for the generation of this deposit. The high concentration of pyrite and, carbonate and

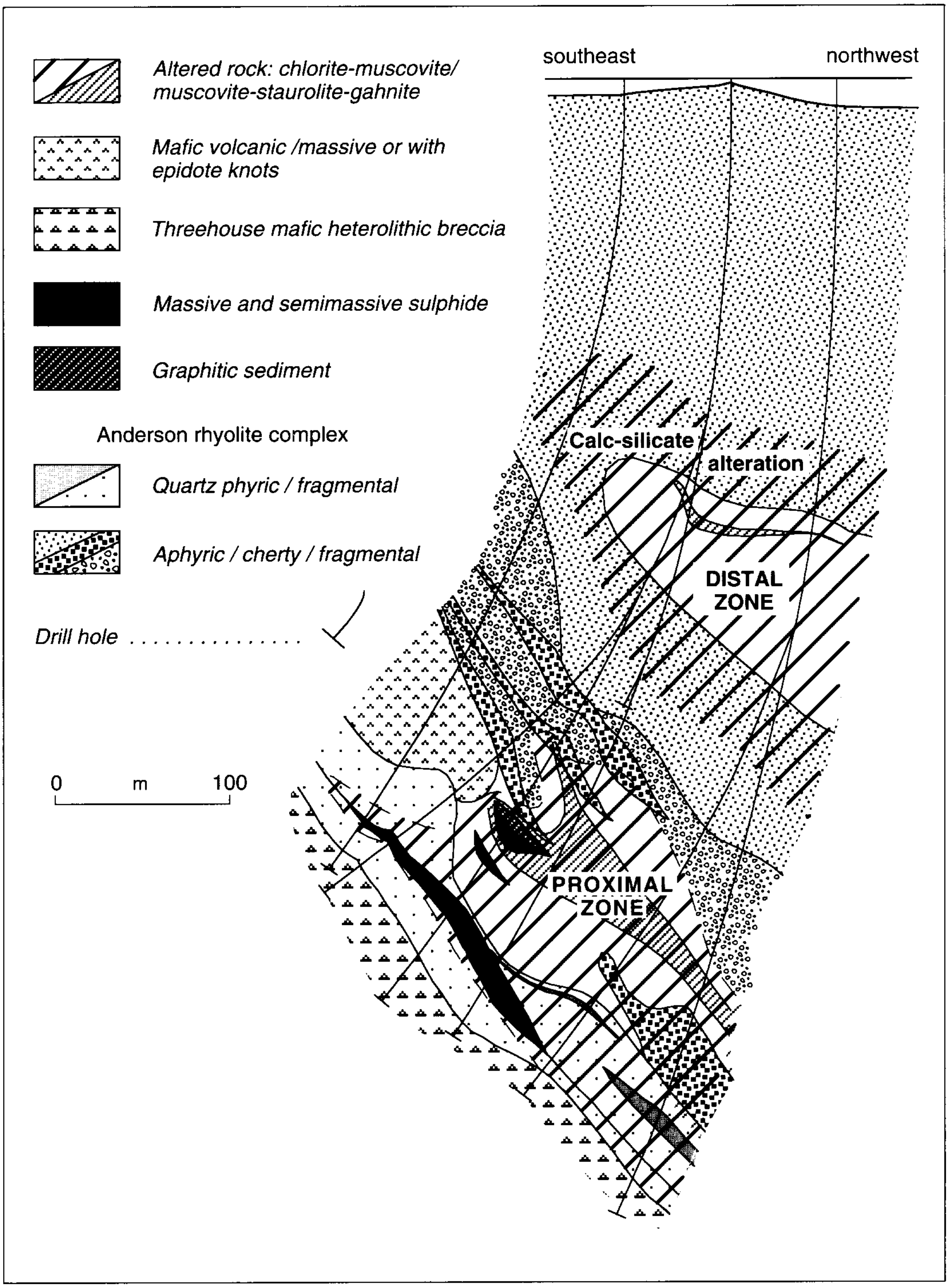

Figure 11. *Subsurface geology of Linda deposit in cross-section looking southwest (modified from Zaleski, 1989).*

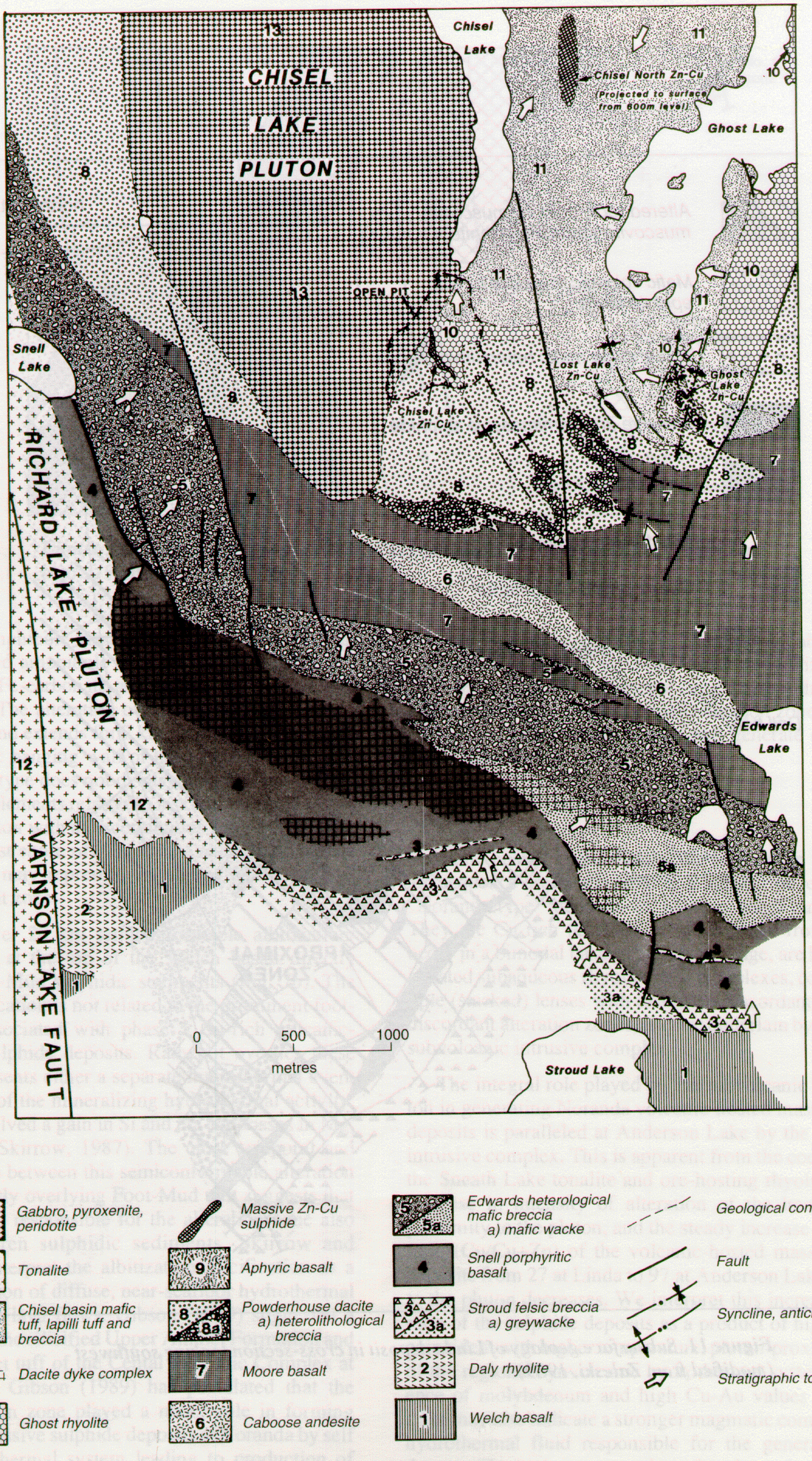

***Figure 12.** Simplified geology of Chisel Lake area.*

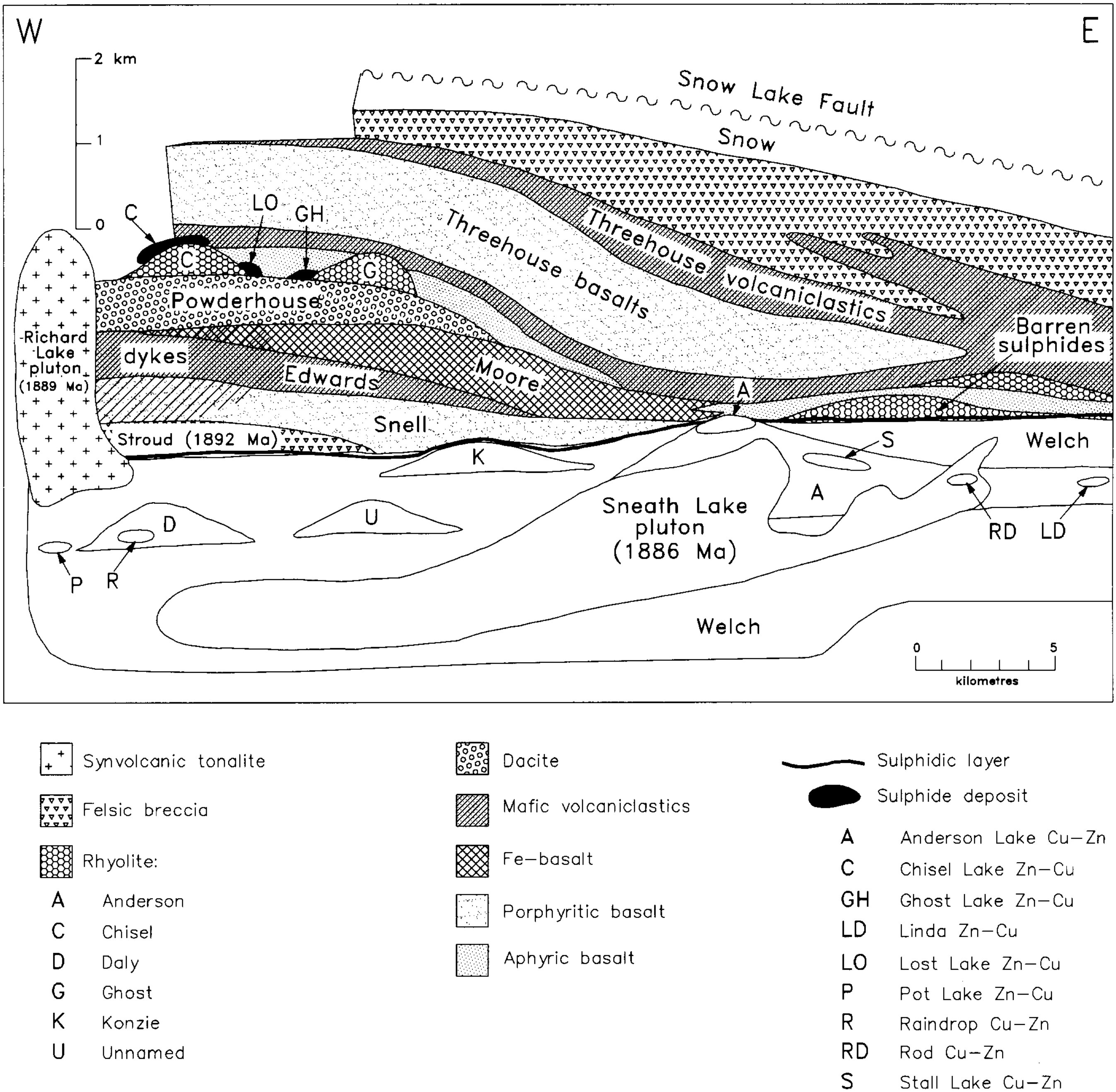

Figure 13. *Schematic geological cross-section of phases 2-4 (evolved arc) volcanic rocks with location of associated Zn-rich massive sulphide deposits:* ***a)*** *geological units,* ***b)*** *distribution of hydrothermally altered rocks.*

low base metal values at the Linda deposit may indicate that a high sulphur, low temperature, moderate pH fluid was responsible for formation of the deposit near the periphery of the pluton-generated regional hydrothermal system.

EVOLVED ARC-HOSTED Zn-RICH DEPOSITS

Introduction

The evolved arc hosts a second episode of base metal sulphide deposition in the Snow Lake area. It consists of four known Zn-rich massive sulphide deposits (Fig. 3, 4, 12, and 13) of which three (Chisel Lake, Lost Lake, and Ghost Lake) have been mined for a total of 7.8 Mt (production plus reserves) grading 0.42% Cu and 10.06% Zn. The fourth deposit (North Chisel), which has been drilled off but is unmined, contains 2.6 Mt grading 0.23% Cu and 8.9% Zn; it occurs 300 m down-plunge from the Chisel Lake deposit at a depth of 600-800 m. All four deposits occur in the same stratigraphic interval. The stratigraphic affinity of a recently discovered Cu-Au rich volcanic-hosted massive sulphide deposit at Photo Lake (Bailes and Simms, 1994), 4 km north of the Chisel Lake area deposits, is uncertain and is not discussed in this paper.

All of the Chisel Lake area massive sulphide deposits occur along the contact between phase 3 volcanic rocks and overlying formations. The Chisel Lake deposit is associated with a rhyolite flow complex (Chisel rhyolite), whereas the other deposits occur at the same stratigraphic position at the top of the Powderhouse dacite. A 1 to 2 m thick sulphide-chert unit with up to several per cent Zn and Ag occurs at the top of the Chisel rhyolite and has been traced continuously along strike from the Chisel Lake to the Chisel North deposits (Galley et al., 1993).

The Chisel Lake 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 deposits are underlain by an extensive system of synvolcanic dykes that are spatially associated with hydrothermally altered rocks. As demonstrated below, the synvolcanic dykes display the same strongly fractionated and LREE geochemical signature as do the ore-hosting phase 3 volcanic cycle.

Stratigraphic footwall

A >4.5 km thick, essentially homoclinal, north-facing stratigraphic footwall section to the Chisel Lake area massive sulphide deposits is well exposed south of Chisel Lake (Fig. 3, 12, and 13). This steeply to moderately north-dipping section consists of 2.5 km of phase 1 volcanic rocks and intrusions (previously discussed in description of rocks hosting the phase 1 Cu-rich Anderson Lake area massive sulphide deposits), 1 km of phase 2 rocks (Stroud, Snell, and Edwards formations), and 1 km of phase 3 (Moore, Powderhouse, and Ghost formations).

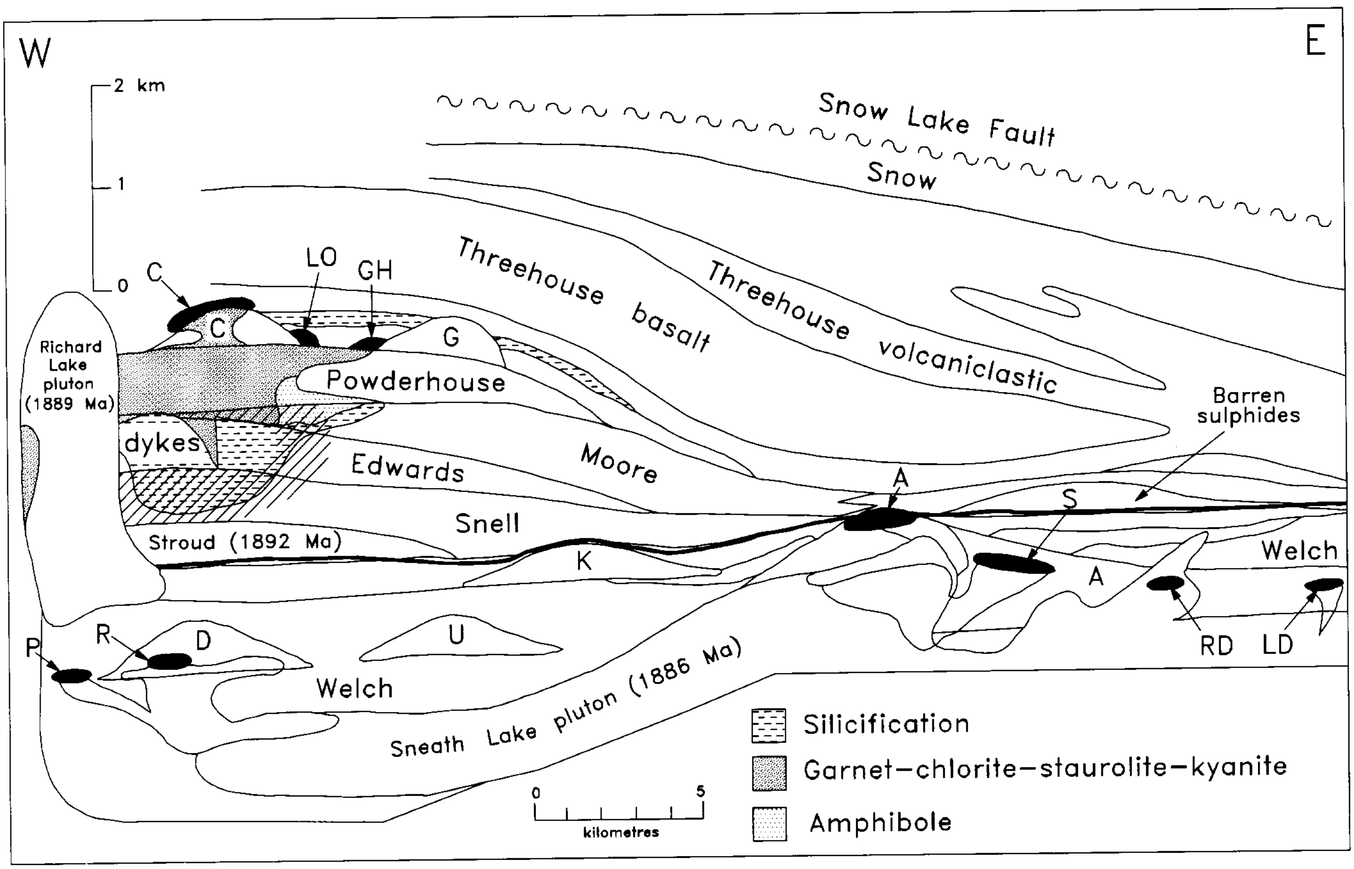

Figure 13b.

Phase 2 volcanic rocks

Phase 2 volcanic rocks are a loosely affiliated sequence of largely volcaniclastic rocks that occur between the phases 1 and 3. The volcaniclastic rocks include both felsic (Stroud) and mafic (Edwards) units that were derived by mass wasting of a source terrane located to the west. The volcaniclastic units are intercalated with basalts (Snell) that are derived from a geochemically distinctive, evolved arc magma source unlike the one that supplied the primitive arc basalts (Welch) of phase 1.

Stroud felsic breccia

This 0-400 m thick unit consists of well bedded heterolithological to monolithological felsic breccia and wacke, locally intercalated with sulphide-bearing intermediate to mafic volcanic wacke. Felsic breccia beds are organized in a manner consistent with deposition by subaqueous debris flows (Cas and Wright, 1984). Most of this unit lies directly upon phase 1 primitive arc volcanic rocks, although rare beds of this felsic breccia occur higher in the section intercalated with the Snell basalt.

Snell basalt

Up to 500 m of porphyritic mafic flows overlie and are locally intercalated with the Stroud felsic volcaniclastic rocks. These mafic flows are interpreted to have accumulated rapidly from a different magma source than the underlying phase 1 Welch basalt. They display the lowest ε_{Nd} values of any mafic flows in the Flin Flon Belt, a feature interpreted by Stern et al. (1992, 1994) to be a consequence of interaction with much older, possibly Archean, lithosphere. The presence of inherited Archean zircons in the Stroud felsic breccia (Machado and David, 1992; David et al., in press) is consistent with this interpretation. Intercalation of Snell mafic flows with Stroud felsic breccias suggests that magma extrusion was contemporaneous with uplift and erosion of felsic complexes.

Edwards heterolithological mafic wacke and breccia

This unit is up to 500 m thick, is upward-coarsening, and consists of fine grained, thin bedded mafic volcaniclastic sediments overlain by a sequence of coarse, thick bedded mafic breccias. East of Edwards Lake the heterolithological mafic breccias are separated from the underlying mafic volcanic wackes by an rapidly gradational boundary. The boundary is marked by an increase in heterogeneity of clast population, in addition to the abrupt increase in maximum clast dimensions (Skirrow, 1987). Organization of breccia beds is consistent with deposition by subaqueous debris flow deposits (Bailes, 1987a; Skirrow, 1987). A local source for the mafic breccias is supported by the presence of very thick beds.

Phase 3 volcanic rocks

Phase 3 rocks consist of a comagmatic mafic to felsic sequence: Moore basalt, Powderhouse dacite, and Ghost rhyolite. This sequence is chemically distinctive and characterized by high incompatible element and elevated light REE abundances. Zinc-rich base metal deposits at Chisel Lake occur at the top of this volcanic cycle, typically associated with Ghost rhyolite flow complexes. Stern et al. (1995) suggest that high HFSE (high field strength element) and light REE abundances of the Moore basalt may indicate involvement of an enriched mantle source component in generation of phase 3 magmas.

The Chisel Lake area is underlain by a swarm of phase 3 dacite sills and dykes that are recognized by their high incompatible and light REE abundances. The dyke swarm is spatially associated with areas of hydrothermally altered rocks indicating that the dykes played a significant role in generating or focusing hydrothermal solutions. The subvolcanic Richard Lake tonalite pluton, with a U-Pb zircon age of 1889+6/-5 Ma (Bailes et al., 1991), cuts across the phase 3 dyke swarm and attendant altered rocks, but still may be part of the phase 3 magmatic event as it displays the characteristic phase 3 high incompatible and light REE geochemical signature.

Moore basalt

This unit is up to 1000 m thick and displays lateral variations in thickness and in flow facies (Fig. 13). Where thickest, 3 km east of Chisel Lake, this unit consists mainly of pillowed basalt. At Chisel Lake the Moore formation is less than 350 m thick and is composed of a less proximal mixture of pillowed flows, amoeboid pillow breccia, and pillow fragment breccia. To the east the Moore formation disappears from the section before Anderson Lake. Moore pillowed flows are characterized by abundant vesicles, including many 2-3 cm long radial pipe vesicles, suggesting a moderately shallow water environment of extrusion.

Powderhouse dacite

A 100-250 m thick unit of Powderhouse dacite tuff and lapilli tuff overlies the Moore basalt, and forms the immediate stratigraphic footwall to the Ghost Lake, Lost Lake, Chisel North, and part of the Chisel Lake Zn-rich massive sulphide deposits. Amygdaloidal Powderhouse dacite flows are also locally intercalated with the Moore basalt. A prominent, footwall dacite dyke complex is chemically identical to and clearly a feeder system to Powderhouse volcanism.

Powderhouse dacite is characterized by 5-15%, 0.5-2 mm tablet-shaped plagioclase phenocrysts and glomerocrysts, and, more rarely, quartz phenocrysts. The dacite tuff is generally massive, featureless, only rarely displays fragments, and is only occasionally well bedded. Heterolithological, coarse debris flow breccia, composed of mixed felsic and mafic detritus, forms an up to 30 m thick unit near the base of the Powderhouse dacite. Well bedded dacite wacke forms a unit up to 20 m thick at the top of the Powderhouse formation.

Ghost rhyolite

Local, domal complexes of massive rhyolite and lobe-hyaloclastite rhyolite flows up to 100 m thick, overlie the Powderhouse dacite. The rhyolite bodies include aphyric and sparsely quartz- and plagioclase-phyric varieties. The Zn-rich massive sulphide deposits occur either in direct association with (Chisel Lake) or along strike from (Lost Lake, Ghost Lake, Chisel North) the rhyolite complexes. A 1-2 m thick, sulphide-chert-wacke unit directly overlies the rhyolite flows and forms an apron about and connects the massive sulphide deposits.

The Ghost Lake rhyolite displays the elevated light REE pattern typical of phase 3 volcanic rocks. The ε_{Nd} value of the Ghost Lake rhyolite (+3.3) is higher than that of the underlying Powderhouse dacite (+2.6 to 3.05) but identical to that of the Richard Lake tonalite (+3.35) (Stern et al., 1992).

Subvolcanic intrusions

A large number of phase 3 subvolcanic intrusions are present in the footwall stratigraphy to the Chisel Lake massive sulphide deposits. They commonly form up to 35% of the Chisel Lake footwall, and were possibly part of a vent facies, or eruptive centre (Williams and McBirney, 1979). The intrusions include a small, layered mafic-ultramafic sill, a quartz-plagioclase porphyritic stock, dykes ranging in composition from peridotite through diorite to dacite, and a large tonalite pluton (Richard Lake). Crosscutting relationships between dyke sets suggest that intrusion was contemporaneous from several magma sources. Many of the intrusions have geochemical characteristics similar to overlying supracrustal volcanic units. Dyke margins in volcaniclastic strata are commonly amoeboid, and this suggests that they were intruded into 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. Of these a dacite sill/dyke swarm west of Edwards Lake and the Richard Lake pluton (Fig. 12 and 13) were the most significant, and the most likely to have focused hydrothermal activity in the Chisel Lake area. The dacite intrusions are similar in composition to the Powderhouse dacite formation that forms the immediate footwall to the Chisel Lake area massive sulphide deposits. This sill/dyke swarm occurs near the base of a semiconformable alteration zone in the Chisel Lake footwall; individual dykes are demonstrably the heat source that focused alteration of adjacent Snell basalts and Edwards Lake wackes and breccias (Fig. 5c; Skirrow and Franklin, 1994).

The Richard Lake pluton is a multi-phase intrusion composed of quartz porphyritic to aphyric tonalite. A U-Pb zircon age of 1886 Ma demonstrates its synvolcanic character. However it intrudes and therefore postdates the dacite sill/dyke swarm and related alteration. The Richard Lake tonalite is geochemically and isotopically identical to the Ghost Lake and Chisel Lake rhyolite that are associated with the Chisel Lake area Zn-rich massive sulphide deposits.

Footwall alteration

Rocks in the stratigraphic footwall to the Chisel Lake area Zn-rich massive sulphide deposits are extensively altered. The alteration includes a semiconformable zone, largely confined to volcaniclastic units, and a disconformable zone, located in the Powderhouse dacite directly below the deposits. The relationship between the semiconformable and disconformable zones of alteration is uncertain, but south of the Chisel Lake deposit the two alteration zones appear to merge.

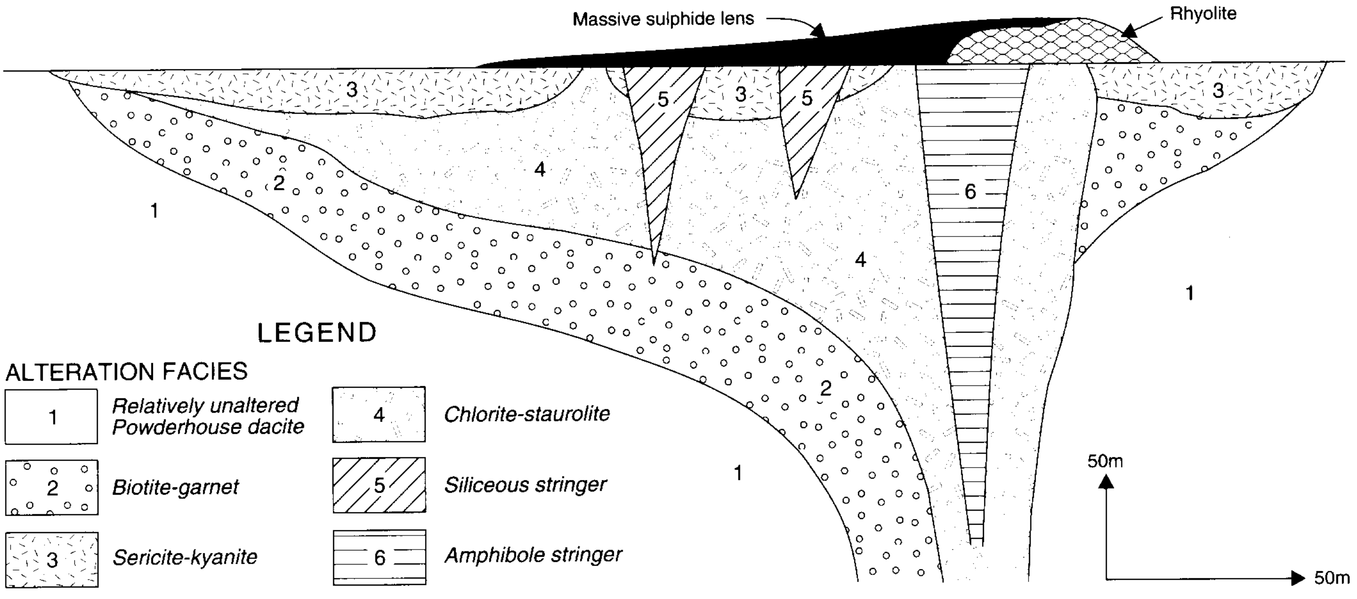

Figure 14. *Schematic cross-section showing distribution of disconformable alteration facies in the footwall of Chisel Lake deposit. (from Galley et al., 1994)*

The semiconformable alteration zone, which is dominated by silicification, is 0.5 to 1 km wide and over 5 km long and occurs 1 to 2 km below the Chisel Lake area massive sulphide deposits. It has two prominent associations: 1) localization in fragmental units, specifically the Edwards Lake heterolithological mafic volcaniclastics and, to a lesser extent, the Moore mafic breccias, and 2) spatial association with a prominent synvolcanic dyke complex. Alteration involved gains in Si, Na, and Ca, and losses in total Fe, Cu, and Zn (Galley et al., 1993; Skirrow and Franklin, 1994). The alteration is clearly related to dyke emplacement as silicification commonly occurs as zones parallel to dyke margins (Fig. 5c). Other forms of silicification, such as mottled varieties with random distribution, alteration of margins of fragments (Fig. 5b), and alteration of matrix between fragments are less clearly related to dyke emplacement, but they do coincide with large concentrations of synvolcanic dykes.

The disconformable alteration zone is tulip-shaped in cross-section (Fig. 14), is characterized by several overlapping alteration facies, and is interpreted to be due to localized hydrothermal discharge along a synvolcanic fault (Galley et al., 1993). The various alteration facies, all derived from a dacite protolith, are easily recognized by characteristic metamorphic mineral assemblages that were formed during subsequent almandine-amphibolite metamorphic recrystallization. They consist of three broad zones (biotite-garnet, chlorite-staurolite, and sericite-kyanite), forming an apron under the sulphide deposit and two crosscutting facies, siliceous stockwork and amphibole stockwork (Fig. 14). The biotite-garnet, chlorite-staurolite, and sericite-kyanite zones represent progressively more altered dacite interpreted to have formed in a broad hydrothermal field through diffuse upflow. Sulphide-bearing, crosscutting siliceous- and amphibole-stockwork zones are interpreted to be the products of more focused hydrothermal discharge that produced the directly overlying sulphide deposits (Galley et al., 1993). A tremolite-rich skarn directly overlies a Cu-Fe rich sulphide stockwork zone at the Chisel Lake deposit. The disconformable alteration zone displays elevated concentrations of Fe, Mg, Ca, Zn, Pb, Ag, and Au relative to "unaltered" dacite, and an overall decrease in Na and Sr (Galley et al., 1993).

Skirrow and Franklin (1994) suggest, and we concur, that the Edwards Lake formation was probably a hydrothermal aquifer that was modified by intrusion of the phase 3 synvolcanic dykes. Intrusion of the dykes probably raised the temperature of silica-rich hydrothermal fluids in the aquifer above 380°C causing them to precipitate silica (Kennedy, 1950). Dyke emplacement likely restricted upward movement of the hydrothermal fluids, similar to the "gable trapping" mechanism described by Lydon and Jamieson (1984) in the Troodos ophiolite complex, and may have produced evolved, metal-rich solutions. In this interpretation the disconformable zone of Mg-Fe enrichment below the Zn-rich massive sulphide deposits at Chisel Lake represents a product of fault-controlled discharge of these evolved, metalliferous solutions onto the paleoseafloor to produce the overlying massive sulphide deposits. This interpretation requires that the two alteration zones be connected. The semiconformable and disconformable zones are close to each other south of the Chisel Lake mine site, but are separated by 400 m with no outcrop. A deep drill hole in this area of no outcrop follows indicates that they are connected as it follows the disconformable alteration down to the projected continuation of the semiconformable zone (Hudson Bay Exploration and Development, pers. comm., 1989).

Massive sulphide deposits

The Chisel Lake, Ghost Lake, Lost Lake, and Chisel North Zn-rich massive sulphide deposits clearly form at or close to the same stratigraphic interval. The two largest deposits, Chisel Lake and Chisel North, are connected along strike by a 1 to 2 m thick sulphidic, siliceous exhalite. Both the Chisel Lake and Chisel North deposits comprise a series of ore lenses that originally formed a more or less continuous sulphide sheet over 2000 m long and 200 m wide, with a gap of 300 m between the Chisel Lake and North Chisel deposits. Although this elongate sulphide sheet parallels the linear alteration "keel", presumed to be the expression of a synvolcanic fault, it occurs 100 m west rather than directly above this feature. The sulphide deposits and host strata are affected by at least two folding events with individual sulphide ore lenses constituting rootless F_1 fold hinges and boudinaged fold limbs. The Ghost Lake and Lost Lake deposits are small, Pb-rich, satellite deposits near the Chisel Lake mine, and were simply accessed by a separate decline rather than from the main Chisel Lake mine workings.

Chisel Lake deposit

The Chisel Lake deposit, discovered in 1956, is the largest Zn-rich ore body in the Snow Lake area at 7.5 Mt, grading 0.32% Cu, 10.1% Zn, 56 g/t Ag, and 2.2 g/t Au (Syme and Bailes, 1993; Table 1). The deposit is described in detail by Martin (1966) and Galley et al. (1993). It consists of seven structurally stacked massive sulphide lenses that strike north-northwest, dip northeast at 65°, and together plunge 45° at an azimuth of 020°. Most ore lenses consist of S-asymetrical rootless folds with an average amplitude of 50 m. These folded ore lenses are truncated to the west by the late kinematic Chisel Lake gabbroic pluton.

Structurally thickened sulphide lenses in the Chisel Lake deposit average 12 m but are locally up to 40 m thick. They consist of crudely interlayered sphalerite-pyrite and sphalerite, plus minor amounts of chalcopyrite, pyrrhotite, galena, and arsenopyrite, with traces of lead-arsenic suphides, tellurides, and native Au, Ag, Bi, and As (Galley et al., 1993). Some ore lenses locally consist of several metres of near-solid sphalerite grading up to 35% Zn. Carbonate, mainly dolomite, occurs in the sulphide ore as lenses, wispy bands and patches, and near the top as matrix to the suphides. Carbonate-rich zones and associated tremolite skarn are locally present along the stratigraphic base of the massive sulphide deposit. They typically contain disseminated suphides, mainly arsenopyrite with lesser amounts of galena, sphalerite, chalcopyrite, pyrrhotite, and bornite. The stratigraphic hanging wall contact of the massive sulphide lens with overlying mafic wacke locally consists of over 1.5 m of coarse grained, euhedral galena in a siliceous argillite matrix. Individual orebodies display a consistent metal zonation, with Cu-Fe-rich stratigraphic bases, and Zn-Fe-Pb-rich tops (Galley et al., 1993).

Zones of disseminated and vein-controlled sulphide mineralization occur locally in the stratigraphic footwall to the massive sulphide horizon. They include sphalerite-pyrite veins, crosscutting siliceous brecciated rhyolite, and chalcopyrite veins, associated with chlorite-biotite-hornblende (or amphibole stringa) zones (Fig. 14). Tectonically remobilized veins of sulphide are also present both in the stratigraphic footwall and hanging wall.

Chisel North deposit

The North Chisel deposit was discovered in 1987 during exploration drilling 1.5 km north of the original Chisel Lake discovery (Fig. 15). The new deposit, which occurs at the same stratigraphic position, contains in excess of 2.58 Mt of 8.9% Zn, 0.22% Cu, 0.4% Pb, 23.3 g/t Ag, and 2.54 g/t Au (Galley et al., 1993). Chisel North, not currently in production, consists of a single, asymetrically folded lens, 300 m long that plunges 10-20° at an azimuth of 020°. The sulphide mineralization occurs 300 m down-plunge from the Chisel Lake deposit. The attenuated limb of the folded sulphide lens is below ore grade, and for mining purposes the deposit consists of two discrete bodies.

Chisel North differs from the original Chisel Lake deposit in that it consists of up to 20 m of silicate-dolomite-rich semimassive suphides rather than massive sulphide ore as at Chisel Lake. The semimassive ore contains thin massive sulphide layers which are characterized by interstitial dolomite or by thin bands of fine grained tremolite-rich siliceous material. The main sulphide minerals are sphalerite and pyrite, but in addition, the Chisel North deposit contains pyrrhotite-rich layers concentrated near the hanging wall contact.

The Chisel North deposit directly overlies altered Powderhouse formation dacite, but unlike the original Chisel Lake deposit, is not directly associated with rhyolite. It occurs 100 m west of a "keel" of altered rocks that is interpreted to be the expression of an altered synvolcanic fault. The southern one-third of the deposit is overlain by the same mafic wackes (Threehouse) that directly overlie the Chisel Lake deposit, but the northern two-thirds has a different hanging wall succession, which includes overlying heterolithological breccia, aphyric mafic flows and a rhyolite complex.

Lost Lake and Ghost Lake deposits

The Lost Lake and Ghost Lake deposits occur 900 and 1100 m, respectively, east of the Chisel Lake orebody. Between 1972 and their closure in 1988 they produced 590 233 t grading 8.6% Zn, 1.33% Cu, 32.61 g/t Ag, and 3.83 g/t Au (G. Kitzler, pers. comm., 1993). There are no published descriptions of either deposit.

The Lost Lake and Ghost Lake deposits occur at the same stratigraphic position as the main Chisel Lake sulphide lens. All three deposits occur directly atop the Powderhouse dacite, with the Chisel Lake and Ghost Lake deposits associated with rhyolite flow complexes. The Chisel Lake and Lost Lake deposits are directly overlain by turbidity current deposited mafic wackes, whereas the Ghost Lake deposit is overlain by a 100 m thick basalt flow and then the mafic volcaniclastic unit.

Stratigraphic hanging wall

The stratigraphic hanging wall to the Chisel Lake massive sulphide deposit consists (in ascending order) of 1 to 2 m of sulphide-bearing cherty sediments that grade upwards into approximately 50 m of well bedded, mafic turbidite wacke, and several hundred metres of poorly bedded, scoria-rich mafic tuff-breccia and heterolithological mafic breccia.

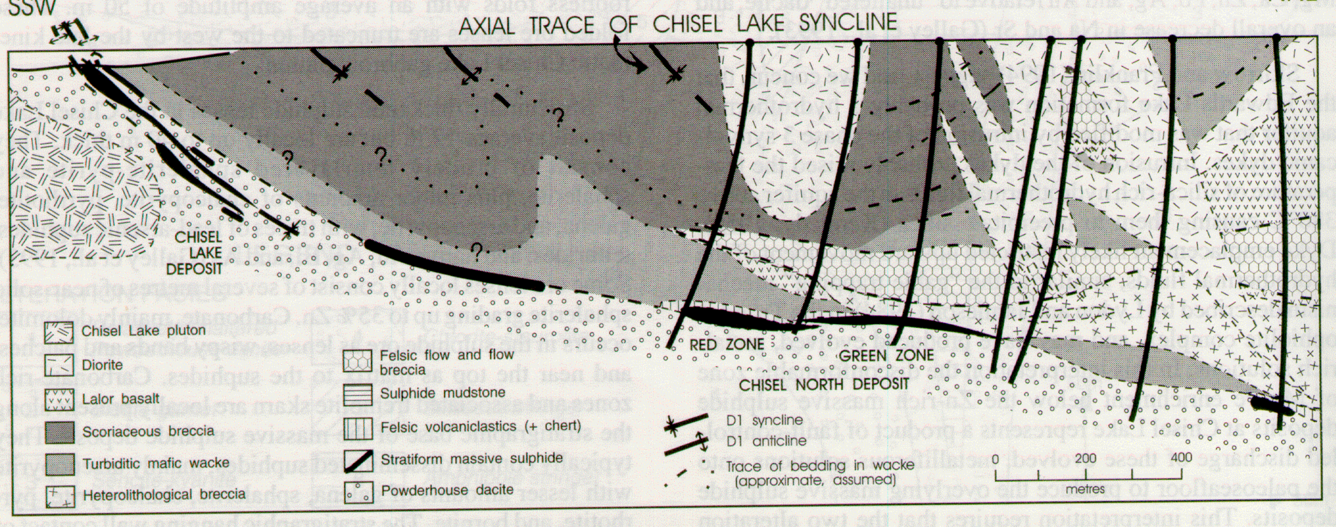

Figure 15. Cross-section illustrating the relationship between the Chisel Lake and Chisel North Zn-rich massive sulphide deposits from Galley et al. (1993). Note the along strike variation in hanging wall stratigraphy.

Contacts between these units, all part of the phase 4 Threehouse formation, are structurally intact and rapidly gradational. The Threehouse mafic volcaniclastics at Chisel Lake most likely accumulated in a topographic depression or basin, shed from an adjacent shallow water to subaerial mafic edifice.

The simple hanging wall stratigraphy at Chisel Lake breaks down at a regional scale and is replaced by a more complex hanging wall succession including a variety of heterolithological breccia units, mafic flows, rhyolite flows, and rhyolite breccia, in addition to the usual Threehouse mafic wacke and breccia. This is apparent above the northern two-thirds of the Chisel North massive sulphide deposit where the hanging wall succession includes heterolithological breccia, basalt flows, and rhyolite flows not present to the south (Fig. 11). In the past this has been attributed to facies variations in postore stratigraphy but the recent identification of an unconformable contact at the base of the Threehouse formation (Bailes and Simms, 1994) suggests that some of the postore units north of Chisel Lake may predate Threehouse formation rocks. Thus, the heterolithological breccia, aphyric mafic flows and rhyolite complex above the northern two-thirds of the Chisel North deposit may be the "intact" hanging wall, with these rocks eroded at the "Threehouse" unconformity above deposits to the south, such as Chisel Lake and Lost Lake.

Summary

Volcanic-hosted massive sulphide deposits in the evolved arc sequence are radically different from deposits in the primitive arc succession. Besides the obvious Zn- versus Cu-rich character they differ in stratigraphic setting, massive sulphide morphology, and associated metamorphosed alteration mineral assemblages. For example the host rocks are part of an evolved arc terrane, are characterized by abundant volcaniclastic rocks, and are lithologically diverse compared to the simple bimodal (basalt-rhyolite) flow-dominated sequence in the primitive arc. In addition, the evolved arc volcanic-hosted massive sulphide deposits are laterally continuous sheets with broad, diffuse, sericite- and carbonate-rich disconformable alteration zones compared to the discrete sulphide lenses and well defined chlorite-rich pipes of primitive arc volcanic-hosted massive sulphide deposits.

The primitive arc volcanic-hosted massive sulphide deposits at Chisel Lake share some of the features of the Archean "Mattabi-type" deposits of Morton and Franklin (1987), but are more comparable to other Paleoproterozoic volcanic-associated such as the Ladysmith-Rhinelander deposits in Wisconsin (DeMatties, 1994) and some of the Bergslagen district volcanic-hosted massive sulphide deposits in Sweden (Lundstrom and Papunen, 1986). This group of deposits are characterized by thick footwall sequences of felsic volcaniclastic rocks, by layered pyrite-sphalerite-chalcopyrite-galena orebodies, by interlayed carbonate-rich sedimentary units and by associated skarns. Analogous to the Chisel Lake area deposits they are characterized by Cu-Zn ratios (Cu/Cu+Zn) <10, by high Ag and, rarely, by high Au values. They also share the sericite-pyrite-aluminosilicate-rich discordant alteration zones cored by more discrete chlorite-chalcopyrite-pyrrhotite alteration noted in the Chisel Lake deposit by Galley et al. (1993).

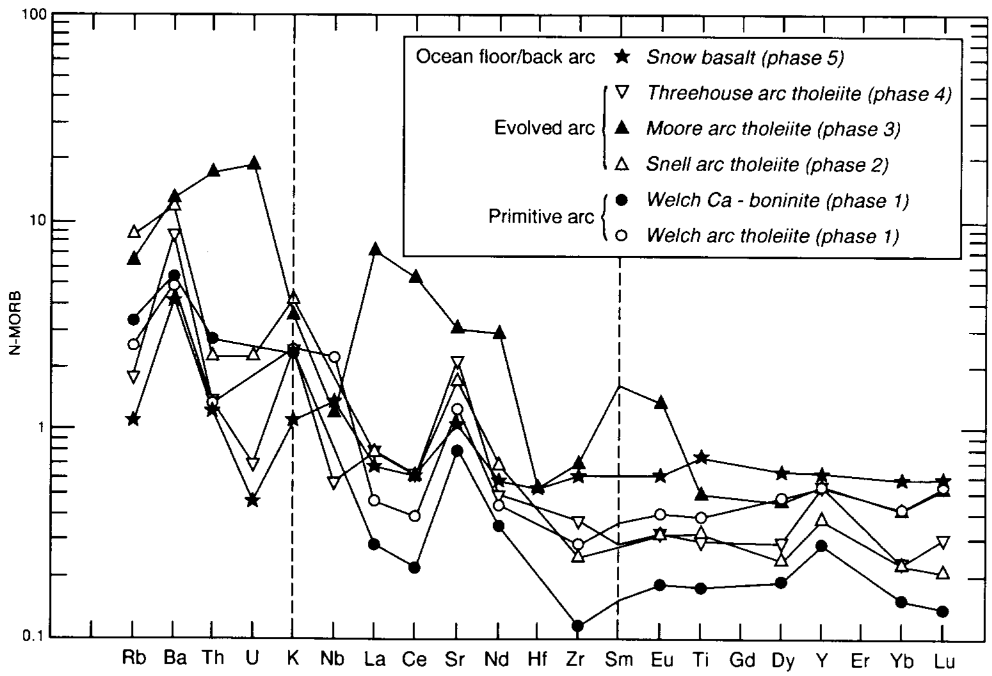

***Figure 16.** MORB-normized trace element patterns for average basalt units at Snow Lake.*

GEOCHEMISTRY

Geochemistry of mafic and intermediate rocks

Major element, trace element, REE, and Nd isotopic compositions show that mafic to intermediate metavolcanic rocks in the Flin Flon Belt formed in variety of tectonic settings (Syme, 1990; Syme and Bailes, 1993; Stern et al., 1995). This permits determination of the tectonic setting of massive sulphide deposits (Syme and Bailes, 1993) and allows exploration to be focused on those tectonic settings with greatest volcanic-hosted massive sulphide potential. Eighty-three whole rock and trace element geochemical analyses, fifty-five REE analyses, and fifteen Nd isotopic analyses have been obtained from least-altered mafic and intermediate volcanic rocks at Snow Lake.

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. On the basis of their geochemistry the mafic flows appear to have formed in three separate tectonic environments (Stern et al., 1995): primitive forearc (phase 1: Welch), evolved arc (phase 2-4: Snell, Moore, Anderson, Threehouse) and back arc/ocean floor (phase 5: Snow Creek and Tramping) (Figures 4b and 4c).

Phase 1 Welch mafic flows, interpreted to have formed in the primitive fore-arc environment, have high contents of large ion lithophile (LIL: e.g. Rb, Ba, Th, Sr) elements, low contents of high field strength (HFS: e.g. Hf, Ti, Zr, Y) elements and very low Ni and Cr relative to N-MORB (Fig. 16). These features are characteristic of subduction-related magmas (Gill, 1981; Tarney et al., 1981) formed within oceanic arc tectonic settings. The particularly low La/Yb ratios, and low Th, Ti, and Zr contents (Fig. 16, 17, 18) are characteristic of primitive arc basalts. This primitive arc genesis for Welch mafic flows is further supported by their intercalation with high-Ca boninites (Stern et al., 1995), a rock type currently found only in the fore-arc regions of primitive Cenozoic island arcs. In the Flin Flon Belt, high Ca-boninites are unique to the Welch basalts at Snow Lake.

Although phase 2-4 mafic flows display the same "decoupling" of large ion lithophile and high field strength elements as do phase 1 flows, they are different in a number of other geochemical attributes. For example, many of the evolved arc basalts are LREE enriched (Fig. 17) and most have higher overall contents of Th, P_2O_5, and Zr. This implies that phase 2-4 mafic flows had a different magmatic evolution than those of the underlying phase 1 basalts. This conclusion is substantiated by the lower ε_{Nd} values of 0 to 2.7 for phase 2-4 mafic flows compared to values near 3 for phase 1 mafic flows (Fig. 19). Stern et al. (1995) interpret the lower ε_{Nd} of phase 2-4 basalts to be a consequence of intracrustal contamination or, less likely, a contaminated mantle source. Intracrustal contamination during phase 2-4 magma genesis is supported by the presence of an inherited zircon population between 2650 and 2824 Ma in the 1892 Ma phase 2 and 3 felsic volcanic rocks (Machado and David, 1992; David et al., in press).

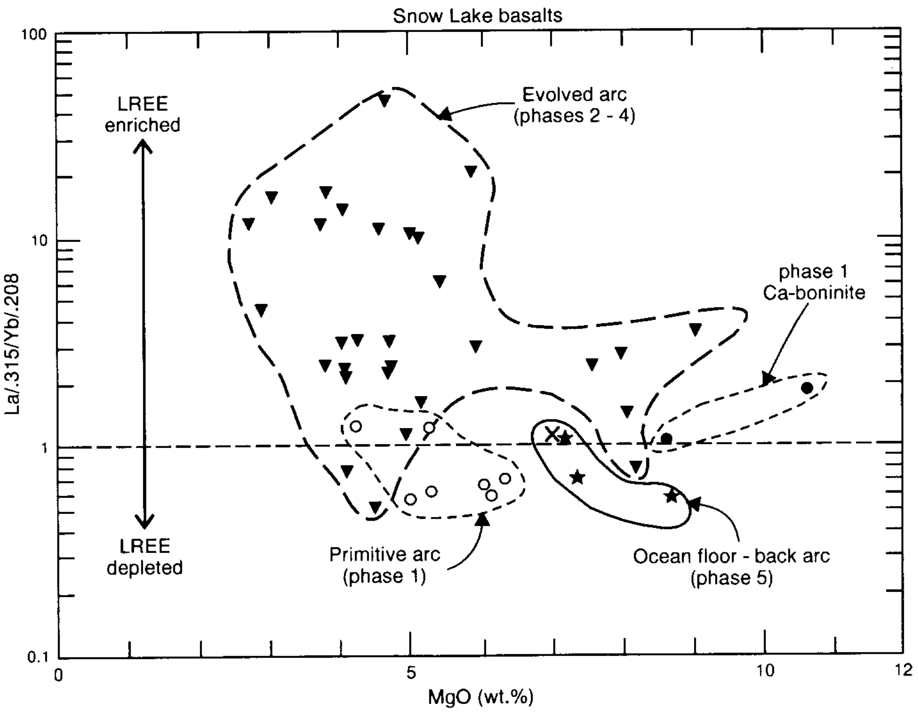

Figure 17. Snow Lake basalts on diagram of La/Yb (normalized) versus MgO (wt.%) (after Stern et al., 1995).

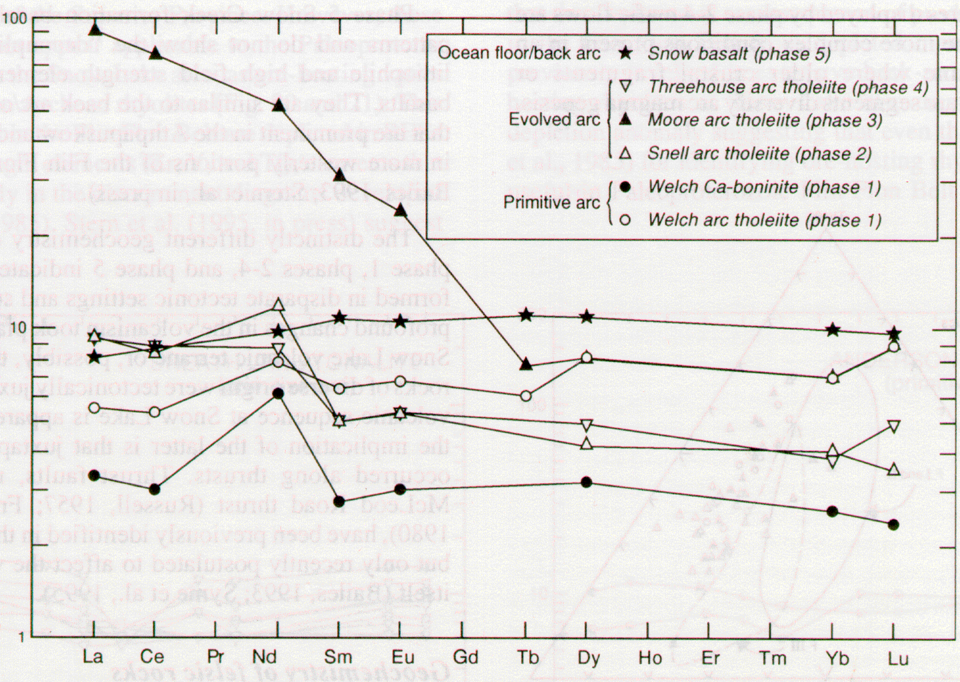

Figure 18. Chondrite normalized REE plots of Snow Lake basalts and basaltic andesites.

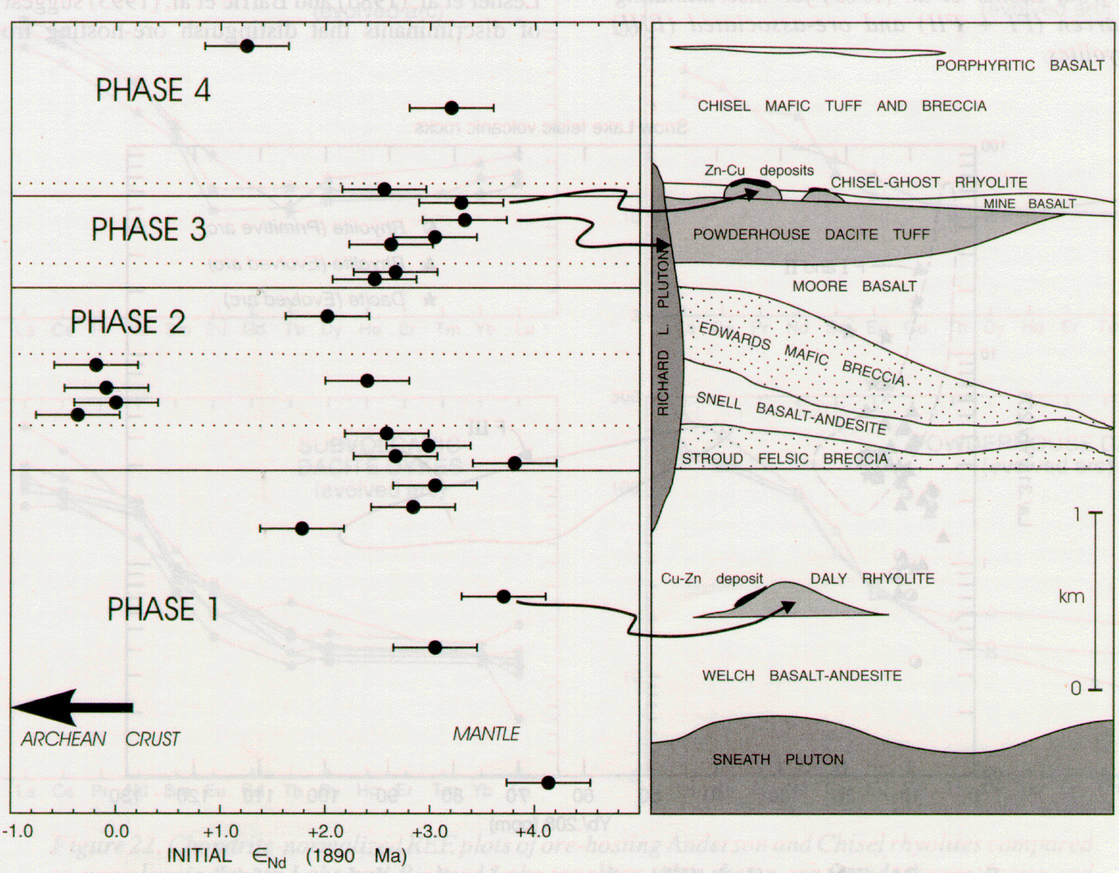

Figure 19. Isotopic and geological stratigraphy of Chisel Lake section at Snow Lake (after Stern et al., 1992).

Geochemical features displayed by phase 2-4 mafic flows are characteristic of the more complex conditions present in an evolved arc terrane where older crustal fragments or previously formed arc segments diversify arc magma genesis.

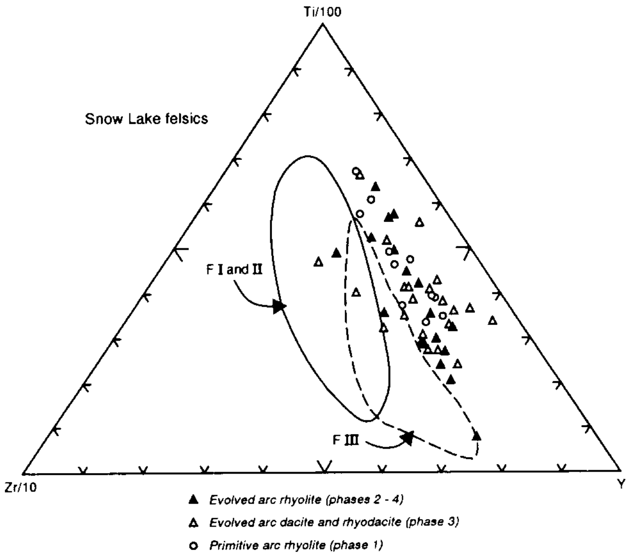

Figure 20. Snow Lake rhyolites plotted on (Zr/10)-(Ti/100)-Y projections from Lesher et al. (1985) for discriminating between barren (FI + FII) and ore-associated (FIII) Archean rhyolites.

Phase 5 Snow Creek formation basalts have flat REE patterns and do not show the "decoupling" of large ion lithophile and high field strength elements typical of arc basalts. They are similar to the back arc/ocean floor basalts that are prominent in the Athpapuskow and Elbow lakes area in more westerly portions of the Flin Flon Belt (Syme and Bailes, 1993; Stern et al., in press).

The distinctly different geochemistry of mafic flows of phase 1, phases 2-4, and phase 5 indicates that these rocks formed in disparate tectonic settings and suggests that either profound changes in the volcanism took place in the evolving Snow Lake volcanic terrane or, possibly, that these volcanic rocks of diverse origin were tectonically juxtaposed. Since the volcanic sequence at Snow Lake is apparently conformable the implication of the latter is that juxtaposition may have occurred along thrusts. Thrust faults, most notably the McLeod Road thrust (Russell, 1957; Froese and Moore, 1980), have been previously identified in the Snow Lake area but only recently postulated to affect the volcanic sequence itself (Bailes, 1993; Syme et al., 1995).

Geochemistry of felsic rocks

The close association between felsic volcanic rocks and base metal massive sulphide deposits in Precambrian terranes in Canada has prompted interest in rhyolite geochemistry as a predictor of their potential to host ore (Campbell et al., 1982). Lesher et al. (1985) and Barrie et al. (1993) suggest a number of discriminants that distinguish ore-hosting from barren

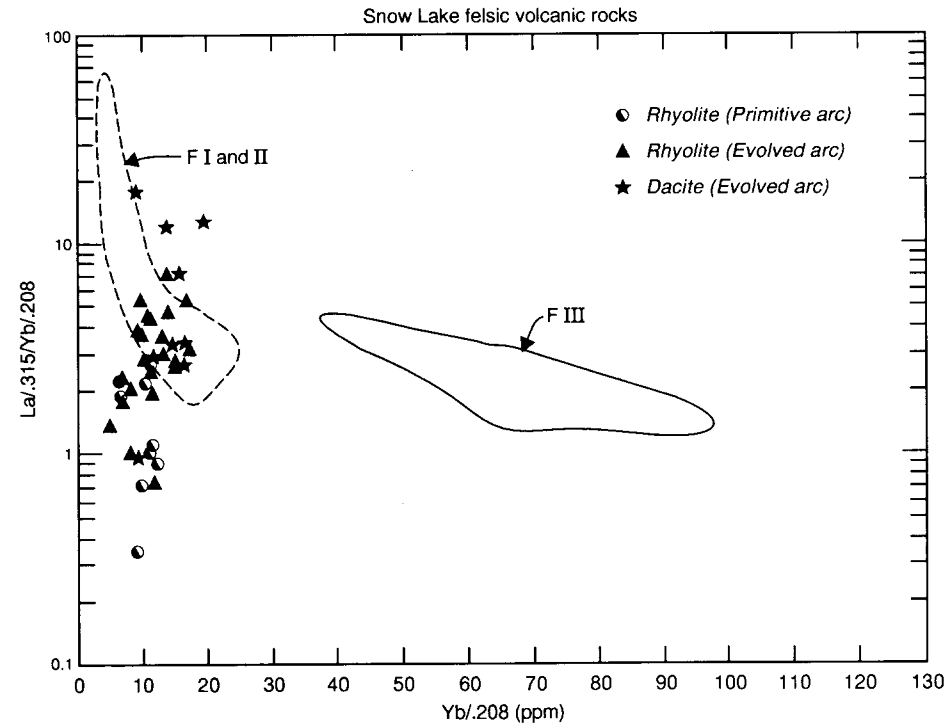

Figure 21. $[Yb]_n$ vs. $[La]_n/[Yb]_n$ plot comparing Snow Lake area felsic metavolcanic rocks to Abitibi belt barren (FI + FII) and ore-hosting (FIII) rhyolites of Lesher et al. (1985).

Archean rhyolites of the Superior Province. However, these discriminants do not appear applicable to the Paleoproterozoic rhyolites from the Snow Lake area, as ore-hosting varieties plot with barren Archean rhyolites (Fig. 20 and 21). This is because magmas in the Flin Flon Belt are depleted in REEs and high field strength elements (Zr, Y, and Ti), elements that are used extensively in the discriminant diagrams developed by Lesher et al. (1985). Stern et al. (1995, in press) suggest that this depletion is a consequence of production of magmas in the Flin Flon Belt from depleted mantle that had been previously involved in extensive back-arc magmatism. Ore-hosting rhyolites at Snow Lake also do not display an Eu depletion anomaly suggesting that even this criteria (Lesher et al., 1985) for identifying ore-hosting rhyolites may not be useful in Paleoproterozoic Flin Flon Belt rocks. Obviously

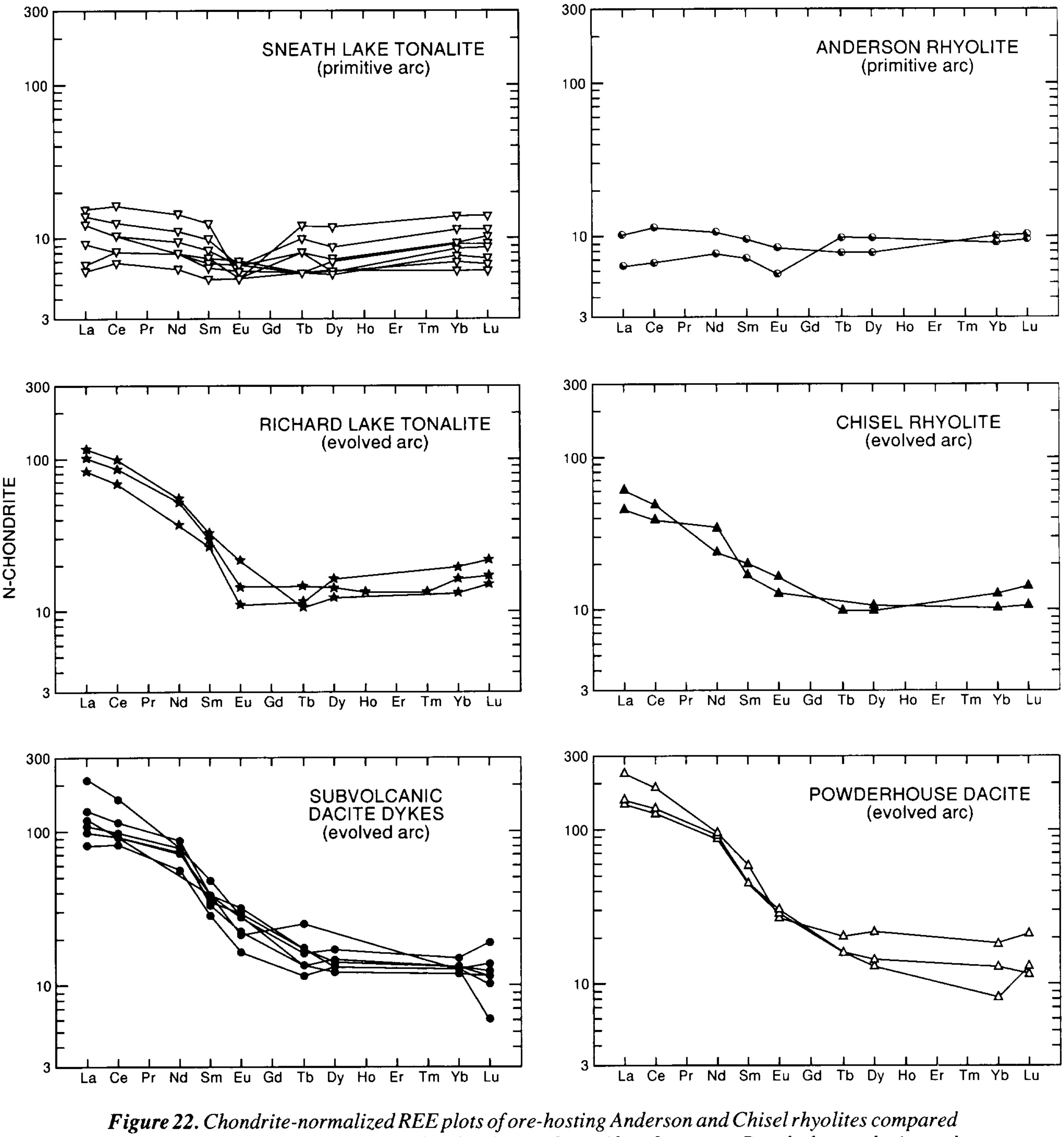

Figure 22. *Chondrite-normalized REE plots of ore-hosting Anderson and Chisel rhyolites compared to synvolcanic Sneath Lake and Richard Lake tonalites. Also shown are Powderhouse dacite and related synvolcanic dacite dykes from footwall succession to Chisel Lake area Zn-rich volcanic-hosted massive sulphide deposits.*

the discriminants proposed by Lesher et al. (1985) must be used with caution in volcanic belts of the Paleoproterozoic Trans-Hudson Orogen.

Geochemical similarities between felsic volcanic rocks at Snow Lake and the stratigraphically underlying tonalites of the Sneath Lake and Richard Lake subvolcanic intrusive complexes suggest that the extrusive felsic rocks are derived directly from near surface magma chambers. For example the phase 1 rhyolites and the Sneath Lake pluton share flat REE profiles at 10 times chondrite, and the phase 3 rhyolites have sloped REE profiles with elevated LREE contents similar to the associated Richard Lake pluton (Fig. 22). The rhyolites and associated tonalite plutons also share similar ε_{Nd} contents (Stern et al., 1992). Higher ε_{Nd} values for the rhyolites than the associated mafic flows (e.g. Welch basalt and Daly rhyolite, Fig. 19) preclude rhyolites from simply forming by fractionation of the same magma that produced the mafic flows. The direct genetic relationship between felsic volcanic rocks and underlying intrusions is also displayed by the phase 3 Powderhouse dacite which is geochemically indistinguishable from a prominent footwall dacite dyke swarm.

The low ε_{Nd} contents of the ore-hosting rhyolites and associated subvolcanic tonalite intrusive complexes makes them the most isotopically juvenile members of the Snow Lake sequence. The implication is that geochemically primitive, mantle-derived felsic magmas may be important for the generation of base metal mineralization in the Snow Lake area (Stern et al., 1992).

DISCUSSION

Role of subvolcanic intrusions in massive sulphide generation

A number of subvolcanic intrusions are clearly related to alteration events, with the Sneath Lake tonalite pluton, the Richard Lake tonalite pluton and the Edwards Lake area dacite dyke complex the most significant. The traditional view of these intrusions is that they are the "heat engine" that drove the hydrothermal system, which in turn was responsible for alteration of the overlying rocks and for deposition of the base metal massive sulphide deposits themselves (Walford and Franklin, 1982). The association of the massive sulphide deposits with rhyolite flows and synvolcanic faults can be viewed as a consequence of the intrusion-derived rhyolite flows using the same zone of weakness as the mineralizing hydrothermal fluids to reach the paleoseafloor.

The Sneath Lake intrusive complex, 22 km long and 2 km wide, and estimated to have been over 1.2×10^{12} t in size, was emplaced at a depth of 0.3 to 2 km below the paleoseafloor. The pluton must have been a major subvolcanic heat source, but has no thermal contact aureole, which strongly suggests that cooling of the pluton occurred by convection of seawater in the overlying volcanic rocks. Cathles (1983) suggests that a 1.5×10^{11} t igneous mass, smaller than the Sneath Lake intrusion, would have been sufficient to drive the hydrothermal system that produced all the known Kuroko base metal mineralization in the Hokuroko basin of Japan. Thus we attribute the considerable alteration above the Sneath Lake body to geothermal-hydrothermal activity necessitated by shallow emplacement of the intrusion.

Portions of the Sneath Lake intrusion are affected by considerable alteration, at least some of which, is due to postcrystallization collapse of the geothermal-hydrothermal system into still hot, fractured portions of the intrusive complex (Fig. 5d). The most prominently altered part of the multiphase Sneath Lake pluton is a mesotonalite body that coincidently contains an order of magnitude more Cu than other phases of the pluton. The mesotonalite is characterized by large areas affected by fracture-controlled epidote and hematite alteration and by more pervasive areas of epidotization and silicification. This alteration may have played a role in generating Cu-rich hydrothermal fluids. The discordant alteration "pipes" that progress up stratigraphy to the Stall Lake and Anderson Lake massive sulphide deposits are "rooted" along the margins of the altered mesotonalite body.

Similar to Sneath Lake tonalite, the Richard Lake tonalite body, 7.3 km by 1.6 km, and estimated to have been over 1.1×10^{11} t in size, is large enough to have driven a prominent geothermal system. This pluton, which is not as altered as the Sneath Lake intrusion, varies from porphyritic in the south to fine grained and equigranular in the north. It has no discernible contact metamorphic halo, suggesting that cooling occurred through convection of seawater above the body. A possible manifestation of this geothermal system is an over 500 m wide sheath of alteration that surrounds the intrusion on its east, north, and west sides. All of the major base metal massive sulphide deposits in the Chisel Lake area are adjacent to this envelope of altered rocks. However, the exact relationship of the Richard Lake body to this alteration zone is complicated by the fact that, in some localities, phases of it clearly cut the altered rocks. Nevertheless, most heat calculations suggest that the formation of massive sulphide deposits, such as those at Chisel Lake, require a heat source of the order of magnitude of the Richard Lake intrusion.

The exact role of a prominent dacite sill/dyke complex west of Edwards Lake is uncertain, but it is clearly involved in hydrothermal activity. Although probably not capable of generating a prominent geothermal-hydrothermal system on its own, this intrusive complex has clearly modified and focused existing geothermal-hydrothermal activity. Rocks adjacent to the dacite dykes have been extensively silicified and epidotized, a feature that Skirrow and Franklin (1994) attribute to a temperature increase above 380°C adjacent to the dykes. They suggest that dacite dyke emplacement prompted already existing silica-rich hydrothermal fluids to precipitate silica, due to a temperature increase and resultant decrease in silica solubility (Kennedy, 1950). In addition to causing local temperature increase, emplacement of the dykes may also have played an important role in producing evolved metal-rich hydrothermal fluids by restricting fluid movement in a manner similar to the "gable trapping" mechanism described by Lydon and Jamieson (1984) in the Troodos ophiolite complex. The clear involvement of the dacite dykes in geothermal-hydrothermal activity and their role as the feeder system for the Powderhouse dacite, a unit that forms the immediate stratigraphic footwall to the Chisel Lake area massive sulphide deposits, demonstrates without doubt that they were involved in the hydrothermal-mineralizing event that produced the Chisel Lake area Zn-rich massive sulphide deposits.

Controls on distribution of massive sulphide deposits

A number of empirical controls that appear to influence the location of base metal massive sulphide deposits at Snow Lake are evident from this study. They are similar to controls on distribution of volcanic-hosted massive sulphide deposits in many Precambrian and Phanerozoic volcanic belts (Lydon, 1984, 1988) and elsewhere in the Flin Flon Belt (Syme and Bailes, 1993). These controls provide a method to focus exploration on most prospective portions of the belt. In order from regional to local, discriminators are: 1) affiliation with volcanic rocks with oceanic arc geochemical signature, 2) proximity to synvolcanic dyke swarms and tonalite plutons, 3) association with areally extensive semiconformable zones of hydrothermally altered rocks, 4) occurrence within or adjacent to rhyolite flow complexes, and 5) proximity to synvolcanic faults.

The association of base metal massive sulphide deposits in the Flin Flon Belt with 1904 Ma to 1885 Ma arc tholeiite volcanic rocks has been well established in recent years (Syme, 1990; Syme and Bailes, 1993; Lucas et al., 1994; Stern et al., 1995). Volcanic sequences belonging to the arc assemblage can be separated from basalt flow-dominated ocean floor-back arc sequences as they typically contain abundant volcaniclastic and felsic units not normally present in the ocean floor-back arc successions. Geochemically, the arc tholeiite mafic flows can be separated from the ocean floor-back arc types by more abundant large ion lithophile elements, moderate to strongly depleted high field strength elements and by strongly depleted Ni and Cr. In the absence of extensive trace element data, a higher Mg/Ni ratio can be used to discriminate between arc tholeiite and ocean floor-back arc assemblages (Syme and Bailes, 1993).

The association of volcanic-hosted massive sulphide deposits with island arc volcanism is not unique to the Paleoproterozoic Flin Flon Belt. For example, in Cambrian and Ordovician rocks of the Dunnage zone of Newfoundland, Swinden (1991) observed that island arc assemblages are "by far the most prolific hosts for volcanogenic massive sulphide deposits" and "many if not most of the back arc sequences are barren". Although the arc sequences of the Flin Flon Belt are more prolific hosts for base metal massive sulphide deposits than the back arc-ocean floor successions, this is unlikely to be universally applicable to other Precambrian volcanic terranes. For example, Barrie et al. (1993) showed that, by tonnage, over 50% of the polymetallic volcanic-hosted massive sulphide deposits in the Archean Abitibi belt are hosted within thickened oceanic rift suites and 35% occur within rifted island arcs.

Snow Lake massive sulphide deposits occur in the stratigraphic hanging wall of two major subvolcanic tonalite intrusions: the primitive arc-hosted Cu-rich deposits above the Sneath Lake intrusive complex and the evolved arc-hosted Zn-rich deposits about the Richard Lake tonalite complex. These intrusions are geochemically similar to overlying ore-hosting rhyolite complexes, which suggests a close genetic relationship between the tonalites, rhyolites, and massive sulphide deposits. In the Chisel Lake area a prominent subvolcanic dacite dyke complex occurs in the footwall to the Zn-rich massive sulphide deposits; this dyke complex is intimately associated with synvolcanic hydrothermal alteration and, perhaps, with ore-forming processes, as was discussed in the previous section.

The ore-hosting volcanic strata at Snow Lake are characterized by volumetrically extensive zones of metamorphosed altered rocks. These zones are interpreted to result from large-scale convection of hydrothermal fluids and resultant fluid-rock interaction above cooling subvolcanic intrusions. Locally, the subvolcanic intrusions are also altered, either reflecting alteration of early phases by hydrothermal activity generated by subsequent phases or collapse of the circulatory hydrothermal system into the intrusive complex as the intrusion cooled. At Snow Lake, three regionally extensive alteration systems are recognized, two of them clearly related to base metal sulphide mineralization; the other is associated with a base metal-poor sulphidic sediment. We consider terranes that contain altered supracrustal rocks together with altered subvolcanic tonalite bodies to be favourable terranes to target for base metal exploration.

The spatial association of massive sulphide deposits with felsic flows is a recurring theme in all major base metal volcanic-hosted massive sulphide districts regardless of age (Franklin et al., 1981; Ohmoto and Takahashi, 1983; Lydon, 1984, 1988). At Snow Lake the association of base metal sulphide deposits with rhyolite flow complexes is clear. All of the Cu-rich deposits in the primitive arc are contained in rhyolite complexes and all the Zn-rich deposits in evolved arc rocks are contained in or along the same stratigraphic horizon as rhyolite bodies. In addition the Snow Lake area volcanic-hosted massive sulphide deposits are much more closely affiliated with subaqueously deposited rhyolite domes and flow complexes than they are with units of felsic volcaniclastic rocks.

Synvolcanic faults have long been recognized as important in the genesis of base metal massive sulphide deposits (Hodgson and Lydon, 1977; Lydon and Galley, 1986; Gibson and Watkinson, 1990; Morton et al., 1990). Focusing of hydrothermal fluids by synvolcanic faults, as is hypothesized for ancient deposits, is supported by observations in many modern sulphide-forming environments (Rona and Clague, 1989; Zierenberg et al., 1993; Goodfellow and Franklin, 1993). At Snow Lake massive sulphide deposits clearly occur above synvolcanic faults. These faults are recognized by their strong alteration by through-going hydrothermal fluids during formation of the overlying base metal deposits. At Anderson Lake the altered, regionally metamorphosed faults are represented by planar, crosscutting, up to 2 km long zones of chlorite-biotite-kyanite, muscovite-kyanite, and chlorite-staurolite-garnet schists that terminate abruptly up-section at the massive sulphide deposits. At Chisel Lake the synvolcanic fault is expressed as a >2 km long by >300 m deep "keel" of chlorite-staurolite rich rocks below the Zn-rich deposits. Recognition of synvolcanic faults is currently restricted to areas, such as Snow Lake, where detailed mapping has identified abrupt stratigraphic facies changes or narrow discordant zones of alteration. Regional-scale stable isotope studies, which can detect isotopic shifts due to fluid-rock interaction, offer another method of delineating hydrothermal upflow zones, as areas with anomalous stable isotopes form larger targets than do the faults (Cathles, 1993).

SUMMARY

Polymetallic base metal deposits in the island arc sequence at Snow Lake occur in two settings: Cu-rich volcanic-hosted massive sulphide deposits (at Anderson Lake) deposited in a primitive forearc-protoarc setting and Zn-rich volcanic-hosted massive sulphide deposits (at Chisel Lake) in an evolved arc setting. Volcanic-hosted massive sulphide deposits in both tectono-magmatic sequences are associated with large subvolcanic tonalite intrusive complexes of similar geochemical character as the host supracrustal rocks.

Volcanic-hosted massive sulphide deposits in both the primitive forearc and evolved arc settings occur in rhyolite flow complexes. The ore-hosting rhyolite flows are geochemically similar to underlying subvolcanic tonalite plutons. For example both rhyolite and tonalite share similar ε_{Nd} contents that are higher than those of associated mafic flows (Stern et al., 1992). This is significant as it precludes formation of the rhyolite and tonalite magmas by fractionation of the same magma that produced the mafic flows. The low ε_{Nd} contents of the ore-hosting rhyolites and associated tonalite plutons identifies them as the most isotopically primitive members of the Snow Lake sequence.

The spatial association of base metal deposits with rhyolite bodies is not unique to the Snow Lake area. In fact the widespread association of volcanic-hosted massive sulphide deposits with rhyolites has prompted use of rhyolite geochemistry as a screening technique to predict their potential to host ore. Although this technique has proven valuable in the Archean Superior Province of Canada (Lesher et al., 1985), the derived discriminants do not appear to be applicable to Paleoproterozoic rhyolites at Snow Lake. Stern et al. (1994) suggest that magmas in the Flin Flon Belt, including those at Snow Lake, were produced by melting of depleted mantle that had previously been involved in back-arc magmatism. This process has yielded volcanic products depleted in REEs and high field strength elements, elements that are used extensively in discriminant diagrams developed by Lesher et al. (1985). The implication is that discriminants developed in one area are not necessarily universal in applicability.

Extensive zones of altered supracrustal rocks occur stratigraphically above the subvolcanic intrusive complexes and below the volcanic-hosted massive sulphide deposits at Snow Lake. The altered rocks are interpreted to be the products of geothermal-hydrothermal activity generated by near surface cooling of the subvolcanic tonalite intrusions. The subvolcanic tonalite bodies are large enough, according to calculations by Cathles (1983) for the Kuroko area, to activate subseafloor seawater geothermal systems capable of generating the Snow Lake area volcanic-hosted massive sulphide deposits. Because rocks in the Snow Lake area are well exposed from the subvolcanic plutons up to the volcanic-hosted massive sulphide deposits, they represent an excellent opportunity to study the nature of the subvolcanic plutons and overlying fossil hydrothermal systems. Further work in the Snow Lake area will focus on the interrelationship between the subvolcanic plutons, hydrothermally altered rocks, and the overlying volcanic-hosted massive sulphide deposits.

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