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PETROLOGY OF MAGMATIC SULPHIDE MINERALIZATION IN NORTHERN LABRADOR: PRELIMINARY RESULTS

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ABSTRACT

The diverse magmatic Ni–Cu–Co sulphide mineralization discovered in northern Labrador, since 1995, can be subdivided through preliminary petrographic studies of drill-core samples from selected prospects. Sulphide mineralization in areas dominated by anorthosite rocks, (mostly north of Nain), is mainly epigenetic, i.e., it shows no relationship to any single regional unit, and invariably postdates crystallization of the anorthosites. There is abundant evidence for progressive thermal erosion, grain-boundary percolation and disaggregation of the wall rocks. However, the sulphide zones show variable spatial association with younger gabbronorite to pyroxenite dykes and veins. In some cases (e.g., OKG prospect), sulphides are mostly confined to veins and dykes, and are syngenetic with respect to these, but epigenetic with respect to the surrounding anorthosites. In other examples (e.g., Cirque prospect), sulphide liquids appear to have segregated entirely from their associated silicate magmas, and veins or dykes are rarely seen. Most sulphide prospects north of Nain fall between these extremes. The mobility of sulphide liquids may have been influenced by the material and thermal state of the wall rocks at the time of emplacement, with the greatest mobility being where wall rocks were still hot and relatively permeable. A fundamentally different type of mineralization exists about 90 km south of Voisey's Bay, where sulphide showings are clearly syngenetic, and are associated with an olivine–gabbro unit traceable on a regional scale. Superb magmatic sulphide textures, reminiscent of those described from Voisey's Bay, are present in these rocks. Minor epigenetic sulphide mineralization is present in gneissic country rocks beneath the gabbro intrusion.

Syngenetic mineralization that can be linked to regionally extensive geological units is by far the most significant type from an exploration perspective. Further mineral exploration within the anorthosite-dominated areas is contingent on recognition of larger bodies of favourable gabbronorite to pyroxenite, and also on the demonstration of potential for economic grades in massive sulphides.

INTRODUCTION

Exploration activity during 1995 and 1996 uncovered many new Ni–Cu showings in northern Labrador, several of which evolved into advanced exploration and diamond drilling projects. A previous report (Kerr and Smith, 1997) concluded that these Ni–Cu prospects are of very diverse character, although most are of "magmatic" origin. This article describes the petrology of sulphide mineralization and associated silicate rocks from selected prospects, and discusses the implications for exploration and metallogenesis; it is based on field samples and about 70 samples collected in 1996 from diamond-drill core. It emphasizes silicate petrology and silicate–sulphide textural relationships, rather than sulphide petrology. The findings must be regarded as preliminary as the database is small, but more extensive field examination and sampling of drill core during the 1997 season generally support the conclusions.

The importance of drill-core information in the study of these sulphide prospects cannot be overemphasized. The intense weathering associated with the presence of sulphides, and the cliff location of many surface showings, makes it difficult or impossible to understand relationships in the field. The fresh material sampled through diamond drilling provides the most valuable textural evidence bearing on genesis, and also provides fresh geochemical samples that can be located precisely in three dimensions.

REGIONAL SETTING

This article discusses samples from six prospects, located in Figure 1. The OKG prospect (Castle Rock Exploration Corporation), License 1514M prospects (Canadian States Resources*), Cirque prospect (Cartaway Resources) and Hilltop prospect (Noranda Exploration and Mining) are all located in the mountainous area north of Nain, within an area

* Canadian States Resources, Inc. changed its name to High North Resources, Inc., effective July 7th, 1997. In this report, the former name is retained, because this is in general usage to refer to the sulphide prospects on licence 1514M, north of Nain.

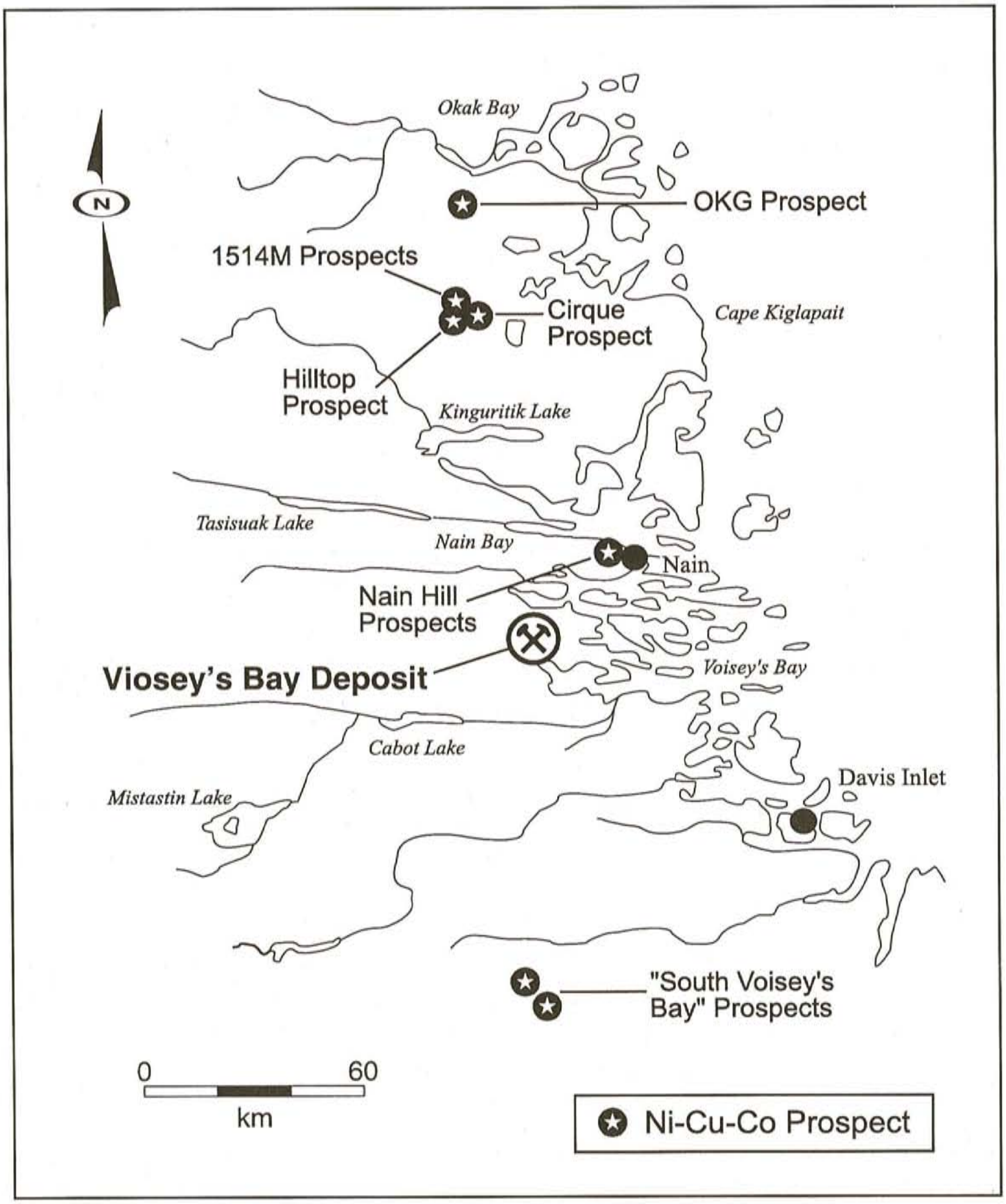

Figure 1. *General location map for Ni–Cu prospects. Details on locations are given on Figure 2, and also the location maps of Kerr and Smith (1977).*

recently mapped by Ryan *et al.* (1997, *this volume*). The Nain Hill prospect (NDT Ventures Limited, project 44) is located immediately adjacent to the community of Nain, in an area that has not yet been covered by regional 1:50 000 scale mapping. The "South Voisey's Bay" project (Donner Minerals and various joint venture partners) is located about 120 km south of Nain, between the Nain and Harp Lake plutonic complexes, largely within an area mapped by Hill (1982) and Thomas and Morrison (1991). All of these prospects lie close to the projection of the tectonic boundary between the Nain and Churchill provinces, and the order of discussion is from north to south.

With the exception of the South Voisey's Bay prospects, all of these prospects lie within areas dominated by massive plutonic rocks, predominantly of anorthositic (*sensu lato*) composition. These rocks have traditionally been assigned to the Mesoproterozoic (1450 to 1270 Ma) Nain Plutonic Suite. However, regional mapping (Ryan *et al.*, 1997, *this volume*) has shown that an older, variably foliated, retrogressed, anorthosite assemblage is also present north of Nain, from which Paleoproterozoic U–Pb ages of 2135 to 2110 Ma were obtained (Hamilton *et al.*, 1997). This older assemblage forms the regional country rocks to the OKG Ni–Cu showings (Kerr, 1997a; Ryan *et al., this volume*). The other Ni–Cu showings north of Nain appear to lie within massive, undeformed anorthosites with primary mineral igneous assemblages, which are presently assumed to be of Mesoproterozoic age. A review of potential controls on magmatic sulphide mineralization in northern Labrador is provided by Kerr (1997b).

OKG PROSPECT

The exploration history and local geology of this prospect were summarized by Kerr and Smith (1997). The surface showing consists of pod-like massive sulphide zones (pyrrhotite, chalcopyrite and minor pentlandite) within anorthosite. However, diamond drilling encountered a different style of mineralization, where sulphides are in "pyroxenite" zones originally interpreted as cumulate zones (Wilton and Baker, 1996). Studies for Castle Rock Exploration Corporation by D. Wilton (Castle Rock, Press Release, April 17, 1997), and the author's observations, suggest that these are more likely younger dykes or veins. Some additional deep drilling was conducted in early 1997, but this did not intersect significant mineralization, and exploration work was curtailed in June 1997. The best results from drilling came from some very narrow massive sulphide zones with up to 1.1% Ni, 0.93% Cu and 0.1% Co. An adjacent property (held by Noront Resources and Golden Trump Resources) also contains a Ni–Cu showing, which was drilled in late 1996. The nature of this mineralization is not well known, but it included a 1.75 m section with 1.57% Ni, 1.02% Cu and 0.12% Co.

LOCAL GEOLOGY

The OKG prospect lies within the area mapped by Ryan *et al.* (*this volume*), and the local geology is now better known than in 1996. The dominant rocks in the showing area are coarse-grained, grey to black anorthosite rocks that superficially resemble typical Nain Plutonic Suite rocks. However, Ryan *et al.* (*this volume*) correlate these with mafic to anorthositic rocks that lie along strike to the southeast, which are now known to be of Paleoproterozoic age (Ryan *et al.*, 1997; Hamilton *et al.*, 1997). Field evidence suggesting an older age includes widespread retrogression of primary igneous pyroxenes to secondary amphibole and/or chlorite, and the presence of common mafic and felsic dykes. Shear zones are commonly developed along the contacts of dykes, and the mafic rocks are locally foliated, suggesting regional deformation. All of these features are seen in the field around the OKG prospect, and are also common in anorthosites seen in the drill core. Mountain top exposures topographically above the OKG prospect consist dominantly of homogeneous hornblende-bearing monzonite, and the contact between these and the anorthosites appears to be subhorizontal. The monzonites are also grouped as Paleoproterozoic by Ryan *et al.* (*this volume*). The pyroxenitic units that host much of the subsurface mineralization at the OKG prospect are rarely seen in outcrop, but small pods are present near the surface showing, and loose blocks are common in a talus pile directly below. Pyroxenites also outcrop at the nearby Noront–Golden Trump showing (*see* Kerr and Smith, 1997, for locations) where they are in contact with black anorthosites, just below the basal contact of the monzonite sheet. The drill core from this project has not yet been examined.

ROCK TYPES AND RELATIONSHIPS

Sections of diamond-drill holes OKG-96-9 and OKG 96-11 were examined and sampled during 1996. Both holes were drilled topographically below the surface showings, and intersected variably textured coarse-grained anorthosites having several discrete intervals of sulphide-bearing pyroxenite. These intervals range in thickness from less than 10 cm to over 10 m, and the contacts, where observed, are sharp (Plate 1a). One such unit, in hole OKG-96-9, includes larger crystals of black plagioclase that resemble those in the surrounding anorthosites, and probably represent xenocrysts. Similar relationships were observed in several other holes logged in 1997, and indicate that the pyroxenites intrude the anorthosites.

The anorthosites show a bewildering variety of textures and colours, ranging from massive, coarse-grained black material to spectacular rocks in which plagioclase is white and mafic minerals bright green. These gradational variations are interpreted to reflect variable retrogression and recrystallization of a primary igneous assemblage, and in some cases the alteration appears to be spatially related to sheared zones and granitoid veins. Drillholes OKG-96-09 and 96-11 contain few diabase or felsic dykes, but these were observed in several other holes logged in 1997. Mylonitic fabrics are locally developed at the dyke contacts, and extend into the dykes and adjacent anorthosites, and retrogression commonly intensifies at the contacts. This deformation is never seen at the contacts of sulphide-bearing pyroxenite units.

Sulphide mineralization is generally restricted to the pyroxenites, in which sulphide content ranges from less than 5 percent to up to 100 percent. The pyroxenites are medium-grained, dark green, equigranular rocks in fresh drill core. Where present in small amounts, sulphides are of disseminated type and are distributed evenly and interstitially, in patches up to 3 mm across. With increasing sulphide content, the patches become larger, up to 1 cm across, and locally

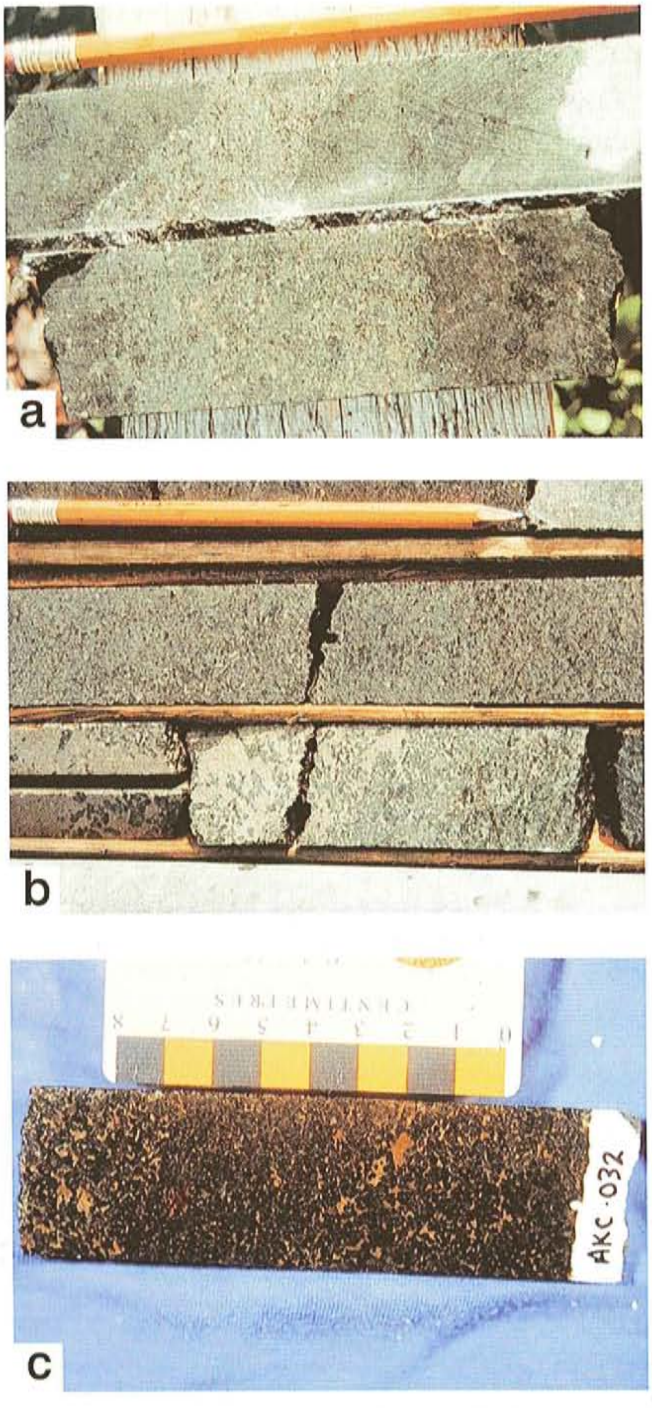

Plate 1. *Mineralized pyroxenites from the OKG prospect. a) Thin, dark green pyroxenite veins with disseminated sulphide, cutting anorthosites; note sharp contacts. b) progressive increase in sulphide content with depth, with small-scale development of massive sulphide near basal contact. c) Variation in habit and abundance of sulphides. All samples are from drillhole OKG-96-9. Drillcore is approximately 4 cm wide.*

coalesce, to give a network-like texture. Semimassive to massive sulphides are rare, and are most commonly seen at the lower (downhole) contacts of the pyroxenite units. Several of the pyroxenite units show downhole increases in sulphide content that are suggestive of gravitational settling of sulphide (Plate 1b); the thicker units may contain two or more "cycles" of sulphide abundance variation. Similar features were noted by Wilton and Baker (1996), and were observed in additional holes logged during 1997. Minor sulphide mineralization occurs locally in anorthosites within a few centimetres of the pyroxenite contacts. Many such zones are essentially extensions of thin massive sulphide zones developed at basal (downhole) contacts, where the sulphide appears to have migrated into the underlying anorthosites. However, thin massive sulphide veinlets are locally also present at upper (uphole) contacts. There are no drill core examples of significant sulphides in the anorthosites more than 25 cm from the contacts of a pyroxenite unit.

PETROLOGY

Anorthosite samples from both drillholes OKG-96-09 and 96-11, show a similar range in texture and mineralogy. The best-preserved are monomineralic plagioclase (about An_{52}) rocks having variable amounts of polygonal recrystallization around the margins of original igneous crystals. Plagioclase is commonly saussuritic (i.e., altered to fine sericite and epidote), but the intensity of this alteration is variable. Original (igneous ?) pyroxene is preserved in one sample, altered to hornblende, but it is not possible to identify the type of pyroxene. More strongly altered samples show increased recrystallization and grain size reduction of plagioclase, coupled with complete retrogression of primary mafic minerals to aggregates of green–brown hornblende and chlorite. Minor fine-grained biotite is not spatially associated with other mafic minerals and may have developed in a separate alteration event.

In contrast, several samples of pyroxenite containing from < 5 percent to almost 50 percent sulphides show well-preserved primary igneous mineral assemblages, with no extensive retrogression; however, in one sample, minor secondary amphibole occurs adjacent to the contact with the anorthosite. Weakly mineralized samples are dominated (>90 percent) by pleochroic orthopyroxene (hypersthene) showing well-preserved crystal shapes. Minor plagioclase (composition undetermined) is present in two samples, where it clearly has an interstitial (intercumulus ?) habit. Interstitial crystals of a more birefringent pyroxene, interpreted as clinopyroxene, are more common. However, a fibrous mineral, suspected to be tremolite, is also observed in some samples, where it appears to replace primary orthopyroxene; this is difficult to distinguish from the clinopyroxene. Minor green hornblende and red biotite are present. Sulphide is confined to interstitial pockets, and commonly mimics the habit of the interstitial silicate phases, but there is evidence of minor thermal erosion of orthopyroxene and contacts with sulphide pockets are commonly curved to scalloped (Plate 2a). Locally, circular sulphide patches are contained within pyroxene. One sample shows interstitial intergrowths of sulphide and plagioclase, suggesting simultaneous crystallization. Pyroxenites containing larger amounts of sulphide (up to 50 percent) are similar in overall mineralogy, but typically develop a "net-texture" in which large orthopyroxenes are surrounded by sulphide, within which they appear to "float" (Plate 2b). The orthopyroxenes generally retain their subhedral shapes, but show variable rounding suggesting mild thermal erosion of the crystals. Cracks within individual orthopyroxene crystals are filled with sulphide, indicating that they were solid and brittle. Minor red biotite in the sulphide-rich varieties grows across sulphide–pyroxene contacts, indicating that it is a later phase. In general, the textures within the pyroxenites suggest that sulphide was a primary magmatic phase, and the sulphide-rich varieties resemble "net-textured ore", where cumulus silicates have settled into a sulphide sublayer (e.g., Naldrett, 1973). Two samples of pyroxenite were collected from pods in a cliff outcrop just above the OKG surface showing, and these are essentially identical to the drill-core samples. Piercey *et al.* (*in press*) indicate that there are two subtypes of pyroxenite dyke, based on crystallization order, and suggest that these are associated with "leucotroctolite" dykes, which have not been observed by this author.

Two samples were collected across pyroxenite- anorthosite contacts to ascertain the relative timing of sulphide development. In both cases, sulphide is most abundant at the contact, locally forming a semicontinuous band. Sulphides are interstial and dispersed in pyroxenite, as noted above, but form small vein-like apophyses into the anorthosite, where they appear to have penetrated along crystal boundaries, and through individual crystals (Plate 2c).

CANADIAN STATES RESOURCES LICENSE 1514M PROSPECTS

The exploration history and general geology of this prospect have been reviewed by Kerr and Smith (1997). Surface mineralization was discovered following airborne EM surveys, and yielded encouraging grades up to 1.8% Ni, 0.3% Cu and 0.17% Co. Similar results over two, 10-m intersections were obtained from shallow drilling at the surface showing, and the surrounding area (termed the "G-zone") was tested with several holes. A second series of EM anomalies associated with gossaned float about 2 km to the northeast (termed the "E-zone"), was investigated during 1996. Drilling in both areas intersected sulphide mineralization, but the grades and widths failed to match those acheived from the

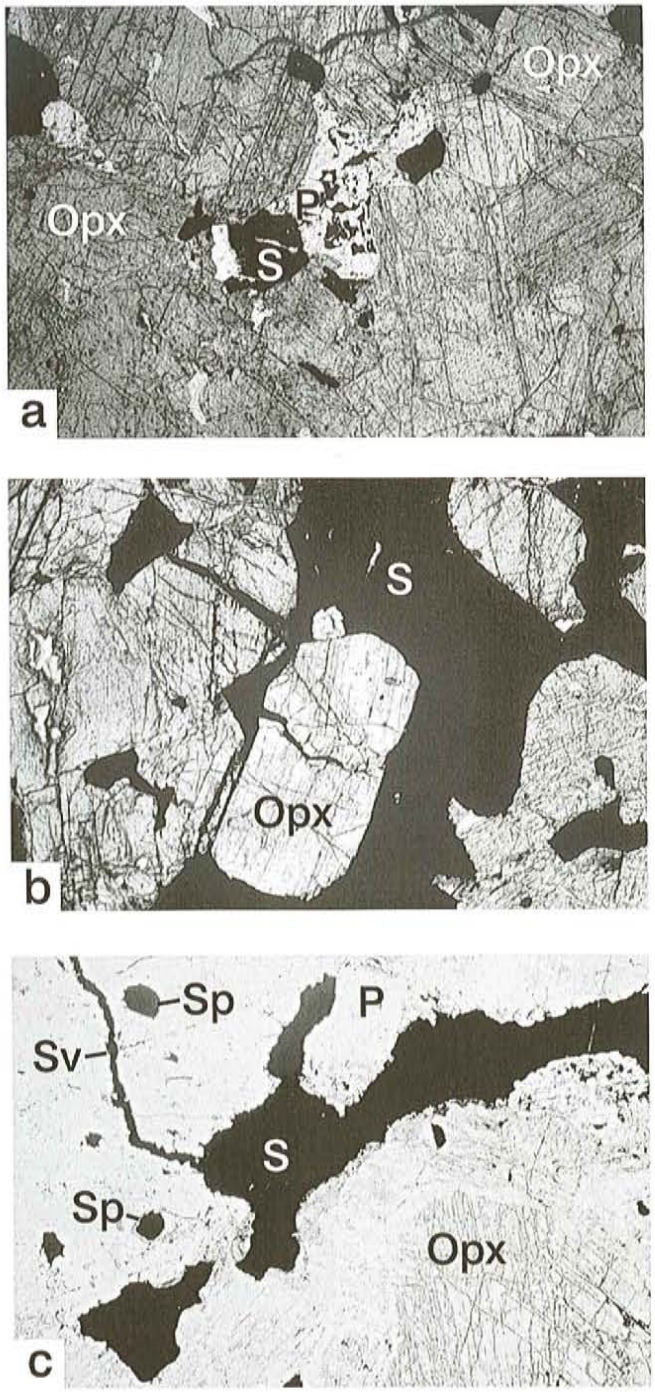

Plate 2. *Thin sections of mineralized pyroxenites from the OKG prospect. a) Typical pyroxenite with minor sulphide, PPL. Note interstitial geometry of sulphide pockets, rounding of orthopyroxene–sulphide contacts and intergrowth of plagioclase and sulphide. b) Net-textured pyroxenite, PPL. Note rounding of orthopyroxene crystals, and sulphide-filled cracks. c) Anorthosite–pyroxenite contact zone with semicontinuous sulphide band, PPL. Note the different habit of sulphide zones on either side of the contact. Field of view approximately 5.5 mm across. Opx = orthopyroxene, P = plagioclase, S = sulphide, Sv = sulphide veinlet, Sp = sulphide percolation zone. PPL = plane polarized light.*

initial drilling at the G-zone surface showing. There was no exploration program on the property during 1997.

LOCAL GEOLOGY

The prospects lie within Unit 10 of Ryan *et al.* (1997), described as "dark grey to buff anorthosite and leuconorite", and the G-zone showing lies close to the lower intrusive contact of a younger mottled troctolite to anorthositic unit that also hosts the nearby Noranda Hilltop prospect (Figure 2). Most outcrops in the immediate area of the showings are coarse-grained buff leuconorite, showing well-preserved subophitic (igneous) textures, and containing ubiquitous clots and crystals of very coarse (up to 25 cm), locally iridescent black plagioclase. These appear to become more leucocratic (anorthositic) to the east. Near the G-zone showings, they are cut by at least two dykes of weakly sheared, brown-weathering, magnetite-rich "ferrodiorite" that trend at 050°, and dip steeply south, probably occupying small fault zones. The showing area also includes a discontinuous northwest-trending zone of olive-green-weathering, medium-grained rock that shows locally well-developed layering, including magnetite cumulates up to 20 cm thick. This was interpreted by Ryan *et al.* (1997) as a large "granulitic" enclave of possible cognate origin, but an alternative explanation is that it represents a discontinuous younger dyke. It contains enclaves of anorthosite, but it is not clear if these equate to the surrounding leuconorite. There is very little outcrop in the region of the E-zone, but the leuconorite appears to be the same unit as at the G-zone.

The G-zone surface showing is clearly a discordant vein- or pod-like zone of massive sulphide (pyrrhotite and chalcopyrite) that displays sharp contacts against barren wall rocks, and includes blocks of anorthosite (Kerr and Smith, 1997). Sulphides are present sporadically within a radius of 150 m, but mostly seem to be small pockets and pods from which massive sulphide has been entirely weathered and leached.

ROCK TYPES AND RELATIONSHIPS

A total of 16 samples collected in 1996 have been examined in detail. Seven of these were collected from short drillholes completed by Canadian States Resources at the G-zone surface showing (LEGO-2, 3, 5, 6 and 7). The remainder come from drillhole 1514-96-21, representing the E-zone. Several more drillholes were logged from each of these areas in 1997.

The material from the G-zone is complex, but represents variable mixtures of two components - wall-rock leuconorite and massive sulphides. All variations exist within this spectrum, from massive sulphide peppered with round plagioclase crystals to massive leuconorite or anorthosite containing apparently intersitial sulphides. The distribution of the sulphide-rich zones and barren zones in the core is chaotic, and the attitudes of contacts are highly variable. In addition to individual crystals, massive sulphides also contain large multicrystal fragments of leuconorite, in some cases transected by vein-style sulphide. In many cases, these veins are chalcopyrite-rich and apparently truncated by the surrounding pyrrhotite-dominated massive sulphide (Plate 3a). However, the massive sulphide zones also contain chalcopyrite "flames" and stringers that appear to be vein-like, and indicate the opposite relative timing. Leuconorite-dominated material commonly shows a reticulate or network-like pattern where sulphides appear to be interstitial to silicates or surround them. This texture is referred to as "pseudo-network" texture because it is believed to originate through thermal erosion and percolation. In some cases, this sulphide is also chalcopyrite-dominated, and truncated by pyrrhotite-rich massive zones (Plate 3b), but pyrrhotite-rich pseudo-network zones are also common.

The E-zone core is similar but has some distinct features. Locally, it contains coarse chalcopyrite and pentlandite, commonly in patches where chalcopyrite forms a ring around the pentlandite. This material is normally present in discrete veinlets that crosscut the leuconorites (Plate 3c) and possibly also cut the pyrrhotite-rich massive sulphides (although this is difficult to establish). There is also further evidence for strong recrystallization and (possibly) alteration at the E-zone. Zones of extreme grain-size reduction to pale-green, totally amorphous material appear to be completely gradational with well-preserved anorthosite. Similar material is also reported from the nearby Cirque and Hilltop prospects (*see below*). Examination of more drill core in 1997 suggests that there is no clear spatial relationship between this recrystallization effect and the presence of sulphides, although the recrystallized anorthosites may be sulphide-bearing.

Fine-grained mafic rocks of uncertain composition are also present in both G-zone and E-zone core, although they were not observed in the short sections sampled in 1996; these samples have yet to be examined in thin section. These fine-grained rocks appear to intrude the leuconorites, and at least, locally, contain fine-grained disseminated sulphide. Similar rocks are prominent at the nearby Hilltop prospect (*see below*).

PETROLOGY

Samples of relatively well-preserved unmineralized wall rock from drill core and surface exposures are anorthositic, rather than leuconoritic, and coarse grained. Plagioclase compositions are estimated at An_{50} to An_{60}. Two of the samples are monomineralic plagioclase rocks, but the others contain minor pyroxene, with orthopyroxene rimmed by clinopyroxene. Recrystallized anorthosites from the E-zone contain remnants of original igneous crystals within diffuse

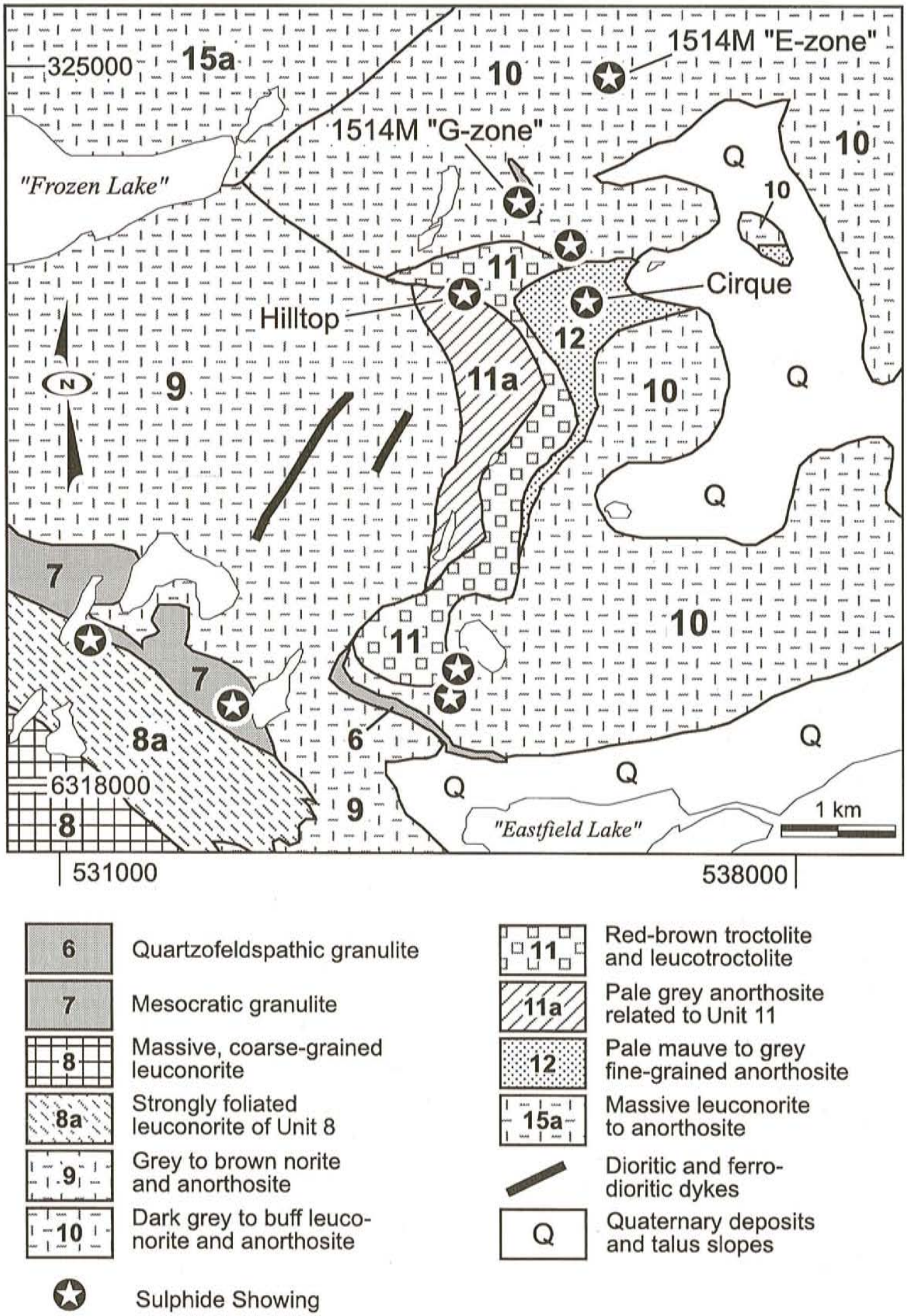

Figure 2. *Location of Ni–Cu prospects in relation to surface geological units in the "Hilltop Massif", Alliger Lake (NTS 14E/01) mapsheet. Geological units after Ryan* et al. *(1997) and Ryan (unpublished data).*

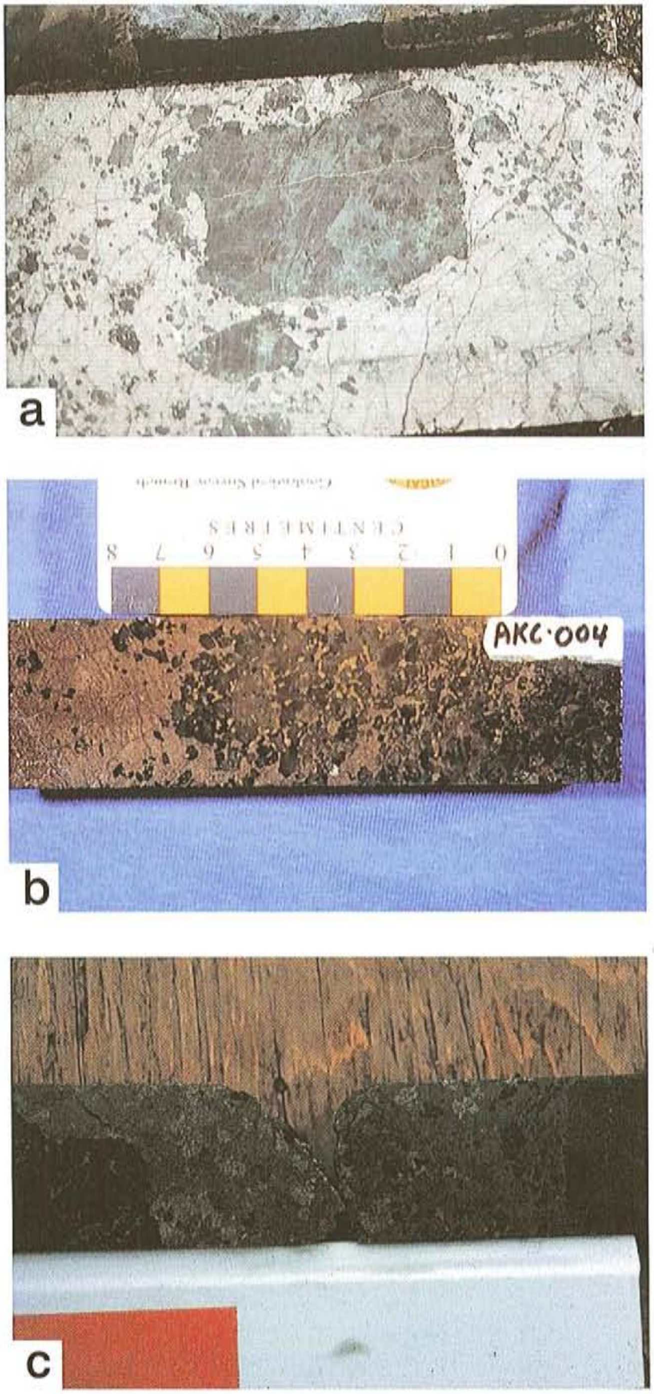

Plate 3. *Sulphide zones from the Canadian States Resources License 1514 prospects. a) Massive sulphide containing multicrystal fragment of wall-rock anorthosite, itself cut by earlier chalcopyrite veinlet. G-zone surface showing. b) "Pseudo-network" texture, where chalcopyrite appears to have percolated and eroded along grain boundaries in the wall rocks prior to arrival of nearby massive pyrrhotite zone. G-zone surface showing. c) Vein of massive sulphide containing coarse chalcopyrite and pentlandite, cutting through large plagioclase crystals in wall-rock anorthosite. E-zone, drillhole 1514-96-21. Drillcore in (a) is approximately 12 cm wide; other cores are approximately 4 cm wide*

zones of fine-grained polygonal plagioclase. Plagioclase shows only mild saussuritization, but pale-green chlorite is present in interstitial and grain-boundary areas, commonly associated with abundant calcite. The amount of chlorite and calcite increases with increasing recrystallization of the plagioclase, suggesting that there is a link between these processes. Sericite is present in the samples, as part of the saussurite alteration, but there is no sign of pervasive sericitization.

Sulphide-bearing samples can be divided into three categories, i.e., massive sulphide with silicate inclusions, anorthosite with pseudo-network sulphide, and anorthosite containing sulphide veinlets. All three categories may be present within a single short core interval, or even within a single thin section.

Massive sulphide samples, locally associated with magnetite, almost invariably contain plagioclase inclusions. The plagioclase ranges from multicrystal fragments, locally with included igneous orthopyroxene, to subhedral slightly rounded crystals, to rounded and pitted spheres. The individual crystals are commonly "peppered" by circular sulphide patches, or bisected by sulphide zones, and tendrils of sulphide have penetrated along cleavage and twin planes (Plate 4a). These features, coupled with the presence of multicrystal fragments, suggest that hot, liquid sulphides have disrupted and thermally eroded previously solidified material. Where plagioclase is in contact with magnetite, a birefringent reaction rim, interpreted as diopside, is present.

Pseudo-network-type sulphides preserve much of the original silicate rock, with variable modification. Worm-like zones of sulphide occupy grain-boundary regions and locally transect plagioclase crystals, which are themselved peppered with circular pockets of sulphide (Plate 4b). Sulphide appears also to have percolated along cleavage and twin planes in plagioclase, as noted earlier. In three dimensions, these rocks are probably sponge-like, with the plagioclase corresponding to the holes in the sponge, and they are completely gradational with the massive sulphide zones. These transitions from pseudo-network sulphides to massive sulphides with plagioclase inclusions record the progressive thermal erosion and disaggregation of the wall-rock anorthosite.

Anorthositic samples containing sulphide veinlets contain a combination of the above features. The sulphide veins contain rounded and resorbed plagioclase, but the margins of

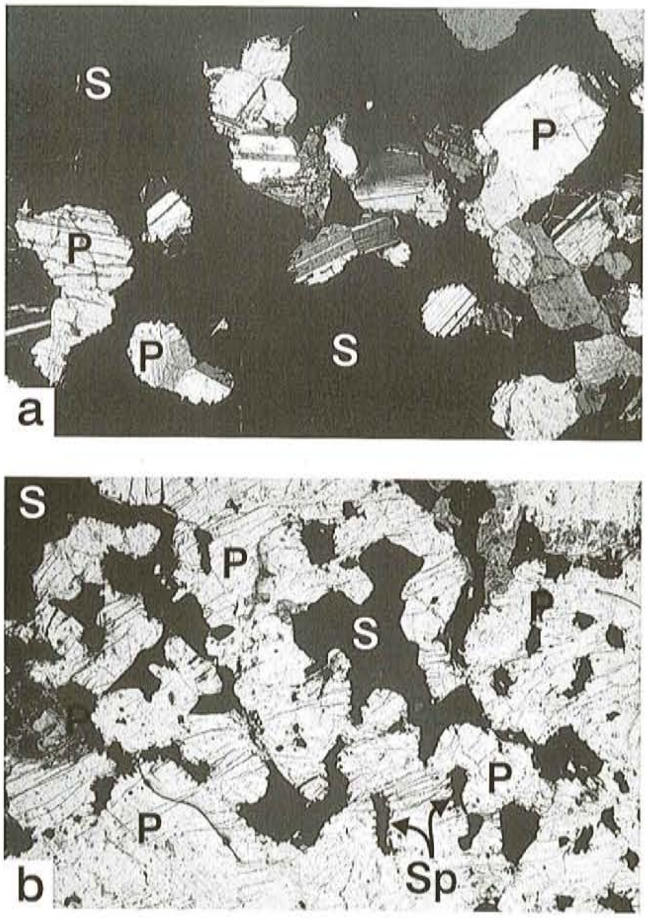

Plate 4. *Thin sections of mineralization from Canadian States Resources License 1514M prospects. a) Massive sulphides (opaque) containing plagioclase crystals in various stages of thermal erosion, XP. Note tendrils of sulphide penetrating along cleavage and twin planes b) Pseudo-network texture developed in anorthositic wall rock, where sulphide (chalcopyrite) has penetrated largely along grain boundaries, PPL. Note "shotgun" perforation of plagioclase crystals by sulphide. Field of view is approximately 5.5 mm across. Opx = orthopyroxene, P = plagioclase, S = sulphide, Sv = sulphide veinlet, Sp = sulphide percolation zone. XP = crossed polars; PPL = plane polarized light.*

the veins show pseudo-network textures, and local detachment of only weakly eroded crystals. In strongly recrystallized anorthosites, the sulphides crosscut zones of grain-size reduction and include partly recrystallized plagioclase, indicating that they postdate the recrystallization event. The variety of inclusions in such veins implies that they were derived from different locations, and had variable residence times in the sulphide liquid.

NORANDA HILLTOP PROSPECT

The Hilltop prospect, explored by Noranda Mining and Exploration in 1995 and 1996, was summarized briefly by Kerr and Smith (1997). A small mineralized outcrop is associated with an EM conductor with a strike length of 800 m and widths of 25 to 75 m (Squires *et al.*, 1997). Six diamond-drill holes were completed in 1996, and two intersected significant sulphide mineralization in the form of sporadic massive and semimassive zones. However, the width of the conductor appears to reflect the presence of several spaced and discontinuous sulphide zones, rather than a single feature. The sulphides contained subeconomic base-metal grades, with the best section assaying 0.43% Ni, 0.26% Cu and 0.14% Co over 0.8 m. Local chalcopyrite-rich zones assayed up to 1.76% Cu, but only over widths of 0.2 m or less (Squires *et al.*, 1997). No exploration work was conducted on the property during 1997.

LOCAL GEOLOGY

The Hilltop prospect lies within subunit 11a of Ryan *et al.* (1997), described as "pale grey anorthosite", which forms the upper part of a sheet-like unit floored by a "mottled reddish-brown troctolite to leucotroctolite" that intrudes their Unit 10, the regional host rock to the Canadian States Resources showings described above. Near the small surface showing, there are also discontinuous outcrops of a medium-grained equigranular rock type that contains disseminated sulphide. B. Ryan (personal communication, 1996) has suggested that these could be older inclusions, but Noranda geologists interpret it as a discontinuous dyke, considered to be genetically related to sulphide mineralization (Squires *et al.*, 1997).

ROCK TYPES AND RELATIONSHIPS

The nine samples examined in detail come from drillhole HT-96-3, which contains the most extensive mineralization. Other holes from the property have not yet been examined. There are essentially three rock types visible in the core, and the relationships between them provide valuable information about the origin of mineralization.

The most abundant rock type in drillhole HT-96-3 is a medium to dark-grey, homogeneous anorthosite that is equivalent to the outcrops seen at surface. This alternates with a finer grained, melanocratic, pyroxene-rich rock that contains variable amounts of disseminated sulphide. The contacts between this rock type and the anorthosite are sharp, but there is no obvious chilling effect. However, fragments of coarse-grained anorthosite are contained within the finer grained rock type and, where present, are surrounded by heavier sulphide concentrations (Plate 5a). These relationships suggest that the finer grained phase is a younger intrusion. Massive to semimassive sulphide mineralization, forming the third component, is in contact with both the anorthosite and the finer grained mafic rock, and appears to be preferentially located along the contacts between them. Within anorthositic

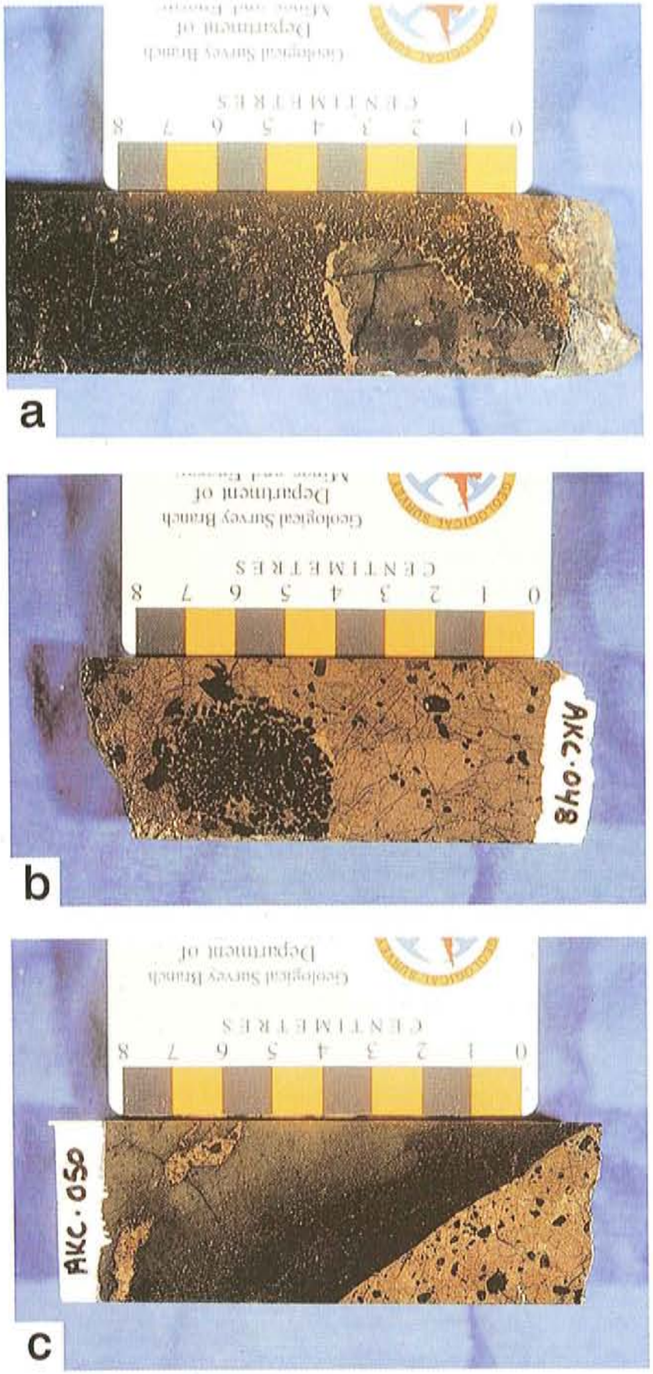

Plate 5. *Relationships in drill core from the Noranda Hilltop prospect. a) Fragment of wall-rock anorthosite within medium-grained gabbronorite containing disseminated sulphide. Note development of heavier sulphide mineralization around fragment. b) Spongy, rounded inclusion of pyroxene-rich material with interstitial sulphide, enclosed in massive sulphides, possibly representing a globule of an associated silicate liquid. c) Intense recrystallization and grain-size reduction of anorthosite at the contact of a massive sulphide zone. All illustrations from drillhole HT-96-03.*

country rocks, textures and relationships are closely similar to those described above from nearby license 1514M, i.e., the sulphides contain detached fragments and crystals from the anorthosite, and grade into pseudo-network-textured zones, which are locally chalcopyrite-rich. The contacts between massive sulphides and the finer grained mafic rock also range from sharp to gradational, but clear evidence of intrusion and fragmentation is absent. The massive sulphides contain variably resorbed plagioclase crystals, but also include rounded, sponge-like masses dominated by pyroxene, with associated interstitial sulphide (Plate 5b). These inclusions are morphologically similar to rounded mafic enclaves observed in granites, commonly interpreted as globules of an incompletely mixed mafic magma. Also, isolated pyroxene crystals are present locally within the massive sulphides.

The core from drillhole HT-96-3 also contains several zones of very fine-grained, pale-green material that is completely gradational with the well-preserved anorthosite wall rocks. This is closely similar to the recrystallization and saussuritization noted above from license 1514M, and is considered by Squires *et al.* (1997) to be spatially associated with the sulphide mineralization. Locally, this does appear to intensify adjacent to sulphide zones (Plate 5c). Extensive recrystallization was also noted in hole HT-96-4, at greater depths (Figure 3), but with only minor sulphide mineralization.

PETROLOGY

Well-preserved anorthosites from drill core and surface outcrops consist of coarse plagioclase (An_{55} to An_{60}), with variable (up to 5 percent) amounts of orthopyroxene, present as small interstitial crystals. Two samples of strongly recrystallized anorthosite were examined. The first, located immediately adjacent to massive sulphides, consists of a fine-grained polygonal aggregate of plagioclase, orthopyroxene (altered to fine-grained chlorite) and fresh clinopyroxene. Although it is broadly anorthositic in composition, there is no relict igneous texture and the rock has a generally "metamorphic" appearance. A second sample, located about 1 m from the nearest sulphide zone, retains a vestigial igneous texture and contains interstitial orthopyroxene altered to brown serpentinitic material and chlorite. Plagioclase contains fine-grained sericitic alteration and carbonate is locally prominent. This rock resembles "recrystallized anorthosites" from nearby license 1514M.

The finer grained, mafic rock observed in drill core consists mostly of plagioclase, orthopyroxene and clinopyroxene (Plate 6a). Typical examples contain about 40 percent plagioclase and 60 percent pyroxenes, but are heterogeneous and locally grade into a pyroxenite on the scale of a single thin section. Both orthopyroxene and clinopyroxene are

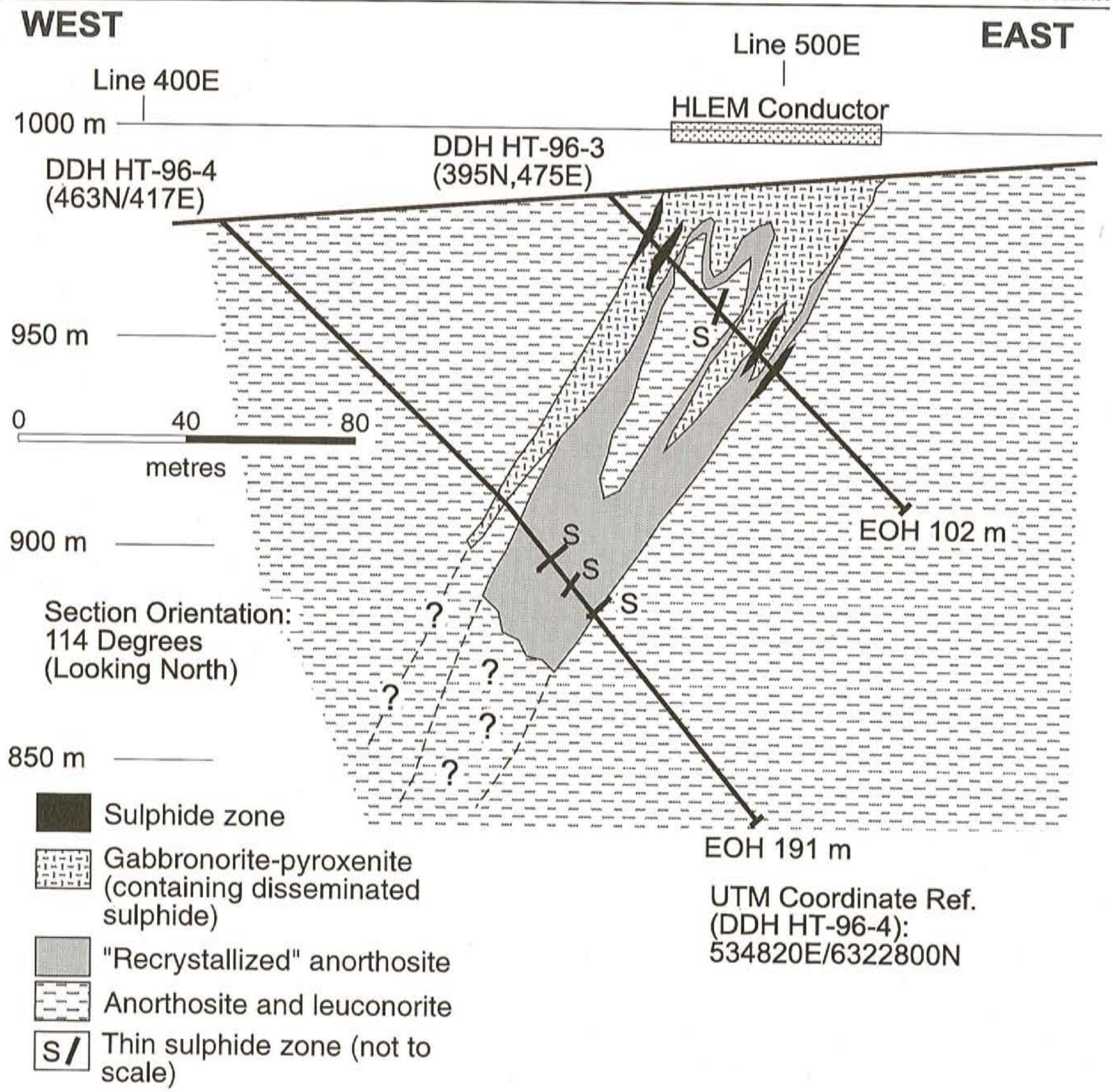

Figure 3. *Drill cross-section from the Noranda Hilltop property, showing the distribution of anorthosite, recrystallized anorthosite, gabbronorite–pyroxenite and sulphide mineralization. Based on core logs by Squires* et al. *(1997) and by the author.*

present, and the latter typically shows polysynthetic twinning and aligned opaque inclusions. Orthopyroxene is strongly pleochroic and contains plagioclase inclusions, and locally appears to be included within the clinopyroxene, suggesting that it is earlier. The ratio of clinopyroxene to orthopyroxene is variable, from 10:1 to 1:10, but most of these rocks are best described as gabbronoritic. Sulphides are more common in the clinopyroxene-rich variants and show a disseminated, interstitial habit, although in detail their contacts against silicates are curved, and the latter are locally embayed. However, more extensive disruption and erosion of silicate crystals by sulphide is not seen. The overall texture of the gabbronorites tends to be polygonal and annealed, and igneous textures (e.g., subophitic pyroxenes) are only locally preserved (Plate 6a). The medium-grained mafic rock exposed at the surface showing is closely similar to the clinopyroxene-rich gabbronorites from the drill core, suggesting that they are equivalent.

The massive sulphide zones invariably contain silicate inclusions; however, there is more variation within the inclusion population than at adjacent prospects. The most common inclusions are variably eroded and resorbed plagioclase crystals and aggregates that are probably derived from the anorthosite. Multicrystal fragments locally include sub-

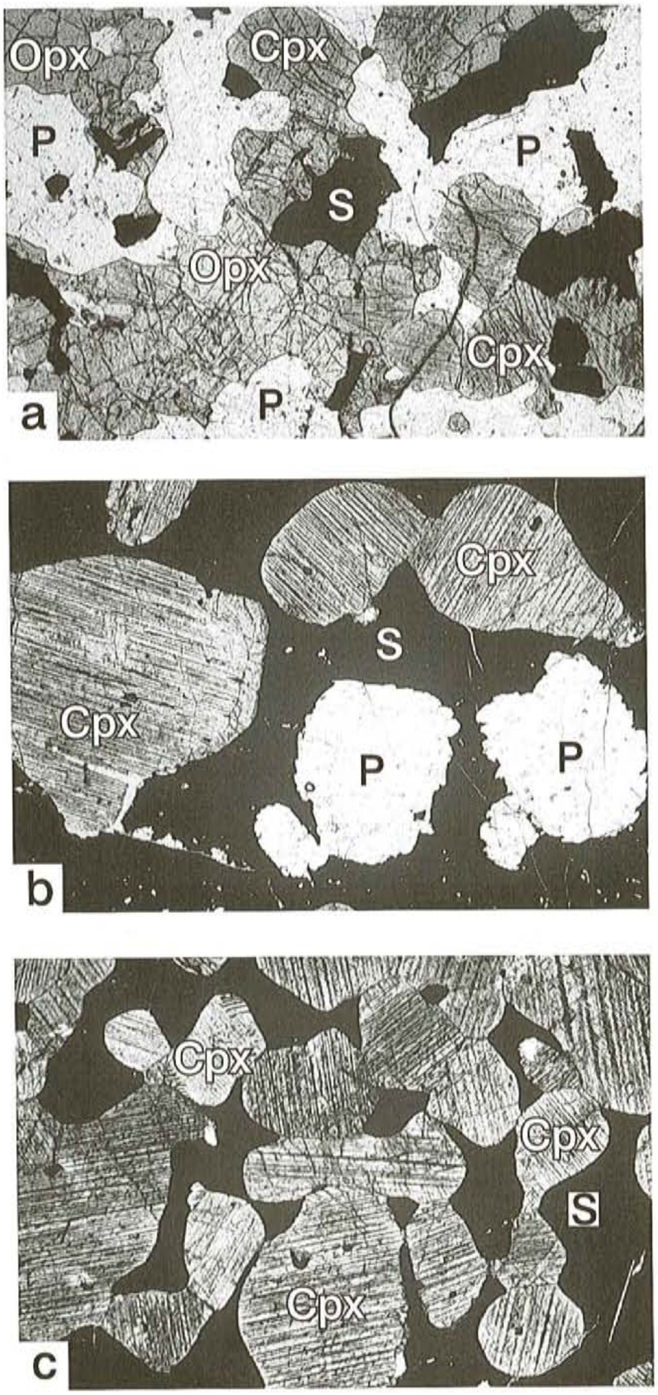

Plate 6. *Thin sections of drill core from the Noranda Hilltop prospect. a) Typical equigranular gabbronorite, showing polygonal, annealed appearance and interstitial sulphide pockets with curved boundaries, PPL. b) Massive sulphide with varied silicate inclusions including thermally eroded plagioclase and large clinopyroxenes with aligned opaque inclusions, PPL. c) Part of one of the spongy, rounded pyroxene-rich inclusions with interstitial sulphides, PPL. Note similarity to the gabbronorite in (a). Field of view is approximately 5.5 mm across. Opx = orthopyroxene, P = plagioclase, S = sulphide, Sv = sulphide veinlet, Sp = sulphide percolation zone, Cpx = clinopyroxene. PPL = plane polarized light.*

ophitic orthopyroxene, indicating that the wall rocks were mostly crystalline at the time of incorporation. Detached fragments of strongly recrystallized, fine-grained, anorthosite are present in adjacent sulphide zones, indicating that this process was also pre-sulphide. Greenish, serpentinitic clots observed in one sample are probably relict olivines, and resemble altered olivine seen in the Unit 11 troctolite of Ryan *et al.* (1997), which is presumed to underly the anorthosites in the Hilltop area. Single and multicrystal inclusions of pyroxene are also common (Plates 6b and c). Clinopyroxene is the most abundant variety, and shows polysynthetic twinning and opaque inclusions; locally, it is associated with, and encloses, orthopyroxene. Single crystals show mild thermal erosion, but lack the marked embayment and dissection typical of plagioclase. Multicrystal aggregates include lesser plagioclase, and show interstitial sulphide patches. These pyroxene-rich inclusions are closely similar to discrete gabbronoritic units containing disseminated sulphide. Pseudo-network-textured zones are locally developed on the anorthositic margins of some massive sulphide zones, and are identical to textures described from license 1514M, i.e., the sulphide appears to have thermally eroded and percolated along grain boundary regions.

CIRQUE PROSPECT

The Cartaway Resources Cirque prospect lies close to the Canadian States Resources and Noranda prospects described above (Figure 2). The exploration history and general geology of the prospect have been summarized by Kerr and Smith (1997). There is an extensive gossan exposed in cliff walls, associated with several airborne EM conductors. Diamond drilling intersected anorthosite containing multiple sulphide-rich zones, which appear to form a series of steeply east-dipping lenses or discontinuous veins. The best assay results were up to 0.44% Ni and 0.27% Cu, but most sections contained less than 0.3% combined Ni and Cu. Attempts to find the downdip extension of the zone through deep drilling in 1996 were not successful, but it was located in late 1997, when a deep hole cored a 45 m intersection containing several sulphide-rich zones. However, the Ni and Cu grades were similar to those obtained from previous drilling. The zone has now been drill tested over a vertical extent of close to 1 kilometre, and there do not appear to be significant grade variations within it.

LOCAL GEOLOGY

The Cirque prospect was located by Ryan *et al.* (1997) within their Unit 12, described as "fine- to medium-grained pale mauve to grey anorthosite", interpreted as a dyke-like body intruding their Units 10 and 11 (Figure 2). However, field observations during 1997 suggest that this interpretation (based on projection from scattered outcrops) is incorrect, and the dominant rock at the Cirque is actually the dark-grey to buff anorthosite (Unit 10) that hosts the nearby license 1514M prospects. But, it is variably recrystallized, and can appear fine grained in the field. It typically contains crystals and aggregates of coarse, black plagioclase.

ROCK TYPES AND RELATIONSHIPS

Examination of core from several drillholes during 1996 and 1997 indicates that all the holes intersected various mixtures of recrystallized anorthosite and disseminated to massive sulphide (mainly pyrrhotite). Nine samples from hole LBN-96-04 were examined in detail, and are probably representative of much of the core from the 1996 drilling. The sulphide zones are irregular to chaotic in distribution, and commonly carry silicate inclusions, dominated by plagioclase crystals and aggregates. The transitions from anorthosite to sulphide range from sharp to gradational, and extensive zones of "pseudo-network" texture are developed in the latter situation. Variable recrystallization of the anorthosites to pale-green, fine-grained material is widespread, but there does not seem to be a clear spatial relationship to individual sulphide zones. Generally, the mineralization resembles the Canadian States license 1514M area, but contains less chalcopyrite and no visible pentlandite. The finer grained, more mafic rocks noted at other prospects are generally absent from the Cirque core, and only one narrow zone of gabbronorite was noted, near the top of hole LBN-96-04. This has sharp contacts with the anorthosite, but its relationship to the latter is unclear. However, L. Dwyer (personal communication, 1998) suggests that pyroxene-rich units are present locally in some holes not observed by the author.

PETROLOGY

The anorthosites are similar to those described from license 1514M and consist mostly of plagioclase (An_{55} to An_{60}) containing minor amounts of orthopyroxene and clinopyroxene. Clinopyroxene surrounds variably altered orthopyroxene, and it appears to have crystallized later. Green, serpentinitic clots containing oxide inclusions, noted in some samples, may represent minor relict olivine, as at the Hilltop prospect. Strongly recrystallized, pale-green, anorthosites partly retain their original igneous textures but are largely reduced to fine-grained polygonal, saussuritized aggregates. As noted elsewhere, they also contain calcite, at least some of which has a vein-like form suggesting that it is relatively late. The single gabbronorite sample is more leucocratic than the equivalent rocks at the Hilltop prospect, and only contains about 30 percent pyroxene, with slightly more orthopyroxene than clinopyroxene. It does not contain any disseminated sulphide, but interstitial magnetite pockets show a texture analogous to that displayed by interstitial sulphide in many of the Hilltop gabbronorite samples.

The massive sulphide zones resemble those described above from other prospects, in that they contain numerous plagioclase crystals and multicrystal fragments, at least some of which were recrystallized prior to their incorporation in the sulphide. Pyroxene-rich inclusions like those from the Hilltop prospect were not observed. Pseudo-network-textured zones developed within the anorthosites marginal to the massive sulphide zones are identical to those described above from nearby prospects, and indicate thermal erosion and disaggregation of the anorthosite.

NAIN HILL PROSPECTS

The Nain Hill prospects (NDT Ventures/Takla Star Resources, Project 44) lie within 3 km of the town of Nain (Figure 1). The exploration history and general geology of this project were summarized by Kerr and Smith (1997). Mineralization was initially recognized in conjunction with airborne geophysical surveys in 1995, and is present in three main areas, termed the Unity west, Unity east and Valley zones, each associated with combined magnetic-EM anomalies (Kerr and Smith, 1997, their Figure 8). Numerous smaller sulphide showings are also present within the area. In 1996, diamond drilling was conducted on the Valley zone (four holes) and the Unity east zone (four holes). The drillholes intersected multiple sulphide–magnetite-rich zones in anorthosites, but the grades were generally low, with less than 0.4% combined Ni and Cu. The highest grades reported from drill core were 1.65% Ni, 0.3% Cu and 0.15% Co over 0.8 m at the Unity east zone. The Unity west zone, which contains the most extensive surface showings, remains untested as the Nain town council refused permission for drilling based on its proximity to the municipal water supply. A limited field program was conducted in 1997 to complete geological mapping of the property.

LOCAL GEOLOGY

The region surrounding Nain has not been covered by 1:50 000-scale regional mapping, and the existing 1:500 000-scale map (Ryan, 1990) is based on compilation of data from a variety of sources. The dominant rock type throughout the property is a variably foliated and recrystallized, coarse-grained, anorthosite to leuconorite or leucogabbro, generally viewed as the deformed marginal zone of a large, diapiric anorthositic pluton, although it could be of Paleoproterozoic age, as demonstrated to the north (Hamilton *et al.*, 1997). An east–west-trending zone of gneiss on the property (*see* Kerr and Smith, 1997, their Figure 8) has previously been denoted as Archean basement, but consists mostly of strongly deformed mafic plutonic rocks, and is suspected by the author to be a shear zone developed within the anorthositic unit. In the vicinity of sulphide showings, finer grained, pyroxene-rich rock types form sheet-like and vein-like units with sharp contacts, and carry disseminated sulphides and magnetite. These are suspected to be younger intrusive rocks, and they are at least locally discordant to the fabric in the surrounding anorthosite. However, they appear to be locally foliated, and their exact relationship to the deformation that affected the anorthosites is unclear.

ROCK TYPES AND RELATIONSHIPS

Sections of drillholes 44-2 (Valley zone) and 44-5 and 44-6 (Unity East zone) were examined in detail and sampled in 1996, but the other drillholes from these areas have yet to be examined. The drill core from the Nain Hill project is probably the most complex yet seen from northern Labrador by the author, and a full understanding of rock types and relationships requires further examination and sampling.

The 56-m-mineralized interval in drillhole 44-2 is divided into two sections. The upper part consists of a dark-grey, medium- to coarse-grained, apparently foliated, mafic rock with less than 50 percent plagioclase. This contains some disseminated sulphide mineralization, and local semimassive pyrrhotite zones. One of these semimassive zones contains large, dark-grey, plagioclase inclusions that are unlike the plagioclase in the gabbronorite, but resemble plagioclase in anorthosites (*see below*). The gabbronorite has a diffuse contact with an underlying white to pale-grey, foliated anorthosite, in which the mafic minerals are variably chloritized. This contains several discrete sulphide and magnetite-rich zones that appear to be discordant veins that intrude and brecciate the anorthosite. A short (0.7 m) interval of a fine- to medium-grained grey mafic rock shows sharp contacts, and contains large plagioclase crystals that resemble the locally iridescent plagioclase in the wall rocks, suggesting that it is a younger intrusion (Plate 7a). This rock type appears unfoliated, and contains heavily disseminated sulphide mineralization. The underlying section is again dominated by coarse-grained anorthosite, intercalated with semimassive to massive sulphide-magnetite zones, including one section over 8 m long. The sulphide zones appear to be discordant, and include individual large plagioclase crystals that resemble those in the anorthosite, multicrystal anorthosite fragments, and aggregates of pyroxene (Plate 7a). The sulphides are invariably associated with magnetite, which in some cases is the dominant phase. Some sulphide-dominated sections contain rounded magnetite beads. Most of the sulphide is pyrrhotite, and minor chalcopyrite.

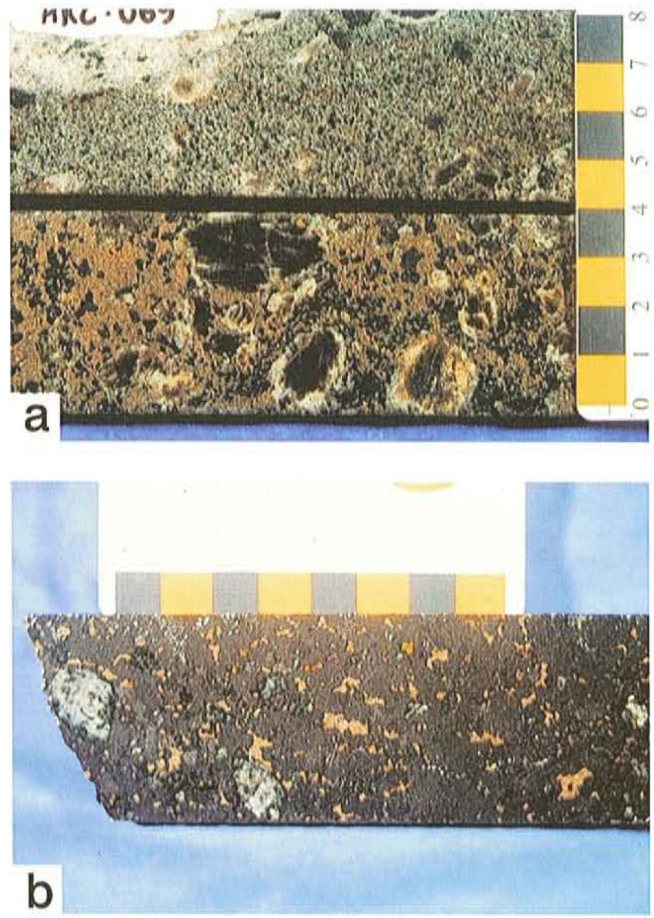

Plate 7. *Relationships in drill core from the Nain Hill prospects. a) Upper section; fine-to medium-grained gabbronorite with disseminated sulphide, containing large plagioclase crystals and aggregates derived from wall-rock anorthosites, and darker pyroxene-rich clots. Lower section; Massive sulphide zone containing identical inclusion types. Drillhole 44-2, Valley Zone. (b) Massive magnetite, with interstitial pyrrhotite, and fragments of wall-rock anorthosites. Drillhole 44-5, Unity east Zone.*

The 40-m-mineralized interval from drillhole 44-6 contains three components. A white- to grey-weathering anorthosite containing chloritized mafic minerals, closely resembles the anorthosite described above from the Valley zone. This is intercalated with a darker, finer grained, apparently foliated, mafic rock type that forms discrete units up to 8 m thick. Two examples of this unit show a distinct asymmetry, with well-banded upper sections that pass downhole into more massive material. The upper contacts are indistinct, but the lower contacts are sharp. The mafic rock type contains disseminated sulphide. Small, discordant zones of semimassive to massive pyrrhotite and magnetite are present within the anorthosite, but wider zones appear to be spatially associated with the contacts between the anorthosite and the finer grained mafic rock. The thickest sulphide–magnetite zones are associated with the lower (downhole) contacts.

Contacts between anorthosite and sulphide-magnetite are sharp, and the latter contains anorthosite fragments and plagioclase crystals; locally, zones of pseudo-network texture are developed in the adjacent anorthosites. The contacts between sulphide zones and the mafic rock type are diffuse and more difficult to interpret. Massive sulphide zones invariably contain magnetite, and those that are poor in silicate inclusions commonly contain rounded magnetite beads, as in the Valley zone.

A short section examined from drillhole 44-5 consists mainly of massive magnetite with interstitial pyrrhotite. It contains plagioclase crystals and multicrystal fragments that clearly resemble the local anorthosites (Plate 7b).

PETROLOGY

A total of 16 samples were examined in detail. The anorthosites consist of partly recrystallized plagioclase (An_{50} or so), with small amounts of variably retrogressed clinopyroxene, locally with cores of orthopyroxene. The pyroxenes are recrystallized to polygonal aggregates, and altered to fine-grained green amphibole, brown biotite, and chlorite. In one example, the transformation is complete, and the amphibole–chlorite aggregates mimic the interstitial to subophitic habit of the original pyroxene. An anorthosite sample from drillhole 44-2, collected at the contact of a massive sulphide–magnetite zone, contains euhedral crystals of a colourless amphibole that statically overprint the chloritic aggregates. This mineral is probably tremolite–actinolite, and its porphyroblast-like habit suggests that it may be of contact metamorphic origin. Similar porphyroblast-like colourless amphibole was noted within altered anorthositic fragments contained inside sulphide–magnetite zones (*see below*).

The finer grained more mafic rocks are of broadly gabbronoritic composition, although some samples from drillhole 44-6 are virtually pyroxenitic. Typical examples consist of orthopyroxene, clinopyroxene, plagioclase, sulphide and minor red biotite. Orthopyroxene is commonly dominant but is locally surrounded by clinopyroxene, suggesting that it was an earlier phase. Where present, sulphide forms disseminated pockets of interstitial habit (Plate 8a), with local minor thermal erosion of adjacent silicates. The original igneous textures are not well preserved, and these rocks generally have a granular, polygonal "metamorphic" appearance (Plate 8a). Although some examples appear foliated in the drillcore, there is no sign of a penetrative fabric in thin section. The fine-grained gabbronorite in drillhole 44-2 contains two types of silicate inclusions. The plagioclase-rich inclusions match the local anorthosites, in that they show recrystallization of plagioclase, and retrogression of the mafic minerals to amphibole and chlorite. Pyroxene-rich inclusions consist of coarse clinopyroxene that has overgrown an earlier orthopyroxene, and essentially resemble coarser, pyroxenite- like, variants of the gabbronorite. These relationships suggest that the gabbronorites intruded the anorthosites, and also that the various gabbronorite units are genetically related. Surface samples from mafic rocks associated with sulphide mineralization range from gabbronorite to pyroxenite, and resemble the drill-core samples in general terms.

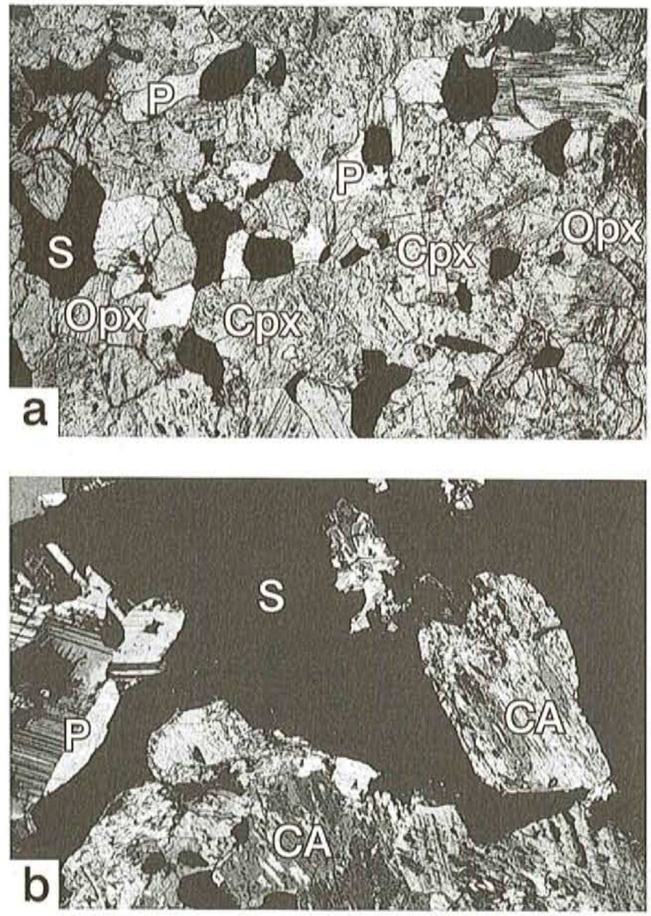

Plate 8. *Thin sections of drill core from the NDT Ventures / Takla Star Resources Nain Hill prospects. a) Granular, polygonal appearance of gabbronorite unit, PPL. Note interstitial sulphide pockets distributed through the sample. b) Previously recrystallized plagioclase crystals and chlorite–amphibole aggregates (after original igneous pyroxene) enclosed by massive sulphide–magnetite rock, XP. CA = chlorite and amphibole. Field of view is approximately 5.5 mm across. Opx = orthopyroxene, P = plagioclase, S = sulphide, Sv = sulphide veinlet, Sp = sulphide percolation zone. PPL = plane polarized light; XP = crossed polarizers.*

Massive sulphide–magnetite zones are discordant and transgressive with respect to the anorthosite. Multicrystal fragments included within them contain recrystallized plagioclase and retrogressed mafic minerals, indicating that both events preceded their incorporation in the sulphides (Plate 8b). As noted above, tremolite–actinolite porphyroblasts overprint chloritic aggregates in some of these fragments. Variably eroded clinopyroxene crystals and aggregates also occur in some of the sulphide zones. A thick sulphide-rich zone in drillhole 44-2 contains plagioclase-rich and pyroxene-rich inclusions that correspond exactly with the inclusion types in the spatially associated fine-grained gabbronorite unit. The textural relationships between sulphide and magnetite indicate that magnetite formed early, and was resorbed to form rounded beads. The interstitial habit of the pyrrhotite in massive magnetite zones from drillhole 44-5 indicates the same relative time relationship.

"SOUTH VOISEY'S BAY" PROJECT AREA

The "South Voisey's Bay" project is a large composite exploration property about 120 km south of Nain (Figure 1), held by Donner Minerals Limited and several joint venture partners, including NDT Ventures, Major General Resources, Northern Abitibi Mining, Cypress Minerals and Thistle Creek Resources. The 1997 program was managed by Teck Corporation, which holds a 12% interest in Donner Minerals, and options to acquire part of the mineral rights. The exploration history of the area (to late 1996) and general geology were summarized by Kerr and Smith (1997). Widespread disseminated sulphide mineralization is present in the basal section of a large sheet-like gabbroic intrusion that intrudes the Churchill Province north of the Harp Lake intrusion. Extensive shallow diamond drilling in 1995 and 1996 defined the extent of disseminated mineralization at the showings, but the best grades were around 0.5% combined Ni and Cu. However, extrapolation from disseminated mineralization to 100% sulphides suggests potentially economic grades.

The 1997 diamond-drilling program moved away from surface showings to blind target areas, and confirmed that sulphide mineralization is a widespread regional feature at the base of the gabbro, and that parts of the gabbro extend to depths of at least 700 m. Massive sulphide mineralization was recently intersected in three drillholes completed on a Donner Minerals/Northern Abitibi Mining claim block. Narrow zones assayed 1.93% Ni, 1.07% Cu and 0.26% Co over 0.6 m and a remarkable 11.75% Ni, 9.7% Cu and 0.43% Co over 1.1 m. A thicker (15.7 m) massive sulphide intersection reported in December 1997 gave average assays of 1.13% Ni, 0.78% Cu and 0.2% Co. These intersections are located at the basal contact of the gabbro unit, or within the footwall gneisses just below the contact. These are the most encouraging results to date from any junior exploration project in northern Labrador outside Voisey's Bay, and an extensive exploration and drilling program is anticipated for 1998.

LOCAL GEOLOGY

The area of interest was mapped in part by Thomas and Morrison (1991) and in part by Hill (1982), and was further investigated by the author in 1997. It is dominated by presumed Paleoproterozoic gneisses of the Churchill Province, which consist of garnetiferous, biotite-rich metasedimentary gneisses and massive, leucocratic garnet-bearing granitoid rocks. The metasedimentary rocks commonly contain minor sulphides and graphite, and are compositionally similar to the Tasiuyak gneiss farther to the north, although they may not be directly correlative (Ryan, 1996). The granites appear to be younger, and were probably derived from the metasediments by partial melting processes. The gneisses are intruded by, and "overlain" by, an undeformed intrusion of broadly gabbroic composition. The age of this intrusion is unknown, but it is younger than the Harp Lake Complex (which it locally intrudes) and it is assumed to be Mesoproterozoic.

The geometry of this intrusion is complex, and its widespread preservation as "mesas" sitting above an apparently flat basal contact indicates that large areas were sheet-like. However, in other areas linear to arcuate external contacts are apparently independent of local topography, suggesting that they are steep, and that the gabbro extends to greater depths. At least locally, sheet-like sections dip eastward, below the gneisses. The gabbro includes at least two discrete phases. A fine-grained, olivine-bearing phase is present in the lower sections, and is associated with sulphide mineralization. This is overlain by a coarser grained, apparently olivine-poor, leucocratic variant that is locally plagioclase–porphyritic. The latter phase is superficially similar to some of the coarse-grained anorthositic rocks of the Nain and Harp Lake Plutonic suites. The relationship between "Lower" and "Upper" gabbro is difficult to assess, but mineralized zones associated with the lower unit are locally truncated by coarse gabbro, suggesting that the latter is at least locally younger.

There are five major surface Ni–Cu showings in the area, and numerous smaller occurrences (*see* Figure 9 of Kerr and Smith, 1997, for locations). All are associated with the basal contact of the gabbro, and consist of disseminated pyrrhotite, chalcopyrite and minor pentlandite in olivine gabbro. The mineralized rocks are texturally variable, and a common knobbly weathering texture is related to the presence of large clinopyroxenes in a recessive sulphide-bearing matrix (leopard texture). Other examples contain coarse clots of sulphide in gabbro, and also variably preserved fragments of country rock gneisses. In general, the geology of this area shows many parallels with the area around Voisey's Bay, and the complex textures of mineralized gabbros and associated breccias (Kerr, 1997a), are very reminiscent of the Reid Brook Intrusion which hosts the Voisey's Bay deposits.

ROCK TYPES AND RELATIONSHIPS

Parts of three drillholes were examined and sampled during 1996, and more detailed examination and sampling of

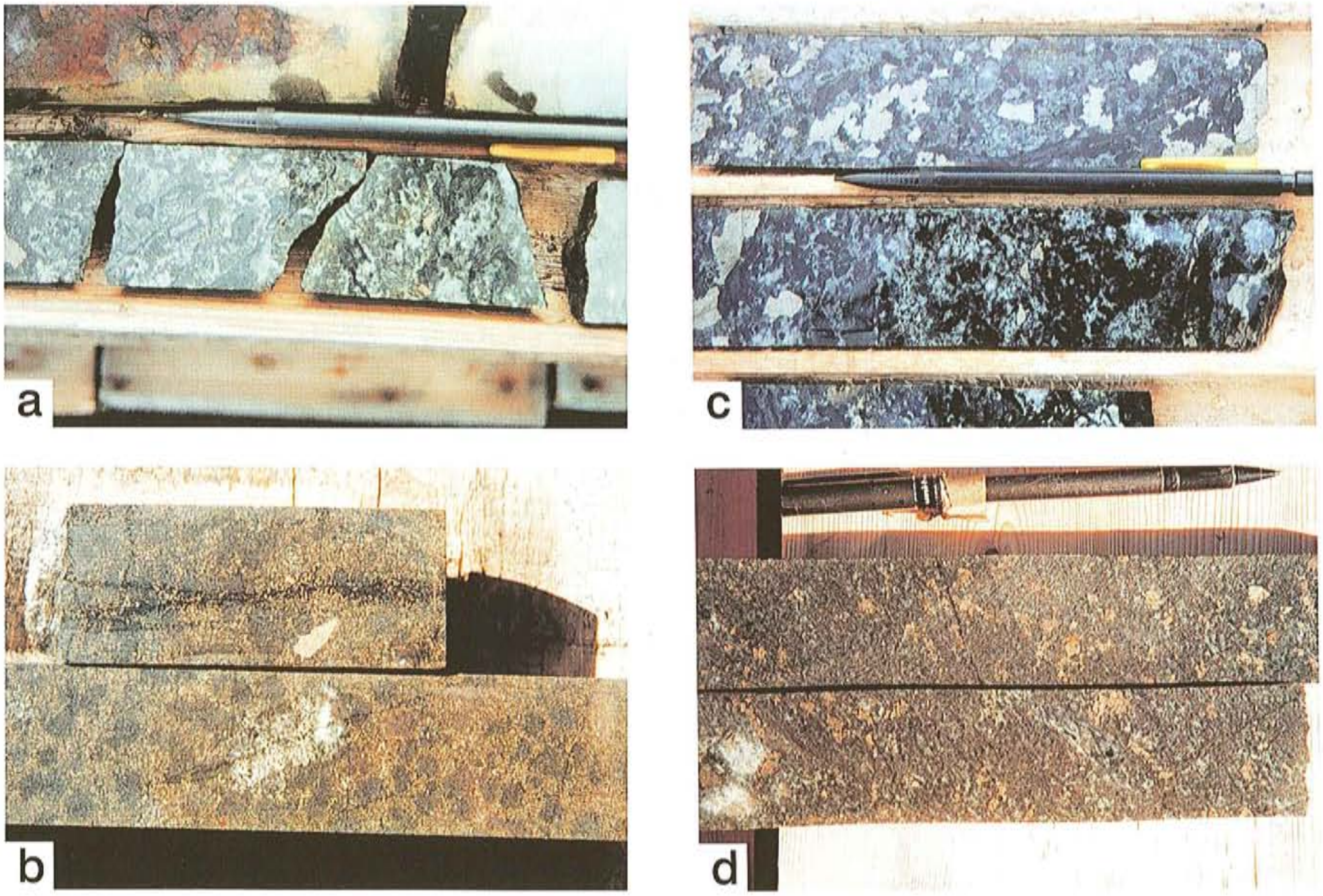

Plate 9. *Rock types and relationships from South Voisey's Bay area prospects. a) Complex breccia showing gabbroic matrix and variably digested granitoid gneiss fragments. GG prospect, drillhole SVB-96-02. b) Leopard-textured gabbro with large clinopyroxene crystals set in sulphide-bearing groundmass. Note larger, angular, patch of massive sulphide, possibly representing a fragment derived from elsewhere. GG prospect, drillhole SVB-96-02. c) Foliated granitoid gneiss from a footwall zone, containing discordant, vein-style sulphide zones. Drillhole SVB-96-07 d) Medium-grained, equigranular olivine gabbro with dispersed patches of sulphide. Mineral Hill prospect, drillhole SVB-96-36. Drill cores are approximately 4 cm wide.*

core was conducted over several days in 1997. Interpretation of the data from recent work is still in progress, and the following descriptions are based mainly on the 1996 work.

Drillhole SVB-96-02, from the "GG" showing (Kerr and Smith, 1997) intersected at least two sections of mineralized gabbro, separated by screens of country-rock gneisses. The upper zone, containing the best mineralization, includes an upper section of massive, fine-grained, dark-grey gabbro containing numerous variably digested siliceous fragments, including recognizable foliated granites, and scattered sulphides. Locally, this unit is extremely fragment rich (Plate 9a). This is underlain by 12 m of sulphide-bearing gabbro with well-developed leopard texture. The leopard-textured gabbro is a spectacular rock with clinopyroxene crystals up to 1 cm in diameter set within a fine-grained sulphide-rich matrix, and also contains larger pockets of massive sulphide up to 2 cm in diameter (Plate 9b). This is underlain by about 28 m of variably heterogeneous gabbro with only minimal sulphide, and scattered small fragments, in turn underlain (no contact preserved) by a coarse-grained, white, foliated granite (part of the basement) containing equant dark-grey patches interpreted as retrogressed garnets. This also contains sulphides, but these are restricted to thin vein-like zones that transgress the foliation. The basement screen is only about 8 m thick, and is underlain by a second gabbroic interval about 24 m thick, containing minor interstitial sulphide, and local coarser sulphide patches up to 1 cm across. As in the first mineralized interval, this contains scattered basement fragments. This passes downhole into a second thin zone of granitoid gneiss, which again contains minor vein-style sulphides. This is underlain by a massive, sulphide-poor diabase-like rock that is chilled at its upper contact, but coarsens downward. Only a few metres of this material was penetrated.

Drillhole SVB-96-07, from the "Major General" showing area, was not examined in detail, but the mineralized section includes fine- to medium-grained gabbro containing disseminated sulphides, underlain by gneisses of uncertain origin, containing significant vein- and pod-like sulphide concentrations (Plate 9c). As in the case of drillhole SVB-96-02, these sulphide zones appear to cut the fabric in the gneiss. Coarse pyrrhotite is intergrown with chalcopyrite and pentlandite, and also coarse, locally skeletal, magnetite.

Drillhole SVB-96-36, from the "Mineral Hill" showing, is dominated by a thick (87 m) upper section of coarse-grained, pale-grey, leucocratic gabbro, which becomes finer grained and locally fragment-rich toward the base. It appears variably retrogressed in the core, with green amphibole developed as alteration of primary pyroxene. The relationship between this and an underlying grey, medium-grained gabbro is not clear, but the latter is compositionally distinct as it contains up to 15 percent sulphides, mostly distributed in patches up to 1 cm across, which are intergrown with the silicates (Plate 9d). The mineralized section is underlain by about 16 m of similar gabbro with only minor sulphide, which becomes increasingly heterogeneous downhole, with diffuse white fragments (basement xenoliths ?) and coarse sulphide clots. This is in turn underlain by heterogeneous fine-grained gabbro that contains minor interstitial sulphide, but also contains some vein-like sulphide concentrations. The hole did not penetrate the underlying basement.

PETROLOGY

Only five drill-core samples have been examined in detail from this area, but these preserve a range of interesting and informative textures.

The leopard-textured gabbro can be divided into two components, i.e., oikocrystic clinopyroxene, and sulphide-bearing groundmass. The oikocrysts are subangular to rounded in shape, and consist of optically continuous grey–purple (likely titaniferous) augite, with included plagioclase (An_{55}) laths. Minor olivine is also present within the oikocrysts. There is no included sulphide within the oikocrysts, but their boundaries with the groundmass are not sharp. The groundmass consists of variably altered olivine (25 to 40 percent), plagioclase, sulphide, and minor augite. All stages in the alteration of the olivine to green serpentinite aggregates are preserved, and it appears to have crystallized synchronously with the silicates, suggesting fairly rapid cooling. The groundmass is essentially troctolitic, and displays superb silicate–sulphide intergrowth textures. The sulphide is interstitial to oikocrystic with respect to plagioclase, and clearly crystallized late. It is dispersed evenly through the groundmass, and shows straight, sharp grain boundaries against associated silicates, with no sign of thermal erosion (Plate 10a). Other field samples of fine-grained and leopard-textured gabbro show essentially identical features, and vary only in their proportion of sulphide.

Gabbros containing coarser sulphide patches from drillholes SVB-96-07 and 96-36 contain essentially the same mineral assemblage, but are coarser grained, with subophitic, rather than oikocrystic, titaniferous augite. Olivine also shows local interstitial textures with respect to plagioclase, but these are not well developed. Minor red biotite of primary appearance is also present. Based on overgrowth relationships, the crystallization sequence appears to have been plagioclase, followed by olivine, followed by clinopyroxene, sulphide and biotite. The margins of sulphide patches show intergrowth textures with plagioclase, and the sulphides include euhedral plagioclase laths. Plagioclase laths protrude into the sulphide zones, but largely retain their shape (Plate 10b). However, on a local scale, there is evidence for minor thermal erosion of the nearby silicates. The rate of cooling appears to have been slower than in the leopard-textured gabbro. The coarse-grained "upper" gabbro was not sampled in drill core, but a surface sample collected near the "Happy Face" showing (*see* Kerr and Smith, 1997, for location) consists of coarse plagioclase, interstitial clinopyroxene and altered olivine. The latter is grey due to oxide dusting, and is locally difficult to distinguish from titaniferous augite. Examination of other "upper gabbro" sections as part of a thesis project (H. MacDonald, personal communication, 1998) suggests that it is commonly olivine-bearing.

A foliated granitoid gneiss from a country-rock footwall screen clearly retains relict igneous textures, and was derived from a coarse-grained granite, which contained widespread graphic quartz–K-feldspar intergrowths suggestive of quenching or high-level emplacement. The mafic minerals are recrystallized aggregates of biotite and chlorite. Prominent equant dark-grey patches observed in hand sample are an altered, cloudy mineral with low birefringence, suspected to be cordierite, probably after primary igneous garnet. The dark colour is due to dusting by very fine-grained opaques and a dark-green mineral suspected to be hercynitic spinel; granular corundum has also been observed. Observations during 1997 indicate that garnet is progressively transformed to cordierite adjacent to the basal contact of the gabbro, and this is likely a contact metamorphic effect. Identical granitoid gneisses that contain vein-like sulphide zones show good thermal erosion textures, and some small-scale zones of "pseudo-network" texture akin to those described from showings in anorthositic rocks, where sulphides appear to have eroded and penetrated along grain boundary regions. The silicate–sulphide textures in the gneisses (Plate 10c) are entirely different from those described from the gabbro.

SUMMARY AND DISCUSSION

This report discusses only a few of the drillholes from a selection of many new Ni–Cu showings discovered in Labrador. More information, including geochemical data, is required to establish the wider applicability of its findings,

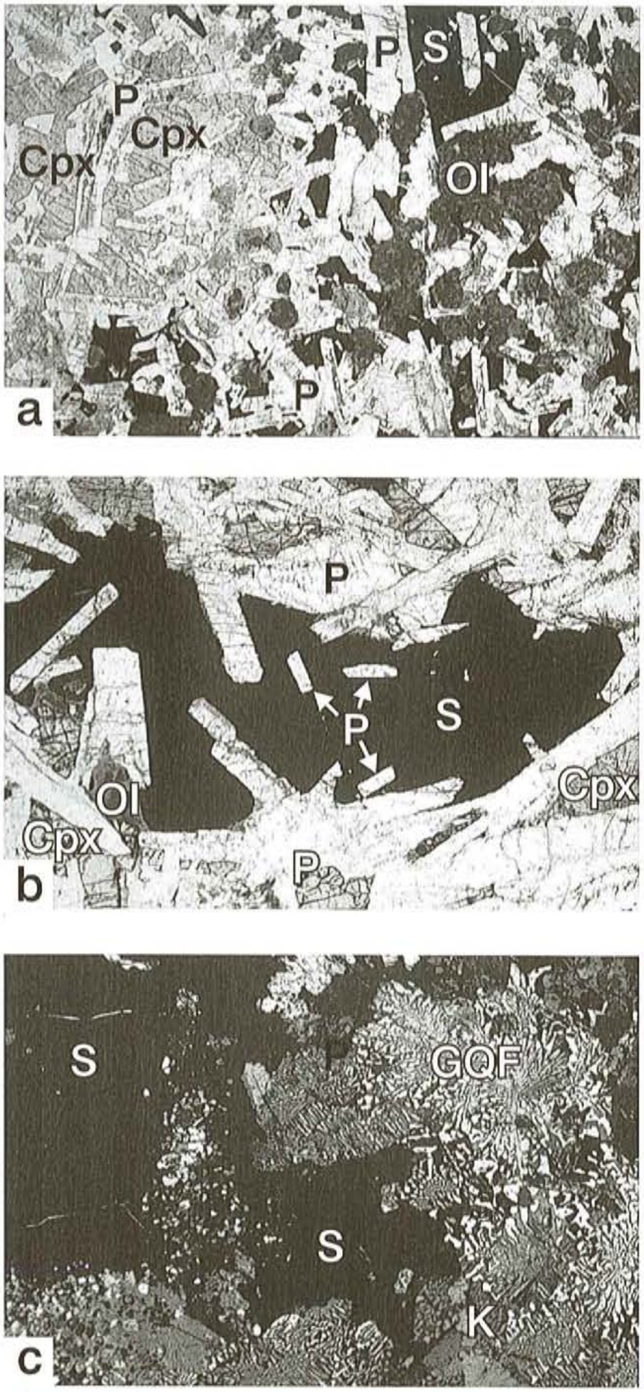

Plate 10. *Thin sections of drill core from the South Voisey's Bay area prospects. a) Intergrown olivine, plagioclase and sulphide from the groundmass of leopard-textured gabbro, with margin of clinopyroxene oikocryst at left, PPL. Note quenched appearance and straight sulphide-silicate boundaries. b) Edge of a larger sulphide patch in gabbro, showing coarser plagioclase crystals protruding into sulphide zone and plagioclase laths included in sulphide, PPL. c) Retrogressed garnet-bearing granitoid gneiss with graphic quartz-feldspar intergrowths and "invading" sulphide veinlets, XP. Opx = orthopyroxene, P = plagioclase, S = sulphide, Sv = sulphide veinlet, Sp = sulphide percolation zone, Ol = olivine, GQF = graphic quartz and feldspar K = potassium feldspar. Field of view is approximately 5.5 mm across. PPL = plane polarized light; XP = crossed polarizers.*

and to fully understand the relationships and textures described. The present study is intended to be descriptive rather than interpretative, but several important conclusions can be drawn from these preliminary data.

The Ni–Cu prospects described here fall into two fundamentally different groups. The samples from the "South Voisey's Bay" project show primary magmatic sulphide textures that indicate a genetic link to spatially associated olivine gabbro, which forms part of a large-scale intrusive unit. In contrast, no such relationship can be established for sulphide prospects that lie within areas dominated by anorthositic rocks. In every one of these, the mineralization postdates, and is unrelated to, the local anorthositic country rocks. Generally, sulphide mineralization in the "South Voisey's Bay" project resembles the Voisey's Bay deposits, in that it is associated with olivine-bearing mafic rocks of relatively primitive character. The anorthosite-hosted sulphide prospects represent a very different style of mineralization in which magmatic sulphides appear to have "migrated" from an external source unrelated to their host rocks, and they cannot be equated directly with Voisey's Bay. This second group can be divided into at least three subtypes, some of which are associated with specific silicate rocks.

SYNGENETIC MINERALIZATION ASSOCIATED WITH PYROXENITE "DYKES"

The OKG prospect is the only member of this group yet known in detail, although at least two other examples were tentatively identified during 1997 field work. At the OKG prospect, virtually all sulphide mineralization is restricted to dyke or vein-like units of orthopyroxenite that intrude the country-rock anorthosites, which are now suspected to be of Paleoproterozoic age (Ryan *et al., this volume*). The sulphide liquid was a primary component of the pyroxenitic magma, and it accumulated within individual pyroxenite units, commonly toward their lower contacts. Sulphide-rich samples show a classic net-texture, where orthopyroxenes appear to have settled into a sulphide sublayer. The orthopyroxenites retain excellent igneous textures, and do not appear to have encountered any of the recrystallization and alteration seen in the surrounding anorthosites. They are suspected to be of Mesoproterozoic age, but a Paleoproterozoic age cannot be ruled out based on field evidence (*see* Ryan *et al.*, *this volume*, for discussion). A second style of mineralization is present on a local scale around the margins of the pyroxenite units, where sulphides have penetrated into the wall-rock anorthosites. The sulphide–silicate textures in these areas are analogous to those seen in other anorthosite-hosted prospects, and the sulphides are epigenetic with respect to their immediate host. At the OKG prospect, mineralization of this style is very minor, and rarely extends more than a few centimetres beyond contacts, except at the surface showing. Nevertheless, it provides an important conceptual link to other styles of mineralization.

There are several unresolved questions about the prospect, including the age and compostional affinity of the pyroxenites, particularly with respect to gabbronorite "dykes" associated with other prospects. Another interesting question is the reason for the virtual confinement of the sulphide component to the dykes, whereas elsewhere it appears to have migrated widely (*see below*). It is possible that the Paleoproterozoic anorthositic country rocks were cooler and more competent than Mesoproterozoic anorthositic country rocks at other showings, and that this influenced the mobility of sulphide liquids and/or the longevity of the mineralizing system.

EPIGENETIC MINERALIZATION ASSOCIATED WITH GABBRONORITE "DYKES"

This is the most abundant style of mineralization in the area north of Nain. The best example described here is the Hilltop prospect, but the License 1514M prospects and the Cirque prospect are also members. Examination of drill core during 1997 from several other properties in the area, including Canadian States License 1558M, Columbia Yukon Resources License 1506M and the Castle Rock "Krinor" project (*see* Figure 5 of Kerr and Smith, 1997, for locations) indicates that they all belong to this group.

The dominant style of mineralization consists of externally derived sulphide veins that intrude and brecciate broadly anorthositic host rocks, and show no spatial relationship to any particular surface unit (Figure 2). On this basis, they are best described as epigenetic. At the microscopic level, tendrils of sulphide have eroded and percolated along grain boundaries, eventually detaching single crystals and multicrystal fragments of plagioclase. The end product of this process is a massive sulphide rock with eroded plagioclase crystals, which superficially cannot be distinguished from a sulphide liquid carrying samples of an associated silicate magma. However, the preservation of all stages in this erosion and disaggregation process reveals its true nature. The inclusion of recognizable anorthosite fragments, which contain subophitic igneous pyroxene, demonstrates that the sulphides were emplaced when the wall rocks were solid. The presence of previously recrystallized fragments, and truncation of recrystallized zones by sulphides, demonstrate that local solid-state recrystallization preceded, and was not directly related to, mineralization. However, it is possible that sulphides preferentially migrated into recrystallized zones, or that recrystallization was linked to the emplacement of associated silicate magmas (*see below*). The sulphide mineralization was locally multiphase, with early Cu-rich zones in some cases, and late Cu-rich veins in others. The simplest explanation for these conflicting time relationships is that individual sulphide pockets fractionated and migrated independently. In this way, a late Cu-rich residual phase from one sulphide zone may be "early" or "late" with respect to adjacent sulphide zones of slightly different timing. It is not interpreted as a reflection of two discrete regional mineralization events.

The Hilltop and License 1514M prospects reveal a spatial association between sulphide mineralization and fine- to medium-grained, pyroxene-rich, gabbronorite units. Locally, these grade into pyroxenites, but these are websteritic (i.e., clino- and orthopyroxene) and mineralogically distinct from the OKG examples. At the Hilltop prospect, mineralization is concentrated at the contacts of a gabbronoritic dyke (Figure 3) and textural relationships show that this intruded the anorthosites, although relationships on surface are equivocal, and it proved difficult to trace the dyke laterally (Squires *et al.*, 1997; Ryan *et al.*, 1997). The common presence of clinopyroxene-rich inclusions in sulphides at Hilltop also suggests a genetic link to the gabbronorite, as noted by Squires *et al.* (1997). At the nearby License 1514M prospects, the spatial relationship between sulphide zones and mafic dykes is less clearcut, but the latter are present, and commonly contain disseminated sulphides. As in the case of the OKG prospect the sulphides appear to be syngenetic with respect to the gabbronorites, but epigenetic with respect to surrounding anorthosites. The Cirque prospect contains sulphide mineralization that is essentially identical to the other examples but, aside from one minor example, it shows no association with gabbronoritic dykes or veins. The gabbronorite units from the Hilltop and Cirque prospects have a granular, polygonal appearance, and only locally preserve vestiges of an original igneous texture. In this respect, they differ from the OKG pyroxenites, which have well-preserved igneous textures.

The Hilltop and Cirque prospects are tentatively regarded as "end-members" within this group, respectively representing minimal and virtually complete separation of the sulphide liquid from a genetically associated silicate magma. The Cirque prospect, which has a vertical extent approaching 1 km, shows that sulphide liquids were able to travel considerable distances in the crust. The Canadian States License 1514M prospects fall somewhere in between these extremes, in that many massive sulphide zones are physically separated from associated silicate magmas but remain spatially associated. Examination of drill core from other nearby prospects during 1997 indicates that they display a similar spectrum of relationships, and it is suspected that all are genetically linked.

There are numerous unanswered questions about this style of mineralization. It is not clear if the gabbronorite "dykes" are compositionally or temporally equivalent at different prospects, nor is their relationship to the OKG pyroxenites known. The polygonal, "annealed" appearance of many gabbronorites may be related to the thermal state of the country rocks at the time of their emplacement, which may also have governed the ability of sulphide liquids to migrate. Hotter, more plastic Mesoproterozoic country rocks may have been easier to erode and percolate through, and would affect the cooling (and crystallization) rates of both the sulphide and the silicate magmas. The apparent grade variations between massive sulphides in closely adjacent sulphide prospects (e.g., the Cirque *versus* 1514M) also require explanation, and have clear economic implications. Are these variations related to "process" (i.e., fractionation of sulphide liquids) or "source" (i.e., a compositionally distinct silicate magma) controls?

EPIGENETIC MAGNETITE–SULPHIDE MINERALIZATION OF UNCERTAIN TYPE

The style of mineralization observed at the NDT Ventures Nain Hill prospects has affinities with the above types, in that both syngenetic and epigenetic mineralization are present. The former is associated with gabbronoritic to pyroxenitic units, which are at least locally dyke- or vein-like in geometry. However, the situation is complicated by the presence of gabbronoritic anorthosites, of which some of the mafic rocks could be compositional relatives (e.g., cumulate zones), and by the generally ambiguous relationship of mafic rocks to deformation. This prospect also shows the only clear example of contact metamorphic effects related to sulphide emplacement, and there are indications that anorthosites were retrogressed prior to mineralization. As noted above, the possibility that the local anorthosite host rocks are Paleoproterozoic, rather than Mesoproterozoic, must be considered. Lastly, sulphide mineralization at Nain Hill is accompanied by, and commonly subordinate to, magnetite-rich material. Although magnetite is present in most of the other sulphide prospects, it is only a minor constituent, and its abundance at Nain Hill implies a more oxygen-rich formation environment. In summary, more data is needed before these prospects can be firmly equated with any of the other groups. The texture and mineralogy of the Nain Hill samples are complex, and this area represents an interesting independent research topic.

SYNGENETIC MINERALIZATION ASSOCIATED WITH OLIVINE GABBRO

The Donner Minerals *et al.*, "South Voisey's Bay" prospect is the only clear example of this style of mineralization yet identified outside Voisey's Bay itself. The textures provide classic examples of primary, syngenetic sulphide developed during the crystallization of the host magmas. The leopard-textured gabbro provides some information about the timing of sulphide separation, as the clinopyroxene oikocrysts containing plagioclase and olivine, developed before sulphide segregation, or at a different location. Based on the textural and mineralogical similarities between oikocrysts and groundmass, *in-situ* growth prior to sulphide exsolution seems more likely. The presence of subangular massive sulphide patches in these rocks is highly significant – this texture is completely foreign to that of the homogeneous (quenched ?) groundmass, and it suggests that the "intrusion path" of this magma included massive sulphide concentrations. Coarser grained, sulphide-bearing gabbro is compositionally similar, and shows textural features indicative of slower cooling rates. In both cases, the straight grain boundaries between silicates and sulphides suggest that they are syngenetic and in thermal equilibrium. The gneissic fragments observed in some breccia-like gabbros show variable digestion and assimilation, which may be an important factor in promoting sulphide segregation (e.g., Ryan *et al.*, 1995; Kerr, 1997a).

Samples from country-rock gneisses beneath the mineralized gabbro show a different style of mineralization where the sulphides have eroded and penetrated older rocks. This is analogous to some of the epigenetic mineralization described from anorthosites, but the distinctive pseudo-network texture is not as widely developed. Again, this may be indicative of the thermal and physical state of the country rocks at the time of sulphide arrival. The transformation of igneous garnet to cordierite and spinel indicates contact metamorphism, presumably related to the gabbro intrusion.

MINERAL EXPLORATION IMPLICATIONS

Demonstration that mineralization is both spatially and genetically linked to a specific geological unit, which can in turn be tracked and followed, is an important step in mineral exploration. Thus, the syngenetic mineralization at the South Voisey's Bay prospect is presently of greater economic significance than the largely epigenetic mineralization that predominates north of Nain. The recent massive sulphide intersections in the South Voisey's Bay area support previous comments about its overall similarity to the immediate area of the Voisey's Bay deposits (Kerr and Smith, 1997; Kerr, 1997b).

However, the predominantly epigenetic mineralization north of Nain is not entirely separated from associated igneous rock types. The clearest example of syngenetic mineralization is at the OKG prospect, where the host rocks are pyroxenitic, rather than gabbroic, and are not olivine-bearing. Similarly, sulphide mineralization at other prospects is probably genetically linked to younger pyroxene-rich gabbronorite units that intrude the anorthosites. In one of these examples (License 1514M), sulphide zones locally contain coarse pentlandite, and there may be potential for better grades than those found to date. The key to further exploration in these areas is to better define the character and extent of genetically associated igneous rocks, and hopefully locate larger bodies that have potential for more significant and geometrically predictable sulphide accumulations. The dyke-like zones of pyroxenite and gabbronorite must have some wider significance, and they may represent feeders to, or conduits from, larger magma chambers that developed within the older anorthosites. If potential for economic-grade massive sulphides can be demonstrated, the location of larger gabbronorite or pyroxenite bodies at feasible depths appears to be the only route for further exploration activity. Deep drilling conducted to date has not accomplished this, but this by no means rules out their occurrence.

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