Current Research (1995) Newfoundland Department of Natural Resources, Geological Survey, Report 95-1, pages 177-204

NICKEL–COPPER-SULPHIDE MINERALIZATION IN LABRADOR: THE VOISEY BAY DISCOVERY AND ITS EXPLORATION IMPLICATIONS

B. Ryan, R.J. Wardle, C.F. Gower and G.A.G. Nunn
Labrador Mapping Section

ABSTRACT

The 1350 to 1290 Ma Nain Plutonic Suite (NPS) has seldom been the focus of base-metal exploration. This has now changed with the discovery of a major Ni–Cu–Co sulphide body in a troctolitic dyke of the NPS at Voisey Bay. The mineralized dyke is situated near the 1800 Ma collisional boundary between the Archean Nain Province and the Paleoproterozoic Churchill Province, and seems to have been a feeder conduit for the nearby Reid Brook intrusion. The main factors that appear to have contributed to the localization of the sulphides in this dyke are i) the probable primitive (picritic?) and sulphur-undersaturated character of the original magma, ii) the rapid transit of the magma from its mantle source, aided by proximity to faults along the Nain–Churchill collisional boundary and iii) the subsequent saturation of the magma in sulphur as a result of passage through the metasedimentary Tasiuyak gneiss. The Ni–Cu–Co sulphides are considered to be the product of separation of an immiscible liquid from the silicate magma following sulphur saturation. It is proposed that this sulphide liquid collected in a chamber above the present erosion level and sank into one of the magma conduits.

Other troctolitic intrusions of the NPS are also known to contain magmatic sulphide accumulations, albeit to a much lesser concentration than in the Voisey Bay dyke. Nevertheless, these intrusions are potential targets for the explorationist. The two largest of these intrusions that host sulphide-enriched layers are the Kiglapait and Newark Island; the Jonathon intrusion has sulphide mineralization in a dyke that intrudes its marginal zone. Additional areas worthy of investigation for mineralized troctolitic rocks are the poorly known interior of the NPS. The noritic members of the NPS may also contain zones of massive sulphide, one such zone being already known in the area. Rocks in other parts of Labrador that have potential for Ni–Cu sulphides and associated mineralization are discussed in terms of their tectonic setting, relating that setting to well-known examples of mineralized rock in similar environments elsewhere. These include Archean komatiitic flows of the Florence Lake Group, the anorthositic Harp Lake Complex, the flood basalts and related sills of the Seal Lake Group, and layered mafic intrusions in the Grenville Province.

> '.......*the excess sulphide must be produced at a critical instant in the emplacement and crystallization of a magma so that the sulphides can settle and concentrate undiluted by the silicates that will also be accumulating as the magma crystallizes.*
>
> –Naldrett and Macdonald, 1980.

INTRODUCTION

The announcement of a significant discovery of Ni–Cu–Co sulphides in mafic rocks along the western edge of the Nain Plutonic Suite (NPS) at Voisey Bay southwest of Nain, by Archean Resources Limited and Diamond Fields Resources Incorporated (herein known as Archean Resources–Diamond Fields), in November, 1994, signified the first major discovery of economically interesting base-metal mineralization in eastern Labrador since the 1950s. It brought the igneous rocks of the Nain area into focus as new exploration targets for base metals. It created a staking rush by other exploration interests and it resulted in numerous requests to the Geological Survey (GS) for geological and geochemical information on the rocks in the general area of the discovery (and for speculations and guidance as to where similar rocks and metals might be found elsewhere in Labrador). At the time of writing, over 14 000 claims have been staked in the Nain area and other potentially mineralized parts of Labrador.

This paper uses the Voisey Bay discovery as a foundation to present an overview of the Ni–Cu sulphide potential of other parts of the NPS and mafic rocks elsewhere in Labrador. It is an expansion of the comments of Swinden *et al.* (1991) on the mineral potential of selected geological environments in Labrador. Initially, an overview is given of the geological setting and genesis of Ni–Cu–Platinum-group-elements (PGE) deposits. This is followed by a summary review of the regional geology of the Nain area, the NPS and the Voisey Bay discovery, as well as some speculations on the origin of the Archean Resources–Diamond Fields deposit and the applicability of the established models to the mineralization. This paper concludes by examining appropriate rocks of

Labrador in light of the foregoing data, and suggests target areas that may have potential for new discoveries of Ni, Cu, Co, and possible platinum-group elements.

The reader should be aware that many geographic localities cited in the text of this paper are not shown on the accompanying figures. This is because in many cases the scale of the figures is not conducive to pin-pointing such locations. The reader is invited to contact one of the authors or a referenced source for details of specific sites.

GEOLOGICAL SETTING OF NICKEL SULPHIDE DEPOSITS

The world's significant nickel–copper (–cobalt–PGE) sulphide deposits are confined essentially to four geological settings (Naldrett, 1989):

1) deposits found within komatiitic and tholeiitic (ferropicritic) lava flows and associated intrusions (Kambalda in Australia, Pechenga in Russia);
2) deposits associated with mafic and ultramafic rocks generated at rifted continental margins (Cape Smith Belt and Thompson Belt of Canada) and within ophiolitic rocks of oceanic basins (Zambales ophiolite of the Phillipines);
3) deposits of cratonic areas related to i) flood basalts (Noril'sk–Talnakh area of the Siberian Trap, Duluth Complex of the Keweenawan lavas of the United States), and ii) stratiform layered intrusions (Sudbury Intrusive Complex of Canada, Bushveld Intrusion of South Africa, and Great Dyke of Zimbabwe), and
4) sulphide mineralization in synorogenic mafic intrusions (Moxie Intrusion of the United States), seemingly not a significant reservoir.

The first and fourth settings are not dealt with at length in this paper because they are not applicable to the Voisey Bay mineralization, but they are addressed briefly in later discussion of possible settings and controls on mineralization elsewhere in Labrador.

The common genetic link among all the rocks above is that they are direct or indirect products of mantle plumes, effusions from which are MgO-rich (picritic) magmas. The sulphide deposits are postulated to be a result of primary magmatic processes, the effects of secondary hydrothermal processes being negligible. Why are these magmas so favourable for such deposits in settings as diverse as ophiolites and flood-basalt provinces? The following summary section outlines the controls on the formation of magmatic sulphides and provides the foundation for subsequent discussion of the Voisey Bay discovery and other areas of potential base-metal mineralization in Labrador. For more information the reader is referred to Naldrett and Cabri (1976), Rajamani and Naldrett (1978), Naldrett and Macdonald (1980), the various papers in Whitney and Naldrett (1989), Lightfoot and Keays (1994) and the numerous collateral studies cited by these authors.

PHYSIOCHEMICAL CONTROLS ON SULPHIDE MINERALIZATION

One of the fundamental aspects of picritic (high MgO) magmas is that they represent significant partial melts of a mantle source region. Under the conditions of partial melting envisioned for production of these magmas, it is probable that the magmas are sulphur undersaturated at the time they are generated. This allows Ni, Cu and PGE's to reside in the magmas for significant periods because the partition coefficients between these elements and sulphur(s) is so great that any appreciable S in the magma will 'scavenge' the metals into a separate sulphide liquid, and negate any prospect of them ascending from their mantle source region. It is thus apparent that once such sulphur-depleted magmas encounter a sulphur source enroute to higher levels they will be ripe for sulphide deposition.

The composition of the magma seems to control the metal content of associated Ni–Cu mineral deposits. For example, ultramafic magmas, such as komatiites, usually produce Ni-dominant sulphide deposits in which the Ni/Cu value is greater than 10. However, mafic magmas, from such settings as layered intrusions and flood basalts, usually produce Ni–Cu–PGE-dominant deposits having low ratios of nickel to copper ($Ni/Cu<2$). This can be viewed in terms of magma fractionation, the crystallization of olivine effectively removing appreciable Ni from the magma at an early stage, and Cu becoming concentrated in the residual liquid because it is not easily accommodated in the early mafic silicates. Cobalt shows some preference for early crystallized silicates, but also tends to increase in the residual basaltic melts until the final stages of crystallization. With respect to their partitioning into a sulphide liquid, it has been determined that Fe, Ni, Cu, and Co are strongly partitioned into such a liquid relative to their partitioning into a silicate liquid, the order of attraction being $Ni>Cu>Co>Fe$. From the above relations, it can be seen, for instance, that if rocks derived from late-stage differentiates of MgO-rich magmas have low levels of both Ni and Cu, then it is possible that these elements have been removed by crystallization of sulphides at an earlier stage of magma evolution. In general, voluminous Ni–Cu-sulphide ores are not enriched in PGE; PGE values are, instead, elevated in rocks that contain disseminated sulphides (and oxides).

Although sulphur contamination plays a major role in the formation of sulphide ore deposits in basic rocks, the contamination of basaltic magmas by SiO_2 also seems to trigger the formation of such deposits by lowering the solubility of sulphur in magma (e.g., the Sudbury ores). However, the discussion here is restricted to the sulphur-contamination models.

THE PROCESS OF SULPHIDE CONCENTRATION

Magmatic sulphide ores are postulated to be products of coalesced droplets of an immiscible sulphide-oxide liquid generated within, and segregated from, a silicate magma. Metallic elements such as Fe, Ni, Cu, Co and the PGE association will partition, as noted above, from the silicate liquid into the sulphide-oxide liquid phase and thus become concentrated within that phase. Because the density of the sulphide-oxide liquid relative to the silicate liquid is about 4 g/cc to 3 g/cc respectively, the former liquid will have a tendency to gravitationally separate from its coeval silicate partner within the magma chamber. Textural evidence for the coexistence of two crystallizing liquids is seen in magmatic sulphide deposits, e.g., blebs of sulphide having a meshed contact against enclosing silicates in the Sudbury ores. The case for coexisting sulphide and silicate liquids can be argued even more stringently on the basis of the so-called net-texture in komatiitic flow deposits, in which sulphides enclose and form interstitial arrays among the silicates. Naldrett (1973) has used a 'beaker of billiard balls, water and mercury' as an analogy for the process of sulphide settling from a crystallizing silicate liquid. Billiard balls (olivine) sink through water to accumulate on the mercury (sulphide liquid); continued accumulation of billiard balls at the surface of the mercury increases their tendency to become depressed into their substrate, giving rise to the net-texture seen in some Ni–Cu deposits.

SUMMARY OF THE GEOLOGICAL EVOLUTION OF THE NAIN AREA AND ITS MAJOR ROCK TYPES

It has been established that a line running between Cape Chidley in the north and Snegamook Lake in the south marks the junction, or suture, across which two continents collided over 1800 million years ago (see Wardle *et al.*, 1990a; Figure 1). This collisional suture, and the deformation and metamorphism that temporally coincides with it, constitute the Torngat Orogen. Archean gneisses of Nain Province lie to the east of the suture; reworked Archean gneisses, along with Paleoproterozoic intrusive and supracrustal rocks, of the eastern Churchill (or Rae) Province lie to the west of it. Of importance to a discussion of the Nain area is the fact that the easternmost part of Churchill Province is a 30-km-wide zone of paragneiss, named Tasiuyak gneiss, and the western margin of Nain Province has been structurally overprinted by a Paleoproterozoic foliation generated by the collision. The collisional boundary zone was invaded between 1350 and 1290 million years ago by massive volumes of magma, a consequence of the formation of a large magma reservoir at the base of the crust in the area at this time (Emslie *et al.*, 1994). The magmas that rose into the crust of Labrador crystallized as a series of igneous rocks that cover some 20 000 km^2 between Okakh Bay and Hunt Lake: these rocks are now collectively referred to as the Nain Plutonic Suite (NPS) (Ryan, 1990; Figure 2). The Suite, to be addressed in more detail below, contains a broad spectrum of rocks, but the main subdivisions are anorthosite, troctolite, diorite and granite, the second of which is disposed as several layered bodies of which the best-known underlies the Kiglapait Mountains north of Nain (Morse, 1969). The first rock type of the NPS mentioned above is exploited as a dimension-stone resource on Paul Island near Nain (Meyer and Montague, 1994), the second type is the host to the Ni–Cu–Co mineralization found by Archean Resources–Diamond Fields near Voisey Bay.

OVERVIEW OF THE NAIN PLUTONIC SUITE IN THE NAIN AREA

An overview of the Nain Plutonic Suite, the lithostratigraphic host to the Voisey Bay mineralization, is presented here as a guide to those unfamiliar with the geology of the Nain area, giving particular attention to the basic rocks. Many general papers on the geology of these rocks are available to the reader, the early works of E.P. Wheeler (cf. Wheeler, 1942, 1960) being benchmarks that are recommended as classic field descriptions. The reader is referred to the compilation map of Ryan (1990) and the fieldtrip guidebook of Berg *et al.* (1994) as reference works for some of the current nomenclature used in the discussion that follows.

It was noted above that the NPS is a multicompositional batholithic assemblage of igneous rocks, constructed by coalescence of numerous plutons, the predominant components of which are anorthositic, troctolitic, dioritic, and granitic (Figure 2). The NPS is considered to have developed between 1350 Ma and 1290 Ma (Ryan and Emslie, 1994), and entails episodic emplacement of the whole spectrum of compositions over that time. There are indications from the radiometric dates that the magmatism began (and ceased ?) in the west before it was initiated in the east (cf. Berg *et al.*, 1994). The NPS is interpreted as an anorogenic igneous terrane, believed to be emplaced in an intracontinental extensional zone above a mantle 'hot-spot' (Berg, 1979; Emslie *et al.*, 1994), much younger than the preceding Torngat Orogen and unaffected by younger tectonism.

ANORTHOSITIC PLUTONS

The anorthositic plutons of the NPS are overwhelmingly dominated by plagioclase cumulate rocks, and include the most leucocratic and coarsest components of the terrane. In these plutons, orthopyroxene is the chief mafic mineral. Wheeler (1942, 1960) subdivided the anorthositic rocks on the basis of their weathering colour into pale, buff, and dark 'facies'; this concept is no longer widely used, but reference to it might help in planning exploration approaches, as will be explained in a subsequent section of this paper. In addition to anorthosite (*sensu stricto*), this subdivision contains significant volumes of leuconorite and norite; gabbro, troctolite and their leucocratic variants occur in those anorthositic plutons that contain augite and olivine, respectively. The anorthositic plutons reflect an array of emplacement styles, varying from solid-state diapirs having foliated margins as a result of ascent from deeper crustal levels, to *in situ* crystallized plutons marked by pristine subophitic textures and layered to massive margins. Some of the plutons representative of the anorthositic and leuconoritic rocks include the Bird Lake massif (BL, Figure 2; Morse, 1983), the Mount Lister intrusion (L, Figure 2; Morse and Wheeler, 1974; Ryan, 1993), the Pearly Gates intrusion (PG,

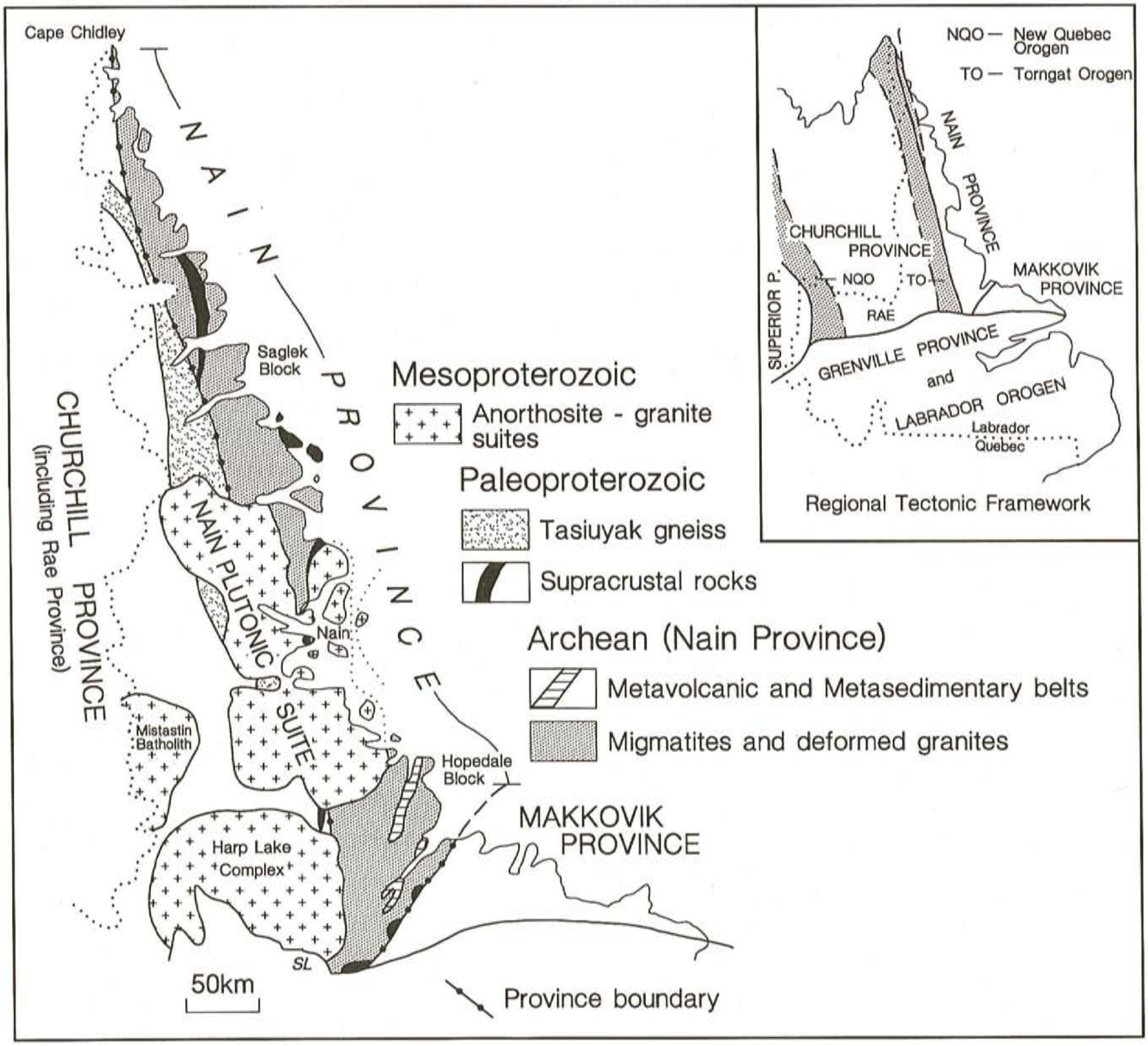

Figure 1. *General geological framework of northern Labrador. Inset shows the various structural provinces and orogens. SL = Snegamook Lake.*

Figure 2; Ryan, 1993), and the Tunungayaluk Island intrusion (TI, Figure 2; Wiebe, 1976). The Port Manvers Run (PM) and Kikkertavak Island (K) intrusions are troctolitic representatives of the anorthositic subdivision (Xue and Morse, 1993). The anorthositic plutons are notoriously difficult to date precisely because they are generally devoid of suitable minerals. Barton (1974) pioneered the dating of the Nain anorthosites by examining the Rb–Sr systematics of clinopyroxene, plagioclase and granophyre from a pluton on eastern Paul Island. Yu and Morse (1993) have approached an emplacement chronology through the use of the $^{40}Ar/^{39}Ar$ isotopic system on plagioclase, the results of which probably reflect the time at which the plutons cooled below the temperature of argon diffusion rather than their emplacement ages. Preliminary U–Pb data reported by Hamilton *et al.* (1994) from zircon collected within pegmatoidal patches in some of the anorthositic plutons are considered to be more representative of crystallization ages of these rocks. Some of the data reported in the aforementioned references can be summarized as follows. Barton (1974) concluded that a Rb–Sr isochron age of 1388 ± 25 Ma obtained from the Paul Island pluton 'closely approximates' the crystallization age of the rock. Yu and Morse (1993, page 1176) questioned the significance of this 'old' date, and report a 1171 Ma argon closure age from plagioclase at Barton's sample site on Paul Island; Hamilton (*in* Berg *et al.*, 1994) gives an emplacement age of 1320 Ma for the same unit. Yu and Morse (*op. cit.*) suggest that the Bird Lake massif crystallized ca. 1328 Ma, based on the argon systematics of hornblende in adjacent country-rock. They also conclude that the Mount Lister

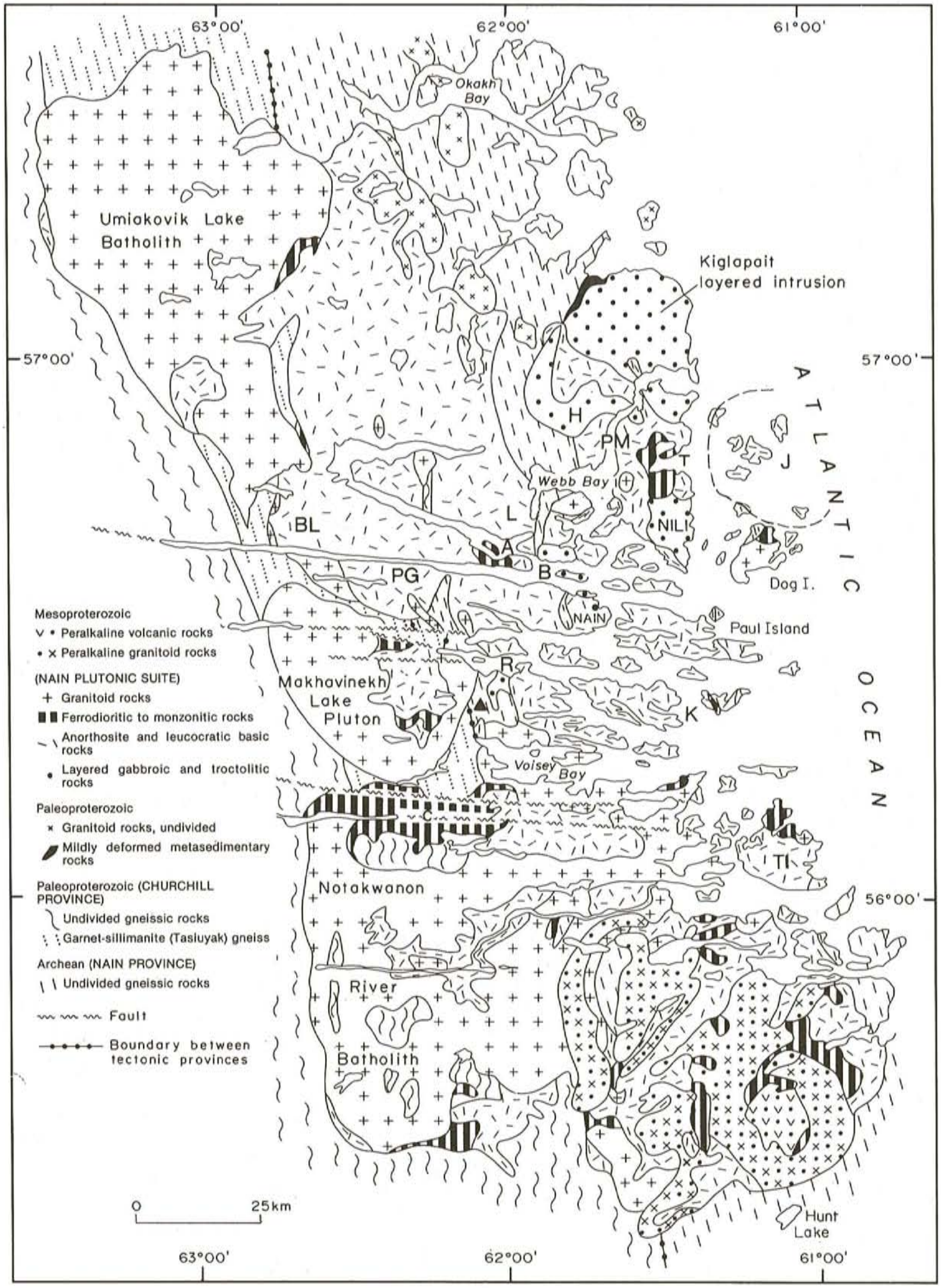

Figure 2. *Map of the Nain Plutonic Suite. Triangle marks the site of the Voisey Bay sulphide discovery. Letters refer to specific units named in the text: H = Hettasch intrusion, PM = Port Manvers Run anorthosite, T = Tigalak intrusion, NILI = Newark Island layered intrusion, L = Mount Lister intrusion, A = Akpaume intrusion, BL = Bird Lake massif, B = Barth Island intrusion, PG = Pearly Gates intrusion, R = Reid Brook intrusion, K = Kikkertavak Island intrusion, C = Cabot Lake Sheet, TI = Tunungayaluk Island intrusion.*

intrusion crystallized ca. 1284 Ma, whereas Hamilton (*in* Berg *et al.*, 1994) suggests intrusion at 1331 Ma [one of us, B.R., believes it is perhaps in excess of 1340 Ma based on data given by Connelly and Ryan (1994)]. Yu and Morse conclude that the Tunungayaluk Island anorthosite crystallized ca. 1276 Ma, and the Kikkertavak Island anorthosite ca. 1233 Ma; Hamilton *et al.* (1994) report that the latter pluton gives a zircon U–Pb age of 1311 ± 2 Ma. Ashwal *et al.* (1992) have calculated a Nd–Sm mineral and whole-rock imprecise isochron age of 1266 ± 152 Ma from a leuconorite on western Paul Island.

TROCTOLITIC PLUTONS

The troctolitic subdivision of the NPS encompasses those plutons in which olivine is a significant mineral. Most of these plutons are layered, and contain rocks that exhibit characteristics indicative of cumulate crystallization and of chilling of liquids. The best known of the layered troctolitic plutons is the Kiglapait intrusion (Morse, 1969) emplaced at 1306 ± 2 Ma (U–Pb zircon age by T. Krogh, quoted by Yu and Morse, 1992) at the northeast corner of the NPS. The Kiglapait intrusion is a classic example of a basin-shaped cumulate series of layered igneous rocks derived from crystallization of a high-alumina olivine tholeiitic magma under closed-system conditions. The mafic rocks are dominated by troctolite and olivine gabbro; ferrosyenite and monzonite are present among the last-crystallized rocks of the intrusion. The crescent-shaped, trough-like, Hettasch intrusion (H, Figure 2; Berg, 1973, 1980), which occurs to the southwest of the Kiglapait intrusion, is less distinctly layered. The main rock types of the Hettasch intrusion are olivine gabbro, olivine leucogabbronorite, troctolite, leucotroctolite, and anorthosite. The whole intrusion is characterized by well-laminated plagioclase, and it locally contains troctolitic layers having unusual radiating plagioclase macrospherulites that have been called 'snowflakes' by Berg (1980). Another unusual feature of the Hettasch intrusion is comb layering, in which acicular plagioclase crystals in one layer have grown perpendicular to the surface of the underlying layer. The Newark Island layered intrusion (NILI, Figure 2; Wiebe, 1988), located along the eastern coastal section of the NPS, comprises a steeply- to moderately-dipping series of cumulate rocks floored by Archean gneiss and truncated at the top by several younger anorthositic plutons. It was emplaced at 1305 ± 5 Ma (Simmons *et al.*, 1986), coeval with the Kiglapait intrusion. It differs from the Kiglapait and Hettasch intrusions in as much as it is a composite body, containing products of both basic and silicic magmas, and hybrid mixtures of the two (Wiebe, 1987, 1988; Wiebe and Snyder, 1993). The lowermost parts of the Newark Island intrusion consist of troctolite, olivine gabbro, and ilmenite-rich cumulates derived solely from tholeiitic injections into the magma chamber. The uppermost preserved part of the Newark Island layered intrusion is a hybrid series of rocks that reflects periodic replenishments of the magma chamber with both basic and silicic liquids. The rocks in this part of the intrusion comprise a broad range of mafic, granitic and hybrid cumulates. The Newark Island layered intrusion is remarkable for its large, widening-upward composite troughs or dykes comprising massive olivine gabbro and pillows of mafic rock suspended in a granitic host (Wiebe, 1988). These troughs are interpreted by Wiebe (1987) as feeder dykes for influxes of silicic magma into the chamber already containing a basic magma; the massive and pillowed gabbro represent the more dense, resident basic component that collapsed into the silicic conduit.

Another composite, layered, troctolitic intrusion along the eastern side of the NPS is the Barth Island intrusion immediately north of Nain (B, Figure 2). It is a basin-shaped body within anorthosite, not systematically mapped in detail since the initial surveys of de Waard in the early 1970s (cf. de Waard and Mulhern, 1973; de Waard, 1976). De Waard (*op. cit.*) envisioned the cross-section structure of the intrusion as similar to a fluted vase top. Within the body, he pictured troctolites as the lowest unit, grading upward and outward into 'jotunite' (ferrodiorite) that contains lenses of 'adamellite' (pyroxene quartz monzonite). His descriptions of the various rock types within the Barth Island body suggest that this intrusion is probably similar to the Newark Island layered intrusion in representing the products of an open-system magma chamber that was subjected to influxes of both basic and silicic liquids.

The Jonathon Island intrusion (J, Figure 2; Berg and Briegel, 1983) is a circular troctolitic body at the eastern margin of the NPS. It comprises a discontinuous outermost zone of layered and migmatite-like basic rocks dominated by olivine gabbro and olivine gabbronorite (Ryan, 1991, 1992; Royse and Ryan, 1995), but it is internally composed of medium- to coarse-grained leuconorite and leucotroctolite (Berg and Briegel, 1983). It is presently questionable whether this intrusion should be grouped with the troctolitic plutons, or whether it is better to consider it a troctolitic member of the anorthositic plutons (R.A. Wiebe, personal communication, 1992). Berg (*in* Berg *et al.*, 1994) stated that the internal part of the pluton is largely unlayered, although plagioclase lamination is widespread. Berg (*op. cit.*) also notes that comb-like arrays of plagioclase are locally present in a border zone of the massive rocks. The central part of the Jonathon Island intrusion is occupied by a younger diorite body. Both the troctolite and diorite have yielded crystallization ages ca. 1312 Ma (Hamilton *et al.*, 1994).

An elongate, synformal, troctolitic-layered intrusion occupies part of the western half of Nukasusutok Island. This body was named the Wyatt Harbour intrusion by Davies (1974) but designated as the Nukasusutok Island intrusion on the compilation map of Ryan (1990). The main rock type in the intrusion is a medium-grained troctolite, but olivine gabbro and olivine norite are also present. Some parts of the intrusion are pegmatoidal. Layering is generally shallowly dipping, and locally exhibits characteristics (such as channel scours, crossbedding, graded layering) indicative of deposition from magmatic currents. Davies (*op. cit.*) has postulated that a dyke at the northern terminus of the unit is the feeder for the intrusion.

FERRODIORITIC PLUTONS

These volumetrically small plutons, and numerous smaller dykes, comprise generally medium- to fine-grained rocks having a high colour-index, interpreted to be the mafic residual components of anorthosite crystallization (Wiebe, 1990a; Emslie *et al.*, 1994). They typically contain two pyroxenes, and fayalitic olivine is also present in some. Textures allow interpretation of the rocks as both cumulate and near-liquid compositions. Until recently, many of these plutons have been referred to as jotunite or monzonorite or monzogabbro because of the preponderance of pyroxenes as the dominant mafic silicates, but this nomenclature has been replaced by 'ferrodiorite' because plagioclase falls in the range of An_{30} to An_{45}, and the mafic minerals are Fe-rich. Some of the ferrodiorite plutons are heterogeneous in overall composition, and may contain rocks ranging from olivine ferrogabbro to quartz monzodiorite, a feature that is particularly pronounced when the dioritic magma has interacted and mingled with contemporaneous granitic magma. The ferrodiorites display a variety of plutonic niches, being present as well-layered cumulate rocks, as massive plutons, and as accumulations of chilled pillows in granitic rocks (cf. Wiebe, 1980).

The oldest of the dioritic plutons identified in the area is the Ukpaume (Akpaume) intrusion (A, Figure 2). This is a compositionally and texturally diverse pluton ranging from ferrodiorite to ferrosyenite (Deuring, 1977) that was emplaced at 1333 ± 2 Ma (Hamilton *et al.*, 1994). The dioritic Tigalak layered intrusion (T, Figure 2) on South Aulatsivik Island is a trough-shaped body that intrudes the Port Manvers Run anorthosite and the Newark Island layered intrusion, and ranges between norite and granodiorite in composition (Wiebe and Wild, 1983; Wiebe, *in* Berg *et al.*, 1994). Hamilton *et al.* (1994) reported an emplacement age of 1306 ± 3 Ma for the Tigalak layered intrusion, suggesting near-coincident magmatism with the abutting Newark Island layered troctolite. The main components of the Tigalak layered intrusion are dioritic cumulates, fine-grained diorite (including chilled pillows of dioritic magma), granodiorite, and hybrid mixtures of diorite and granodiorite. The Cabot Lake sheet (C, Figure 2) is a gently dipping, locally diffusely layered, olivine-bearing ferrodioritic intrusion sitting atop anorthosite and gneisses southwest of Voisey Bay. At its southern extent it exhibits evidence of having mingled with contemporaneous granitic magma of the Notakwanon River batholith. The contemporaneity of the two magmas in this area is supported by ages of 1298 ± 2 Ma for the diorite (Hamilton *et al.*, 1994) and 1292 ± 2 Ma for the adjacent granite (Ryan *et al.*, 1991).

GRANITIC PLUTONS

The silicic plutons and batholiths of the NPS are nearly as areally abundant as the anorthositic component. They have mineralogical and chemical characteristics that are comparable to those exhibited by the rapakivi batholiths of Finland (Emslie and Stirling, 1993), and are derived from high-temperature water-poor magmas. Their compositions generally encompass medium- to coarse-grained rocks ranging from early fayalite- and pyroxene-bearing quartz monzonite to later hornblende–biotite granite. They normally show intrusive relations into anorthosite and other mafic rocks, but Emslie *et al.* (1994) propose that ascent and emplacement of the granites into upper-crustal magma chambers actually predated the arrival of the anorthositic rocks at the same position. Some examples of the granitic intrusions (Figure 2) include the Makhavinekh Lake pluton (Ryan, 1991) crystallized at 1322 ± 1 Ma (Ryan *et al.*, 1991) and the Umiakovik Lake batholith (Emslie and Russell, 1988) crystallized at 1319 ± 2 Ma (Emslie and Loveridge, 1992), both along the western margin of the NPS. The Dog Island granites crystallized at ca. 1295 Ma (Krogh and Davis, 1973) and the Notakwanon River (–Voisey Bay) batholith crystallized at 1292 ± 4 Ma (Ryan *et al.*, 1991).

GEOLOGY OF THE VOISEY BAY AREA RELEVANT TO THE MINERAL DISCOVERY

The Geological Survey of the provincial Department of Natural Resources conducted a mapping program in a 60-km-wide corridor from Voisey Bay to the Quebec border between 1985 and 1987. The main objective was to examine the area for peralkaline granites that could prove to be hosts to rare-metal mineralization, such as that discovered at Strange Lake (cf. Miller, 1986). No such granites were found, but the mapping did significantly modify the existing geological database of the region, especially with respect to the distribution of the NPS and its constituent rock types (Ryan and Lee, 1986). Among the latter, a previously unrecognized layered and massive troctolitic mafic intrusion was partially delineated north of Voisey Bay (R, Figure 2; Ryan and Lee, 1989), and was subsequently named the Reid Brook intrusion (Ryan, 1990). In addition, a prominent gossan zone, hosted by a troctolitic dyke of the Reid Brook intrusion, was highlighted. Although the gossan was sampled and assayed at the time, no anomalous metal concentrations were detected; in retrospect, this result reflected the leaching of metals from the deeply weathered surficial cap. This gossan zone has since proven to be the surface expression of a major sulphide body within the dyke (see below). The Reid Brook intrusion seems to be of importance in the localization of the mineralization, so some of its salient features are presented below and illustrated in Figure 3.

The Reid Brook intrusion is disposed as a fault-dissected elongate (12 km long by 0.5 to 2.5 km wide) north–south-trending body atop and within the mylonitically refoliated Archean gneisses of the Nain Province east of Reid Brook. Geochronological investigations of the gneisses using the U–Pb method have yielded a Late Archean age of 2843 ± 11 Ma, but there is an indication in the isotopic data of a Paleoproterozoic tectonic overprint related to the Churchill–Nain collision (Ryan *et al.*, 1991). This tectonism is believed to be responsible for the mylonitic fabric and laminar layering that locally characterizes the gneisses, and also for the deformation and metamorphism of an amphibolite dyke swarm that occurs within the gneisses. The age of the Reid Brook intrusion is unknown, but olivine-bearing noritic rafts (resembling some of the massive rocks associated with the layered rocks to the east) are enclosed by the 1322 ± 1 Ma Makhavinekh Lake granite to the west. This implies that the Reid Brook intrusion was already in place at this crustal level prior to 1322 Ma, constituting part of the wall-rock that

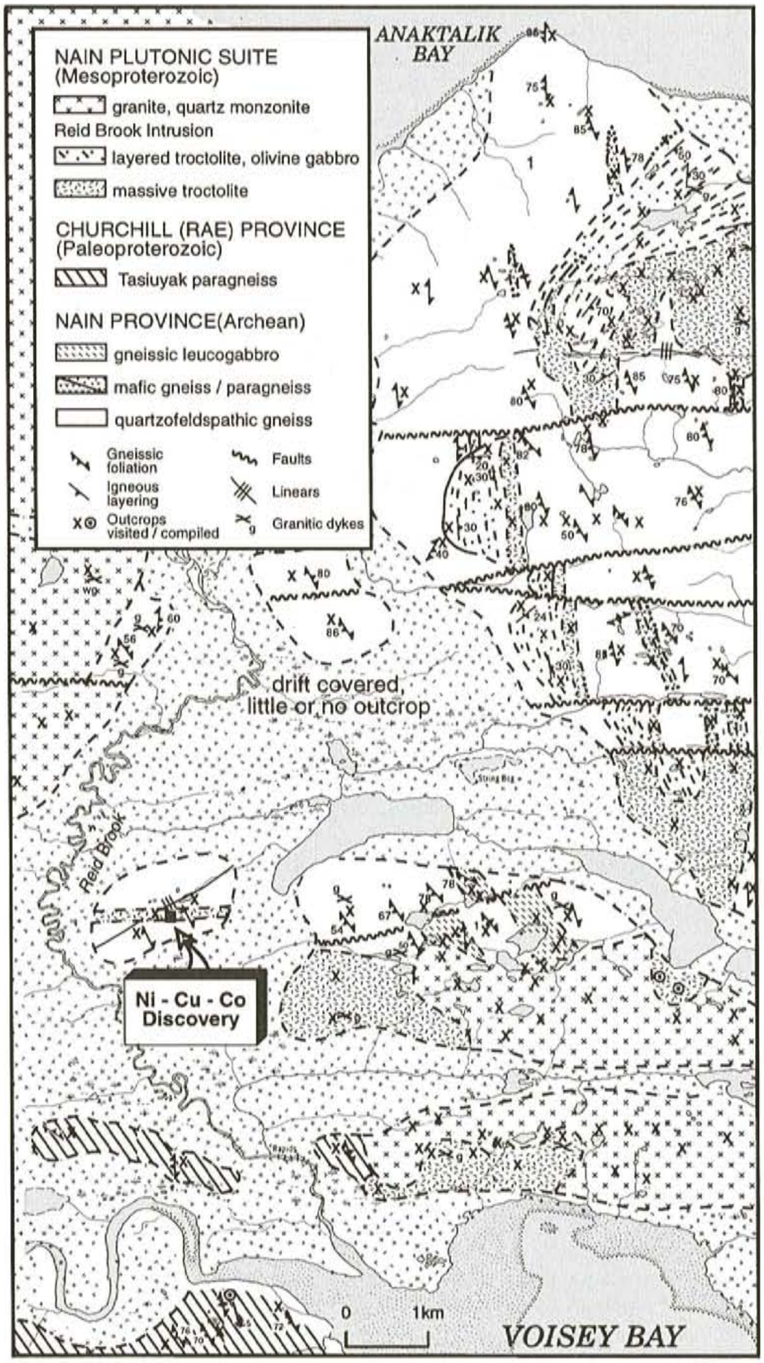

Figure 3. *Geology of the northwest side of Voisey Bay showing the distribution of the Reid Brook intrusion and the location of the Diamond Fields-Archean Resources sulphide discovery.*

foundered into the magma chamber to the granite. If this interpretation of the norite in the granite is correct, it may also be relevant to the mineralization (as will be discussed below). The southern part of the intrusion is invaded by the undated (ca. 1300 Ma?) Voisey Bay granite. Granitic dykes are common throughout the mafic rocks.

The Reid Brook intrusion, as defined on the basis of the 1985 survey, includes both a layered olivine-bearing succession and several disparate areas of massive troctolitic rocks, as well as a dyke that occurs to the west of the main outcrop area of the intrusion (Figure 3; see below). The western margin of the intrusion is a monoclinal layered sequence that dips gently eastward against the gneisses; erosion has given the outline of the contact a lobate form. The eastern and southern parts of the intrusion are composed of a more massive troctolite. The eastern contact of the central part of the intrusion follows a pronounced linear, and may be fault controlled, but no tangible evidence for a faulted contact was seen in the field. An exposed contact between gneiss and massive troctolite in the northern block is marked by a well-developed 50-cm-wide (gabbroic?) chilled margin. The reconnaissance mapping across the main body suggests that the shallowly dipping layered succession is intruded by the more steeply dipping massive troctolite, but the temporal difference between the two has not been determined. These two units may represent different phases of a single-event intrusion, but for now the assumption is that the layered succession is not magmatically continuous with the massive rocks. The main features of each of the major divisions are as follows.

The western part of the intrusion is a well-layered to massive succession of red-brown-weathering troctolitic, melatroctolitic, noritic, gabbroic and gabbronoritic rocks containing cumulus plagioclase and olivine; intercumulus pyroxene locally forms poikilitic spots several centimetres in diameter. This part of the intrusion dips gently to the east above a "basement" of gneisses, but the actual contact between the igneous and metamorphic rocks has not been directly observed. The layered parts show compositional variations on the order of centimetres to tens of centimetres. Some layers exhibit primary lamination of plagioclase parallel to layer trend, but others display comb structure in which the feldspar has grown normal to the layering. Massive parts of this melanocratic layered succession locally contain scattered prismatic plagioclase phenocrysts. The layered rocks of the Reid Brook intrusion are fresh, characterized by varying proportions of plagioclase, olivine and pyroxene. The plagioclase is locally clouded by needles and dusty inclusions of opaque oxide, a feature that may reflect the thermal effects of the younger granitic rocks. Olivine is generally unaltered, except to magnetite along fractures and margins; some serpentinization of olivine has occurred in the melatroctolites. Pyroxene includes inverted pigeonite, and discrete grains of hypersthene and pale mauve (titaniferous?) augite. Minor primary reddish-brown hornblende is present in some rocks.

The eastern and southern parts of the Reid Brook intrusion comprise massive, grey- to purplish-black-weathering leucotroctolite, troctolite and norite that clearly intrude the layered sequence, the latter appearing to be steeply upturned against a dyke-like body of the massive rocks in the centre of the outcrop area. The olivine-rich rocks of this subdivision tend to weather into a coarse gravel, and appear to be the main constituent of the dyke to the west that hosts the sulphide mineralization. The grey to purplish-weathering massive rocks are mostly medium grained, and ophitic to subophitic in texture, but they locally exhibit prismatic plagioclase up to 10 by 2 cm arranged in a stellate array. The feldspar in the massive parts of the intrusion shows the same clear to clouded character of the layered rocks. The orthopyroxene in the noritic parts of this subdivision has exsolution lamellae of clinopyroxene, implying the original pyroxene was pigeonite. Locally, the primary pyroxene in these rocks has been replaced by a green hornblende. Biotite porphyroblasts are developed adjacent to granitic veins.

SPECULATION ON MINERALIZATION CONTROLS AT THE ARCHEAN RESOURCES–DIAMOND FIELDS DISCOVERY

The results of previous mapping (Ryan and Lee, 1986, 1989), combined with the details released by Archean Resources–Diamond Fields, indicate the mineralization at Voisey Bay is within an east–west-trending, north-dipping, troctolitic or olivine-bearing gabbroic dyke west of the main outcrop area of the Reid Brook intrusion[1]. The dyke is interpreted to be a feeder through which magmas ascended into the chamber of the overlying Reid Brook intrusion (see below). The dyke has been traced along strike by geophysical surveys and drill intersections for over a kilometre. It has a pinch-and-swell morphology, varying from approximately 20 to 100 m thick, and appears to broaden into a bulbous intrusion in the east. There seems little doubt that the sulphide ore (pyrrhotite, pentlandite and chalcopyrite) at the Voisey Bay site is of magmatic origin. Published cross-sections indicate that the ore is confined to the centre and lower contact of the dyke, but the exact genetic relationship between the sulphides and the intrusion is unknown. With respect to the last point, published announcements by Diamond Fields have not indicated if the sulphides are considered to be an integral part of the troctolitic intrusion, or if the sulphides constitute a distinct younger dyke that intrudes the troctolite or whether the troctolite has intruded the sulphides. It seems likely, based on 1) the descriptions of 'disseminated', 'semi-massive' and '95 m of massive' sulphide, 2) the restriction of the mineralization to the dyke, and 3) the probable magmatic nature of the ore, that the mineralization is directly related to the olivine-bearing rock in which it occurs. It is unlikely to be a secondary replacement, or a raft of older sulphides, but represents, instead, gravitational accumulations within a dyke that fed into (or out of) a magma chamber elsewhere.

The mineralization can be considered in terms of two chief factors controlling sulphide deposition as outlined earlier, viz. 1) a sulphur-undersaturated, picritic, parental magma and 2) subsequent sulphur saturation to precipitate the Ni–Cu–Co sulphides. From the first perspective, Berg (1980) and Berg and Pencak (1981) have proposed that some parts of olivine-bearing intrusions in the NPS (such as the Hettasch and Jonathon Island) are derived from high-temperature, olivine-rich magmas more primitive than basalt, and quite likely picritic. Berg (*op. cit.*) bases his thesis on the petrological and geochemical characteristics of some border zones and unique fine-grained replenishment layers in the intrusions, and on textural evidence indicating that some layers or small intrusions were plagioclase-supersaturated and supercooled upon emplacement. In addition, Emslie (1985) and Wiebe (1990b) postulate that the parental subcrustal magmas for the whole anorthosite 'family' could be picritic, and Emslie *et al.* (1994) favour generation of the parental magmas from a mantle plume or hot spot. Emslie *et al.* (1994) have presented data indicating that the melatroctolites of the Reid Brook intrusion are MgO-enriched, although the data are from cumulate rocks and are not representative of the parental liquid composition (R.F. Emslie, personal communication, 1994). Thus, the sources of some of the olivine-bearing intrusions are typical of mantle-derived magmas postulated to be conducive to sulphide deposition after ascending into the crust and encountering favourable conditions for sulphide precipitation. Chief among such 'favourable conditions' is contamination with crustal derived sulphur, most likely assimilated from sedimentary rocks in the crustal region through which these magmas pass or in which they come to rest.

The setting of the Voisey Bay mineralization can be accommodated within a model of a picritic magma host and with the triggering of sulphide precipitation as a result of increased S in the liquid. As noted above, the mineralized dyke and Reid Brook intrusion are located close to the junction between the Nain and Churchill provinces in the Voisey Bay area. This junction is not exposed here, but, like its counterpart in the north (cf. Van Kranendonk and Ermanovics, 1990), is considered to be a subvertical fault, the consequence of uplift adjustment within the major zone of continental collision at 1800 Ma. If it is assumed that this

---

[1] The north-northwest strike of the dyke shown on the Ryan and Lee (1989) map of the Reid Brook area has been demonstrated to be incorrect as a result of geophysical surveys carried out by Archean Resources–Diamond Fields. The trend portrayed on that map was based on cursory examination of three outcrops in the area–one of troctolite between two of gneisses–and on the generally northerly strike of similar rocks to the east.

fault is a crust-penetrating structure, then it becomes capable of conveniently tapping mantle magmas, especially if it was reactivated during the crustal extension that prevailed at the time of NPS emplacement. Thus, derivatives from the mantle picritic melts would find a conduit for rapid leaking from mantle to upper crust. Xue and Morse (1993) have suggested that rapid transit from mantle to crust is probably a characteristic that all the troctolitic members of the NPS have in common. Assuming this, one of the criteria necessary for Ni–Cu–PGE sulphide deposits is met: a MgO-rich hot magma rapidly expelled from its mantle source without significant in-transit fractionation. The second criterion–a ready source of sulphur–is also met at the Voisey Bay site. The mineralized dyke is located in reworked Archean gneiss adjacent to a 30-km-wide unit of the Paleoproterozoic, sulphide-rich, granulite-facies Tasiuyak paragneiss, a unit that may be as much as 13 km thick along the collisional boundary of the Nain and Churchill provinces (Feininger and Ermanovics, 1994). There is Nd evidence (Emslie *et al.*, 1994) that Proterozoic rocks could extend eastward beneath the Nain craton for as much as 20 km, a fact that may be interpreted to be the result of the latter crustal block having overridden the Rae Province during collision. Tasiuyak gneiss below the Voisey Bay site thus provides an elegant explanation for sulphide-enrichment of ascending picritic magmas, satisfying the combination of circumstances giving rise to such deposits world-wide.

It is worthwhile to look at the site of the sulphide mineralization in another context. If it is in a subvertical dyke (as preliminary drill data suggest), then it is somewhat anomalous with respect to other deposits of this type that tend to occur in basin-shaped layered intrusions. The one significant exception seems to be the Jinchuan intrusion of China, a 6 km by 300 m dyke that hosts the world's second largest Ni–Cu deposit (Chai and Naldrett, 1992a). An answer to the origin of the mineralization at Voisey Bay may lie in the evolution of the Reid Brook intrusion, several possible models being presented below.

The probable disposition of the rocks of the Reid Brook intrusion and an evolutionary sequence for the area is shown in Figure 4, which is based on the mapping of Ryan and Lee (1986, 1989). It is assumed that as a result of Churchill–Nain collision at ca. 1860 Ma, the Tasiuyak gneiss (and other gneisses) of the eastern margin of the Rae Province was wedged beneath the reworked western Nain margin (Figure 4a). The original collisional boundary remained active along subvertical faults until ca. 1740 when the last movement appears to have occurred (Figure 4b; Bertrand *et al.*, 1993). It is suggested that during the subsequent development of the NPS, mafic (picritic?) magma(s) migrated upward along the Churchill–Nain boundary, facilitated by an existing Nain–Churchill boundary fault, a through-going structure between crust and upper mantle (Figure 4c). During ascent along the Nain–Churchill boundary faults, the magmas encountered the Tasiuyak paragneiss, scavenging S from the gneiss and transporting it to a high-level magma chamber. Episodic magma replenishments into this crustal chamber led to the development of the layered part of the Reid Brook intrusions by both cumulate (troctolitic rocks) and supercooling (comb layer) processes. Emplacement of the massive part of the intrusion could have occurred at this time, or perhaps later. Several possibilities for the timing of sulphide deposition can be tied to several models for the development of the Reid Brook intrusion: 1) It is possible that during the evolution of the layered sequence that the sulphur-saturated silicate magmas began to expel immiscible droplets of metal-enriched sulphide liquid, which sank to lower levels in the chamber, collecting in localized fault-formed topographic depressions on the floor, and sinking into deep fractures or feeder dykes that had penetrated the base of the chamber. 2) An alternative viewpoint toward the connection between mineralization and the Reid Brook intrusion can be advocated by considering the role that the massive troctolites may have played in sulphide deposition. These rocks could represent rapid overturn, homogenization and crystallization of resident magma, giving rise to sulphide deposition analogous to that in the Munni Munni complex of western Australia (Hoatson and Keays, 1989). 3) Another possibility is that the massive troctolites represent a distinct pulse of new magma, one that was particularly enriched in metals. One of the conduits (the main one?) for this intrusion may have been the opening now occupied by the Voisey Bay troctolite dyke. This model is attractive because it allows faulting of the layered sequence prior to injection of the massive troctolites, a mechanism that can account for the monoclinal attitude of the layered rocks and the dyke-like form of the massive rocks in the centre of the outcrop area because the latter has exploited the fault. All three scenarios (sulphide deposition coeval with cumulate layering, sulphide deposition triggered by convective overturn, sulphide deposition triggered by a younger intrusive event) can be used to provide a model for mineralization in the dyke.

In the first instance, sulphide magma resident in the chamber as a result of episodic replenishments at the time of development of the layered sequence, tumbled back down a slowly feeding conduit at the time that the silicate magmas were producing the layered troctolitic cumulates. In this model, it could be expected that sulphides would have accumulated at the base of the magma chamber and also as scattered trapped droplets within the layered rocks because of the rapid deposition of these rocks. No such distribution of sulphides from the layered sequence is known. This model, however, opens up potential for sulphides in the main layered rocks and also within topographic lows within the original chamber as noted above. The second model–that of convective overturn of 'excess' magma resident in the chamber related to the cumulates of the layered sequence–is similar to the above, the main difference being the process of convective homogenization initiating the sulphide deposition. Disseminated sulphides would not occur through the layered sequence under this model, but would, instead, be collected at only the upper part of the sequence that abutted the massive rocks. This is the model that has been used to explain the setting of the sulphides at Munni Munni as noted above. Sulphides are not known to occupy this stratigraphic horizon in the Reid Brook intrusion. The third model, that of a new magma feed, is more appealing than the others because it allows for this replenishment to be the carrier of the sulphides

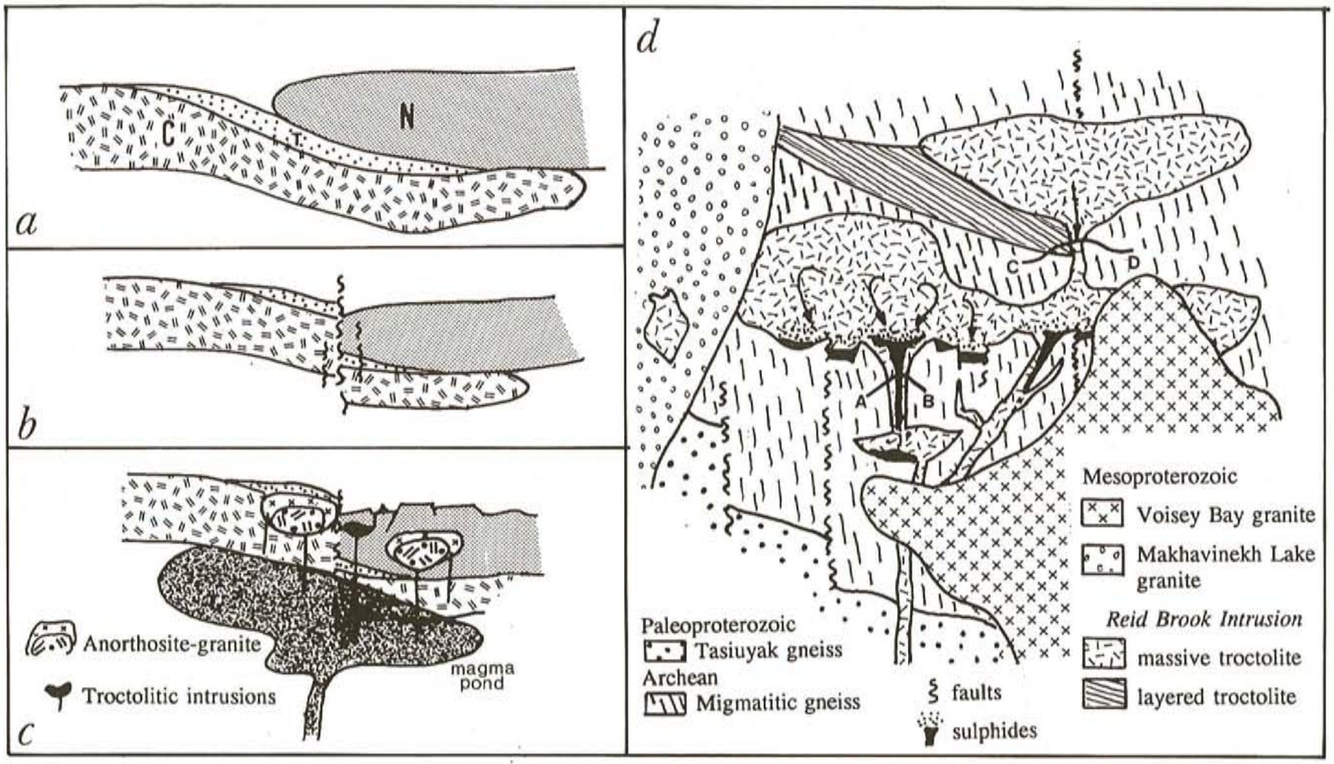

Figure 4. *Schematic diagram to illustrate the possible geological evolution of the Voisey Bay area, the emplacement of the Reid Brook intrusion and the formation of the sulphide-bearing dyke. a) As a result of continental collision at 1860 Ma Churchill (Rae) Province (C) and its cover of Tasiuyak gneiss (T) are wedged eastward beneath Nain Province (N). b) Uplift along boundary zone faults at ca. 1794–1740 Ma marks the end of orogenic activity. c) Nain Plutonic Suite, predominantly anorthosite and granite, emplaced between ca. 1350 and 1290 Ma as a result of the ponding of mantle-derived magma at the crust–mantle interface. Little-evolved magmas migrate upward along Nain–Churchill boundary faults, assimilating sulphur from passage through Tasiuyak gneiss. d) Possible geological relationships in the Voisey Bay area, assuming that model 3 of the text is applicable to the development of the Reid Brook intrusion and the mineralization. Initial magmatism led to formation of a layered sequence of troctolitic rocks within the Archean gneisses. The eastern part of the layered intrusion was subsequently faulted off, and then the sequence was intruded by the massive troctolite that exploited the earlier fault in places. The younger intrusion is assumed to be the sulphide-enriched magma, the sulphide liquid separating from the silicate magma and accumulating at the base of this chamber and sinking back into a feeder dyke. Line A-B represents the erosional level of the Voisey Bay sulphide-bearing dyke; C-D represents the erosional level of the layered and massive rocks exposed on the highland to the northeast.*

(Figure 4d). Emplaced into an already faulted (and totally crystallized?) layered sequence, conditions of S-saturation in the new magma initiated precipitation of sulphides. The coarser grained nature of the main troctolite mass suggests that its crystallization was a slow process, thus allowing an easy mechanism for the dense sulphides to gravitationally settle back down through the crystallising silicate magma. Cooling and nucleation of silicate crystals along the conduit walls would also provide traps for the collection of intercumulus ('disseminated') sulphides. To allow the sulphides to settle back down from the higher sites of accumulation, the conduit would have to be kept open and active. It could be thus anticipated that sulphides in the Voisey Bay dyke would exhibit textures indicative of silicate crystal accumulation in sulphide liquid, sulphide liquid between silicate grains, and intermingling of silicate and sulphide liquid resulting from passage of silicate liquid upwards through the setting sulphide magma. The model advocated here is like that proposed by Wiebe (1987) to explain some of the localized granitic troughs in the Newark Island layered intrusion (see above), in which pillows of troctolitic rock are net-veined by granite, and granite forms the walls to the troughs. Wiebe (*op. cit.*) argues that the troughs represent feeder systems by which granitic magma entered a partly crystallized troctolitic magma, above which the resident magma was still molten. Upon reduction of the pumping pressure of the granitic feeder system, the more dense troctolitic magma tumbled into the granite magma, congealing as pillows because the mafic magma was effectively chilled within the silicic host. The sinking of sulphides into the feeder dykes in mafic magmatic systems thus seems to be a plausible counterpart to the mafic–silicic relations in the Newark Island layered intrusion. Indeed, R. Keayes (personal communication, 1994) believes that the sulphides in the sills at Noril'sk are concentrates that have sunk through the feeders for the plateau lavas, and Chai and Naldrett (1992a,b) have advocated this mechanism for the sulphide deposits in the Jinchuan dyke. A potential test for application of the sulphide-settling model to the Voisey Bay dyke-hosted mineralization could be metal zonation with depth in the dyke–the higher Cu-liquid will reside above the Ni-rich fraction, if allowed to unmix before arrested by solidification. (In Noril'sk for instance, blebs of sulphide within the gabbro host can be used to tell 'tops' because chalcopyrite overlies pentlandite in the globules). One of the interesting propositions arising from the Noril'sk model is that there may be a larger pocket of troctolite below the present erosional level of the Voisey Bay dyke, that could have served as the collection chamber for the sulphide liquid that drained back down the dyke. Also, there is the probability that sulphide may underlie the massive troctolitic rocks directly east of the mineralized dyke.

The above models of sulphide concentration as a result of collapse and draining of liquid from a collection chamber above the present level of exposure of the dyke are predicated on the density differences between silicate and sulphide liquids. It is possible that earlier separated sulphide liquid ascended as an immiscible fraction within the silicate magma; without detailed first-hand examination of the discovery zone we cannot entirely rule this out. If this is the case, it is probable that 'globules' of such sulphide could have been carried to higher levels in the chamber, and should be found as sulphide concentrations throughout the Reid Brook intrusion. Similarly, the possibility that the Voisey Bay occurrence represents extraneous segregated sulphide liquid that has been injected into the troctolitic dyke conduit at some later time cannot be discounted.

AN EXPLORATION VIEW OF OTHER PARTS OF THE NAIN PLUTONIC SUITE IN RELATION TO THE VOISEY BAY DISCOVERY

The proposition that the Voisey Bay dyke, and thus the Ni–Cu–Co-sulphide mineralization, is genetically related to the troctolitic Reid Brook intrusion, has implications for future mineral exploration in the Nain area. If it is accepted that the Reid Brook intrusion is an integral, perhaps early, member of the NPS as suggested above, then the potential of other parts of the NPS as reservoirs for other sulphide concentrations of this type can be seriously considered. The 'first-conclusion' approach would be to argue that because the discovery is hosted in a troctolitic dyke that may be a feeder to part of the Reid Brook intrusion, then other such 'primitive' intrusions are prime targets for similar discoveries. While this may be true, there are several other observations regarding the setting of the Voisey Bay mineralization that need to be taken into account: 1) It seems that the Reid Brook intrusion may be one of the earliest mafic intrusions in the NPS and, therefore, represents effusions from a mantle source at an early stage of NPS construction. If this is a critical factor, does it rule out the potential targets offered by the younger (and more evolved?) Kiglapait and Newark Island intrusions? 2) The Reid Brook, like Kiglapait, seems to have developed in a closed-system magma chamber that was not contaminated by influx of silicic magmas. Does this then make the Kiglapait, Jonathon Island and Hettasch intrusions good exploration targets, but negate any potential for Newark and Barth? 3) If it is valid to link the Voisey Bay mineralization to the fact that it occurs close to the Nain–Churchill collisional boundary, and particularly to the presence of the Tasiuyak gneiss, does this mean that exploration should be dedicated only to the western side of the NPS? 4) Does the composition of the host to the Voisey Bay discovery eliminate the possibility that other (olivine-free) rock-types in the NPS may host sulphide mineralization? These are some of the factors that must be borne in mind when considering what other areas offer prospective targets for Ni–Cu mineralization in the NPS. Data for several of the other mafic intrusions of the NPS are now presented; also there is some evidence to consider other rock types in the area as worthy of further examination. The reader will note that the following sections on the layered intrusions deal only with those intrusions that are known to host sulphides. The information on these layered intrusions includes some descriptive data already presented in a foregoing section, but is repeated here in the context of the setting of the sulphides.

KIGLAPAIT INTRUSION

Initially mapped and described by Morse (1969), this is probably the best known of the layered mafic intrusions in Labrador. It was explored initially by Kennco (Barr, 1970) for base-metal mineralization, and more recently by International Platinum Canada Incorporated for its PGE potential (Atkinson, 1986; Walls, 1988). The intrusion, dated at ca. 1306 Ma, has an overall basinal shape and is about 9 km thick (Morse, 1969). Its base is defined by an outer border zone (OBZ) consisting of fine-grained, granular-textured gabbro, olivine gabbro and pyroxenite, which is locally intermingled with country rock in a manner that is suggestive lit-par-lit injection by the gabbro. Morse (1969) suggests part of the OBZ to be a sill that is partially detached from the main Kiglapait intrusion. The OBZ grades into an inner border zone (IBZ) of olivine gabbro, which in turn passes gradationally upwards through a lower zone (LZ) of well-layered troctolitic rocks, an upper zone (UZ) of olivine gabbro (marked by the appearance of augite) in association with ferrodiorite–ferrosyenite, and finally into an upper border zone (UBZ) of troctolite and olivine gabbro. The similarity of the IBZ and UBZ led Morse to suggest that the intrusion 'grew' simultaneously from base and top (Morse, 1969). The intrusion has a bulk composition of high-alumina tholeiite and displays a strong Fe-enrichment trend, as demonstrated by the abundance of Fe-bearing mineral phases in the UZ.

The most prominent mineralization is seen as a horseshoe-shaped zone of cumulus Fe–Ti oxides intergrown with olivine, referred to as the Main Ore Band, which occurs as a strongly gossaned unit within the UZ. Within this zone, oxide layers up to a metre thick may contain up to 80 percent Fe–Ti oxide, and represent accumulations from oxide-supersaturated liquids (Morse, 1980). Above this, toward the top of the UZ, is a thin subzone marked by cumulus pyrrhotite, chalcopyrite and cobaltian pentlandite that represents the level at which the magma became saturated with sulphur, and precipitated cumulus minerals from a sulphide liquid phase (Shirey, 1975). This subzone may contain up to a maximum 1 percent disseminated sulphide. PGE exploration work reported by Atkinson (1986) failed, however, to reveal significant values from this otherwise favourable horizon. Two sulphide occurrences are also known from the OBZ (Barr, 1970; see Figure 5). The northern one, near Kiglapait Harbour, consists of lenticular masses of pyrite–pyrrhotite (with 0.5 percent Cr) mineralization; an eastern one at Topaz Point comprises vein-hosted pyrite–pyrrhotite–chalcopyrite containing up to 0.14 percent Cu. The northeastern contact of the intrusion is against the sulphide-bearing metasediments of the Snyder Group and it may be this area that offers the best prospect for Ni mineralization in the border zone of the intrusion. This potential was recognized by Atkinson (1986) who described patches of granular pyrrhotite in 'dykes' of melagabbro and zones of 'well-mineralized pyroxenite' in the OBZ in apparent association with the adjacent Snyder Group.

NEWARK ISLAND LAYERED INTRUSION

The main attributes of the Newark Island layered intrusion have been given in a previous section. The subdivisions of the intrusion are referred to by Wiebe (1988) as a lower layered series (LS) and an upper hybrid series (HS). These are transected by several troughs that served as conduits for the periodic invasion of silicic magma into the partially consolidated mafic magma. The LS is a steeply dipping unit confined to a 3-km-wide strip along the eastern part of the intrusion (Wiebe, 1988; Wiebe and Snyder, 1993). It mesoscopically resembles the layered part of the Reid Brook intrusion, and comprises cumulate rocks dominated by troctolite, olivine gabbro and oxide-rich cumulates, exhibiting magmatic current structures such as crossbedding and modally graded layering. Wiebe (1988) and Wiebe and Snyder (1993) advocate at least four periods of magma replenishment during deposition of the LS, each being represented by a cumulate rhythmic unit. Sulphide, in the form of pyrrhotite, is present as a cumulate phase in oxide-rich layers near the top of several of the rhythmic units (cf. Wiebe and Snyder, 1993), but there are no indications of its concentration.

JONATHON ISLAND INTRUSION

The Jonathon Island intrusion is the name coined by Berg and Briegel (1983) for an oval leucotroctolitic to leuconoritic intrusion occupying several islands on the eastern side of the NPS. Its dominant features are a Border Zone of fine- to coarse-grained orthopyroxene leucotroctolite and a Main Zone comprising olivine leuconorite. The Main Zone is characterized by an igneous lamination to cumulate plagioclase, but small-scale layering typical of intrusions such as Kiglapait is absent. The Jonathon Island intrusion is characterized on its western side by a discontinuous, layered olivine-bearing gabbronoritic rind that separates the main oval pluton from the surrounding gneisses. This olivine-bearing unit has previously been considered to be part of the country-rock assemblage, but there seems to be strong mineralogical and textural evidence for assigning it to the plutonic rocks instead (Royse and Ryan, 1995), perhaps representing a sill complex developed by protracted magma injection prior to arrival of the main pluton. Previous cursory examination of the layered unit along the northern shore of Jonathon Island by Ryan (1992) revealed a rusty zone in which white anorthosite fragments are hosted by a sulphide-rich norite. The earlier interpretation of the noritic host to the fragments—as being the same as a network of purplish noritic sheets and veins that are common in the layered unit (Ryan, 1992)—appears to be incorrect because microscope examination of the sulphide-bearing rock indicates that it is texturally different from the noritic sheets. The noritic host here may be an offshoot from the main pluton. Assay results from a bulk sample of several hand-specimens of the sulphide-bearing rock yielded the following results: 2170 g/t Ni, 1120 g/t Cu, and 350 g/t Co. No Au or Pt was detected in the assay.

OTHER PROSPECTIVE PARTS OF THE NAIN PLUTONIC SUITE

In addition to the above plutons and other troctolitic intrusions shown on the regional compilation map of Ryan (1990), there are a few other areas of the NPS that may contain unrecognized zones of such rocks. It was stated earlier that Wheeler had mapped the anorthositic intrusions on the basis of a colour 'facies' (cf. Wheeler, 1960, 1969). He recognized that his dark-coloured rocks commonly contained olivine, and he was able to draw boundaries on his maps that outlined some of the subdivisions so defined. Subsequent work by several investigators under the decade-long Nain Anorthosite Project (Morse, 1971–1983) has shown that some of Wheeler's 'dark facies' along the eastern coastal fringe of the NPS actually represent distinct troctolitic intrusions, such as Hettasch and Newark Island, which are both older and younger than nearby and abutting anorthosites. Without recourse to the work carried out during the Nain Anorthosite Project, Ryan (1990) would not have been able to differentiate and portray these intrusions as a separate class on the compilation map of the Nain area. It thus follows that if the correlation of Wheeler's 'dark facies' with troctolites was to be applied, then his published sketch maps can be used to postulate that such rocks may occur elsewhere in less-investigated areas of the NPS (cf. Xue and Morse, 1993). A large area of 'dark facies' occurs in the northernmost lobe of the anorthosites, south of Okakh Bay (Wheeler, 1960). A smaller body of this type is apparently present along the northwestern margin of the Umiakovik Lake batholith (Wheeler, 1969). A region of 'dark facies' also fringes the north shore of Anaktalik Bay as far east as Kauk Bluff Island (Wheeler, 1969; Rubins, 1971), corresponding at its western end with a dark-grey olivine gabbro and olivine norite that resembles the Reid Brook intrusion and that dips southward atop an older leuconorite and anorthosite (Ryan, 1993). If the data presented by Xue and Morse (1993, Figure 7) are considered, these Anaktalik Bay olivine-bearing rocks are probably continuous with troctolitic anorthosite through Akuliakatak Peninsula, Satosoak Island, and Kikkertavak Island. It is interesting to note that Xue and Morse (op. cit., page 3932) have documented an unusual 'olivine-rich melatroctolite' layer from the latter area that they surmise may be derived from a magma similar to the picritic magmas that Berg (1980) postulated, as noted above, for parts of the Hettasch intrusion.

Wheeler (unpublished manuscript) has documented enigmatic foliated and layered rocks associated with some of the anorthositic plutons as 'granulite of uncertain origin'. Ryan (1992) briefly visited some of these 'granulite' zones, discovering that several such zones comprise foliated noritic rocks that form the margins of diapiric plutons, but at least one of them seems to be a remnant of a melatroctolitic- to anorthositic-layered intrusion. This latter body occurs about 10 km north of Kingurutik Lake and is about 6 by 1 km in size. Its relationship to rocks on its western side is not known, but the eastern edge of the body is intruded by a noritic pluton of unknown size. The discovery of such layered olivine-rich rocks within the interior part of the NPS indicates that other rocks of this type may exist in this little-surveyed area.

Indications that sulphide-mineralized rock are present in parts of the NPS that have not yet been surveyed in detail, and not necessarily troctolitic in composition, come from a reconnaissance examination of the region south of Nain Bay by Ryan (1992, 1993). A prominent rusty slope on a small hill 5.5 km southeast of the mouth of the Fraser River in this area is underlain by a coarse-grained norite that is interpreted to be a dyke, of unknown extent, intruded into granular and foliated anorthosite and leuconorite. The rusty colour of the slope arises from oxidized sulphides in the dyke—coarse-grained pyrrhotite and pentlandite(?), between which are blebs and intergranular areas of chalcopyrite. Also present within the massive sulphide are tiny 'beads' and clusters of ovoidal apatite, considered to be a contemporaneous cumulate with the sulphide. Assays of several grab samples collected from boulders and *in situ* mineralization at this site yielded maximum values as follows: 8736 g/t Ni, 9076 g/t Cu, 1738 g/t Co, 125 g/t Zn and 25 g/t Pb (revised from Ryan and Swinden, 1992). Gold and platinum results from one sample yielded 210 ppb and 125 ppb, respectively.

Other rusty zones on the south side of Nain Bay were investigated by BRINEX in the mid-1950s. One of these was briefly examined by Ryan (1993), indicating it to comprise sulphide-bearing rafts in anorthosite and disseminated sulphide in the anorthosite itself. Grimley (1955) noted 'more massive material' at the base of a nearby scarp, which suggests to us the possibility of mineralization like that described in the noritic dyke above.

OTHER KNOWN AND POTENTIAL NI-SULPHIDE ENVIRONMENTS IN LABRADOR

Up to this point, we have given an overview of the process of Cu–Ni-sulphide formation in magmatic systems and presented details on bedrock geology of the Nain region that could be employed in considering exploration of that area from the perspective of the discovery at Voisey Bay. Other areas of Labrador that could contain similar sulphides (Figure 5) are now discussed. This regional assessment is constructed based on the classification scheme of Naldrett (1989), summarized at the beginning of this paper, which uses tectonic setting as a general guide to differing Ni-sulphide environments (see legend to Figure 5). The geochronological framework for many of the units discussed in this section is presented in Table 1.

Table 1. Chronology of dated mafic intrusions, Labrador

Age–Ma	UNIT
Mesoproterozoic	
1133-1123	Atikonak River anorthosite–granite intrusion
1250-1220	Seal Lake Group gabbros (Naskaupi sills)
1280-1274	Nain and Harp dyke swarms
1330-1290	NPS anorthosite–granite intrusions including layered troctolitic intrusions of Kiglapait and Newark Island
1380	Mealy dykes
1459-1426	Shabogamo–Michael gabbros
1460-1450	Harp Lake and Michikamau anorthosite–granite intrusions
Paleoproterozoic	
1639-1623	Ossok Mountain Intrusive suite
1625	North West River anorthositic suite
>1641	White Bear Arm Complex
1649	Adlavik Intrusive Suite
1645-1635	Mealy Mountains Intrusive Suite
1883-1874	Montagnais Gabbros (Labrador Trough): cycle 2
2169	Montagnais Gabbros (Labrador Trough): cycle 1
2234	Kikkertavak dykes
2450-2200	Napaktok–Dome 5 dykes
Archean	
post 3105 pre 2838	Ultramafic (komatiitic?) flows and sills–Florence Lake Group
3258-3105?	Hunt River Group
pre 2835	Ultramafic–mafic bodies of Saglek block

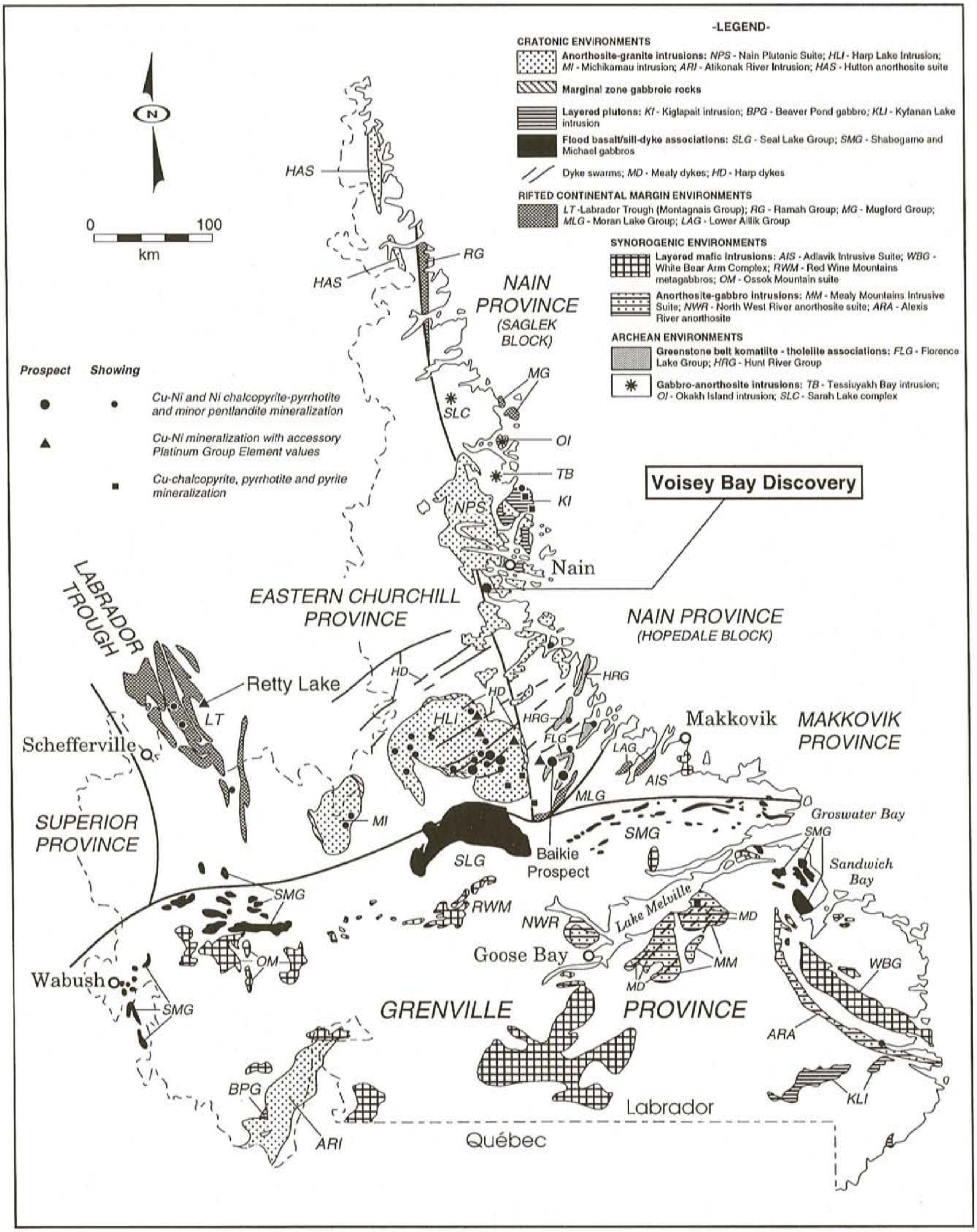

Figure 5. *Mafic magmatic associations and potential Ni-sulphide environments of Labrador*

CRATONIC ENVIRONMENTS

This is the most voluminous class with respect to known and potential mineralization environments in Labrador and is dominated by basic intrusions, such as the NPS, of Mesoproterozoic age (Figure 5).

Anorthosite–Granite Terranes

This type of plutonic association has not traditionally been regarded as an important host rock for Ni mineralization. The Voisey Bay discovery, however, may require revision of this concept. Typically, these associations comprise a bimodal assemblage consisting of an anorthositic core partially to completely enveloped by younger, but broadly coeval, granitoid plutons. The classic example of this type of terrane is the NPS described earlier. At deeper levels, the granitic envelope may be seen only as a partial rim on anorthositic rocks; at high levels of exposure the anorthosite core may be completely concealed beneath the roof of the granitic envelope (cf. Ryan, 1991; Emslie *et al.*, 1994). (Note that associated granitic plutons are not shown on Figure 5).

Smaller layered intrusions of troctolite–norite composition, like those of the NPS, are associated with the more widespread anorthositic and granitic rocks elsewhere in Labrador and are shown separately on Figure 5. These intrusions are more comparable to the layered mafic complexes (e.g., Sudbury, Bushveld, Stillwater) that form some of the main sources of Ni and PGE mineralization in the world and, following the Voisey Bay discovery, probably constitute the main target for Ni exploration within anorthosite–granite terranes.

The Harp Lake Intrusion

This intrusion (Figure 5; Emslie, 1980) forms a roughly circular body that, on the basis of its magnetically transparent character, probably has a relatively thin, sheet-like or lopolith form. The interior of the intrusion is dominated by several coalesced plutons of anorthosite, leuconorite and leucotroctolite whereas the periphery, where not intruded by younger granites, is formed by a thin zone of olivine gabbro (Figure 5). This marginal zone dips outward, suggesting that it probably represents the roof of the intrusion. Olivine gabbro and troctolite also form small, discordant, massive to layered bodies ranging from 1 to 10 km^2 within both the border zone and interior of the intrusion. The latest stages of mafic magmatism are represented by small ferrodiorite intrusions.

Mineralization is represented by numerous Cu–Ni sulphide gossans, within olivine-bearing rocks (Emslie, 1980), discovered by Kennco Explorations (Canada) Limited in the early 1970s (McAuslan, 1973a,b; Jones, 1975) and subsequently explored by International Platinum Canada Incorporated and Falconbridge Limited. These gossans are developed over stratiform zones of disseminated chalcopyrite, pyrrhotite and minor pentlandite up to 650 m long. Values for Cu ranging from 0.03 to 0.07 percent and for Ni from 0.12 to 0.32 percent were reported by Jones (1975). One zone of 1600 m of disseminated 5 percent chalcopyrite and pyrrhotite was reported by Reusch (1986). PGE values of 185 ppb Pt, and 150 ppb Pd, were also reported by Jones (1975) although lower values were determined in later work by Reusch (1986). The geographic distribution of the mineral occurrences does not appear to show any systematic rock-type association, the majority occurring scattered along a north–south axis in the anorthositic east-central part of the intrusion. When considered in relation to the internal subdivisions of the intrusion shown by Emslie (1980, Figure 18), however, many seem to be within a large east-dipping subunit that occupies the region of Harp Lake itself. The distribution of sulphides through other subunits and within the marginal phase gabbros indicate that all parts of the Harp Lake intrusion are prospective targets for Ni–Cu sulphides. Even though Emslie (1980) has concluded that the intrusion is too evolved to be a depository of economic concentrations of sulphide, one has only to cite the Voisey Bay discovery to indicate what may lie hidden.

The Michikamau Intrusion

The ca. 1460 Ma Michikamau Intrusion (Emslie, 1970) is located in central Labrador where it was emplaced into reworked Archean gneisses (Nunn, 1993; James and Mahoney, 1994) and their Proterozoic cover of Petscapiskau Group metasedimentary and mafic volcanic rocks. Emslie (1970) has suggested that the intrusion, which has a funnel shape, was intruded along the Archean–Proterozoic contact. Internally, the intrusion comprises layered units ranging from centimetres to kilometres in thickness. An igneous lamination of plagioclase ± olivine is present in many layered units. Primary layering has been disturbed and rotated throughout the intrusion by a reticulate pattern of faults.

Anorthositic rocks of troctolitic affinity comprise the bulk of the intrusion. Leucotroctolite and anorthosite are, volumetrically, the most important rock types, with leucogabbro, gabbro, troctolite, olivine gabbro and ferromonzogranite being present in lesser amounts. Gabbroic rocks and troctolite, probably representing the early products of crystallization from an aluminous basaltic magma (Emslie, 1970, 1985), are concentrated in a thin marginal halo, which includes a very narrow chill zone, and also near the roof of the intrusion. Along the southeast edge of the intrusion the marginal zone dips shallowly westward and coincides with a strong aeromagnetic anomaly. The aeromagnetic map indicates the presence of larger quantities of magnetic, marginal-zone rocks beneath the southern lobe of the intrusion and a possible fault repetition of these rocks. The interior part of the intrusion comprises a layered series, the base of which is formed by olivine dominated rocks, notably troctolite. These pass upward through leucotroctolite into an overlying anorthosite unit, which contains pyroxene rather than olivine, and then an irregular cap of roof-zone gabbro.

Sulphide mineralization occurs as intergranular and/or globular patches in marginal-zone olivine gabbro, possibly as the product of immiscible sulphide liquids. The sulphides comprise pyrrhotite, intergrown with minor chalcopyrite, in irregular patches up to 3.5 cm across and locally forming gossans of about 1 km² surface area near the eastern margin of the intrusion (Nunn, 1993, Figure 16). Locally, the rocks forming the southern gossan have been metamorphosed, and some mineralization appears to have been remobilized along faults and redeposited in adjacent gabbro and in supracrustal xenoliths.

A second type of mineralization is represented by Fe and Fe–Ti oxides, which occur as cumulate minerals in troctolitic and some gabbroic rocks of the layered series and the marginal zone (Emslie, 1970). Mineralized zones range from centimetre-scale layers to metre-wide zones across a strike length of 300 m.

No Ni and/or Cu values have been reported from the sulphide occurrences. The mineralized zones have recently been drilled by Kennecot Limited, but results are, as yet, confidential. The probability that the basal part of the Michikamau intrusion may have assimilated Fe-sulphide-bearing metasedimentary rocks of the Petscapiskau Group may enhance the Ni potential of the intrusion.

The Atikonak River Intrusion

The ca. 1150–1100 Ma Atikonak River intrusion (Emslie *et al.*, 1986; Nunn *et al.*, 1986) is located within the Grenville Province in southwest Labrador and adjacent regions of Quebec (Figure 5). Its country rocks consist of Labradorian paragneiss, granitoid and gabbroid rocks.

Most of the intrusion has been variably affected by the Grenvillian orogeny. A major ductile shear zone cuts the massif in the northeast but much of the interior has been affected only by a static recrystallization that has produced secondary corona assemblages around olivine and orthopyroxene. This has only partially affected the northern part of the intrusion but is more complete in the south where it has rendered the identification of original minerals difficult.

The greater part of the northern area of the intrusion appears to be a single, large-scale layered intrusion of troctolitic rocks, which is partially rimmed and overlain by predominantly noritic rocks. The troctolitic rocks are commonly laminated whereas most noritic rocks have an intergranular texture. The troctolitic rocks also enclose xenoliths of anorthosite and norite, some of which contain orthopyroxene megacrysts that crystallized at much greater depth than the host rocks (Emslie *et al.*, 1986). Layered rocks in the south of the area may be a part of the same layered body as in the north or may belong to separate intrusions. Two small, layered intrusions are also present; the northern one, the Beaver Pond pluton, being a gabbro of 7 km² (Figure 5), and the southern one a similar size ferrodiorite. These, and their host rocks, are, in turn, intruded by dykes and bodies of coarse- to very coarse-grained, intergranular-textured norite.

Mineralization in the Atikonak River intrusion occurs chiefly as oxide concentrations that form clots, pods and layers up to 1 m across. Most are strongly magnetic; a few contain minor pyrite. Both of the small layered intrusions contain oxide concentrations, commonly in layers or pods aligned in layers. The Beaver Pond gabbro contains several percent of sulphide including pyrrhotite, pyrite and chalcopyrite. The ferrodiorite intrusion is rich in magnetite.

A weak Ni and Cu anomaly is apparent in the lake sediment data covering the troctolitic rocks of the intrusion (H.S. Swinden, personal communication, 1994).

Other Anorthositic Intrusions

The Hutton anorthositic suite of northern Labrador is a linear body of strongly deformed anorthosite and anorthosite gneiss of Early Paleoproterozoic or possibly Late Archean age located within reworked Nain Archean crust in the eastern Churchill Province (Figure 5). The suite varies from leucogabbro to leuconorite in composition and contains minor layered metagabbro–amphibolite units, locally including thin metapyroxenite layers, which are prevalent near its margins. Northern parts of the suite contain thin, discontinuous gossan zones developed within layered metagabbroic and anorthositic rocks. These have been assayed but have not revealed any abnormal base-metal values (Wardle *et al.*, 1992; unpublished data).

Layered Mafic Plutons: the Kyfanan Lake Intrusion

Layered plutons include the Kiglapait intrusion and Beaver Pond gabbro, which have been previously described under the NPS and Atikonak River intrusion, respectively. Another is the Kyfanan Lake layered mafic intrusion situated in the southeastern Grenville Province (Figure 3; see also Gower *et al.*, 1995). This is a large body, having a strike length of about 110 km and a width of up to 12 km. The intrusion comprises ultramafic rocks (websterite and clinopyroxenite), gabbronorite, gabbro, leucogabbronorite, anorthositic gabbro and anorthosite. Smaller, layered mafic bodies are scattered throughout nearby areas, including gabbronorite intrusions at Red Bay and west of Pinware. No geochronological investigations have been carried out on any of these bodies but Gower *et al.* (1995) suggest that the intrusions may have been emplaced between 1450 and 1150 Ma.

No mineralization has been confirmed in any of these intrusions in the Grenville Province although Bostock (1983) reported that local people in the Red Bay area showed him chalcopyrite- and ilmenite-bearing samples that were claimed to have been found in the drift close to the community. The assertion that these intrusions are viable mineral-exploration targets rests on Ni–Co–V–(Ag) lake-sediment anomalies that correlate with known occurrences of ultramafic rocks. Three specific targets at the margins of the Kyfanan Lake intrusion have been identified by Gower *et al.* (1995). Elevated lake-sediment concentrations for these elements also occur close to some of the smaller mafic intrusions, but relationships to the intrusions themselves are not clear.

Flood Basalt–Sill Environments

This class of intrusion is not known to be associated with Ni mineralization in Labrador. There may be potential, however, by analogy with areas such as the Siberian Trap where picritic sills within an olivine basalt pile host the Noril'sk–Talnakh Ni–Cu ores. In Labrador, the class includes the sheet-like intrusions of the Shabogamo–Michael gabbros, the Mealy Dykes and the younger rocks of the Seal Lake Group and Harp dyke swarm. All of these rocks are of continental tholeiite affinity and have been interpreted as the products of a continental rift environment (Gower *et al.*, 1990). Uplift associated with the Grenvillian Orogeny has resulted in the exposure of progressively deeper levels of this environment to the south.

Shabogamo–Michael gabbros and Mealy dykes

The terms Michael Gabbro and Shabogamo Gabbro refer to ca. 1460 to 1430 Ma mafic intrusive rocks emplaced along the northern margin of the Grenville Province in eastern and western Labrador, respectively (Gower *et al.*, 1990; Figure 5). Similar rocks occurring in the intervening region are not so abundant and have been termed Michael or Shabogamo gabbro according to the 'type' area to which they are adjacent. The intrusions mostly comprise massive, medium- to coarse-grained gabbro, the margins of which are commonly foliated and transformed to amphibolite as a result of Grenvillian tectonism. Some minor ultramafic rock, anorthositic gabbro and norite have been grouped with Michael or Shabogamo gabbro in their respective areas, but, given the co-existence of known Labradorian mafic intrusions, it must be acknowledged that all rocks may not have been correctly assigned. The ca. 1380 Ma Mealy dykes form an extensive east-northeast-trending swarm emplaced into the Mealy Mountains Intrusive Suite and are grouped on the basis of their age with the Michael–Shabogamo intrusions. Olivine gabbro and diabase are the dominant rock types.

All three groups of intrusions are tholeiitic, subalkaline transitional to alkaline basalts and can be petrotectonically classified as within-plate basalts. Chemical parameters demonstrate that the Michael and Shabogamo gabbros are very similar. The Mealy dykes are more comparable to the Michael–Shabogamo intrusions than other Mesoproterozoic intrusions in Labrador, but some differences are apparent (Gower *et al.*, 1990).

Evidence of mineralization is meagre, but this may be partly a function of the limited exploration attention these rocks have received. One area that deserves re-investigation in eastern Labrador is around Black Island, on the north side of Groswater Bay. Here Kirwan (1960) reported pyrite, pyrrhotite and chalcopyrite, over strike lengths of up to 120 m, at the contact between gabbro and granitoid gneisses. Two grab samples assayed 0.25 to 0.30 percent Cu and 0.02 to 0.03 percent Ni. Gower *et al.* (1983) have shown the existence of three Cu showings on Black Island, two of which occur in metasedimentary gneiss and one in orthogneiss. The metasedimentary gneiss in this area may well represent a source of sulphur governing mineralization within, or adjacent to, the gabbros.

Potential for Ni mineralization may also exist in western Labrador, where several shallowly dipping sheets of Shabogamo Gabbro intrude the low-grade metasedimentary rocks of the Knob Lake Group (Labrador Trough) at high crustal level (Ware and Wardle, 1979). The metasedimentary rocks contain abundant pyrite, and represent a potential source of sulphur to contaminate the mafic intrusions and produce Ni–Cu sulphide mineralization.

Seal Lake Group

This Mesoproterozoic unit consists of a thick (varyingly estimated at 5 000 to 14 000 m), sequence of red beds, shale, quartzite and subaerial basalt flows, intruded by numerous olivine diabase and gabbro sills (Naskaupi sills) of alkali-basalt to tholeiite composition (Brummer and Mann, 1961; Baragar, 1981; Wilton, 1989). The thicker sills are generally fractionated, having medium-grained ophitic gabbros in their lower parts and pegmatitic zones at higher levels. Baragar (1981) and Wilton (1989; unpublished data) have compared them to continental flood basalts, Wilton (unpublished data) observing that they show only slight evidence of crustal contamination. Cadman *et al.* (1994) also noted the chemical similarity of Seal Lake volcanics and Harp dykes and suggested a common genetic origin in which a mantle plume first produced the Harp dykes and then, as crustal rifting accelerated, the Seal Lake magmatic rocks.

Wardle (1987) noted the similarities of the Seal Lake setting to that of the Siberian basalts and their Noril'sk deposits. More recent work on the setting of the Noril'sk deposits indicates, though, that the mineralized rocks are generally picritic (Naldrett, 1992). Rocks of picritic composition are not known from the Seal Lake area. Mineralization associated with the Seal Lake magmatic rocks consists predominantly of Cu minerals, Ni being absent.

RIFTED CONTINENTAL MARGINS

Intrusions of this class locally host large ore bodies, for example the Thompson deposits in Manitoba and the Raglan deposit of the Ungava Peninsula. In Labrador, rocks of this class are found as sills associated with Paleoproterozoic continental margin sequences around the Superior and Nain cratons.

Superior Craton Margin Sequences

These rocks form part of the eastern Labrador Trough and are part of the same circum-Superior continental margin sequence that hosts the Thompson and Raglan deposits. The main sill swarm is known as the Montagnais Group and intrudes deep-water turbiditic shales, siltsones and basalts of the Knob Lake Group. The sills form two age groups (cycles 1 and 2; Table 1) that are very similar in appearance and composition, but most appear to belong to the younger (cycle

2) group of ca. 1880 Ma age. Massive diabase and gabbro are the most common rock types, but to the east, there are differentiated varieties that possess central zones of coarse-grained, glomeroporphyritic gabbro. These contain large xenocrystic aggregates of plagioclase that were probably derived from plagioclase cumulates in deeper level magma chambers. These intrusions are spatially associated with peridotite and composite peridotite–gabbro sills in which gabbro forms a thin, discontinuous upper layer (Fahrig, 1962; Baragar, 1967). The easternmost part of the Labrador Trough, the Doublet Group, consists of voluminous pillow basalt intruded by the Retty peridotite sills; these rocks, however, are largely restricted to Quebec. The Montagnais sills are believed to have been generated in a rifting environment located at the edge of the Superior continental crust close to its transition into oceanic crust (Skulski *et al.*, 1993).

There are several pyrite–pyrrhotite–chalcopyrite showings associated with gabbroic rocks in the Howse Lake area (the majority are associated with inter-sill sedimentary rocks). According to Birkett *et al.* (1991), the mineralization occurs as disseminated to semi-massive pyrrhotite with minor pyrite and chalcopyrite, and may represent immiscible sulphide accumulations within the basaltic liquid that developed following assimilation of sulphur from the host shales. The Retty Peridotite in Quebec contains numerous Ni–Cu showings, several of which (e.g., the Retty Lake prospect–Figure 5) contain elevated levels of Pt and Pd (Scott, 1988).

Nain Craton Margin Sequences

Sequences in the northern Nain craton, i.e., the Ramah and Mugford groups (Figure 5), comprise low-grade, predominantly siliciclastic rocks, capped in the case of the Mugford Group by a thick accumulation of mafic volcanic rocks.

The Ramah Group contains numerous diabase sills, one of which is zoned with a serpentinized ultramafic (metaperidotite?) core at least 10 km long (Morgan, 1975). The Mugford Group (Smyth, 1976; Wilton, 1994; Hamilton, 1994) is dominated by mafic flows having the chemical signature of continental alkaline basalts. It contains many basaltic sills and one ultramafic intrusion described by Barton (1975) as a basaltic komatiite. Chalcopyrite–pyrrhotite blebs occur within a brecciated zone at the bottom of this ultramafic sill (Wilton, 1994).

The Moran Lake and Lower Aillik groups represent similar sedimentary–volcanic sequences developed on the southern margin of the Nain craton including its extension into the Makkovik Province (Gower and Ryan, 1986). Sills, however, are lacking in these units and mafic plutonism appears restricted to a few small gabbroic plugs.

SYNOROGENIC ENVIRONMENTS

This class is represented predominantly by Paleoproterozoic plutons (Figure 5), most of which occur in the interior of the Grenville Province, where they have been variably deformed at amphibolite to granulite facies, and have undergone marginal recrystallization to amphibolite–mafic granulite. Most of these plutons were intruded during the late stages (1650 to 1620 Ma) of the Labradorian orogeny; their genesis, however, whether the result of arc-related plutonism, syn-collisional magmatism or late orogenic crustal extension, is far from clear. In this respect, there is probably considerable overlap, in terms of classification, with plutonic rocks of the cratonic environment.

Layered Mafic Intrusions

These are mostly gabbronorite bodies, but range in composition from ultramafic to anorthosite and their metamorphic derivatives. All intrusions dated so far are mid- to late-Labradorian (1650 to 1620 Ma). A particular characteristic of the rocks is that they contain a relatively high proportion of hydrous minerals.

The most northerly example is the ca. 1649 Ma Adlavik Intrusive Suite, which occurs in the Makkovik Province (Figure 5). This is an undeformed multiphase body, which is fractionated from ultramafic rock to monzodiorite, displays clear cumulate layering and has a hydrous (amphibole–biotite) mafic mineral assemblage. Similar rocks, although more severely metamorphosed, occur throughout the northern Grenville Province of eastern Labrador. The largest of these is the White Bear Arm complex (dated at >1641 Ma by Kamo *et al.*, 1995), which is about 20 km wide and extends continuously along strike for 150 km. Mafic bodies west and northwest of Sandwich Bay may be genetically related to the White Bear Arm complex and were perhaps once linked to it, but dismembered during subsequent, probably Grenvillian, orogenesis. The dominant rock type is gabbronorite, but anorthositic to leucogabbronoritic and monzonitic to granitic rocks are also present. Thin ultramafic layers occur sporadically throughout the body. Farther northwest, along the northeast edge of the Lake Melville terrane, most of the bodies are two-pyroxene mafic granulites. North of Lake Melville, rocks in a comparable structural setting termed leucomonzonitic granulite by Gower (1986) are probably part of the same genetic package.

In the Grenville Province of central Labrador, layered mafic intrusions in the Red Wine Mountains area (Figure 5) include minor ultramafic rocks, gabbronorite, gabbro, hypersthene monzodiorite and quartz monzonite. These are intruded into high-grade supracrustal rocks, including some units possibly derived from mafic lavas, a setting analogous to the mafic pillow lavas in the Paradise metasedimentary gneiss belt adjacent to the White Bear Arm complex. Farther west, in the Lake Joseph terrane, comparable layered mafic rocks are found in the ca. 1639 Ma Ossok Mountain Intrusive Suite (James, 1994).

Large areas of undated and unnamed mafic plutonic rocks also occur south of Lake Melville near the Quebec border (Figure 5). For the most part, these are known only from reconnaissance mapping (e.g., Stevenson, 1967) and are reported to include anorthosite, gabbro and diorite. Work by Wardle *et al.* (1990b), on the northwestern part of this unit, indicates that biotite gabbro and monzogabbro are the main rock types, and that at least part of the unit probably belongs to the Mealy Mountains Intrusive Suite (see below). Other parts of the unit may, however, be of different age and association.

The mineral potential of the Labradorian layered mafic intrusions remains largely unknown. Few mineralized localities have been identified, but there are significant lake-sediment geochemical anomalies associated with many of the intrusions. The White Bear Arm complex, for example, has pronounced Ni, Co and Cu anomalies, especially in its eastern half. A gossan at Mountain Brook, in the White Bear Arm complex, gave assay values of 0.15 percent Cu and 0.13 percent Ni (Douglas, 1976).

Anorthosite–Gabbro Plutons

The Mealy Mountains Intrusive Suite, although usually considered an anorogenic AMCG (anorthosite–mangerite–charnockite–granite) suite akin to the Mesoproterozoic examples described above, can be conceptually grouped with the mid- to late-Labradorian layered mafic intrusive suites on the basis of its comparable ca. 1645 to 1635 Ma age and similar tectonic setting.

Very little is known about this intrusion but according to Emslie (1976) it is composed predominantly of leucotroctolite in the southwest and anorthosite–leucogabbro in the northeast. Smaller, mafic sub-intrusions or border zones have not been recognized, but this might simply be a function of the reconnaissance scale at which Emslie's mapping was carried out. A more detailed image of the intrusion will be available following mapping of its southern part by one of the authors (CFG) during the 1995 field season.

Spatially associated with the Mealy Mountains Intrusive Suite is the ca. 1625 Ma North West River anorthositic suite (Wardle *et al.*, 1990a), which consists of a basal, layered metagabbro–amphibolite unit and an upper, layered to massive anorthosite–leuconorite zone.

The 150-km-long layered Alexis River anorthosite (Figure 5) is probably also a Labradorian intrusion, although it remains undated at present.

Mineralization in the Mealy Mountains anorthosite consists mainly of Fe–Ti oxide concentrations but Emslie (1976) reported several gossan zones, some nearly 100 m across, containing small amounts of disseminated pyrrhotite and chalcopyrite (Figure 5). The Alexis River anorthosite also contains three small pyrite–pyrrhotite–chalcopyrite occurrences, two of which are reported to contain minor Cu–Ni values and one also having minor Co values (Douglas, 1976). Gower *et al.* (1987) described 3 by 2 m pods of a nonmagnetic, black, metallic mineral associated with anorthositic rocks in the intrusion, located 45 km northwest of Port Hope Simpson. The mineral is thought to be ilmenite, but unfortunately the sample collected was lost before analysis could be carried out.

SYNVOLCANIC (ARCHEAN) ENVIRONMENTS

Archean volcanic and mineralization environments were, in some respects at least, different form those of the Proterozoic and have been considered by Naldrett (1989) in a separate category. This may not be entirely valid but provides a convenient method of organizing description.

Komatiite and Tholeiite Environments

Archean greenstone belts are known to contain Ni sulphides in association with flows and sills of komatiitic composition. An example of these deposits is the Kambalda district of Western Australia (Lesher, 1989), where Ni mineralization occurs at the base of komatiitic flows and sills.

Archean volcanic belts in Labrador are represented by the Florence Lake and Hunt River groups of the southern Nain Province (Hopedale block–Figures 1 and 5). The Florence Lake Group (Ermanovics, 1993) consists of strongly foliated, greenschist-facies, mafic volcanic rocks intercalated with lesser amounts of intermediate to felsic volcanic rocks, pelitic metasediment, and ultramafic rocks. The ultramafic rocks are generally preserved as talc–amphibole–serpentine schists up to 8 km in length by 300 m in width. Very few primary minerals or textures are preserved, but analytical work by Brace (1990) has indicated a komatiitic composition. Whether these rocks represent flows or sills (or both) is not clear.

The Hunt River Group, which is believed to be older than the Florence Lake Group (Figure 5), consists predominantly of amphibolite schists of uncertain extrusive and/or intrusive origin, minor amounts of pelitic schist, and deformed anorthosite and ultramafic intrusions. The anorthosites occur as kilometre scale and smaller remnants that are locally layered and contain minor amounts of metagabbro and ultramafic rocks. The ultramafic rocks consist of hornblende, tremolite and serpentine schists (Jesseau, 1976), and occur as concordant sills and/or dykes up to 4 km in length and 50 m in width.

Archean supracrustal belts are abundant in the northern Nain Province (Saglek block, Figures 1 and 5) where they comprise thin (generally <1 km in width) discontinuous units of massive to layered amphibolite–mafic granulite intercalated with metasedimentary gneiss, anorthosite and podiform ultramafic rocks (Bridgwater *et al.*, 1975; Ryan and Martineau, 1992). Inclusions of ultramafic (metadunite to metapyroxenite) rock, mafic gneiss and anorthosite are also plentiful in the surrounding granitoid gneisses, where they form the remnants of originally continuous units that have been exploded by tonalite intrusion and subsequent migmatization and deformation.

The Saglek block also contains the small gabbro–anorthosite–ultramafic intrusions of Okakh Island (Van Kranendonk, 1992), Tessiuyakh Bay (Wiener, 1981) and the Sarah Lake Complex (Van Kranendonk, 1992). These are deformed layered intrusions that are probably larger and more completely preserved examples of the smaller disrupted bodies described above.

Fe–Ni–Cu mineralization is known from the Florence Lake Group within the Hopedale block. Several occurrences of pyrrhotite–pyrite–pentlandite–chalcopyrite are hosted by ultramafic rocks (Figure 5). The most prominent of these is the Baikie prospect where mineralization is found in a discontinuous (tectonically disrupted?) talc–carbonate–chlorite schist. The prospect was discovered by BRINEX in 1960 and has more recently (1991-93) been explored by Falconbridge Limited. Brace (1990) has interpreted the Ni mineralization as komatiite-hosted and has compared it with Kambalda-type deposits. Elevated PGE values, up to 497 ppb Pt and 1020 Pd, were initially reported from the prospect but could not be substantiated by subsequent investigation (see Wilton, 1987). On the basis of this and later work (Brace, 1990), maximum values of 93 ppb Pt and 1209 ppb Pd appear more typical. The Hunt River belt, to the north of the Florence Lake Group, contains several pyrite–pyrrhotite showings, but to date is not known to host Ni mineralization, although its rock-type assemblage and postulated environment of formation would appear suitable for komatiite- or tholeiite-hosted mineralization.

Mafic gneisses exposed on some of the islands east of Nain contain at least one rusty Ni–Cu-bearing zone (Ryan and Swinden, 1992). Samples collected from this occurrence assayed at 2417 g/t Cu, 5466 g/t Ni, and 1220 g/t Co. Assays for Au, Pd, and Pt returned 60 ppb, 60 ppb and 10 ppb, respectively.

Unlike the Hopedale block, the Saglek block is not presently known to contain any rock units that have abnormal abundances of base metals. Elevated signatures for Ni in stream and lake sediments (McConnell and Honarvar, 1993) may provide a guide to such mineralization but, on the other hand, may be simply a reflection of the abundance of ultramafic inclusions that exist within the gneiss terrain.

EPILOGUE

This paper has presented information for use by explorationists who are new to Labrador and suggets avenues to pursue in light of the recent significant Ni–Cu–Co sulphide discovery in the Nain Plutonic Suite at Voisey Bay. The approach we have taken has been to review prospective areas based on bedrock targets and environments, and we have given little attention to other parameters such as geochemistry and geophysics. This is solely a function of space limitations. Regional geochemical element data from surface waters and sediments have been released for all of the areas we have discussed, and some bedrock geochemistry is also available in the literature. Elsewhere, the bedrock geochemical signatures have been used as a guide to refining the focus of exploration programs (for example, extreme depletion of basaltic lavas in Ni and Cu at Noril'sk indicating extraction of metals in the plutonic setting). Such data could serve the same purpose in Labrador in the future–for instance, establishing signatures from the Voisey Bay area that could be applied to the other basic rocks of the Nain area, or comparing the Seal Lake basaltic flows with the Naskaupi sills. We recommend that readers interested in further data from Labrador consult with personnel of the Geological Survey for additional information regarding the availability of whole-rock data, geochemical maps, geological maps, and mineral-occurrence maps for those areas in which they may wish to mount exploration programs.

ACKNOWLEDGMENTS

This paper draws on an accumulated body of knowledge within the geological surveys of Newfoundland and Canada and at various universities. Accordingly, we acknowledge the many contributions of our colleagues, particularly R. Emslie, I. Ermanovics, S. Swinden, D. James and D. Wilton, to ideas concerning the mafic plutonic environments of Labrador. Ryan acknowledges the support of funds from the Executive level of the Department that enabled him to attend a one-day short course on magmatic sulphide deposits held in Toronto in December of 1994, and thanks A.J. Naldrett, R.R. Keays and P.C. Lightfoot for enlightening discussions during that time. Ryan also wishes to thank Albert Chislett and Chris Verbiski of Archean Resources for sharing the excitement of the Voisey Bay discovery, taking it from a 'gossan zone' on a map to one of the most significant massive sulphide discoveries in Canada in recent years.

REFERENCES

Ashwal, L.D., Wiebe, R.A., Wooden, J.L., Whitehouse, M.J. and Snyder, D.

1992: Pre-Elsonian mafic magmatism in the Nain igneous complex, Labrador: the Bridges layered intrusion. Precambrian Research, Volume 56, pages 73-87.

Atkinson, J.R.

1986: Report on the geological and geochemical investigations of the Kiglapait property, Labrador. Unpublished report for Platinum Exploration Canada, Newfoundland Department of Natural Resources, Geological Survey File [Lab 769], 15 pages plus appendix.

Baragar, W.R.A.

1967: Wakuach Lake map area, Quebec–Labrador (23O). Geological Survey of Canada, Memoir 344, 174 pages.

1981: Tectonic and regional relationships of the Seal Lake and Bruce River magmatic provinces. Geological Survey of Canada, Bulletin 314, 72 pages.

Barr, D.A.

1970: Geology and geochemical surveys of the Kiglapait intrusion, 1970. Unpublished report for Kennco Exploration (Canada) Ltd. Newfoundland Department of Natural Resources, Geological Survey File [14F/6], 16 pages.

Barton, J.M., Jr.

1974: Progress of isotopic and geochemical investigations, coastal Labrador, 1973. *In* The Nain Anorthosite Project, Labrador: Field Report, 1973. *Edited by* S.A. Morse. University of Massachusetts, Geology Department, Contribution No. 13, pages 19-28.

1975: The Mugford Group Volcanics of Labrador: age, geochemistry and tectonic setting. Canadian Journal of Earth Sciences, Volume 12, pages 1196-1208.

Berg, J.H.

1973: Geology of the Hettasch Lake area. *In* The Nain Anorthosite Project, Labrador: Field Report, 1972. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 11, pages 49-64.

1979: Physical constraints and tectonic setting of the Nain Complex. Geological Association of Canada–Mineralogical Association of Canada, Program with Abstracts, Volume 4, page 39.

1980: Snowflake troctolite in the Hettasch Intrusion, Labrador: Evidence for magma-mixing and supercooling in a plutonic environment. Contributions to Mineralogy and Petrology, Volume 72, pages 339-351.

Berg, J.H. and Briegel, J.S.

1983: Geology of the Jonathon intrusion and associated rocks. *In* The Nain Anorthosite Project, Labrador: Field Report, 1981. *Edited by* S.A. Morse. University of Massachusetts, Department of Geology and Geography, Contribution No. 40, pages 43-50.

Berg, J.H., Emslie, R.F., Hamilton, M.A., Morse, S.A., Ryan, A.B. and Wiebe, R.A.

1994: Anorthositic, granitoid, and related rocks of the Nain Plutonic Suite. Guidebook to a field excursion to the Nain area, August 4-10, 1994. International Geological Correlation Program Projects #290 and #315, 69 pages.

Berg, J.H. and Pencak, M.S.

1981: Troctolitic rocks in the Nain Complex. *In* The Nain Anorthosite Project, Labrador: Field Report, 1980. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 38, pages 59-64.

Bertrand, J-M., Roddick, J.C., Van Kranendonk, M.J., and Ermanovics, I.

1993: U–Pb geochronology of deformation and metamorphism across a central transect of the Early Proterozoic Torngat Orogen, North River map area, Labrador. Canadian Journal of Earth Sciences, Volume 30, pages 1470-1489.

Birkett, T.C., Watanabe, D.H., Richardson, D.G., Findlay, J.M. and Fowler, A.D.

1991: Non-ferrous mineral resource assessment, western Labrador, north of 54 degrees latitude. Geological Survey of Canada, Open File 2370, 27 pages.

Bostock, H.H.

1983: Precambrian rocks of the Strait of Belle Isle area. *In* Geology of the Strait of Belle Isle, Northwestern Insular Newfoundland, Southern Labrador, and Adjacent Quebec. *Edited by* H.H. Bostock, L.M. Cumming, H. Williams and W.R. Smyth. Geological Survey of Canada, Memoir 400, pages 1-73.

Brace, T.D.

1990: Geology, geochemistry and metallogeny of the Archean Florence Lake Group and associated ultramafic and trondhjemitic rocks, Nain Province, Labrador. Unpublished M.Sc. thesis, Memorial University, St. John's, Newfoundland, 265 pages.

Bridgwater, D., Collerson, K.D., Hurst, R.W. and Jesseau, C.W.

1975: Field characters of the early Precambrian rocks from Saglek, coast of Labrador. Geological Survey of Canada, Paper 74-1A, pages 287-296.

Brummer, J.J. and Mann, E.L.

1961: Geology of the Seal Lake area, Labrador. Geological Society of America Bulletin, Volume 72, pages 1361-1382.

Cadman, A., Tarney, J., Baragar, W.R.A. and Wardle, R.J.

1994: Relationship between Proterozoic dykes and associated volcanic sequences: evidence from the Harp Swarm and Seal Lake Group, Labrador, Canada. Precambrian Research, Volume 68, pages 357-374.

Chai, G. and Naldrett, A.J.

1992a: Characteristics of Ni–Cu–PGE mineralization and genesis of the Jinchuan Deposit, Northwest China. Economic Geology, Volume 87, pages 1475-1495.

1992b: The Jinchuan Ultramafic Intrusion: cumulate of a high-Mg basaltic magma. Journal of Petrology, Volume 33, pages 277-304.

Connelly, J.N. and Ryan, B.

1994: Late Archean and Proterozoic events in the central Nain craton. *In* Eastern Canadian Onshore-Offshore Transect (ECSOOT). *Edited by* R.J. Wardle and J. Hall. Report of Transect Meeting (December 10-11, 1993), University of British Columbia, LITHOPROBE Secretariat, Report 36, pages 53-61.

Davies, H.M.
1974: Geology of Nukasorsuktokh Island. *In* The Nain Anorthosite Project Labrador: Field Report 1973. *Edited by* S.A. Morse. Department of Geology, University of Massachusetts, Contribution Number 13, pages 81-97.

de Waard, D.
1976: Anorthosite-adamellite-troctolite layering in the Barth Island structure of the Nain complex, Labrador. Lithos, Volume 9, pages 293-308.

de Waard, D. and Mulhern, K.
1973: The Barth layered structure. *In* The Nain Anorthosite Project, Labrador: Field Report, 1972. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 11, pages 71-80.

Deuring, D.E.
1977: The Akpaume layered intrusion: further investigations. *In* The Nain Anorthosite Project, Labrador: Field Report, 1976. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 29, pages 35-40.

Douglas, C.
1976: Mineral occurrence tables, Labrador. To accompany mineral occurrence map of Labrador (Map 761). Newfoundland Department of Mines and Energy, Mineral Development Division, Open File Lab 326, 94 pages.

Emslie, R.F.
1970: The geology of the Michikamau Intrusion, Labrador (13L, 23I). Geological Survey of Canada, Paper 68-57, 85 pages.

1976: Mealy Mountains Complex, Grenville Province, southern Labrador. *In* Report of Activities. Geological Survey of Canada, Paper 76-1A, pages 165-169.

1980: Geology and petrology of the Harp Lake Complex, central Labrador: an example of Elsonian magmatism. Geological Survey of Canada, Bulletin 293, 136 pages.

1985: Proterozoic anorthosite massifs. *In* The Deep Proterozoic Crust in the North Atlantic Provinces. *Edited by* A.C. Tobi and J.R.L. Touret. NATO Advanced Study Institute, Series C, Volume 158, D. Reidel, Dordrecht, pages 39-60.

Emslie, R.F., Hamilton, M.A. and Thériault, R.J.
1994: Petrogenesis of a Mid-Proterozoic anorthosite-mangerite-charnockite-granite (AMCG) complex: isotopic and chemical evidence from the Nain Plutonic Suite. Journal of Geology, Volume 102, pages 539-558.

Emslie, R.F. and Loveridge, W.D.
1992: Fluorite-bearing Early and Middle Proterozoic granites, Okak Bay area, Labrador: Geochronology, geochemistry and petrogenesis. Lithos, Volume 28, pages 87-109.

Emslie, R.F., Lefebvre, C.E., Kjarsgaard, B. and Sherlock, R.
1986: Atikonak River Massif, Labrador. *In* Current Research, Part A. Geological Survey of Canada, Paper 86-1A, pages 755-758.

Emslie, R.F. and Russell, W.J.
1988: Umiakovik Lake batholith and other felsic intrusions, Okakh Bay area, Labrador. *In* Current Research, Part C. Geological Survey of Canada, Paper 88-1C, pages 27-32.

Emslie, R.F. and Stirling, J.A.R.
1993: Rapakivi and related granitoids of the Nain Plutonic Suite: geochemistry, mineral assemblages and fluid equilibria. Canadian Mineralogist, Volume 31, pages 821-847.

Ermanovics, I.
1993: Geology of the Hopedale Block, southern Nain Province, and the adjacent Proterozoic terranes, Labrador, Newfoundland. Geological Survey of Canada, Memoir 431, 161 pages.

Fahrig, W.F.
1962: Petrology and geochemistry of the Griffis Lake ultrabasic sill of the central Labrador Trough, Quebec. Geological Survey of Canada, Bulletin 77, 39 pages.

Feininger, T. and Ermanovics, I.
1994: Geophysical interpretation of the Torngat orogen along the North River–Nutak transect, Labrador. Canadian Journal of Earth Sciences, Volume 31, pages 722-727.

Gower, C.F.
1986: Geology of the Double Mer White Hills and surrounding region, Grenville Province, eastern Labrador. Geological Survey of Canada, Paper 86-15, 52 pages.

Gower, C.F., Neuland, S., Newman, M. and Smyth, J.
1987: Geology of the Port Hope Simpson map region, Grenville Province, eastern Labrador. *In* Current Research. Newfoundland Department of Mines, Mineral Development Division, Report 87-1, pages 183-199.

Gower, C.F., Noel, N. and Gillespie, R.T.
1983: Groswater Bay map region. Newfoundland Department of Mines and Energy, Mineral Development Division, Map 8343.

Gower, C.F., McConnell, J.W. and van Nostrand, T.
1995: New mineral exploration targets in the Pinware terrane, Grenville Province, southeast Labrador. *In* Current Research. Newfoundland Department of Natural Resources, Geological Survey, Report 95-1, pages 15-24.

Gower, C.F., Rivers, T. and Brewer, T.S.
1990: Middle Proterozoic mafic magmatism in Labrador, eastern Canada. *In* Mid-Proterozoic Laurentia-Baltica. *Edited by* C.F. Gower, T. Rivers and A.B. Ryan. Geological Association of Canada, Special Paper 38, pages 485-506.

Gower, C.F. and Ryan, B.
1986: Proterozoic evolution of the Grenville Province and adjacent Makkovik Province in east-central Labrador. *In* The Grenville Province. *Edited by* J.M. Moore, A. Davidson and A.J. Baer. Geological Association of Canada, Special Paper 31, pages 281-296.

Grimley, P.H.
1955: Showings in Nain and Tikkoatokak Bay areas, Labrador. Unpublished report for BRINEX, Newfoundland Department of Natural Resources, Geological Survey File [14D/9 (12)].

Hamilton, M.A.
1994: Tholeiitic and weakly alkalic basaltic volcanism of the Mugford Group, northern Labrador: preliminary geochemical results. *In* Current Research, Part C. Geological Survey of Canada, Report 1994-1C, pages 333-342.

Hamilton, M.A., Emslie, R.F. and Roddick, J.C.
1994: Detailed emplacement chronology of basic magmas of the Mid-Proterozoic Nain Plutonic Suite, Labrador: insights from U-Pb systematics in zircon and baddeleyite. Eighth International Conference on Cosmochronology and Isotope Geology. United States Geological Survey Circular 1107, page 124.

Hoatson, D.M. and Keays, R.R.
1989: Formation of platiniferous sulphide horizons by crystal fractionation and magma mixing in the Munni Munni layered intrusion, West Pilbara Block, Western Australia. Economic Geology, Volume 84, pages 1775-1804.

James, D.T.
1994: Geology of the Grenville Province in the Lac Joseph and Ossokmanuan Lake areas (23A/NW and 23H/SW), western Labrador. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 94-2, 58 pages.

James, D.T. and Mahoney, K.L.
1994: Structural, metamorphic and intrusive relations in the hinterland of the eastern Churchill Province, western Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 93-1, pages 371-385.

Jesseau, C.W.
1976: A structural, metamorphic and geochemical study of the Hunt River supracrustal belt, Nain Province, Labrador. Unpublished M.Sc. thesis, Memorial University of Newfoundland, St. John's, Newfoundland, 211 pages.

Jones, R.A.
1975: Harp Lake Intrusion, central Labrador progress report. Unpublished report for Kennco Explorations (Canada) Ltd., Newfoundland Department of Natural Resources, Geological Survey File [Lab 310], 49 pages.

Kamo, S.L., Wasteneys, H., Gower, C.F. and Krogh, T.E.
1995: U-Pb geochronological constraints on Labradorian events in the eastern Grenville Province of Labrador. Geological Association of Canada, Program with Abstracts, Volume 20.

Krogh, T.E. and Davis, G.L.
1973: The significance of inherited zircons on the age and origin of igneous rocks—an investigation of the Labrador adamellites. Carnegie Institution of Washington Yearbook, Volume 72, pages 610-13.

Kirwan, L.D.
1960: Rocky Cove sulphide showing, Nipishish—Pottles Bay, Labrador Concession. Gunnex Ltd. Unpublished report for BRINEX, Newfoundland Department of Natural Resources, Geological Survey File [13I/5 (3)].

Lesher, C.M.
1989: Komatiite-associated nickel sulphide deposits. *In* Ore Deposition Associated with Magmas. *Edited by* J.A. Whitney and A.J. Naldrett. Reviews in Economic Geology, Volume 4, pages 45-101.

Lightfoot, P.C. and Keays, R.R.
1994: New approaches to targeting giant magmatic Ni-Cu-PGE deposits in Ontario. Short Course Notes from a one-day seminar held in Toronto, December 8, 1994, 158 pages.

McAuslan, D.A.
1973a: Report on reconnaissance program—1972 Harp Lake Intrusion, central Labrador. Unpublished report for Kennco Explorations (Canada) Limited, Newfoundland Department of Natural Resources, Geological Survey File [Lab 235], 29 pages.

1973b: Report on reconnaissance program—1973 Harp Lake Intrusion, central Labrador. Unpublished report for Kennco Explorations (Canada) Limited, Newfoundland Department of Natural Resources, Geological Survey File [Lab 337], 29 pages.

McConnell, J.W. and Honarvar, P.
1993: First year results of detailed stream-sediment and water geochemical survey in northern Labrador. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File Lab 0969, 31 pages.

Meyer, J. and Montague, E.
1994: The Ten Mile Bay anorthosite quarry, northern Labrador. *In* Ore Horizons. *Edited by* A. Hogan and H.S. Swinden. Newfoundland Department of Mines and Energy, Geological Survey Branch, Volume 2, pages 129-141.

Miller, R.R.
1986: Geology of the Strange Lake Alkalic Complex and the associated Zr-Y-Nb-Be-REE mineralization. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 11-20

Morgan, W.C.
1975: Geology of the Precambrian Ramah Group and basement rocks in the Nachvak Fiord—Saglek Fiord area, North Labrador. Geological Survey of Canada, Paper 74-54, 42 pages.

Morse, S.A.
1969: The Kiglapait Layered Intrusion, Labrador. The Geological Society of America, Memoir 112, 204 pages.

1980: Kiglapait Mineralogy II: Fe-Ti oxide minerals and the activities of oxygen and silica. Journal of Petrology, Volume 21, pages 685-719.

1983: Reconnaissance geology of the Bird Lake massif, Labrador. *In* Nain Anorthosite Project, Labrador: Field Report, 1981. *Edited by* S.A. Morse. Department of Geology and Geography, University of Massachusetts, Contribution No. 40, pages 37-41.

1971-1983: Nain Anorthosite Project, Labrador: Field Reports. Department of Geology, University of Massachusetts, Contributions 9, 11, 13, 17, 26, 29, 38 and 40.

Morse, S.A. and Wheeler, E.P.
1974: Layered anorthosite massifs along Tikkoatokhakh Bay. *In* The Nain Anorthosite Project, Labrador: Field Report, 1973. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 13, pages 129-132.

Naldrett, A.J.
1973: Nickel sulphide deposits—their classification and genesis with special emphasis on deposits of volcanic association. Transactions of the Canadian Institute of Mining and Metallurgy, Volume 76, pages 183-201.

1989: Introduction: Magmatic deposits associated with mafic rocks. *In* Ore Deposition Associated with Magmas. *Edited by* J.A. Whitney and A.J. Naldrett. Reviews in Economic Geology, Volume 4, pages 1-3.

1992: A model for the Ni-Cu-PGE ores of the Noril'sk region and its application to other areas of flood basalt. Economic Geology, Volume 87, pages 1945-1962.

Naldrett, A.J. and Cabri, L.J.
1976: Ultramafic and related mafic rocks: their classification and genesis with special reference to concentration of nickel sulphides and platinum-group elements. Economic Geology, Volume 71, pages 1131-1158.

Naldrett, A.J. and Macdonald, A.J.
1980: Tectonic settings of Ni-Cu sulphide ores: their importance in genesis and exploration. *In* The Continental Crust and Its Mineral Deposits. *Edited by* D.W. Strangway. Geological Association of Canada, Special Paper 20, pages 631-637.

Nunn, G.A.G.
1993: Geology of the northeastern Smallwood Reservoir (NTS map area 13L/SW), Labrador. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 93-3, 140 pages.

Nunn, G.A.G., Emslie, R.F., Lefebvre, C.E., Noel, N. and Wells, S.
1986: The Atikonak River massif and surrounding area, western Labrador and Quebec. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 125-145.

Rajamani, V. and Naldrett, A.J.
1978: Partitioning of Fe, Co, Ni and Cu between sulphide liquid and basaltic melts and the composition of Ni-Cu sulphide deposits. Economic Geology, Volume 73, pages 82-93.

Reusch, D.
1986: A rock and stream sediment sampling program to evaluate copper-nickel showings in the Harp Lake Complex, Labrador (NTS: 13K, 13L, 13M, 13N) for platinum and palladium, August and September, 1986. Unpublished report for Platinum Exploration Canada Inc. Newfoundland Department of Natural Resources, Geological Survey, File [Lab 770].

Royse, K.R. and Ryan, B.
1995: Structural evolution and emplacement of the Nain Plutonic Suite in the Dog Island area. *In* Current Research. Newfoundland Department of Natural Resources, Geological Survey, Report 95-1, pages 37-45.

Rubins, C.C.R.
1971: The Barth Island troctolite body: granulite-adamellite-anorthosite relations at the northern margin. *In* The Nain Anorthosite Project, Labrador: Field Report, 1971. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 9, pages 34-42.

Ryan, B.
1990: Geological map of the Nain Plutonic Suite and surrounding rocks (Nain-Nutak, NTS 14SW). Newfoundland Department of Mines and Energy, Geological Survey Branch, Map 90-44, scale 1:500 000.

1991: Makhavinekh Lake pluton, Labrador, Canada: geological setting, subdivisions, mode of emplacement and a comparison with Finnish rapakivi granites. Precambrian Research, Volume 51, pages 193-225.

1992: Nain area geology: observations on selected islands, and the area south of Nain Bay (NTS 14C/6,14; 14D/9). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 92-1, pages 381-398.

1993: Further results of mapping gneissic and plutonic rocks of the Nain Bay area, Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 92-1, pages 61-75.

Ryan, B. and Emslie, R.F.
1994: Pre-Elsonian mafic magmatism in the Nain Igneous complex, Labrador: the Bridges layered intrusion—comment. Precambrian Research, Volume 68, pages 179-181.

Ryan, B., Krogh, T. E., Heaman, L., Schärer, U., Philippe, S. and Oliver, G.
1991: On recent geochronological studies in the Nain Province, Churchill Province, and Nain Plutonic Suite, north-central Labrador. *In* Current Research. Newfoundland Department of Mines, Geological Survey Branch, Report 91-1, pages 257-261.

Ryan, B. and Lee, D.
1986: Gneiss-anorthosite granite relationships in the Anaktalik Brook—Kogaluk River area (NTS 14D/1,8), Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 86-1, pages 79-88.

1989: Geological map of the Reid Brook area (14D/8), 1:50 000. Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File 89-18.

Ryan, B. and Martineau, Y.
1992: Geology of the Saglek Fiord—Hebron Fiord area, Labrador (NTS 14L/2,3,6,7). Newfoundland Department of Mines and Energy, Geological Survey Branch, Open File Map 92-18 and Geological Survey of Canada, Open File 2466, 1:100 000 scale.

Ryan, A.B., Martineau, Y., Bridgwater, D., Schiøtte, L. and Lewry, J.
1983: The Archean—Proterozoic boundary in the Saglek Fiord area, Labrador: Report 1. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 83-1, pages 91-98.

Ryan, B. and Swinden, S.
1992: Cu-Ni sulphide mineralization in the Nain area. *In* Report of Activities, 1992. Newfoundland Department of Mines and Energy, Geological Survey Branch, pages 101-102.

Scott, F.
1988: Exploration for Platinum-Group Elements in the Labrador Trough, Canada. *In* Geo-platinum 87. *Edited by* M. Pritchard, P.J. Potts, J.F.W. Bowles and S.J. Cribb. Elsevier, pages 211-214.

Shirey, S.B.
1975: Sulphides and sulphur content of the Kiglapait layered intrusion, Labrador. Unpublished M.Sc. thesis, University of Massachusetts, Amherst, 76 pages.

Simmons, K.R., Wiebe, R.A., Snyder, G.A. and Simmons, E.C.
1986: U—Pb zircon age for the Newark Island layered intrusion, Nain anorthosite complex. Geological Society of America, Abstracts and Program, Volume 18, page 751.

Skulski, T., Wares, R.P. and Smith, A.D.
1993: Early Proterozoic (1.88—1.87 Ga) tholeiitic magmatism in the New Quebec Orogen. Canadian Journal of Earth Sciences, Volume 30, pages 1505-1520.

Smyth, W.R.
1976: Geology of the Mugford Group, northern Labrador. *In* Report of Activities. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 76-1, pages 72-79.

Stevenson, I.M.
1967: Geology Minipi Lake, Newfoundland. Geological Survey of Canada, Map 6-1967.

Swinden, H.S, Wardle, R.J., Davenport, P.H., Gower, C.F., Kerr, A., Meyer, J.R., Miller, R.R., Nolan, L., Ryan, A.B. and Wilton, D.H.C.
1991: Mineral exploration opportunities in Labrador: A perspective for the 1990's. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 91-1, pages 349-390.

Van Kranendonk, M.J.
1992: Geological evolution of the Archean Nain Province and the Early Proterozoic Torngat Orogen as seen along a transect in the North River—Nutak map area, northern Labrador, Canada. Unpublished Ph.D. thesis, Queen's University, Kingston, Ontario, Canada, 477 pages.

Van Kranendonk, M.J. and Ermanovics, I.F.
1990: Structural evolution of the Hudsonian Torngat Orogen in the North River map area, Labrador; evidence for east-west transpressive collision of Nain and Rae continental blocks. Geoscience Canada, Volume 17, pages 283-288.

Walls, J.R.
1988: Report on the geological, geophysical and geochemical exploration program on the Kiglapait property, Labrador, volume I of II, July 13 to August 7 1988. Unpublished report for International Platinum Corporation, Newfoundland Department of Natural Resources, Geological Survey File [Lab 800], 30 pages plus appendix.

Wardle, R.J.
1987: Platinum-Group-Element potential in Labrador. *In* Current Research. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 87-1, pages 211-223.

Wardle, R.J., Ryan, B. and Ermanovics, I.
1990: The Eastern Churchill Province, Torngat and New Quebec orogens: An overview. Geoscience Canada, Volume 17, pages 217-222.

Wardle, R.J., Ryan, A.B., Philippe, S. and Schärer, U.
1990a: Proterozoic crustal development, Goose Bay region, Grenville Province, Labrador, Canada. *In* Mid-Proterozoic Laurentia-Baltica. *Edited by* C.F. Gower, T. Rivers and B. Ryan. Geological Association of Canada, Special Paper 38, pages 197-214.

Wardle, R.J., Crisby-Whittle, L.V.J. and Blomberg, P.
1990b: Geology of the Minipi River area (NTS 13C/NW). *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 90-1, pages 267-276.

Wardle, R.J., Van Kranedonk, M.J., Mengel, F. and Scott, D.
1992: Geological mapping in the Torngat Orogen, northernmost Labrador: preliminary results. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 92-1, pages 413-429.

Ware, M.J. and Wardle, R.J.
1979: Geology of the Sims—Evening Lake area with emphasis on the Helikian Sims Group. Newfoundland Department of Mines and Energy, Mineral Development Division, Report 79-5, 22 pages.

Wheeler, E.P.
1942: Anorthosite and associated rocks about Nain, Labrador. Journal of Geology, Volume 50, pages 611-642.

1960: Anorthosite-adamellite complex of Nain, Labrador. Geological Society of America Bulletin, Volume 71, pages 1755-1762.

1969: Minor intrusives associated with the Nain anorthosite. *In* Origin of Anorthosite and Related Rocks. *Edited by* Y.W. Isachsen. New York State Museum Science Service, Memoir 18, Albany, New York, pages 189-206.

Whitney, J.A. and Naldrett, A.J.
1989: Ore Deposition Associated with Magmas. Reviews in Economic Geology, Society of Economic Geologists, Volume 4, 250 pages.

Wiebe, R.A.
1976: Geology of northern Tunungayualok Island and vicinity. *In* The Nain Anorthosite Project, Labrador: Field Report, 1974. *Edited by* S.A. Morse. Geology Department, University of Massachusetts, Contribution No. 17, pages 37-47.

1980: Commingling of contrasted magmas in the plutonic environment: examples from the Nain anorthosite complex. Journal of Geology, Volume 88, pages 197-209.

1987: Rupture and inflation of a basic magma chamber by silicic liquid. Nature, Volume 6108, pages 69-71.

1988: Structural and magmatic evolution of a magma chamber: the Newark Island layered intrusion, Nain, Labrador. Journal of Petrology, Volume 29, pages 383-411.

1990a: Dioritic rocks in the Nain Complex, Labrador. Schweizerische Mineralogische und Petrographische Mitteilungen, Volume 70, pages 199-208.

1990b: Evidence for unusually feldspathic liquids in the Nain Complex, Labrador. American Mineralogist, Volume 75, pages 1-12.

Wiebe, R.A. and Snyder, D.
1993: Slow, dense replenishments of a basic magma chamber: the Newark Island layered intrusion, Nain, Labrador. Contributions to Mineralogy and Petrology, Volume 113, pages 59-72.

Wiebe, R.A. and Wild, T.
1983: Fractional crystallization and magma mixing in the Tigalak layered intrusion, the Nain anorthosite complex, Labrador. Contributions to Mineralogy and Petrology, Volume 84, pages 327-344.

Wiener, R.W.
1981: Tectonic setting, rock chemistry and metamorphism of an Archean gabbro-anorthosite complex, Tessiuyakh Bay, Labrador. Canadian Journal of Earth Sciences, Volume 18, pages 1409-1421.

Wilton, D.H.C.
1987: Report on the geology of the Baikie Property, northeast of Florence Lake, Labrador. Unpublished report for Platinum Exploration Canada Inc. Newfoundland Department of Natural Resources, Geological Survey, File [13K/15/174] (microfiche).

1989: Studies in the Seal Lake Group, central Labrador, Part II: Geochemistry of diabase sills. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey of Newfoundland, Report 89-1, pages 35-36.

1994: The Mugford Group, northern Labrador, revisited: notes from a continuing study. *In* Current Research. Newfoundland Department of Mines and Energy, Geological Survey Branch, Report 94-1, pages 409-414.

Xue, S. and Morse, S.A.
1993: Geochemistry of the Nain massif anorthosite, Labrador: magma diversity in five intrusions. Geochimica et Cosmochimica Acta, Volume 57, pages 3925-3948.

Yu, Y. and Morse, S.A.
1992: Age and cooling history of the Kiglapait Intrusion from an ^{40}Ar/^{39}Ar study. Geochimica et Cosmochimica Acta, Volume 5, pages 2471-2485.

1993: ^{40}Ar/^{39}Ar chronology of the Nain anorthosites, Canada. Canadian Journal of Earth Sciences, Volume 30, pages 1166-1178.

Note: Geological Survey file numbers are included in square brackets.