

# The 1997 Howard Street Robinson Lecture: The Mesoproterozoic Nain Plutonic Suite in Eastern Canada, and the Setting of the Voisey's Bay Ni-Cu-Co Sulphide Deposit

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Résumé de l'article

La région nord du Labrador renferme l'un des exemples classiques de terrane magmatique d'origine anorogénique de la planète, la Suite plutonique méso-protérozoïque du Nain (SPN). Cette suite est constituée d'une gamme étendue d'intrusions basiques et acides agglomérées qui se sont mises en place de part et d'autre d'une suture paléo-protérozoïque continentale, il y a environ 1,35 et 1,29 Ga. Les modèles tectoniques de mise en place de cette SPN nous renvoient aux géomécanismes qui se produisent là où une venue matellique en panache touche la base de l'écorce terrestre. La SPN est en grande partie, un terrane igné bimodal dont les types lithiques prédominants sont anorthositiques et granitiques. Les roches troctolitiques et les diorites riches en fer constituent des groupes d'importance secondaire. L'intrusion de Reed Brook qui est le plus vieux pluton troctolitique de la SPN à ce jour, est l'hôte d'un important gisement magmatique de sulfures de Ni-Cu-Co, et qui a été découvert en 1993 au nord de la baie de Voisy. Les concentrations minérales se retrouvent dans trois contextes minéraux différents, soit dans un dyke troctolitique (Discovery Hillet Western Extension), dans une zone en forme de cuvette constituée principalement de sulfures massifs et reposant sur un gneiss (VOvoid), ainsi que dans les couches inférieures d'une importante intrusion de troctolite, les Easterns Deeps. L'un des modèles qui pourraient expliquer la configuration géométrique des éléments du gisement de la baie de Voisy est basé sur les mécanismes physiques et chimiques qui accompagnent l'ascension et les précipitations associées à un magma mantellique acide saturé en sulfures, s'élevant dans la partie médiane à supérieure de la croûte, dans une chambre de dilatation. En recoupant des paragneiss paléo-protérozoïques saturés en sulfures dans la partie profonde de la croûte, le magma acide aurait pu libérer un autre magma de sulfures non miscible toutefois, la solution saturée en sulfures pourrait tout aussi bien être entièrement d'origine mantellique juvénile. L'origine de la minéralisation, la définition de toutes les zones minéralisées ainsi que de la forme tridimensionnelle de l'intrusion troctolitique hôte sont actuellement l'objet d'études, et nul doute que les résultats de ces études entraîneront des révisions du modèle de travail présenté ici. Il n'y a pas de doute non plus qu'une fois les exigences de l'entreprise privée, des gouvernements et des populations autochtones auront été satisfaites en ce qui a trait aux conditions de sa mise en valeur, l'exploitation de cette importante ressource de nickel-cuivre-cobalt de classe mondiale aura des retombées économiques positives durant des décennies à venir, autant pour la province de Terre-Neuve et le Labrador que pour tout le Canada.

# The 1997 Howard Street Robinson Lecture<sup>1</sup>



## The Mesoproterozoic Nain Plutonic Suite in Eastern Canada, and the Setting of the Voisey's Bay Ni-Cu-Co Sulphide Deposit

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### SUMMARY

Northern Labrador is home to one of the world's classic anorogenic magmatic terranes, the Mesoproterozoic Nain Plutonic Suite (NPS), comprising a broad spectrum of coalesced basic and silicic intrusions emplaced ca. 1.35-1.29 Ga astride a Paleoproterozoic continental suture zone. Tectonic models for the development of the NPS relate it to processes associated with a mantle plume impinging on the base of the crust. The NPS is largely a bimodal igneous terrane, of which the predominant rocks belong to the anorthositic and gra-

nitic components. Troctolitic and iron-rich dioritic rocks are subordinate. The Reid Brook intrusion, the oldest-recognized troctolitic pluton within the NPS, hosts a major ore deposit of magmatic Ni-Cu-Co sulphide minerals that was discovered north of Voisey's Bay in 1993. The ore is concentrated in three main settings: in a troctolitic dyke (Discovery Hill and the Western Extension), in a bowl-shaped zone (the Ovoid, largely massive sulphide) resting on gneiss, and at the lower levels of a massive troctolite body (the Eastern Deeps). One model for the geometry and distribution of the Voisey's Bay deposit can be constructed by application of physical and chemical processes that would accompany the ascent and deposition of a sulphide-saturated, mantle-derived silicate magma into a mid- to upper-crustal dilational chamber. The silicate magma may have liberated a separate immiscible sulphide magma because of sulphide saturation promoted by interaction with Paleoproterozoic sulphur-bearing paragneisses at a deeper level, or the sulphide liquid may be totally of juvenile mantle extraction. The origin of the sulphide ore, the complete distribution of the ore, and the three dimensional shape of the hosting troctolitic intrusion are subjects of active study, and no doubt there will be revisions to the present working model. There is also no doubt — when all private sector, government, and aboriginal concerns about the Voisey's Bay mine development are addressed — that the exploitation of this major world-class nickel-copper-cobalt resource will accrue economic benefits to the province of Newfoundland and Labrador, as well as the rest of Canada, for decades to come.

### RÉSUMÉ

La région nord du Labrador renferme l'un des exemples classiques de terrane magmatique d'origine anorogénique de la planète, la Suite plutonique méso-protérozoïque du Nain (SPN). Cette suite est constituée d'une gamme étendue d'intrusions basiques et acides agglomérées qui se sont mises en place de part et d'autre d'une suture paléo-protérozoïque continentale, il y a environ 1,35 et 1,29 Ga. Les modèles tectoniques de mise en place de cette SPN nous renvoient aux

géométries qui se produisent là où une venue mantellique en panache touche la base de l'écorce terrestre. La SPN est en grande partie, un terrane igné bimodal dont les types lithiques prédominants sont anorthositiques et granitiques. Les roches troctolitiques et les diorites riches en fer constituent des groupes d'importance secondaire. L'intrusion de *Reed Brook* qui est le plus vieux pluton troctolitique de la SPN à ce jour, est l'hôte d'un important gisement magmatique de sulfures de Ni-Cu-Co, et qui a été découvert en 1993 au nord de la baie de Voisy. Les concentrations minérales se retrouvent dans trois contextes minéraux différents, soit dans un dyke troctolitique (*Discovery Hill* et *Western Extension*), dans une zone en forme de cuvette constituée principalement de sulfures massifs et reposant sur un gneiss (*l'Ovoid*), ainsi que dans les couches inférieures d'une importante intrusion de troctolite, les *Easterns Deeps*. L'un des modèles qui pourraient expliquer la configuration géométrique des éléments du gisement de la baie de Voisy est basé sur les mécanismes physiques et chimiques qui accompagnent l'ascension et les précipitations associées à un magma mantellique acide saturé en sulfures, s'élevant dans la partie médiane à supérieure de la croûte, dans une chambre de dilatation. En recoupant des paragneiss paléo-protérozoïques saturés en sulfures dans la partie profonde de la croûte, le magma acide aurait pu libérer un autre magma de sulfures non miscible toutefois, la solution saturée en sulfures pourrait tout aussi bien être entièrement d'origine mantellique juvénile. L'origine de la minéralisation, la définition de toutes les zones minéralisées ainsi que de la forme tridimensionnelle de l'intrusion troctolitique hôte sont actuellement l'objet d'études, et nul doute que les résultats de ces études entraîneront des révisions du modèle de travail présenté ici. Il n'y a pas de doute non plus qu'une fois les exigences de l'entreprise privée, des gouvernements et des populations autochtones auront été satisfaites en ce qui a trait aux conditions de sa mise en valeur, l'exploitation de cette importante ressource de nickel-cuivre-cobalt de classe mondiale aura des retombées économiques positives durant des décennies à

<sup>1</sup> Bruce Ryan was the 1997 Howard Street Robinson Distinguished Lecturer, chosen by GAC's Precambrian Division. Robinson Fund Distinguished Lecturers are chosen by GAC's Precambrian Division or Mineral Deposits Division on an annual alternating basis. Topics and lecturers are chosen to illustrate exciting new findings in Precambrian research or mineral deposit studies. Bruce's lecture on the Nain Plutonic Suite and its importance to the wondrous Voisey's Bay Ni-Cu-Co deposit superbly represents both Precambrian research and mineral deposit studies.

venir, autant pour la province de Terre-Neuve et le Labrador que pour tout le Canada.

## INTRODUCTION

The discovery in 1993 of a major deposit of magmatic nickel-copper-cobalt sulphides within a small troctolitic intrusion north of Voisey's Bay — near Nain, Labrador — sparked considerable academic and exploration interest in the whole terrane of igneous rocks surrounding the deposit. These igneous rocks, termed the Nain Plutonic Suite (NPS), encompass numerous basic, intermediate and silicic plutons that were emplaced during Mesoproterozoic time into crust comprising largely Archean and Paleoproterozoic gneisses. The purposes of this contribution are to i) provide an overview of the setting of the NPS and its compositional diversity, ii) describe the general attributes of the troctolitic host-rock to the Voisey's Bay sulphide deposit, iii) review the main characteristics of the Voisey's Bay deposit and discuss its origin within the context of genetic models advocated for the formation of magmatic sulphides elsewhere, and iv) show how the discovery of the Voisey's Bay deposit — and the unfolding events with respect to its development — have affected, and will affect, the province of Newfoundland and Labrador.

This is a review paper. In part it includes verbatim extracts from data presented elsewhere (Ryan *et al.*, 1995; Ryan, 1997), but also includes updates, revisions and expansions of these data. It draws upon numerous sources in other relevant geological literature — only a sprinkling of which are credited within the body of this paper — and brings together disparate topics in an attempt to provide a unified picture of the geology of the Nain area and the formation of the Voisey's Bay deposit. In addition to the non-specialist general reader, this paper is aimed at senior undergraduate level classes; it uses published information on the Nain area in concert with literature on various aspects of plutonic rocks and sulphide genesis to integrate crust/mantle processes, magma chamber processes, igneous petrology, and economic geology. I hope that through this approach student readers will recognize that concepts introduced in their daily curriculum should not be considered in isolation. These disparate concepts can be unified, each contributing a little to building the foundation on which to broaden one's perspective of other aspects of geoscience.

## SETTING AND FORMATION OF MAGMATIC SULPHIDE DEPOSITS

The Voisey's Bay sulphide deposit is of magmatic origin. To understand the possible controls on its birth it is necessary to consider briefly the host-rocks and paleotectonic setting of other magmatic Ni-Cu-Co deposits, and the factors that give rise to sulphide ores. Naldrett (1989a) has reviewed such deposits, concluding that the world's significant concentrations of nickel-copper (-cobalt-PGE) sulphides occur within rocks that fall broadly into four geological settings. These settings, with examples of ore deposits within them (exclusive of Voisey's Bay) are:

1) komatiitic and tholeiitic (ferropicritic) lava flows and associated intrusions (Kambalda, Australia; Pechenga, Russia).

2) mafic and ultramafic rocks generated at rifted continental margins (Cape Smith Belt [Raglan] and Thompson Belt, Canada) and within ophiolitic rocks of oceanic basins (Zambales ophiolite, Philippines).

3) cratonic areas related to (i) flood basalt provinces (Noril'sk-Talnakh area of the Siberian Trap; Duluth Complex of the Keweenaw lavas, United States), and (ii) stratiform layered intrusions (Sudbury Igneous Complex, Canada; Bushveld intrusion, South Africa; Great Dyke, Zimbabwe).

4) synorogenic mafic intrusions (Moxie intrusion, United States) and ultramafic intrusions (Vammala belt, Finland (Peltonen, 1995)), presently not considered significant metal reservoirs, but with future potential.

The common genetic link among most of the rocks above is that they are direct or indirect products of mantle plumes, effusions from which are MgO-rich (picritic) magmas. Sulphide deposits within these rocks are postulated to result from primary genetic processes within the magmatic precursors rather than later hydrothermal metal enrichment. Why are these magmas so favourable for sulphide deposits in settings from ophiolites to continental flood basalts? The following summary outlines the physicochemical controls thought necessary for sulphide formation, and provides background for subsequent discussion of the Voisey's Bay deposit (see also Kerr, 1997). For more information on the complex processes that overlap and interact in the generation of magmatic sulphide deposits, as outlined here, see: Naldrett and Cabri (1976), Rajamani and Naldrett (1978), Naldrett and Macdonald (1980), Ripley (1986), Naldrett, (1992), Lightfoot and Keays (1994), Keays (1995),

Barnes *et al.* (1997), the various papers in Whitney and Naldrett (1989), and the numerous collateral studies cited by these authors.

One of the fundamental aspects of picritic (high MgO) magmas is that they represent significant partial melts derived from a mantle source region. Under the conditions of partial melting envisioned for production of these silicate magmas, it is probable that they are sulphur undersaturated at the time they are generated. This permits Ni, Cu and PGEs to reside in rapidly ascended and little-fractionated magmas for significant periods of time because the partition coefficients between these elements and sulphur are so great that any appreciable S in the silicate magma will combine with the metals to produce a separate, dense, immiscible sulphide liquid (magma). Once the conditions are achieved under which a sulphide liquid can form (see discussion below), separation is initiated as droplets of sulphide-oxide liquid within the silicate magma. As noted above, metallic elements such as Fe, Ni, Cu, Co and the PGEs will partition from the silicate liquid into the sulphide-oxide liquid phase and thus become concentrated within that phase. (The degree of concentration of metals into the sulphide liquid is dependent on the volume of that liquid relative to the volume of silicate magma with which it is in equilibrium, a relationship described by the "R factor" *cf.* Campbell and Naldrett, 1979). The density of the sulphide-oxide liquid relative to the silicate liquid is roughly 4 to 3, so the former liquid tends to become gravitationally divorced from its coeval silicate partner. Should this happen early in the evolutionary history of the silicate magma, the sulphide magma likely remains within or near the mantle source region. It is thus apparent that any rising metal-enriched sulphur-undersaturated magma will be ripe for sulphide deposition when it encounters a crustal sulphur source, either enroute to higher levels from its mantle staging area, or upon taking up residence within or upon the crust. For example, it is postulated that the sulphides in the gabbros of the Duluth Complex are in part a product of the contamination of the precursor basic magma by passage through sulphur-bearing sedimentary rocks en route to the presently exposed level of emplacement (*cf.* Lee and Ripley, 1995). Similarly, the Kambalda deposits are postulated to have been formed within komatiitic lavas when these lavas encountered and assimilated sul-

phur-bearing sediments upstream from the deposit sites (Leshner and Campbell, 1993; see, however, Foster *et al.*, 1996).

From an economic standpoint, it is of little practical advantage to "shock" metal-laden silicate magmas into liberating a sulphide magma unless there are collection sites at which that sulphide can accumulate and subsequently be extracted as ore. This is fundamental to magmatic sulphide exploration and mining, and governs whether or not a sulphide ore deposit forms. The Duluth Complex, for example, contains an incredible resource of Cu-Ni sulphide minerals (perhaps in excess of 6 billion tonnes; Listerud and Meineke, 1977), yet they are so dispersed that exploitation is not viable. On the other hand, the sulphide ores within the Kambalda belt, Australia, are confined to narrow shoots that appear to represent the downstream deposition of sulphide liquid within discrete channels and depressions carved by komatiitic lava flows (*cf.* Leshner, 1989).

Although, as noted in the foregoing discussion, sulphur contamination plays a major role in the formation of sulphide ore deposits in basic rocks, the contamination of basic magmas by SiO<sub>2</sub> also seems to trigger the formation of such deposits by lowering the solubility of sulphur in magma. Silica increase within a basaltic magma is considered by Naldrett (1989b) to have been the main influence on the formation of the Sudbury ores, largely confined to mafic rocks derived from magma that is postulated to have encountered a vast volume of silicic crustal melt within a meteorite impact structure. Silica contamination is also considered to have been the first "trigger" in the promotion of sulphide saturation at Noril'sk (*cf.* Naldrett *et al.*, 1996a, p. 768).

#### SUMMARY OF THE GEOLOGICAL EVOLUTION OF NORTHERN LABRADOR

Labrador is located on the easternmost part of the Canadian Shield, and encompasses intersecting remnants of several of the major structural provinces (orogens) that make up the shield. These orogenic subdivisions are superficially simple when viewed on the Canada-wide scale of Shield architecture, but are, in fact, overlapping and complex "on the ground." Of relevance to the regional setting of the Voisey's Bay deposit are the Archean Nain Province and the Paleoproterozoic Churchill Province, and the Mesoproterozoic Nain Plutonic Suite that partly ob-

scures the junction between them.

The last three decades of work in Labrador have firmly established that a fundamental geological boundary, defining a linear zone trending between Cape Chidley in the north and Snegamook Lake in the south, marks a suture across which two Archean continents collided ca. 1860 Ma (*cf.* Wardle *et al.*, 1990; Van Kranendonk and Ermanovics, 1990; Van Kranendonk, 1996; Fig. 1). Archean gneisses of the Nain Province, and unconformably overlying Paleoproterozoic supracrustal rocks, occur to the east of the suture; reworked Archean gneisses, along with tectonized Paleoproterozoic intrusive and supracrustal rocks, of the eastern Churchill (or Rae) Province lie to the west of it. This collisional suture, and the straddling deformation and metamorphism that temporally coincide with it, constitute Torngat Orogen (*cf.* Hoffman, 1988). One post-docking phase of tectonism along the collisional suture involved sinistral transpression between 1845 Ma and 1820 Ma (Bertrand *et al.*, 1993), best exemplified by the granulite-facies mylonites of the Abloviak shear zone (Korstgård *et al.*, 1987). The final movements along the Nain-Churchill contact were largely sub-vertical translation along one or more steeply-dipping, west-side-up, reverse faults, represented by several pseudotachylite-veined mylonite and ultramylonite zones, that may have been active until 1740 Ma (Bertrand *et al.*, 1993), and may have breached the crust to mantle depths.

One of the outstanding geological components of the Nain-Churchill collisional boundary is the Tasiuyak gneiss (Wardle, 1983; Theriault and Ermanovics, 1997), a distinctive Paleoproterozoic unit of accreted (?), locally graphite- and sulphide-enriched, garnetiferous pelitic to psammitic paragneiss up to 40 km wide. It forms the eastern edge of the Churchill Province throughout northern Labrador (Fig. 1), and is disposed as a wedge that thickens eastward to more than 12 km along its contact with the Nain Province (Feininger and Ermanovics, 1994). For most of its length the Tasiuyak gneiss is coincident with the Abloviak transcurrent ductile shear zone (Fig. 1; Korstgård *et al.*, 1987).

The conjoined Nain and Churchill provinces formed a single coherent continental crustal block following the final welding at ca. 1740 Ma. Subsequent geological events of regional significance did not affect this part of the crust until nearly 400

million years later when, between 1350 Ma and 1290 Ma, the boundary zone was invaded by massive volumes of basic to silicic magmas. These magmas crystallized as a series of igneous rocks, collectively referred to as the Nain Plutonic Suite (NPS) (Ryan and Morse, 1985; Ryan, 1990) that cover some 20,000 km<sup>2</sup> between Okak Bay and Hunt Lake (Fig. 2). The Suite, to be addressed in the following section, contains a broad spectrum of rocks, but the main regional subdivisions are anorthosite, troctolite, diorite and granite. The geological setting of the NPS is that of a "stitching batholith" across the Nain-Churchill collisional boundary. This setting is analogous to other similar Proterozoic anorogenic plutonic welts in North America, implying that inherent crustal weaknesses, such as collisional suture zones, influenced the siting of such intrusions (*cf.* Gower and Tucker, 1994; Scoates and Chamberlain, 1995). The NPS fits the criteria of an anorogenic igneous terrane: much younger than the preceding Torngat Orogen, emplaced into crust that as a whole was tectonically quiescent, and unaffected by subsequent orogenic events in Labrador.

#### OVERVIEW OF THE NAIN PLUTONIC SUITE IN THE NAIN AREA

The following overview of the Nain Plutonic Suite, the regional lithostratigraphic host to the Voisey's Bay deposit, draws upon numerous sources. Many general papers on the geology of these rocks are available to the reader, the pioneering works of E.P. Wheeler II (*cf.* Wheeler, 1942, 1960) being benchmarks that are recommended as classic field descriptions. The compilation map of Ryan (1990) and the field-trip guidebook of Berg *et al.* (1994) can be consulted as reference works for some of the current nomenclature used in the discussion that follows.

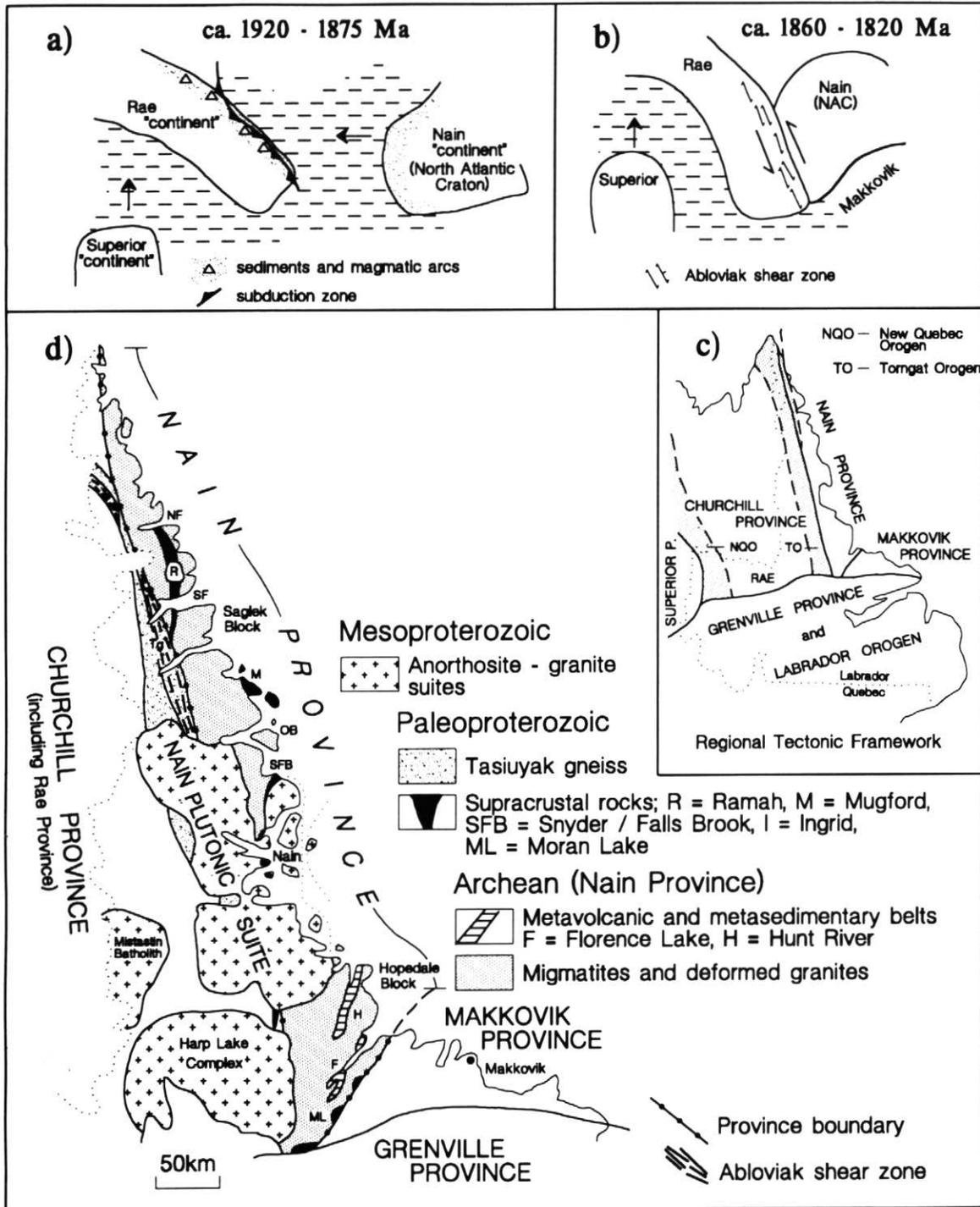
It was noted above that the NPS is a multicompositional batholithic assemblage of igneous rocks. Within this batholith are numerous aggregated plutons of anorthositic, granitic, troctolitic and dioritic rocks that attest repetitive magmatism for some 60 million years: between 1350 Ma and 1290 Ma (Ryan and Emslie, 1994; Hamilton *et al.*, 1994). There are indications from geochronological studies of the NPS that the magmatism began (and ceased?) in the west before it was initiated in the east (*cf.* Berg *et al.*, 1994; Miller *et al.*, 1997).

Large anorthositic terranes such as the

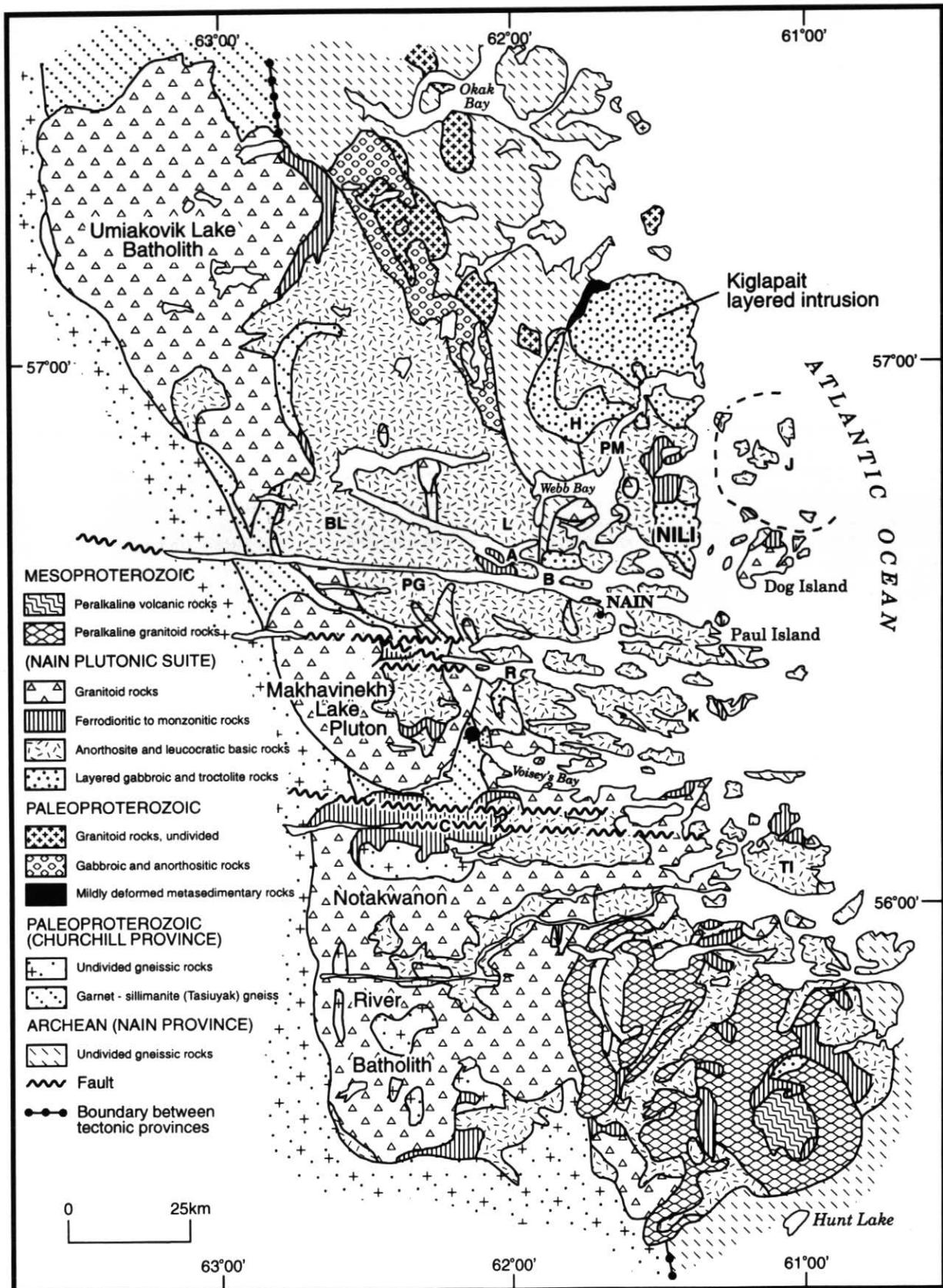
NPS have been a petrological enigma for many decades, and numerous petrologists and geochemists have dedicated years attempting to understand the genesis of the plagioclase-rich magmas that must have produced such unique largely monomineralic rocks (see Ashwal, 1993).

A genetic model for the development of the NPS has recently been proposed by Emslie *et al.* (1994). The fundamental feature of the model is that the compositional range of rocks within the NPS can be accommodated by processes associated with the impingement of a mantle plume

or hot-spot on the base of the crust. One of the consequences of mantle plume activity below continental regions is that the arrival of a plume at the base of the crust, and the emplacement of large intrusions arising therefrom, can produce broad regional upwarping and crustal



**Figure 1** Map of central and northern coastal Labrador, with an outline of the regional tectonostratigraphic subdivisions (from Ryan, 1997). The panels at the top of the figure (a, b) illustrate the tectonic development of Torngat Orogen and the Abloviak sinistral transcurrent shear zone through collision between the Rae and Nain "continents" (cf. Van Kranendonk, 1996). Note the distribution of the Nain Plutonic Suite, as a Mesoproterozoic stitching batholith across the Paleoproterozoic collisional suture between the Nain and Churchill provinces. Geographic features (d) shown as NF, SF, and OB refer to Nachvak Fiord, Saglek Fiord, and Okak Bay.



**Figure 2** Major components of the Mesoproterozoic Nain Plutonic Suite and its immediate envelope (modified from Ryan, 1997). Note the position of the Voisey's Bay sulphide deposit (shown by the large dot) relative to the Tasiuyak paragneiss and the Archean gneisses to the east, a contact that defines the Churchill-Nain boundary. Anorthositic plutons identified are: PM, Port Manvers Run; L, Mount Lister; BL, Bird Lake; PG, Pearly Gates; K, Kikkertavak Island, and TI, Tunungayualok Island. Troctolitic intrusions, in addition to Kiglapait, are identified by: H, Hettasch; NILI, Newark Island; J, Jonathon; B, Barth Island, and R, Reid Brook. See text for descriptions.

foundering at higher levels (*cf.* McKenzie, 1984; Saltus and Thompson, 1995). Accordingly, it is likely that the development of the NPS was aided by extensional tectonics in the mid to upper crust (*cf.* Berg, 1979). The genetic model proposed by Emslie *et al.* (*op cit*) can be summarized as follows.

Upon arriving at the base of the crust, magmas associated with the head of an upwelling mantle plume fanned out laterally to generate a large magma pond. The heat liberated from these mantle magmas induced anatexis (melting) of lower crustal levels, and the silicic melts that were produced coalesced and ascended to higher levels as granitic plutons. In the NPS the granitic rocks are clearly derived from hot, relatively anhydrous magmas, and display many of the characteristics of the classic Finnish rapakivi intrusions (*cf.* Emslie and Stirling, 1993; Ryan, 1991). The removal of silicic components from the lower crust left a residuum of mafic granulite composition. The assimilation of this residual granulite by the plume magmas contributed to local plagioclase-enrichment, thus generating "anorthositic" magmas. These collected in local deep-crustal magma chambers and some underwent significant crystallization prior to ascending to higher levels. The anorthositic intrusions that resulted from this process ran the gamut from solid-state diapirs to crystal-deficient magmas (Wiebe, 1992). Emslie *et al.* (*op cit*) opine that some of these intrusions ascended along pathways already "prepared" by the earlier passage of the granites, and came to rest beneath partly crystallized granitic magmas resident in the crust from the earlier anatexis. Residues that remained from the fractionation of the anorthositic magmas were iron rich and basic; these produced the ferrodioritic members of the NPS. The dioritic magmas were dense and did not ascend into mid-crustal levels, but where they were emplaced — in some cases, perhaps, as expulsions from proximal anorthositic plutons — they mingled with partially crystalline granitic magmas to produce rocks that display enigmatic intrusive relationships (*cf.* Wiebe, 1990, 1992). Little-fractionated or "primitive" magma periodically escaped from the plume, and ascended into the crust to crystallize as troctolitic rocks (*cf.* Xue and Morse, 1993).

In spite of some weaknesses (*i.e.*, not all the NPS granites are "early") the above model has the capacity to account for a wide range of rocks within anorogenic igneous terranes such as the NPS, terranes

which in broad terms can be referred to as bimodal. From an areal perspective, the NPS is primarily composed of anorthositic and granitic rocks (Fig. 2); the troctolitic and dioritic members are subordinate, but are petrologically important to the suite. For the sake of brevity, the salient characteristics of only the anorthositic and troctolitic "families" within the NPS are given below. Details of the granitic and ferrodioritic rocks can be found in: Emslie and Stirling (1993), Wiebe (1990), Berg *et al.* (1994), and references therein.

#### Anorthositic Plutons

The anorthositic plutons of the NPS probably number several hundred. They are overwhelmingly plagioclase cumulate rocks, but orthopyroxene is nearly universally present as an intercumulus phase. Thus, in addition to anorthosite (*sensu stricto*), this subdivision contains significant volumes of leuconorite. Leucogabbro and leucotroctolite are local components in those anorthositic plutons that contain augite and olivine, respectively. The anorthositic plutons reflect an array of emplacement styles, varying from those that may have originally been solid state diapirs to those that are products of *in situ* crystallization within local magma chambers. The diapiric plutons locally contain large megacrysts of aluminous orthopyroxene, considered to be evidence for the onset of magma crystallization at lower crustal depths (Emslie, 1975). These plutons are also characterized by foliated and recrystallized margins (Fig. 3a), the fabric of which formed either as a result of near-solid-state ascent from deeper crustal levels or from being emplaced into active shear zones (Royse, 1997). The *in situ* plutons are marked by pristine subophitic textures (Fig. 3b) and by layered to massive margins. Some of the plutons shown on Figure 2 that are representative of the anorthositic and leuconoritic rocks include the Bird Lake massif (BL), the Mount Lister intrusion (L), the Pearly Gates intrusion (PG), and the Tunungayaluk Island intrusion (TI). The Port Manvers Run (PM) and Kikkertavak Island (K) intrusions are leucotroctolitic representatives of the anorthositic subdivision.

The anorthositic plutons of the NPS traditionally have been considered to be notoriously difficult to date precisely because they were generally thought to be devoid of suitable minerals from which reliable magmatic crystallization ages could be gleaned. This perception has been altered within the last decade by the realization

that careful examination of these rocks may reveal the presence of zircon, a mineral from which crystallization ages can be obtained through U-Pb isotopic analyses. Although a few local Rb-Sr and K-Ar ages were reported from the NPS in the 1970s, the first systematic areal geochronological data on the NPS were given by Yu and Morse (1993), who employed the  $^{40}\text{Ar}/^{39}\text{Ar}$  isotopic system on plagioclase to establish a regional emplacement sequence for a dozen anorthositic intrusions. These data reflect the times at which the plutons cooled below the temperature of argon diffusion rather than their crystallization ages, although some country-rock data may be considered to be reliable as intrusion-related thermal disturbance ages. U-Pb data reported by Hamilton *et al.* (1994), derived from zircon crystallized within intergrain pegmatoidal granitic patches in some of the anorthositic plutons, are better representatives of crystallization ages of these rocks.

Some of the data reported in the aforementioned references can be summarized as follows: Hamilton (in Berg *et al.*, 1994) gave an emplacement age of 1320 for a pluton on Paul Island. Yu and Morse (1993) proposed that the Bird Lake massif crystallized *ca.* 1328 Ma, based on the argon systematics of hornblende in adjacent country-rock. Hamilton (in Berg *et al.*, 1994) suggested emplacement of the Mount Lister intrusion *ca.* 1331 Ma [the author believes it is perhaps nearly 1350 Ma, based on an age of *ca.* 1343 Ma from a foliated fayalite monzonite that cuts it (Connelly and Ryan, 1994)]. Hamilton *et al.* (1994) reported that the Kikkertavak Island pluton yields a zircon U-Pb age of  $1311 \pm 2$  Ma.

#### Troctolitic Plutons

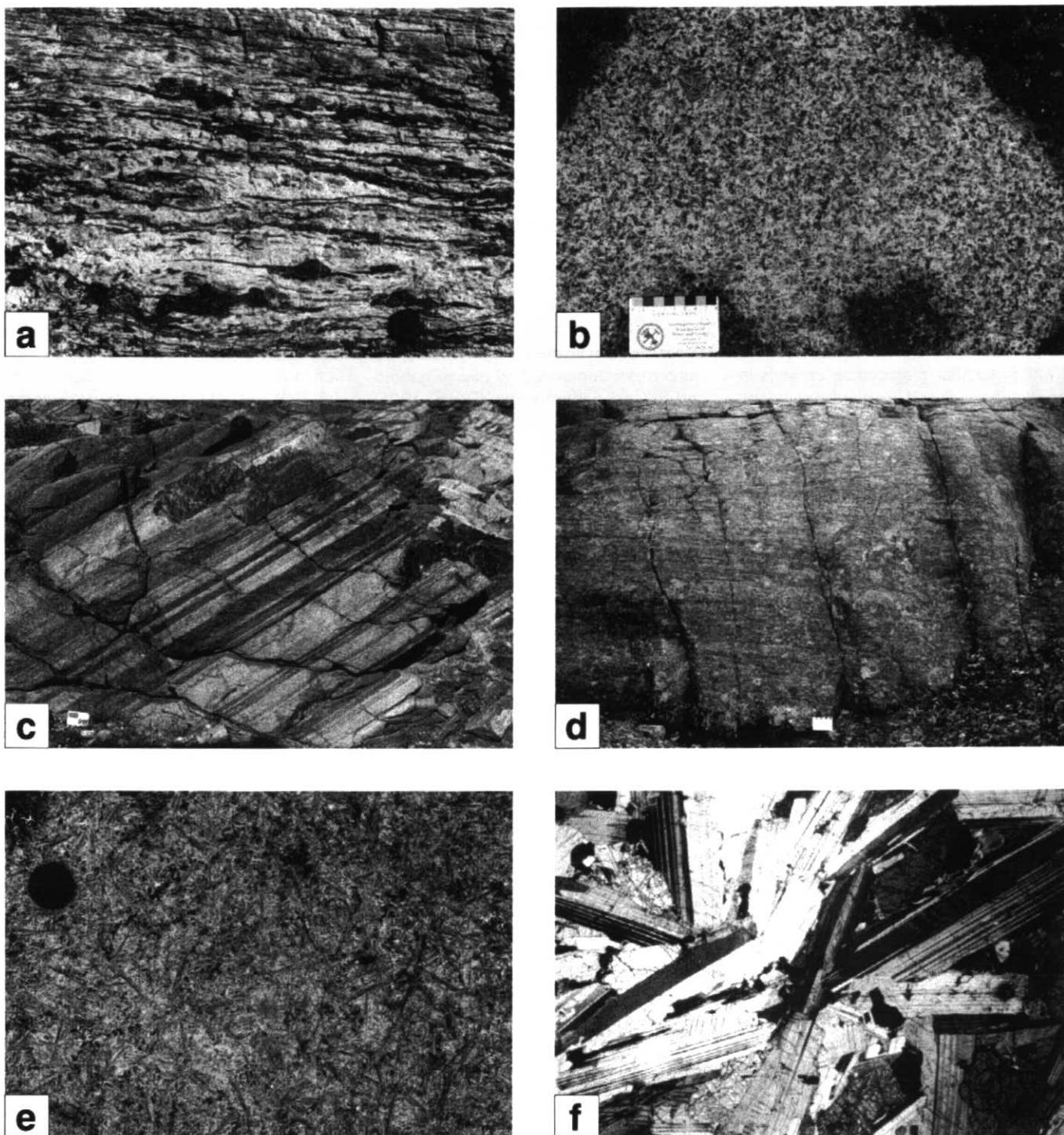
The troctolitic subdivision of the NPS includes all those plutons in which olivine is a significant mineralogical component, because by definition (Streckeisen, 1975) troctolites are plagioclase+olivine rocks. The troctolitic intrusions also contain olivine-bearing gabbros. One of the troctolitic intrusions might be better classified into the anorthositic subdivision (see below). Most of these plutons are layered, and their rocks exhibit textural characteristics indicative of derivation by cumulate crystallization and by chilling of liquids.

The best-known of the layered troctolitic intrusions is the Kiglapait, a funnel-shaped pluton located along the northeast edge of the NPS (Fig. 2). The petrology, geochemistry, and petrogenesis of this intru-

sion have been described in numerous publications over the last 25 years by S.A. Morse (*cf.* Morse, 1969, 1979, 1996). It was emplaced at a crustal depth of approximately 9 km at ca.  $1306 \pm 2$  Ma (U-Pb

zircon age by T. Krogh, quoted by Morse, 1996), exploiting an existing contact between an anorthosite pluton and Nain Province gneisses. The Kiglapait is a classic example of a basin-shaped or synclinal

intrusion consisting of a series of layered igneous rocks (Fig. 3c) derived from crystallization of a high-alumina olivine tholeiitic magma under closed-system conditions; this magma took about one million



**Figure 3** Plates illustrating some features of NPS plutons. Scales used are as follows: camera lens-cap in (a) and (e), 5 cm; graduated scale in (b) and (d), 8 centimetres; notebook in (c), 20 cm. (a) Foliated leuconoritic rocks from the solid-state-deformed margin of the Mount Lister intrusion. (b) Subophitic texture of orthopyroxene and plagioclase within a massive pluton. (c) Well defined compositional layering near the base of the Kiglapait intrusion. (d) Diffuse layering in troctolitic rocks on the west side of the Reid Brook intrusion. (e) Radial plagioclase arrays (stellate texture) in massive leucotroctolite in north-trending dykes on the east side of Reid Brook intrusion. (f) Thin section view (width is 1.2 cm) of massive leucotroctolite from (e), showing the prismatic stellate plagioclase and several olivine grains (high relief).

years to solidify. Both the floor cumulates and a downward-crystallizing roof sequence can be recognized in the intrusion. The mafic rocks are overwhelmingly 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, Fig. 2; Berg, 1973, 1980), which occurs to the southwest of the Kiglapait, is less distinctly layered than the Kiglapait. The main rock types are olivine gabbro, olivine leucogabbro, troctolite, leucotroctolite and anorthosite. The whole intrusion is characterized by well-laminated plagioclase, and locally it 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, Fig. 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  $1305 \pm 5$  Ma (Simmons *et al.*, 1986), coeval with the Kiglapait intrusion. It differs from the Kiglapait and Hettasch 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 intrusion consist of troctolite, olivine gabbro, and ilmenite-rich cumulates derived solely from multiple basic magma injections into the magma chamber. The uppermost preserved part of the Newark Island intrusion is a hybrid series of rocks that reflects periodic replenishment of the magma chamber with both basic and silicic liquids. The rocks in this part of the intrusion include a broad range of mafic, granitic and hybrid cumulates. The Newark Island intrusion is unique 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 were 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 pluton, the Barth Island intrusion, occurs along the eastern side of the NPS north of Nain (B, Fig. 2). It is a fault-segmented basin-shaped body within anorthosite (cf. de Waard, 1976). Troctolites at the base of the intrusion grade upward and outward into "jotunite" (ferrodiorite) that contains lenses of "adamellite" (pyroxene quartz monzonite). De Waard's descriptions of the various rock-types within the Barth Island body can be interpreted to indicate that this intrusion is probably similar to the Newark Island 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, Fig. 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 gabbro (Ryan, 1995; Royce 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 leucotroctolitic member of the anorthositic plutons (R.A. Wiebe, pers. commun., 1992). Berg (in Berg *et al.*, 1994) stated that the internal part of the pluton is largely unlayered, although plagioclase lamination is widespread. Berg also noted that comb-like arrays of plagioclase are locally present in a border zone of the massive rocks. The central part of the Jonathon intrusion is occupied by a younger diorite body. Both the leucotroctolite and diorite have yielded crystallization ages ca. 1312 Ma (Hamilton *et al.*, 1994).

One of the smallest troctolitic units presently known within the NPS is the Reid Brook intrusion (R, Fig. 2). This is a poly-phase, layered to massive intrusion north of Voisey's Bay, and is the host to the Voisey's Bay sulphide deposit. It is treated in detail in a separate section below.

Fe, Ni and Cu sulphide minerals are present as sporadic concentrations in most of the layered intrusions mentioned above, but outside the Voisey's Bay deposit, none seems to be in sufficient quantity to make economic recovery of the base metals viable. For example, the Kiglapait intrusion is practically devoid of a sulphide phase except in rocks that formed after more than 90% of the magma had crystallized (Shirey, 1975). The separation of

sulphide liquid followed the deposition of a major oxide-rich layer within the intrusion, the Main Ore Band (Morse, 1969), but the quantity and copper-nickel contents of the sulphide minerals never reached significant levels to make them an economic commodity. The NILI has sulphide-oxide concentrations in the lower layered sequence, but like Kiglapait, these do not appear presently to have significant economic potential.

#### PAST EXPLORATION HISTORY OF THE NPS AND THE DISCOVERY OF THE VOISEY'S BAY DEPOSIT

It is striking to observe how perceptions of the mineral potential of regions change on the basis of single discoveries. Eastern Labrador had never been, until the announcement of the Voisey's Bay discovery in 1994, the focus of interest by multitudes of explorationists. The only exception to this was the so-called Central Mineral Belt west of Makkovik (Fig. 1), some 200 km south of Nain, where numerous prospecting and exploration programs have been conducted since the late 1920s (cf. Wilton, 1996, pages 4-5). This lack of attention by explorationists certainly applies to the Nain Plutonic Suite, where the major components — the anorthositic and granitic members — are plutonic rocks which have been viewed traditionally by the exploration fraternity as low priority targets for base metals. Over the last twenty-five years the Newfoundland Department of Mines and Energy promoted Labrador as an underexplored frontier region, one that at the start of this decade Swinden *et al.* (1991) felt was ripe for exploration in light of contemporary ore deposit models. The following summary, more-or-less verbatim from Ryan (1997), provides an overview of the pre-1993 work on the NPS, and gives a capsule account of the Voisey's Bay discovery. Numerous media have reported on the latter subject, and the reader is referred to such publications as the *Northern Miner* (for example, volume 80, number 39) and *Canadian Geographic* (September/October 1995 issue) for the "story behind the story."

British Newfoundland Exploration (BRINEX), a company that held mineral concessions to much of Labrador between 1953 and 1980, undertook a quest for mineral deposits in the Nain area during the early stages of its tenure. Within the first five years of its exploration program in Labrador the company found, or was made aware of, rusty zones containing ilmenite and sulphides in some of the

anorthositic rocks near the community of Nain (Grimley, 1955, 1956). The BRINEX exploration reports on file at the Newfoundland Geological Survey indicate that surface examination of several of these zones revealed non-economic quantities of base metals. BRINEX subsequently shifted the locus of its exploration in Labrador to uranium and copper mineralization within supracrustal rocks of the Central Mineral Belt, where it conducted a sustained exploration program for the next two decades.

In more recent times the Kiglapait intrusion, noted above as one of the troctolitic layered bodies of the Nain Plutonic Suite, was examined by Kennco Exploration in 1970 (Barr, 1970) and International Platinum Canada Incorporated in 1986 and 1988 (Atkinson, 1986; Walls, 1988). The former company was focussed mainly on evaluating the base metal potential of the intrusion; the latter was exploring for precious metals. A few minor nickel and copper sulphide prospects were encountered, but no anomalous concentrations of platinum nor palladium were found, and no further work was done.

Diamond Fields Resources Incorporated (DFR) became active in Labrador in 1993. Base metal exploration was not the main impetus for their arrival on the Labrador scene; rather, it was diamonds. Two Newfoundland prospectors, Albert Chislett and Chris Verbiski of Archean Resources Limited, a Newfoundland-based company, were aware of the diamond discoveries made in 1991 within kimberlitic intrusions of the Slave Province in the Northwest Territories (*cf.* Pell, 1997), and reasoned that the Archean Nain Province of Labrador could be a potential host to diamondiferous kimberlites. After researching their target areas, they obtained financial backing from DFR to undertake a regional diamond and kimberlite exploration program. In the course of the 1993 kimberlite exploration survey, Chislett and Verbiski spotted a prominent gossanous outcrop within a troctolite dyke, part of the Reid Brook intrusion (see below), on a hillside north of Voisey's Bay, and sampled it for base metal assay. The assays from these samples returned encouraging values of copper and nickel, and the immediate area of the gossan was staked. Archean Resources undertook further prospecting, surveying and sampling of the area in the summer of 1994. Subsequent drilling in the fall of 1994, guided in part by the results of geophysical surveys, intersected exceptional quan-

ties of sulphide mineralization within the troctolitic dyke. Diamond Fields reported the drill data as a "potentially significant occurrence of base metal mineralization" in early November of 1994, and staked claims over most of the other troctolitic intrusions that were known within the Nain Plutonic Suite. Assay results from the mineralized drill core were released later that month, at which time DFR concluded that it had made a "major nickel, copper and cobalt discovery" in Labrador. This announcement illuminated the NPS as a reservoir of base metals, and it precipitated a record-breaking staking-rush during the winter of 1994-1995 for ground underlain by the NPS and by similar plutonic rocks elsewhere in Labrador (*e.g.*, Harp Lake Complex; Fig. 1).

#### THE REID BROOK INTRUSION AND THE NICKEL-COPPER-COBALT DEPOSIT AT VOISEY'S BAY

##### The Reid Brook intrusion

The Reid Brook intrusion (Ryan and Lee, 1989; Ryan, 1990; Emslie, 1996), the host to the Voisey's Bay deposit, is a fault-dissected, elongate (12 km long by 0.5-2.5 km wide), north-south trending body within and atop Archean gneisses of the Nain Province, close to the junction with the Churchill Province, on the north side of Voisey's Bay and about 30 km southwest of Nain (Figs. 2, 4). As originally defined, it includes both a layered 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 (Ryan *et al.*, 1995). It can be divided into at least two geographic subdivisions: a north-south oriented body in the north, and an east-west oriented body in the south. It may be the oldest mafic intrusion within the NPS. The maximum age for the Reid Brook is not clear; the only observation that limits it is that it intrudes rocks overprinted by tectonism of the ca. 1.8 Ga Torngat Orogen. The probable minimum age is based on the observation that olivine-bearing noritic rafts, resembling some of the massive rocks of the Reid Brook intrusion, are enclosed by the 1322±1 Ma Makhavinekh Lake rapakivi granite to the west (Figs. 4, 5c). No other troctolitic intrusions are presently known to occupy this temporal niche.

The layered component (Fig. 3d) of the Reid Brook intrusion occurs along the western side of the northern part of the body, and defines a monoclinical (locally synclinal) structure dipping gently east-

ward. It comprises red-brown weathering troctolitic, melatroctolitic, gabbroic and gabbro-noritic rocks having cumulus plagioclase and olivine and intercumulus pyroxene.

The eastern and southern parts of the Reid Brook intrusion are predominantly massive, grey-to-purplish-black weathering troctolite, leucotroctolite and norite that intrude the layered sequence. These massive rocks are mostly medium-grained and ophitic to subophitic in texture, but they locally exhibit prismatic plagioclase up to 10 x 2 cm arranged in a stellate or criss-crossing array (Figs. 3e,f). In the central part of the outcrop area of the Reid Brook intrusion the massive rocks form north-south trending dyke-like bodies against the eastern side of the layered rocks, but have a more irregular interfingering form in the north (Figs. 5a,b). Massive rocks are predominant in the south, and here the feeder dyke and the main troctolite mass has an overall east-west orientation (Fig. 5c). One possible explanation for this contrast from north to south is that the two troctolites are different intrusions. Another possible explanation is that the southern part represents a lower level of intrusion, and that the central and northern parts represent the overlying roof of gneisses and older layered rocks; in this scheme the chamber roof to the younger part of the Reid Brook intrusion was breached along a fault or fracture oriented normal to the floor feeder (Ryan *et al.*, 1995, Fig. 4).

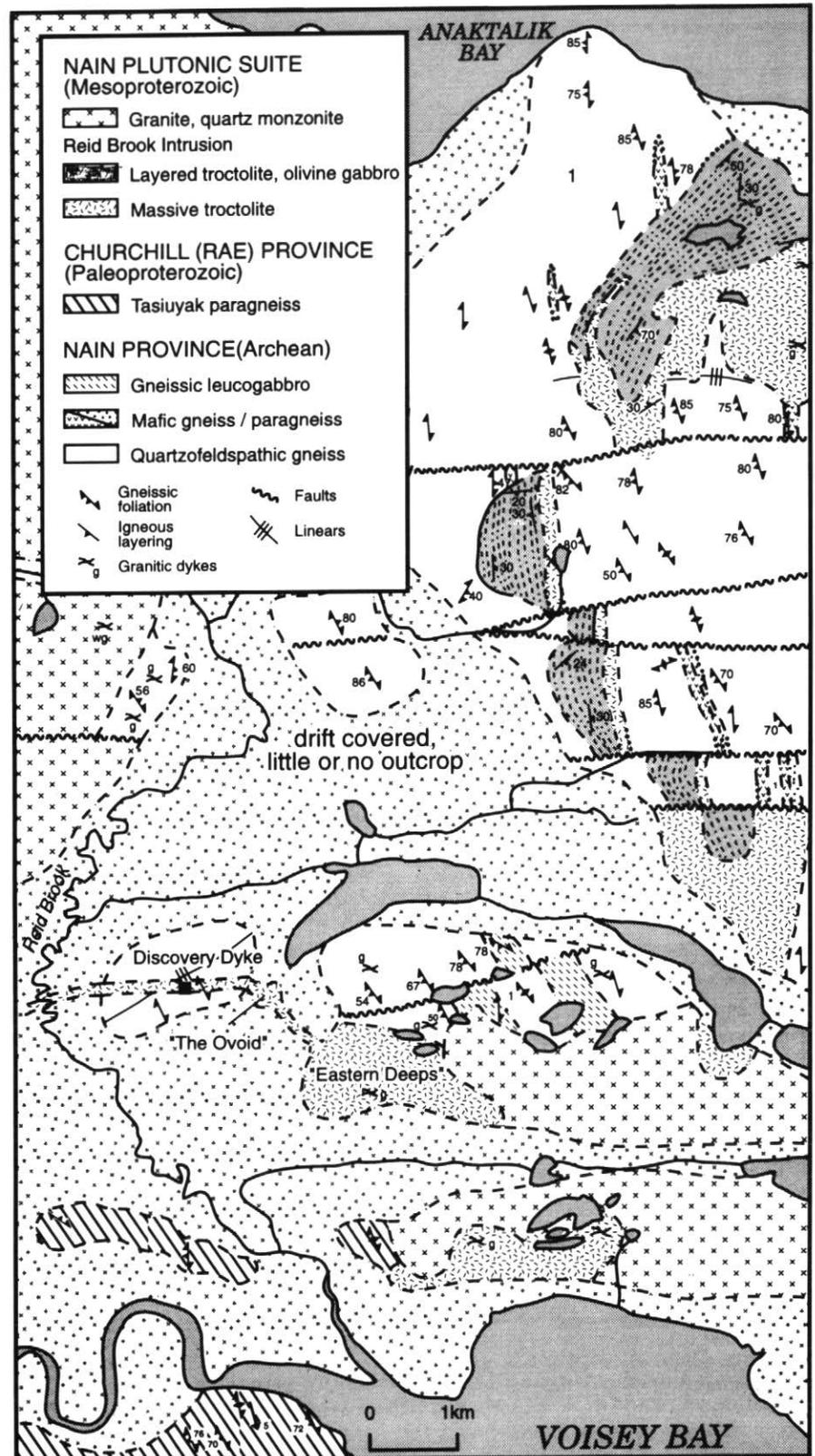
##### The Sulphide Deposit

The sulphide mineralization discovered by Archean Resources and Diamond Fields Resources at Voisey's Bay comprises predominantly pyrrhotite, pentlandite, and chalcopyrite (Naldrett *et al.*, 1996b). It is locally exceptionally coarse grained, and it is disposed in several differing settings. Without exception, however, the host rock to the sulphide mineralization is the massive troctolitic rocks of the southern part of the Reid Brook intrusion, rather than the layered succession to the north, and thus the carrier of the sulphides is considered to have been the precursor magma to the massive subdivision of the intrusion (Ryan *et al.*, 1995). The original discovery outcrops are located within an east-west trending, north-dipping, troctolitic dyke, having a maximum thickness on the order of 100 m (Figs. 4, 5, 6) and exhibiting a well-developed internal stratigraphy of troctolitic rock and sulphide mineralization (Naldrett *et al.*, 1996b). Subsequent exploration of a drift-covered

area to the east of the initial discovery outcrops revealed a major ore body, a bowl-shaped accumulation of sulphides, separated from underlying gneiss by a rind of troctolite containing numerous fragments of older rock (the Basal Breccia Sequence of Naldrett *et al.*, 1996b). This sulphide mass is roughly elliptical in plan-view and is referred to as "the Ovoid" (Figs. 4, 6); it is approximately 450 X 250 meters, and contains massive Ni-Cu-Co sulphide in excess of 100 m thick. The reserves in "the Ovoid" are estimated to be 31.7 million tonnes, having an overall grade of 2.83% Ni, 1.68% Cu, and 0.12% Co.

Drilling of massive troctolite to the east of "the Ovoid" encountered significant sulphide near the contact between troctolite and the underlying gneiss, at a depth of over 600 m. This discovery is referred to as "the Eastern Deeps" zone (Figs. 4, 5, 6), hosted by troctolite that displays a variety of textural types (Naldrett *et al.*, 1996b). Its resource estimate, given in the fall of 1996 by INCO Ltd., now the owners of the deposit, is on the order of 50 million tonnes. Grades reported from "the Eastern Deeps" are 1.36% Ni, 0.67% Cu and 0.09% Co. Recent drilling on the "Western Extension" (Fig. 6) of the original discovery dyke has shown that significant concentrations of sulphide reside in the down-dip extension of the intrusion (INCO press release, 31 January 1997), and opens up other target areas for continued exploration. It is now anticipated that the total volume of ore in the Reid Brook intrusion will greatly exceed 150 million tonnes.

Ryan *et al.* (1995), using knowledge of the local geology and the limited drill-hole data publicly available in late 1994 from Diamond Fields Resources, modelled the original Voisey's Bay dyke-hosted discovery as representing sulphide accumulations within a steeply dipping conduit that formed part of the plumbing system that fed the (eroded) massive troctolitic part of the Reid Brook intrusion, and predicted that similar concentrations were likely resident at the base of the magma chamber represented by the massive troctolitic rocks to the east of the dyke (Fig. 5c). This predictive model was verified in the fall of 1995 by the announcement of the Eastern Deeps discovery (Figs. 4, 6), and later reinforced by the more detailed examination of the Voisey's Bay deposit by Naldrett *et al.* (1996b), based on examination of more than 250 exploratory drill-holes within the deposit area. The existing data indicate that the main sulphide-bearing



**Figure 4** Geological map of the area immediately northwest of Voisey's Bay, showing the geological setting and the general geology of the Reid Brook troctolite intrusion (modified from Ryan *et al.*, 1995), and the spatial distribution of the main ore zones within the southern lobe.

feeder dyke into the Eastern Deeps massive troctolite was shallowly dipping (Naldrett *et al.*, 1996b). If the whole feeder system was originally shallowly inclined it implies that the initial discovery outcrops represent part of this dyke that had been subsequently steepened by fault rotation. Alternatively, the dyke may have had a primary complex zig-zag geometry, or there may be multiple feeders having differing attitudes (see Addendum to Ryan *et al.*, 1995). The "Ovoid" is interpreted by Naldrett *et al.* (*op cit*) to reflect the preserved remnants of the base of the originally overlying magma chamber, where the dense sulphide liquid accumulated

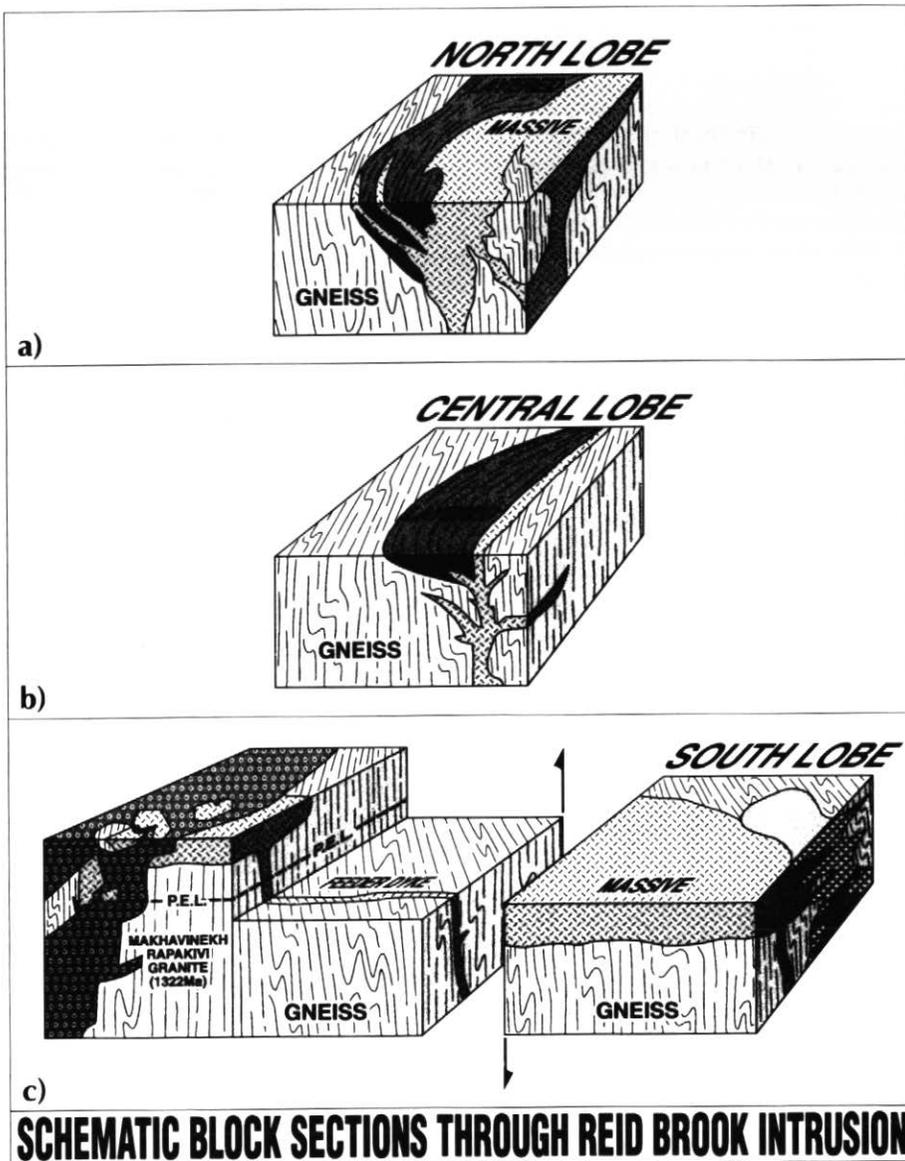
(Fig. 6). The "Eastern Deeps" setting is also interpreted as the lower part of a magma chamber, as modelled by Ryan *et al.* (1995), proximal to the site where the troctolitic feeder dyke to the Reid Brook intrusion emptied into the chamber and relinquished its immiscible sulphide magma. In the "Eastern Deeps" setting, the overlying troctolitic rocks have not been eroded sufficiently to expose the ore-bearing basal part of the chamber (Figs. 5c, 6).

Whereas the distribution of sulphides and troctolite at Voisey's Bay lend themselves to the above geometric model (Fig. 6), it is not the only model that can be

entertained. The writer, in a May 1995 addendum to the earlier Ryan *et al.* (1995) paper, suggested that contemporary data lent some credence to models advocating lateral magma migration and the concentration of sulphides in "aneurisms" or elongate dilational subchambers on the dyke. It was suggested that the geometry of the "Ovoid" could be modelled as such, topographically and structurally below the dyke that is exposed at a higher elevation on "Discovery Hill" to the west. It was postulated that additional concentrations of ore may thus underlie the original discovery outcrops, as a strike extension of the "Ovoid" subchamber. It is tempting to suggest that the mineralized "flattened cylinder" of troctolite, recently outlined by INCO drilling (press release of 31 January 1997) of the "Western Extension" just off "Discovery Hill," is verification of such a down-dip subchamber on the dyke, and bodes well for the discovery of additional concealed ore at Voisey's Bay.

**ORIGIN OF THE SULPHIDE MINERALS IN THE VOISEY'S BAY DEPOSIT**

The origin of the sulphide deposit at Voisey's Bay is presently interpreted to conform to established models, outlined at the outset of this article, in which two chief physicochemical factors control such mineralization: i) a sulphur-undersaturated, metal-enriched, parental silicate magma ascended from a mantle plume, and ii) subsequent contamination and sulphur saturation produced a dense, immiscible Ni-Cu-Co sulphide liquid that separated from the silicate magma. Ryan *et al.* (1995) noted that, in the absence of definitive contemporary data, several temporal relationships could be cited as connections between the silicate magma of the Reid Brook intrusion and the sulphide magma of the Voisey's Bay deposit. It seemed clear from the intimate association between the intrusion and the ore, however, that the surface and subsurface extent of the massive troctolite and the feeder dyke(s) likewise represented the distribution of the ore zones. On the other hand, it was unclear if the sulphide liquid was genetically related to the host, whether the sulphide was an exotic liquid "captured" from a deeper pool by the through-going silicate magma, or whether the sulphide magma was a separate intrusion that exploited an already existing conduit being used by a silicate magma. The recent work of Naldrett *et al.* (1996b) concluded that the two are probably re-



**Figure 5** Block sections illustrating possible relationships between rock units in the northern, central and southern lobes of the Reid Brook intrusion (modified from Ryan, 1997). Note that in the lower section (c) the feeder dyke is portrayed as being subvertical; Naldrett *et al.* (1996b) have shown that where it enters the eastern magma chamber it is subhorizontal (see Fig. 6). P.E.L. (c) is the probable present erosional level through the Makhavinekh Lake pluton.

lated in the manner originally suggested by Ryan *et al.* (1995), namely that the silicate and sulphide magmas are parent and off-spring, respectively.

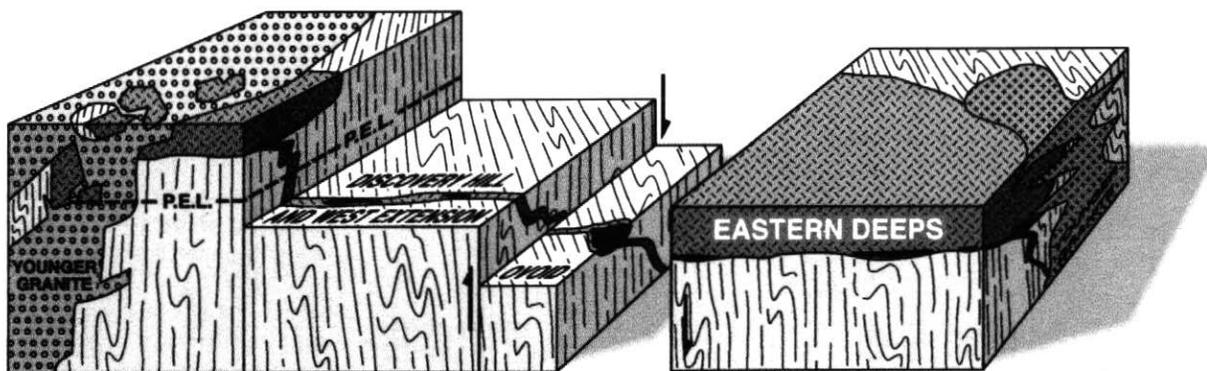
The study of the Voisey's Bay deposit and its setting is still in its infancy when compared to the intense scrutiny that some similar mineral deposits have undergone. In spite of this, some obvious regional and local controls on the possible generation of the deposit can be proposed (Ryan *et al.*, 1995). The best preserved parts of the troctolitic host intrusion to the deposit are located close to the collisional junction between the Nain and Churchill provinces, and the intrusion probably was a much larger body that initially straddled this boundary: Tasiuyak gneiss of the Churchill Province occurs west of the Reid Brook intrusion, Tasiuyak gneiss intruded by Reid Brook troctolite forms large rafts in a granite to the west of the deposit, and the most completely preserved part of the intrusion rests atop and within Archean gneiss of the Nain Province (Ryan and Lee, 1989). This collisional junction setting may or may not be significant to the generation and localization of the mineral deposit, but the deep crustal conduit offered by the collisional boundary probably would enhance ascent of mantle magmas into mid-crustal collection chambers, especially if that boundary was intersected by east-west faults generated at the time of NPS emplacement. Unlike northernmost Labrador, the actual location of the Nain-Churchill boundary in the Voisey's Bay area is difficult to pinpoint (Ryan, 1996), in part because of glacial and glaciofluvial overburden. Based on local geology, the boundary is assumed to be located in the vicinity of "the Ovoid" (*cf.* Ryan and Lee, 1986;

Ryan, 1996), and to be a steeply dipping reverse fault as in the area to the north. Assuming that this is the case, one of the criteria necessary for Ni-Cu magmatic sulphide deposits is met: a metal-enriched, MgO-rich, hot magma rapidly ascended along the Nain-Churchill boundary from its mantle source region, possibly encountering cross-faults at this crustal level, to produce the massive troctolitic rocks of the Reid Brook intrusion.

The second criterion — a ready source of sulphur — is also met at the Voisey's Bay site. The main part of the Reid Brook intrusion was emplaced in Archean gneisses, located adjacent to the Paleoproterozoic, granulite-facies Churchill Province Tasiuyak paragneiss, the latter having numerous sulphide-graphite pelitic units as part of its assemblage (Ryan and Lee, 1989). It is certainly obvious from the preservation of Tasiuyak gneiss in contact with troctolite within large rafts surrounded by the Makhavinekh Lake granite (Fig. 5c) that the troctolite invaded the paragneiss as well, and it is conceivable that this paragneiss was wedged eastward beneath the Archean rocks during the penultimate transpressional stage of the development of Torngat Orogen. Sulphide-bearing pelitic Tasiuyak gneiss below the Voisey's Bay site thus provides an elegant crustal source for sulphur-contamination and sulphur-enrichment of ascending metal-bearing mantle magmas, satisfying the combination of circumstances giving rise to such deposits world-wide. The probable contamination of the Reid Brook magma by assimilation of underlying Tasiuyak gneiss gains substantial credence from the recognition by Naldrett *et al.* (1996b) of remnants of paragneiss in the feeder dyke and the lower levels of

the Reid Brook intrusion at the Eastern Deeps. At this stage of investigation of the Reid Brook intrusion and its sulphide ores, however, it is not possible to entirely rule out the possibility that the sulphide liquid that produced the Voisey's Bay deposit was generated by silica contamination of the precursor magma; the Tasiuyak gneiss is a siliceous gneiss (generally in excess of 70% SiO<sub>2</sub>) and locally contains quartzite. Alternatively, the sulphide magma may have separated from mantle magma in the deep crust as a result of normal fractionation processes (*cf.* Lee and Ripley, 1995), and thus may not be in any way linked to contamination by Tasiuyak gneiss or any other crustal component in the immediate area.

Another feature of the Reid Brook intrusion — its probable pre-1320 Ma time of emplacement — may also be important in that it may signify that only the earliest mafic intrusions of the NPS transported significant metals to this level in the crust. This would eliminate from exploration consideration any of the younger intrusions, such as the 1306±2 Ma Kiglapait. The validity of this correlation between age of intrusion and content of sulphides must await the results of continuing investigation and exploration of the Reid Brook and other intrusions in the Nain area. It is of considerable interest to note that new discoveries of sulphide mineralization in the northern part of the NPS, brought to public attention in numerous press releases from several junior exploration companies over the past three years, are in a similar regional geological setting (though apparently different hosts, *cf.* Kerr and Smith, 1997) to the Voisey's Bay deposit. That is, their distribution straddles the extrapolated Nain-Churchill



**Figure 6** Schematic diagram of the main ore zones at Voisey's Bay, superimposed upon the assumed geometry of the troctolitic body comprising the southern lobe of the Reid Brook intrusion (modified from Ryan, 1997, Fig. 4c). Here the feeder dyke is portrayed as having a variable dip, based on the conclusions of Naldrett *et al.* (1996b) and various company data released over the past three years. Sulphide mineralization is shown in black; P.E.L. is the probable erosional level represented by the Makhavinekh Lake pluton (Younger Granite).

boundary, and they are located within plutons that may have encountered Tasiuyak gneiss during emplacement. This reinforces the probable importance of the Nain-Churchill boundary and the Tasiuyak gneiss to the localization of such sulphide mineralization, and maintains this setting as a viable exploration target for additional discoveries.

In summarizing the present state of knowledge of the Voisey's Bay sulphide deposit, then, it is possible to state the following. A logical comparison between the present genetic models of magmatic sulphide deposits and the Voisey's Bay Ni-Cu-Co deposit implies the separation of the sulphide liquid from a crustally contaminated (picritic?) magma that was the source of the Reid Brook massive troctolite as suggested by Ryan *et al.* (1995). The magmatic setting of the mineralization in the troctolitic dyke and at the lower levels of the Reid Brook troctolite body nearby (Fig. 6) can be interpreted to imply that the dyke represents part of the plumbing system feeding the magma chamber in which the larger massive troctolite body accumulated. It is, therefore, not surprising that the massive rocks to the east of the dyke discovery zone are mineralized: the "Eastern Deeps" zone is probably a collection site for the sulphides that settled at the base of the magma chamber near where the dyke entered the chamber as surmised by Ryan *et al.* (1995) and supported by Naldrett *et al.* (1996b). Assuming that the magma was carrying sulphide when it arrived at the present erosional level, other hidden parts of the intrusion — such as dilational sub-chambers on the feeder dyke, intersecting dykes, and elbows — are rational exploration targets for additional ore bodies.

#### EPILOGUE: VOISEY'S BAY AND ITS IMPACT ON EXPLORATION AND THE ECONOMY OF NEWFOUNDLAND AND LABRADOR

The Voisey's Bay deposit has proven to be the most significant base metal discovery in many decades in Canada. The announcement of the Voisey's Bay discovery in late 1994 had an enormously positive effect on re-igniting exploration interest for base metals in Canada and elsewhere.

The immediate impact of the discovery on Newfoundland and Labrador was statistically phenomenal. The Department of Mines and Energy was inundated by a stampede of junior explorationists and

claim-stakers. Ground-holdings in Labrador jumped from approximately 20,000 claims held by 20 companies in 1994, to over 280,000 claims held by more than 200 companies and individuals in late 1995; this dropped to 196,000 in 1996 and is forecasted to be 125,000 in 1997. (A claim represents 0.25 km<sup>2</sup>.) The annual exploration expenditure leaped from about \$12.5 million in 1994 to more than \$70 million in 1995. A preliminary evaluation of statistics for the 1996 exploration season indicates that total expenditures for the province were in excess of \$90 million, and the forecast for 1997 is more than \$70 million. The influx of new exploration capital has manifested itself at a personal level as job opportunities for a significant number of people from Newfoundland and Labrador, jobs that in some cases have proven to be the stepping-stone to long-term employment.

Elsewhere, the Labrador discovery was a shot-in-the-arm that revived interest in the grass-roots search for such deposits. This was demonstrated in Canada, for example, by a sudden upturn in claim-staking and investment in Quebec following the announcement of the Voisey's Bay discovery (Brassard, 1996). Interest is now high in eastern Quebec because of the recent discovery of a significant Ni-Cu prospect within a mafic dyke near Lac Volant (Perreault *et al.*, 1996), a setting that some have pointed out is superficially analogous to the discovery outcrops at Voisey's Bay. On the international stage, the Voisey's Bay discovery prompted a spill-over of Labrador exploration across the North Atlantic into the Precambrian intrusive rocks of Greenland (*Greenland Minex News*, July 1996). The upturn in base metal (and precious metal) exploration by junior exploration companies has also been apparent at meetings of the Prospectors and Developers Association of Canada held annually in Toronto, which for the last couple of years have been attended by more than 4000 international delegates.

The future mining, smelting and refining of the Voisey's Bay ore is anticipated to have major short- and long-term benefits to the economy of Newfoundland and Labrador. The mine operation will comprise both open pit and underground extraction, and is projected to have a life of approximately 20 years. The Voisey's Bay deposit was expected to be on-stream by the end of the decade, but Voisey's Bay Nickel Company, the wholly owned subsidiary of INCO Ltd. responsible for bring-

ing the deposit into production, has recently announced a revision to its development calendar, brought on by the terms of reference for the Environmental Impact Study being conducted for the development of the mine. Airstrip and road construction at the future mine site were curtailed in the summer of 1997 after Labrador aboriginal groups successfully argued before the Newfoundland Supreme Court of Appeal to halt work already in progress. The aboriginal groups maintained that such infrastructure was part of mine development, and needed to be assessed through the environmental review process prior to commencement. Voisey's Bay Nickel has indicated that the time-frame needed to complete the comprehensive environmental review of the mine project has dictated a delay in mine, mill and smelter/refinery construction for at least a year beyond original forecasts, making the year 2000 as its current target date for ore production.

When the present issues regarding site development are resolved, the Voisey's Bay project presumably will proceed as originally planned. This will create a stable economic base for several thousand persons from Labrador and the island of Newfoundland. Voisey's Bay Nickel has indicated that some 700 people will be employed during the construction and development phase of the mine and concentrate mill, and about 400 direct jobs will be created with the 7-year open pit mining of "the Ovoid"; subsequent underground mining will employ between 1500 and 2000 persons (see *Atlantic Progress* magazine, October/November 1997 issue). A large smelter and refinery complex will be built at Argentia on the south coast of the Avalon Peninsula of Newfoundland for the beneficiation of the ore from Voisey's Bay. It is expected that approximately 2700 people will be employed during the construction phase, and about 900 jobs will be directly created when the smelter and refinery are in production. The complex will produce 270 million pounds of nickel (about 13% of global demand) and 7 million pounds of cobalt annually, as well as sulphuric acid. (A study of the feasibility of smelting the copper in the province has concluded that the projected annual copper production of 65,000 tonnes from the Voisey's Bay mine is insufficient to support a copper smelter (see *Voisey's Bay News*, October 1997 issue).)

#### A FINAL THOUGHT TO PONDER

A myriad of new sulphide discoveries in

Labrador resulted from the exploration frenzy of 1995, but none has yet proven to pass the "economically viable" test of initial exploratory drilling. It is unlikely that "another Voisey's Bay" will be discovered in the NPS. That is not to say that another sulphide deposit may not be found, but rather that finding another deposit having the geological and geographic setting of the one at Voisey's Bay is highly improbable.

It is perhaps sobering at this point to mentally disengage from science briefly, to ponder how "Mother Nature" works in wonderful ways to contribute to our welfare. The magnificent sulphide deposit at Voisey's Bay, which will be a fundamental building block in the economic future of Newfoundland and Labrador, and, indeed all of Canada, for decades to come, has been sitting undisturbed by human touch for millennia. This paper has shown that the formation and preservation of the deposit was the result of an interplay between a fortunate series of circumstances. It originated because a mantle-derived magma was ripe with metals, and that magma became saturated in sulphide en route from the mantle to a mid- to upper-crustal magma chamber. The silicate magma did not relinquish its sulphide liquid in the deep crust, but deposited it at the base of a chamber now represented in the Reid Brook intrusion and its associated dyke. Crustal erosion, aided by several different process (uplift, glaciation) over the last 1300 million years, has removed some 8-10 km of crust overlying the magma chamber in which the Reid Brook intrusion had accumulated, and quite probably a significant part of the original full contents of the chamber. Yet it is that same process of erosion which has fortuitously revealed — but also preserved — that part of the magma chamber which contained perhaps the greatest concentration of the sulphides. The most economically desirable part of the deposit lies at or within a kilometer of the present Earth's surface, but if there had been this additional depth of erosion it is likely that the Voisey's Bay deposit, as we now know it, would have been totally removed. Perhaps a greater part of the metals in the original sulphide deposit at Voisey's Bay, and other deposits of similar nature within the NPS have, in fact, ended up in such a dispersed form, scattered across the Labrador Shelf and into the Atlantic Ocean.

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The scheduling and success of the Robinson Lecture tour was in a large part due to the masterminding of Mike Easton (Precambrian Division) in Sudbury, who canvassed potential venues and set the calendar. Agents at Harvey's Travel (St. John's) and Ottawa Travel accomplished an unbelievable job of smoothing out the sometimes convoluted ground and air movements to ensure that I got to my designated sites on time. My hosts in the cities and towns visited — too many to name — are thanked for their hospitality: the grub was great, the refreshments were refreshing, the cots were cosy, and the conversation was convivial. I was warmed by the positive and encouraging personal comments, letters and e-mail messages that were directed my way during and after the tour.

This paper reflects the influence of those who have helped shape my vision of the Nain Plutonic Suite and its environs. Over the last 25 years in Labrador I have been fortunate to have had the opportunity to have been in the field with, or come under the verbal influence of, many highly esteemed geologists. I would like to thank all for their counselling and lively debate. At the risk of omitting some very worthy names, and without detailing specifics, I recognize the following: Ken Collerson, Ron Smyth, Brian Marten, Tony Morse, Bob Wiebe, Ron Emslie, and Tony Naldrett. I cannot stand on an outcrop of anorthosite in the rugged uplands of the Nain area without thinking of the late E.P. Wheeler II, a pioneer in mapping the NPS by foot, canoe and dog-team over a re-

markable career in Labrador that spanned nearly half a century beginning in 1926.

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