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EVALUATION AND CHARACTERIZATION OF THE Ni–Cu SULPHIDE AND PGE POTENTIAL IN THREE MAFIC–ULTRAMAFIC INTRUSIVE COMPLEXES: PRELIMINARY RESULTS

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ABSTRACT

In the summer of 2004, three mafic to ultramafic intrusions in central and western Newfoundland were mapped and sampled. The Steel Mountain anorthosite (ca. 1270 Ma), located in the southern Long Range Fault Zone, hosts several magnetite deposits and, locally, the anorthosite contains unusual pink to purple plagioclase associated with norite bodies proximal to the Long Range Fault Zone. The norite bodies are bounded by almost concentric shear zones that separate pink plagioclase anorthosite and norite from "normal" megacrystic to granular, recrystallized anorthosite. Layering is only locally preserved, although shearing and deformation during emplacement produced mineral segregations.

The Taylor Brook gabbro suite (430.5 ± 2.5 Ma) is a heterogeneous, weakly layered intrusion hosted by the Long Range gneiss complex. The composition ranges from gabbro to ferrogabbro in the south, to pegmatitic gabbro in the north. Layering dips toward the centre of the intrusion in the south, but there are consistent deviations whereby layering dips to the north, away from the core of the intrusion. Xenoliths are abundant in the TBGS, and large xenoliths are present for over a kilometre inside the intrusion. There is evidence for physical magma mixing between mafic and felsic magmas throughout the southern portion of the intrusion. Several locations host weak sulphide mineralization in brittle fracture systems within melagabbro to pyroxenite.

The Red Cross Lake intrusive suite is a small mafic to ultramafic layered intrusion hosted by the Victoria Lake Group in central Newfoundland. Layering is well developed to the southwest in melatroctolite, olivine cumulates, troctolite and olivine gabbro, but in the north, layering is poor in biotite to anorthositic gabbro. Where present, layering exhibits typical cumulate textures and gradational layering of olivine. Field mapping identified numerous, layer-parallel belts of variable size, containing 25 to 85 percent heterolithic xenoliths, which locally resemble hydrothermal or intrusion breccia. These belts are located along basal contacts and more commonly, in the centre of the intrusion. Sulphides up to a few percent are present throughout the most mafic basal units, and comprise pyrrhotite, pyrite, chalcopyrite, and pentlandite. Previous work indicates sulphides have a high Ni tenor. Preliminary petrography indicates the presence of pentlandite within pyrrhotite.

INTRODUCTION

During the summer of 2004, field mapping and rock samples were collected from three separate mafic to ultramafic intrusive suites and portions of three other plutons from within the study area in Newfoundland. Figure 1 shows the locations of the three main areas that are described below. The three other smaller areas examined during the field program are not discussed here, and are, therefore, not shown in the figure. The principal objective of this research is to evaluate the intrusive complexes for their potential to host economic Ni–Cu–PGE mineralization. The three areas discussed below comprise the Steel Mountain anorthosite (SMA), Taylor Brook gabbro suite (TBGS) and the Red Cross Lake intrusive suite (RCLIS).

Of key interest in prospecting and exploring for orthomagmatic base- and precious-metal sulphide deposits are the contact relationships between the intrusions and their host rocks, the reason being that the physical and geochemical processes which lead to sulphide mineral precipitation are typically focused at contacts. As such, sample density was greatest proximal to the contacts in the hope of defining textural, whole-rock and mineral geochemical trends that might be characteristic of orthomagmatic Ni–Cu–PGE deposit types.

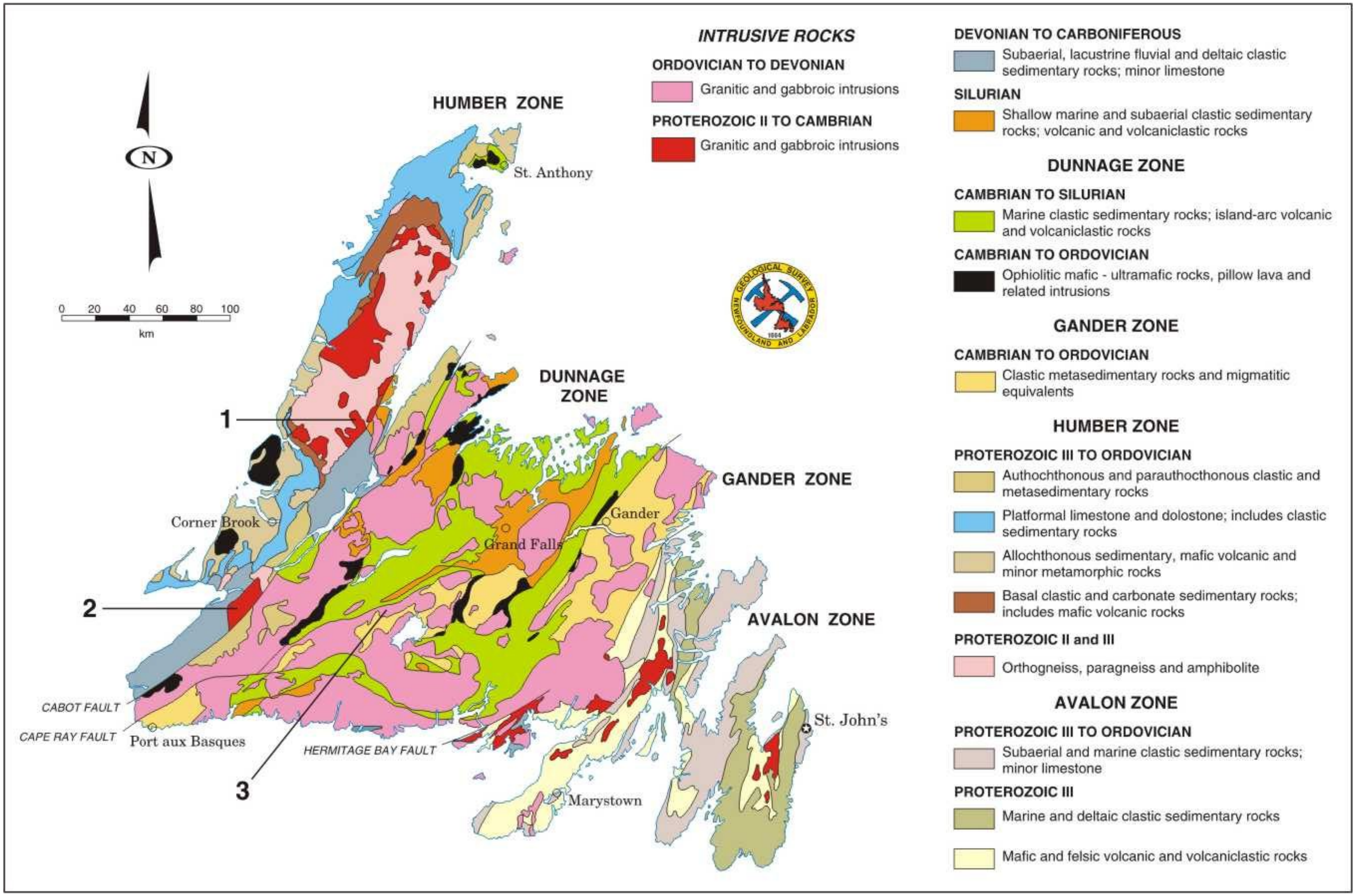

Figure 1. *Map of Newfoundland showing 1) Taylor Brook gabbro suite, 2) Steel Mountain anorthosite, 3) Red Cross Lake intrusive suite.*

Initial mapping of the individual field areas has been completed, but at present, map-unit designations are based solely on field descriptions and hand-sample examination. Upon derivation of whole-rock geochemical and petrographical data, map units will likely require refinement. The scale of mapping ranged from 1:10 000 to 1:50 000, and was principally a function of amount of exposure and accessibility. Geology maps presented herein are at a scale of 1:20 000.

Over 150 samples were collected from the various intrusive and host rocks. These will be prepared and analyzed in the laboratories of the Department of Earth Sciences, Memorial University. Amongst the work to be completed on a selection of the samples will be whole-rock, major- and trace-element geochemistry by X-Ray Fluorescence, REE geochemistry by ICP-MS, sulphur isotope ratios by GS-MS, and dating of intrusive phases, where possible, by LAM-ICP-MS. Platinum-group elements (Pt, Pd and Au) analyses are being conducted at a commercial laboratory under contract with the Geological Survey, Newfoundland and Labrador Department of Natural Resources.

STEEL MOUNTAIN ANORTHOSITE

The SMA is located in the southern Long Range Mountains of the Humber Terrane, about 15 km east of Stephenville. Van Berkel *et al.* (1987) further subdivided the southern Long Range into tectonic terranes, the easternmost being the Steel Mountain terrane. The SMA is a north–south elongate body approximately 40 by 15 km long, which is truncated to the east by the Long Range Fault Zone (LRFZ). According to van Berkel *et al.* (1987), who produced the most recent map of this area, the SMA is characterized by white to mauve, medium-grained, recrystallized anorthosite having a colour index of less than 10. This project does not deal with the SMA as a whole, but focuses instead on a region adjacent to the LRFZ, which was noted by van Berkel *et al.* (1987) to contain several small bodies of norite. Tonalite–diorite enclaves are also locally present in this region, but were not investigated.

The goals for research on the noritic portions of the SMA were threefold. First, the SMA hosts several small to large magnetite deposits, and contains variable amounts of magnetite in association with pyroxene. With regard to magnetite, the question arises as to whether it is orthomagmatic, or formed by metasomatic or metamorphic reactions, or some combination of both. In addition, what are the PGE distributions in the magnetite, and can a source of PGEs be determined? Second, although rare, sulphides are locally present, and are associated with PGE anomalies in at least two locations in the SMA (Bradley, 1995; Pilgrim and Regular, 1998; L. Muise, personal communication, 2004). Characterizing the PGE distribution in sulphides will also be undertaken. Third, as noted above, plagioclase in the SMA varies from mauve or lilac to dark purple. What causes this colour? During field mapping, the colour and distribution of purple to mauve plagioclase was noted; this unusual mineralogical characteristic will be subject to petrographic and geochemical investigations.

FIELD WORK

The map area is located at the end of Flat Bay Brook Road, approximately 15 km along a well-maintained gravel road. This road starts approximately 500 m north of an Ultramar gas station located several kilometres south of the Stephenville Crossing exit ramp on the Trans-Canada Highway. At the end of Flat Bay Brook Road is the Lookout Pond hydroelectric generating station, where access to a private secondary road is controlled by Newfoundland Hydro. At the top of this very steep access road, a 2 km walk is required to access the areas of interest; ATV access is possible from the top of the road.

Mapping and initial petrography identified several interesting textural features in the SMA and was successful in further delineating the extent of norite bodies (Figure 2). First, mapping was able to delineate between a lilac to purple anorthosite and normal white to grey anorthosite, as described by van Berkel *et al*. (1987) in the SMA. The lilac to purple anorthosite is associated with orthopyroxene and clinopyroxene, and locally forms irregular lens-shaped bodies within normal, white-grey anorthosite. Although the contacts between all units in the map area are gradational and often recrystallized, it is possible to locally define a boundary between white, megacrystic to granular plagioclase anorthosite (normal anorthosite), and lilac to purple medium-grained recrystallized anorthosite.

Orthopyroxene and clinopyroxene, which commonly occur together in a ratio of ~ 4:1, exhibit three, and locally four, distinctive textures in the map area. First, along the margins between normal and pink anorthosite, there is an increased amount of leucogabbro compared to leuconorite, although they are texturally identical. Pyroxene ranges from 10 to 15 percent, occurs as deformed sheets, lenses, and discontinuous stringers, and is surrounded by granular, recrystallized, penetratively deformed fine- to medium-grained white anorthosite (Plate 1). The pyroxene is deformed with the main fabric of the anorthosite to leucogabbro or leuconorite, and there is an advanced degree of chloritization and/or uralitization in these rocks.

Second, in units mapped as norite by van Berkel *et al.* (1987), plagioclase becomes pink, and shearing diminishes slightly, although initially pyroxene grains were still altered

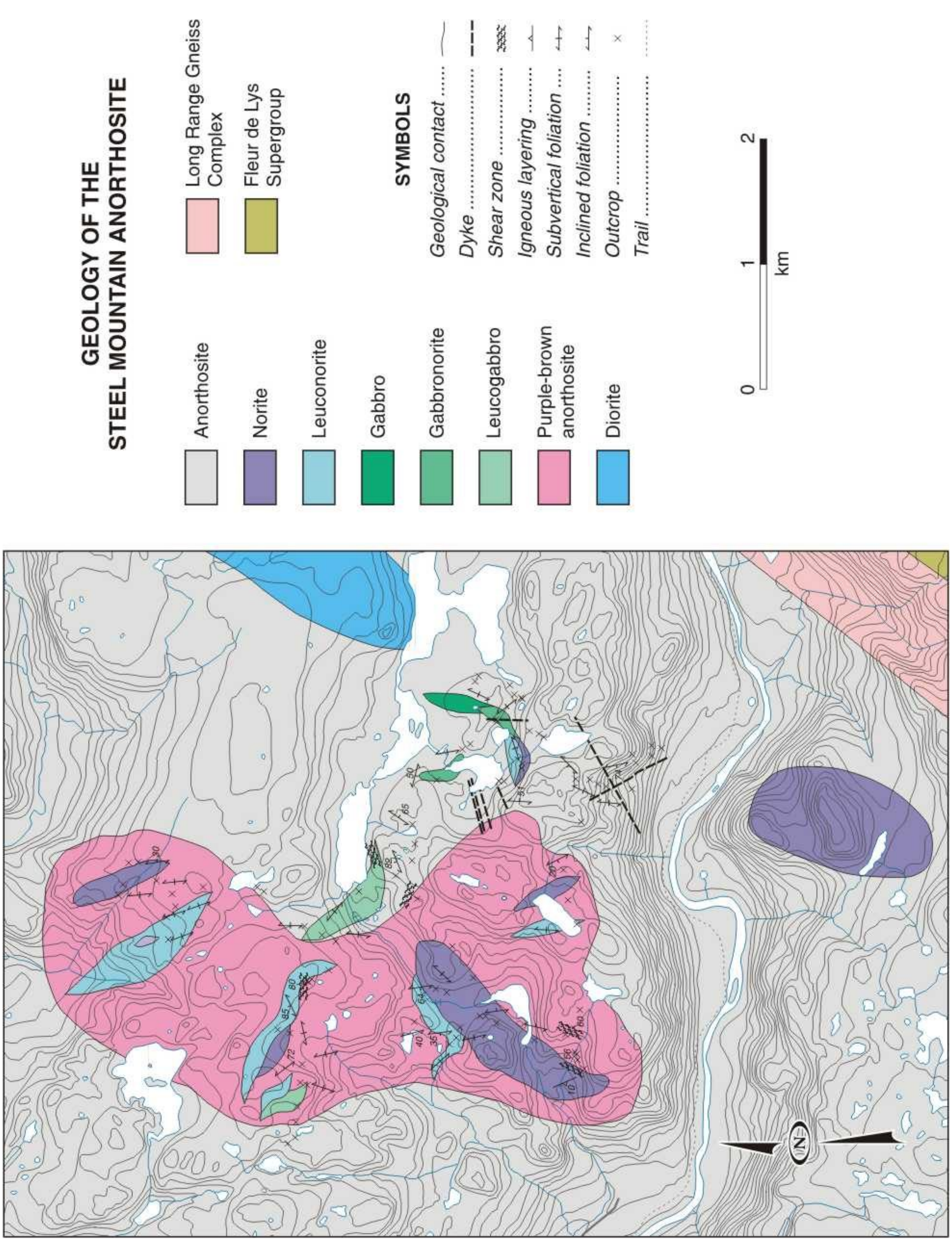

Figure 2. *Geology of the Steel Mountain anorthosite. This map is only a portion of the larger anorthosite body, and highlights the most mafic component of the Steel Mountain anorthosite (regional geology from Colman-Sadd and Crisby-Whittle, 2004).*

Plate 1. *Marginal leucogabbro to anorthosite; rocks in this region commonly show deformation. Porphyroclasts in this area define a sinistral shear sense; note pen for scale.*

Plate 2. *Sheared leuconorite proximal to the margin with "normal" anorthosite. Inward from the contact, shearing is reduced and foliation changes from subvertical to subhorizontal; mineralogy remains relatively constant.*

to amphibole and chlorite. Orthopyroxene is the dominant pyroxene in the interiors of the norite bodies, and occurs as sheared, weakly porphyroclastic, and locally, approximately equigranular crystals, or aggregates of crystals, that make up to 20 percent of the rock. In many instances, orthopyroxene appears to be metastable and it is partially altered to lower grade assemblages (Plate 2).

Finally, the two other predominant textures of pyroxene commonly occur together, although it is not apparent if there is a linkage between them. Orthopyroxene occurs as mega-poikocrysts, locally up to 20 cm in diameter, in association with pink to dark pink-purple plagioclase. This texture is found only in the most mafic units of the map area, and is spatially associated with non-poikilitic megacrystic pyroxene (Plate 3a). Texturally, the non-poikilitic pyroxene appears to have formed later than the poikilitic pyroxene. As noted in Plate 3b, where the non-oikocrystic pyroxene occurs, a large halo free of pyroxene commonly surrounds the mafic clusters, and is essentially pure plagioclase. The process that would lead to this texture is unknown, but it is possible that it results from remobilization of interstitial (mafic) melt during high-temperature emplacement and recrystallization within a partially solidified crystal framework. (Lafrance *et al*., 1996; Hunter, 1996; R. Voordouw, personal communication, 2004).

Recrystallization in plagioclase is ubiquitous, but variable degrees of recrystallization do occur. Along the margins between "primary" plagioclase and "coloured" plagioclase, small angular, fragmental porphyroclasts of pale pink plagioclase are suspended in a granular white plagioclase matrix, implying mixing between the two, probably during deformation related to emplacement. Plagioclase in the pink anorthosite or norite rarely occurs as megacrysts, and instead is generally equigranular on an outcrop scale, although medium- to coarse-grained purple porphyroclasts in the pink matrix plagioclase are common. This type of texture is quite typical of massif-type anorthosites, and is indicative of widespread recrystallization during emplacement (cf. Hunter, 1996).

Magnetite occurs in association with large, very coarse-grained lenses or clusters of orthopyroxene, where it forms irregular clots, cubes, rims, or replaces pyroxene. Smaller clusters of orthopyroxene locally display thin coronas of rounded red garnets (Plate 4).

In one area, an irregularly shaped pod, approximately 10 m^2 of altered norite having a distinctive rim of magnetite, was observed in contact with granular, white, fine-grained anorthosite. It is possible that alteration of pyroxene in the norite produced this magnetite. Sulphides are very rare, comprising pyrite and less commonly chalcopyrite, associated with orthopyroxene and magnetite, and were noted as inclusions within magnetite in some cut slabs.

Initial reflected light petrography has identified two distinctive microtextures in magnetite. In large clots, or interstitial massive magnetite, planar exsolution lamellae of ilmenite are ubiquitous, whereas along fractures in orthopyroxene and clinopyroxene, magnetite is also present as much finer grained aggregates or individual grains that rarely, or never, contain any exsolution textures. Furthermore, subrounded grains of exsolution-free magnetite are suspended in larger, or more massive, magnetite with exsolution textures, constraining the relative timing of magnetite forma-

Plate 3a. (left) *Norite exhibiting megacrystic poikilitic and non-poikilitic orthopyroxene textures. Note strong mafic–felsic mineral segregation and resulting pods of pure anorthosite in top left corner;* **3b.** (right) *Close up of megacrystic orthopyroxene crystals. These crystals may form later than poikilitic orthopyroxene, perhaps influenced by tectonically induced filter pressing or mineral segregation.*

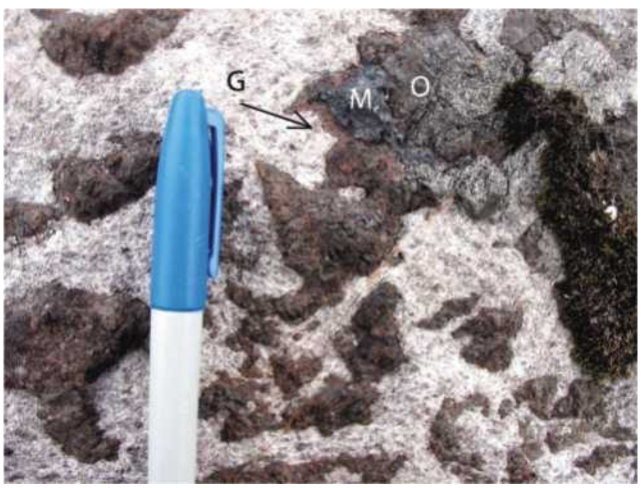

Plate 4. *Thin coronas of garnet (G) are developed at the contact between orthopyroxene–magnetite (O and M respectively) and plagioclase.*

tion and suggesting that there are at least two generations of magnetite. Further petrography will examine these textures in detail and EMPA and/or LAM-ICP-MS analysis will be employed to reveal any chemical differences between these distinctive magnetite populations.

Finally, a diabase dyke swarm was mapped on the eastern margin of the map area in a location previously mapped by van Berkel *et al.* (1987) as two small norite pods.There is no evidence, however, for norite bodies here. The dykes are parallel over a width of about one kilometre, have variable thicknesses (from 1 m to approximately 4 m) and irregular dyke spacing. The most extensive dyke marks the edge of an ~150-m-high cliff, where its thickness varies along strike from 2 to 4 m. The margins of the dykes are commonly sheared subparallel to their strike angle, and chilled margins were not observed. The dykes are never observed to cut the coloured plagioclase anorthosite or norite bodies, and are restricted, therefore, to the normal anorthosite. The areas where the dykes are most predominant are characterized by white to cream plagioclase having a distinctly sugary, recrystallized texture, implying that they have provided heat to drive local recrystallization. In thin section, the recrystallized plagioclase has granoblastic/mosaic textures, and recovery recrystallization. The dykes contained magnetite, pyrite and rare chalcopyrite.

SUMMARY

Mapping in the SMA has delineated several norite bodies. The purple plagioclase zones appear to be associated with the more mafic rocks, and are weakly bounded by shear zones in the centre of the map area. Mapping has reduced the size of the norite map units of van Berkel *et al.* (1987), and allowed further subdivision of mafic rocks. Identification of new diabase dyke swarms was also accomplished during this mapping project, and an attempt to date these dykes will be undertaken, to see if they belong to the Long Range dykes. Detailed geochemical analyses and petrographic studies will be required to answer detailed geological and mineralization questions pertaining to this study; however, this is not the focus of the results presented here.

TAYLOR BROOK GABBRO SUITE

The Taylor Brook gabbro suite (TBGS) is located in northwestern Newfoundland, southwest of White Bay, approximately 20 km west of the town of Hampden. It is accessible by well-maintained gravel logging roads that begin approximately 25 km south of Sop's Arm, along Highway 420. The access road heads west into the Northern Peninsula, parallel to the Upper Humber River, and branches several times to the north and west. Field areas mapped in the TBGS begin approximately 15 km along the main logging road, at a fork to the northeast. Two main areas were mapped in the TBGS, and both were accessed by logging roads that fork off the main road. Herein, the northern portion will be called the "Taylor Brook gabbro pegmatite" (TBGP), based on its distinctive composition and texture and the remainder is called the "Taylor Brook gabbro" (TBG). This is shown in Figure 3, which displays the recent mapping, based on field descriptions and hand-sample examination.

REGIONAL GEOLOGY

The TBGS is intrusive into crystalline basement rocks of the Precambrian Long Range Inlier, the largest exposure of basement rocks in the Appalachians (Heaman *et al*., 2002). The oldest rocks in the Inlier comprise leucocratic to mesocratic polydeformed quartzofeldspathic gneisses, as well as thick lenses of granitic orthogneiss, which according to Erdmer (1986) were derived mostly from plutonic protoliths. Supracrustal rocks, which locally crop out proximal to the TBGS, include graphitic and hematitic quartzite, sillimanite schist, diopside marble and calc-silicate, quartz- and muscovite-rich schist, biotite psammite and quartz-rich gneiss (Erdmer, 1986). The youngest units in the Inlier, excluding the TBGS, include numerous small mafic plutons and dykes that were deformed and metamorphosed to amphibolite and metagabbro, as well as weakly foliated hypersthene diorite, and leucogabbro. The ages of the Precambrian units range widely. Uranium–lead results from Heaman *et al.* (2002) indicate that basement rocks range from 1530 ± 8 Ma for the Cat Arm Road gneiss (which may actually be as old as 1631 Ma), to 933 ± 7 Ma for the Potato Hill charnockite. Although previously thought to be Precambrian, the TBGS was recently dated by U–Pb methods at 430.5 ± 2.5 Ma, making it the first known occurrence of Silurian magmatism in the Long Range Inlier (Heaman *et al*., 2002).

The TBGS was chosen for mapping for much the same reasons as the SMA: a lack of exploration in an area that had been mapped only at a reconnaissance-level in the past, combined with prospective Ni–Cu–PGE host rocks. As well, there are soil- and lake-sediment anomalies for Ni–Cu–Co (Davenport, 1989; Rose, 1998; Harris and Rose, 1997). Lithogeochemical analysis indicates a positive correlation between nickel and olivine (Rose, 1998). Furthermore, mapping by Owen (1986, 1991) and Rose (1998) indicates that the gabbroic rocks of the TBGS have potential to host sulphide zones. Part of the northern TBGS was mapped by Owen (1986) as a pegmatitic gabbro, and as such, is compositionally distinct from the remainder of the TBGS, which was mapped as a weakly layered gabbro.

In 1999, several small, but high-grade, Ni–Cu–PGE occurrences (Layden Showing; Fitzpatrick *et al*., 2000), were discovered in Grenvillian rocks approximately 5 km from the western margin of the map area, however, these are unrelated to the TBGS.

FIELD WORK

Mapping in the TBGS was conducted over 10 days with five days devoted to each map area. Mapping in the southern TBG was conducted mostly along logging roads and to a lesser extent by foot traverses, but outcrops are scarce away from logging roads. In the TBGP, two logging roads were used to access the map areas for foot traversing and canoe work.

Taylor Brook Gabbro

The TBG is heterogeneous and is characterized by variable gabbroic to ferrogabbroic compositions; in the northern TBG, small zones of pyroxenite are more common. The TBG ranges from medium-grained equigranular, to coarse-grained or porphyritic in texture.

Layering is present locally, and where discernable, is defined by changes in grain size and/or relative modal mineral abundances. Layer composition varies from pyroxenite to melagabbro to anorthositic gabbro, although gabbro is the dominant composition. Ferrogabbro layers are also locally present, and contain up to 15 percent magnetite, which may decrease in abundance upward from the base of individual layers. The average magnetite content of the TBG, however, is about 1 percent. Pyroxenite, which is commonly altered to fibrous amphibole and chlorite, is typically spatially associated with melagabbro and may represent a less differentiated component of the TBG.

Rarely, layers have been disrupted by blocks or fragments of igneous rock, likely autoliths from within the TBG. Apparently, these blocks dropped from above, and dragged and distorted layers as they passed through (Plate 5). Layering in the TBG generally dips shallowly into the centre of the complex, but this is not consistent, and in some locations, layering dips north where it would have been expected to dip east or west (Figure 3).

Contact relationships in the TBG are complex. All contacts between the TBG and host rock, except for the south-

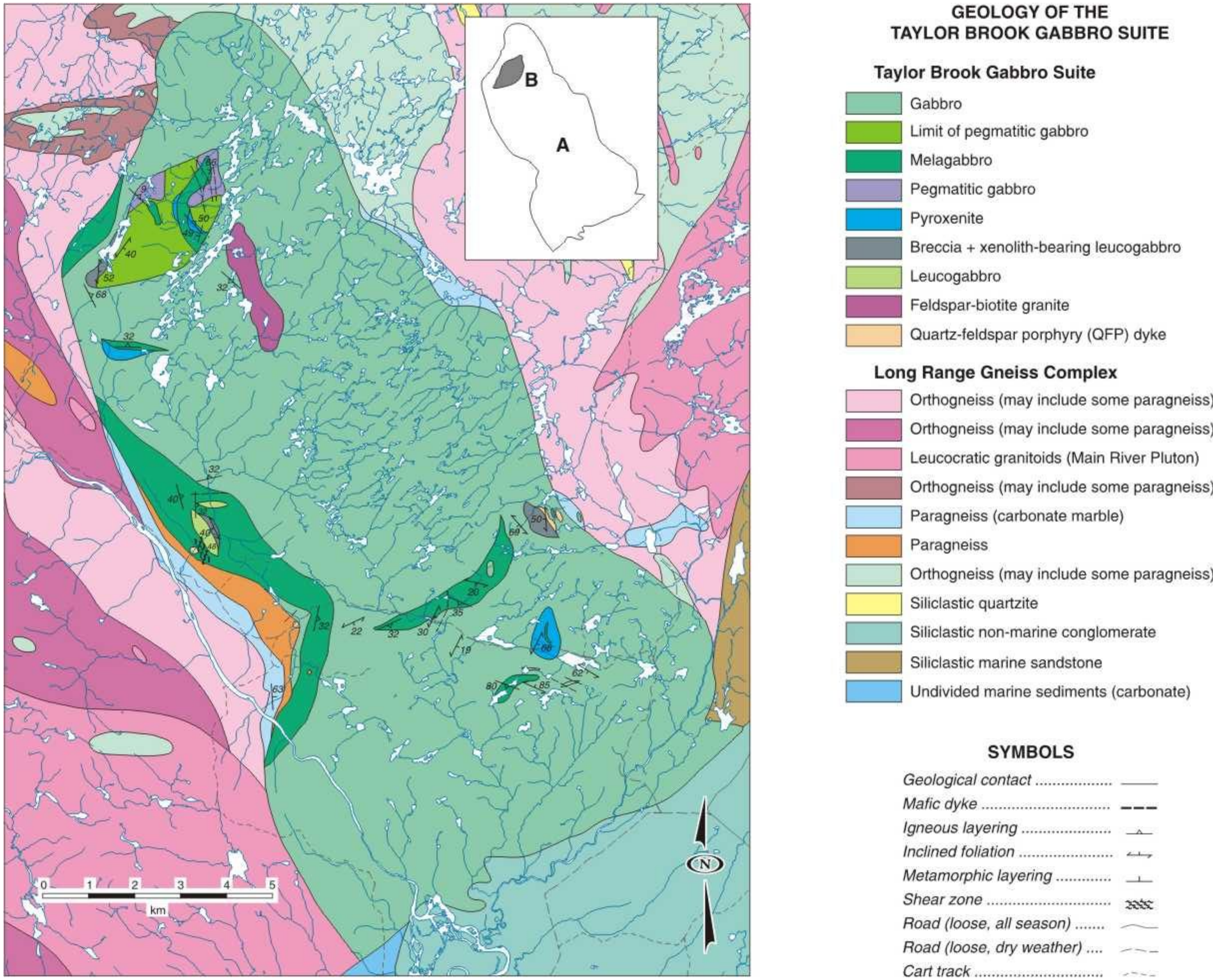

Figure 3. *Geology of the Taylor Brook gabbro suite, northwestern Newfoundland. Inset A) main mass of the TBGS; B) Pegmatitic gabbro (TBGP); (regional context from Colman-Sadd and Crisby-Whittle, 2004).*

Plate 5. *Disrupted layering and first generation mafic dykes. Two subrounded blocks of anorthositic gabbro (G) of unknown origin (i.e., autolith or xenolith?) appear to have passed through the mafic units; blocks appear to have moved from bottom left and right corners toward centre of image.*

ern margin, are with Grenville orthogneiss, paragneiss and metacarbonate/calcsilicate; there is a minimal amount of marble and calcsilicate in the east (Owen and Erdmer, 1986). In the extreme south, the TBG is unconformably overlain by Paleozoic conglomerates of the Deer Lake Basin. The southern unconformable contact and the north-eastern contact were not part of this study, but a transect across the central TBG was completed, as well as several other transects across internal igneous contacts.

The eastern contact is poorly defined due to thick vegetation and sediment cover. Further complications are posed by the presence of country-rock xenoliths up to 750 m across and even one xenolith that is more than 1 km from the contact. In addition, east of the contact, pods of gabbro >5 m^2 intrude calcsilicate and marble country rock. Along the western margin, the contact is less ambiguous because there is a lower frequency of xenoliths within the TBG. In one location, however, approximately 300 m from the contact, a strongly deformed mafic dyke was observed within the country-rock paragneiss. This dyke is deformed and has extensive reaction rims; and if derived from the TBG, it would suggest that the TBG has experienced some of the deformation seen in the country rocks.

Xenoliths are widely distributed in the southern TBG, and generally have similar compositions to country rocks. These xenoliths, as indicated above, are present for approximately 1 km inside the TBG, and have been observed in various states of alteration or metamorphism. Xenoliths exhibit partial melt textures consistent with being partially consumed by the magma rather than a primary metamorphic texture. For example, veins of magma locally intruded parallel to the gneissic fabric of the xenoliths, and often a thin leucosome rim is preserved. In addition, xenoliths are locally deformed and appear to have behaved plasticly (Plate 6). In some locations, xenoliths comprise 15 to 25 percent of the rock.

Another feature noted in the TBG is the presence of pegmatite pipes, or zones, that have a variable spatial association with xenoliths. These pipes or zones range in size from less than 10 cm up to ~50 cm and are locally associated with dendritic and irregular veins that extend for several metres into the gabbro. The pipes appear to have metasomatized the surrounding rocks, as demonstrated by a greater abundance of euhedral to subhedral and megacrystic plagioclase, adjacent to the pipes. In several locations, the cores of the pipes (located over 500 m from the external contact) contain well-preserved paragneiss xenoliths, locally, over 1 m in length (Plate 7). Neither sulphide nor oxide mineralization have been found to be associated with these features,

Plate 6. *Strongly deformed and partially melted paragneiss xenolith. Partial melting may have liberated fluids from the xenolith to generate the wispy pegmatite material surrounding the xenolith. Note partial melting is also occurring inside the xenolith along foliation planes and rims forming leucosome phase.*

Plate 7. *A large xenolith of paragneiss more than 1 km from the country-rock contact. Its orientation approximately coincides with the orientation of the surrounding pegmatite pipe. It is possible the pipe either transported this xenolith from depth, or simply envelops a xenolith that was already present.*

and in general, they are devoid of mafic minerals. These pipes are different from pipes observed in the TBGP.

Along the western margin, within 500 m of the contact with country rocks, a sulphide-bearing fracture system hosted by melagabbro to pyroxenite was discovered. This fracture system hosts 2 to 3 percent sulphide including pyrite, pyrrhotite, chalcopyrite and magnetite. Fracturing appears to be relatively late, as it is characterized by brittle jointing and brecciation.

At least three texturally distinct forms of dykes were observed in the southern TBG; locally, four phases of dykes may exist. Mafic dykes in the TBG are ubiquitous, and at least one generation of mafic dyke is present in many of the outcrops studied. The oldest generation of mafic dyke has textures that suggest it was emplaced before the TBG had completely crystallized. Evidence for this is the highly discontinuous, boudinaged or stretched nature of the dykes, irregular and embayed or cuspate contacts, a lack of chilled margins, partial melting and metamorphic/metasomatic reaction of the margins, and general appearance of recrystallization (Plate 8a). These dykes cut primary textures of the TBG, such as magmatic layering, but are cut by all other veining or alteration. The second, less common phase of mafic dyke has plagioclase-phyric cores, and chilled margins (Plate 8b). These dykes do not exceed 50 cm in thickness. Less commonly, they were observed to be assimilated or strongly deformed (Plate 8c), and locally cut the first generation of dykes. The final mafic dyke morphology in the southern TBG is the least common, and was observed at only three outcrops, but is distinct enough to separate from the other types. At approximately 2 m wide, they are considerably wider than the other two generations. They lack chilled margins, but locally have irregular or cuspate margins, suggesting very high-temperature emplacement and dykes have a massive texture, and locally contain finely disseminated sulphides. There are no crosscutting relationships with other dykes, but texturally, they appear to have undergone the least amount of modification, suggesting they are the youngest.

In addition to mafic dykes, several locations in the TBG contain quartz-feldspar porphyry dykes (QFP dykes). The contacts are rarely visible, but in one outcrop, a true thickness of approximately 2 m was determined. The contacts, where observed, are straight, and appeared unmodified, although the contacts were observed in only one location, and this may not be representative of each QFP dyke occurrence. In addition to QFP dykes, several small outcrops of a more potassic, biotite-bearing igneous rock that contained only quartz phenocrysts were noted in several widely spaced locations. Here, it was not possible to determine the geometry of the bodies, hence no genetic classification can be assigned.

A final aspect of the southern TBG is the presence of magma mixing textures, which occur throughout its southern part. Despite their occurrence over a wide area, the textures are similar at all locations. These outcrops exhibit the mixing or immiscibility between a mafic magma and felsic magma, possibly leucomonzonite, of the TBG (Plate 9). It is not possible, from the limited exposure, to determine which phase intruded into the other, but injection of mafic magma into the felsic phase is more likely, based on field relationships. It is unlikely that the mafic magma has been injected as dykes because the double contacts necessary to confirm dyke geometry are not seen. It is possible that these textures developed at the edge of mafic dykes, but in some locations, there is a large amount of mafic magma, and a dyke geometry is not evident. Furthermore, in one location, the mixing is associated with development of thin, wispy to dendritic pegmatite textures. It is possible that this texture is related to local pulses of fresh magma, although the widespread nature of these textures suggests a more localized, yet consistent process.

Taylor Brook Gabbro Pegmatite

The Taylor Brook gabbro pegmatite (TBGP) (Figure 3, B in inset) is compositionally, texturally, and morphologically different from the rest of the TBG. Field observations indicate that the TBGP has a more mafic composition overall, and is characterized by more abundant pyroxene compared to TBG. More significant are the textural differences between the pegmatitic zone (TBGP) in the north and the

Plate 8a. (top left) *Smooth and embayed or concave contact between a first generation mafic dyke and gabbro; note also the partially digested paragneiss xenolith parallel to the contact;* **8b.** (top right) *A deformed and altered second generation mafic dyke. This dyke cuts magmatic layering, and is itself cut but veining (not shown);* **8c.** (bottom right) *Plagioclase phenocryst-rich cores in mafic dykes that characterize the second generation of mafic dykes developed in the Taylor Brook gabbro suite. Note the well developed chill margins.*

rest of the TBGS. The northern portion of the TBGS was classified as a pegmatitic gabbro and mapped as a separate map unit by Owen (1986). Mapping for this project confirmed that this should remain a separate map unit.

The TBGP is generally coarse to medium grained, and locally contains megacrystic zones. On an outcrop scale, grains are equigranular, or bimodally equigranular (i.e., the pyroxenes are coarse grained, whereas the plagioclase is medium grained). In most instances, grains are subhedral to anhedral and cumulate textures are rare. Small (<15 cm) patches of pegmatitic material are common, as are larger, locally, circular-shaped pods, which may be pegmatite pipes (Plate 10). Where these pods occur, mafic minerals are common either as crystals or as fragments.

Although layering is rare in the TBGP, weak layering, defined by grain-size variation or modal layering is seen locally. A variation of the layering observed in several outcrops consists of patchy to subplanar zones of pegmatoidal textures bounded by normal-textured gabbro or coarse-grained gabbro. Locally, cumulate textures are developed, but these are not widespread, and have locally been modified by alteration or metasomatism, resulting in the destruction of primary textures.

In the TBGP, mafic dykes are common, but do not exhibit the textural varieties observed in the TBG. It is possible that this is a reflection of the lack of good quality outcrop in the TBGP. Generally, the dykes do not exceed 50 cm in width, dip vertically to subvertically, and have a diabasic texture in most outcrops. Compared to the TBG, they are not strongly disrupted or deformed, do not contain plagioclase-phyric cores, and are not strongly altered. Due to the thick lichen cover it was not possible to determine if these dykes have preserved chilled margins. Some of the dykes contain rare blebs of pyrite with magmatic textures. Where outcrop is better, it was possible to observe parallel dykes across a

Plate 9. *Typical magma mixing or immiscibility textures that occur in several locations in the southern portion of the Taylor Brook gabbro suite. Note the lobate nature of the leucomonzonite–gabbro contact.*

Plate 10. *Pegmatite pipes, which are different from those in the main mass of the Taylor Brook gabbro suite, contain mafic fragments or crystals. These pipes are not common in the Taylor Brook gabbro pegmatite.*

width of 50 to 150 m that have roughly the same strike and dip, implying emplacement as part of a consanguineous suite.

Xenoliths in the TBGP are much less common than in the TBG. This may be due to the greater distance of the TBGP from the country rocks, as this is an internal unit. In the TBGP, xenoliths are commonly fine-grained gabbro that could have been derived from the TBG, if there is a temporal difference between the main mass of the TBG and the TBGP, or they could have been more locally derived. In the absence of suitable geochemical data, it is not possible to choose between these alternatives.

In the TBG, xenoliths were observed as a "train", of large rafts along strike for approximately 1 km. These xenoliths are quite unusual in terms of size (the largest is ~ 6 m^2), texture, composition, and location within the TBG. Plate 11a is an example of one of the best occurrences of these xenoliths (a gneiss). The xenoliths display well-defined layering, which although diffuse or patchy on a small scale is defined mainly by compositional variation. The xenoliths also contain porphyroclast kinematic indicators (Plate 11b), implying that the xenoliths had undergone strong deformation and metamorphism prior to incorporation and are probably derived from the Grenville country rocks. Most striking are the layers of magnetite, which occur up to 25 cm thick in several of the xenoliths (Plate 11c). The mineral assemblage is clearly deformed and metamorphosed but its composition is unknown. In some locations, the xenoliths appear to be metaplutonic in origin. The rafts of xenoliths occur less than 1 km from the contact with country rock but are quite different in composition from the mafic country-rock gneisses. Furthermore, these rafts occur parallel to an internal igneous contact, which may define the boundary between the TBG and TBGP. More work, particularly geochemical and petrographical, is required to understand these rocks. There are several speculative explanations for the origin of these unusual xenoliths. It is possible that these represent country rock from deeper levels in the crust, brought to the surface during emplacement of the pluton. Another explanation is that these rocks represent a deformed basal or marginal facies of the TBG that has been entrained in the melt during emplacement. Given that some of the xenoliths resemble metaplutonic rocks whereas others have gneissic textures, a combination of both hypotheses may prove most accurate.

The final point of interest in the TBGS is the occurrence of a relatively large feldspar–biotite granite intrusion near the eastern TBG–TBGP contact. The intrusion occurs over a strike length of approximately 2.5 km, and has a sill-like morphology. Mineralogy and textures are consistent throughout the unit. Where the sill-TBG contact was observed, the sill does not appear to have caused any textural or mineralogical modification of the TBG. In one location, a mafic dyke constrains the relative timing of emplacement of the alkali-feldspar granite. It has a thickness of approximately 30 cm, and has a sharp contact with the TBG, but where it cuts the sill, it is partially digested, dismembered and altered. The fragments of mafic dyke in the sill are restricted to a plane that is approximately parallel to the strike of the dyke in the gabbro, implying that the dyke intruded the sill, but the sill was not completely crystallized, and thus partially reacted with the dyke. This unit was not recognized by Owen (1986), likely because it is exposed along a relatively new logging road. This intrusion and sev-

Plate 11a. (top left) *A large raft of irregularly layered gneiss. Dark layers are primarily magnetite;* **11b.** (bottom left) *Porphyroclasts of unknown composition; kinematics indicate dextral sense of shearing. Note the fine, thin layer-parallel bands of magnetite in the white layer;* **11c.** (top right) *Thick, irregular layers of magnetite; note the lack of magnetite near mafic dyke (D) contact in top left corner.*

eral other felsic intrusions within the TBG, and evidence for magma mixing textures, imply bimodal magmatism during late stage crystallization, and implies that at least some of the mafic dykes cutting the TBGS are relatively young.

Summary

Overall, the TBGS is heterogeneous on all scales, from outcrop-scale textures, to the scale of the separate pegmatitic gabbro unit in the north. The heterogeneities between the TBG and TBGP include texture, composition, alteration styles, xenolith composition and morphology, and presence of late felsic intrusions. Although previous U–Pb zircon dating indicates an age of ~ 430.5 ± 2.5 Ma (Heaman *et al*., 2002), the amount of deformation, and other types of textural modification, variable alteration zonation, different generations of dykes, suggest that material previously dated might not have been representative of the entire TBGS.

The lack of sulphide mineralization reduces the prospectivity of this intrusion. However, several mineralized locations may have potential to host PGE mineralization, evidence for multiple phases of magmatism, and lack of geochemical data still make this an intriguing exploration target. Further mapping of the central portion of the complex should be undertaken.

RED CROSS LAKE INTRUSIVE SUITE

The RCLIS, also known as the Rodeross intrusive complex or the Redcross Lake intrusion (Barbour, 1998) is located in central Newfoundland, approximately 50 km south of Buchans. This intrusion was accessed by helicopter from a major Abitibi Consolidated logging road that transects much of south central Newfoundland, and connects to the Burgeo Highway. The naming of this intrusion is complicated because the lake after which the intrusion is named is referred to as Rodeross Lake on some maps and as Red Cross Lake on others. The most recent maps use the name Red Cross Lake, and it is suggested that the intrusion be referred to as the Red Cross Lake intrusive suite.

This intrusion (Figure 4), like the previous two, was chosen for this study because of a lack of recent detailed mapping and because previous work had indicated rock compositions that might be favourable for orthomagmatic

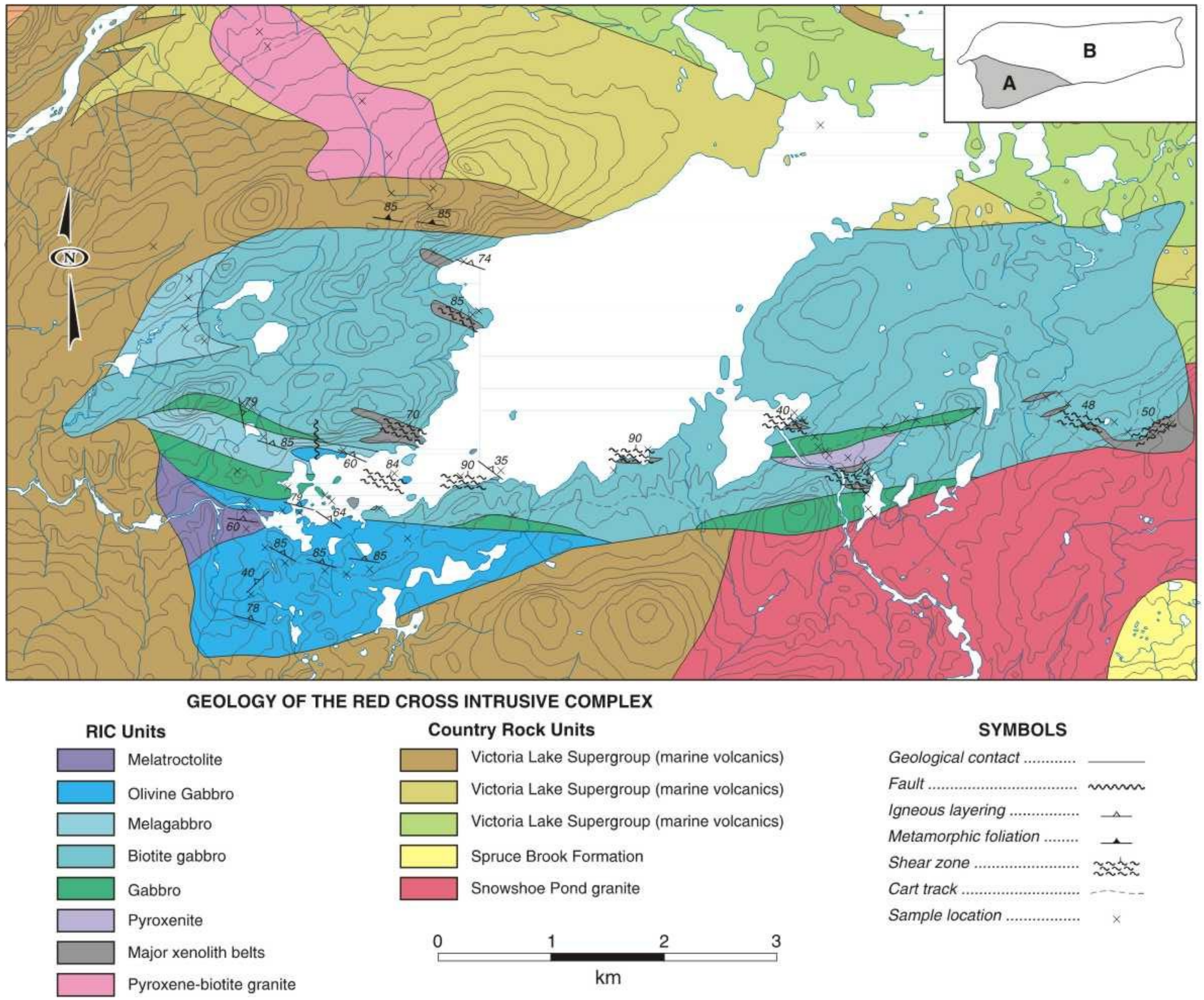

Figure 4. *Geology of the Red Cross Lake intrusive suite, central Newfoundland. Inset A) Lower Series; B) Upper Series; (regional geology from Colman-Sadd and Crisby-Whittle, 2004).*

Ni–Cu–Co ±(PGE) mineralization. Although most recently investigated by Barbour (1998), no systematic mapping has been conducted, and only seven samples have been analyzed. The conclusion of the most recent exploration program (Barbour, 1998) was that further mapping should be undertaken. During the 2004 field mapping, several outcrops were discovered that had recently been channel sampled, but investigation of these sample locations indicated that at least one of the locations was actually a boulder that was dissimilar to local outcrop.

FIELD WORK

The RCLIS is a layered mafic to ultramafic intrusion that has intruded biotite schist and quartzofeldspathic gneiss of the Victoria Lake Group (Kean, 1977). Layering is variably developed, strikes consistently east–west, and dips steeply to the north. Layering is well developed in the more mafic to ultramafic southern portion of the intrusion, and is nearly absent in the northern portion.

In the south, rocks have compositions ranging from melatroctolite to troctolite and olivine gabbro, and display layering on a centimetre to decimetre scale. Layering is defined primarily by the relative abundance of olivine and plagioclase. It is common to observe well-developed normal graded layering in the olivine gabbro units (Plate 12), which indicates, that the layers top to the north. Layering in the south is consistent overall, and at outcrop scale, layers are generally continuous, although they may undulate slightly and thickness is somewhat variable along strike. In the northern part of the intrusion, rocks comprise anorthositic gabbro, biotite gabbro and/or biotite diorite (Kean, 1977) and layering is all but absent. Hereafter, ultramafic to mafic rocks that display layering will be referred to as the "Lower Series" (Figure 4, inset A), and the biotite gabbro that does not display layering will be referred to as the "Upper Series", (Figure 4, inset B) reflecting the spatial distribution of different compositions and layering in the complex.

To the north of the RCLIS lies a separate intrusion of pyroxene–biotite-bearing granite. Previous workers have suggested that this intrusion is related to the RCLIS (Kean, 1977). However, mapping this summer indicates that this late phase is not in direct contact with the RCLIS body, as previously indicated and thus may not be related.

Layering in the Lower Series rocks has adcumulate, mesocumulate and orthocumulate textures. The bases of well-developed layers have an adcumulate texture, whereas farther up each layer, the rocks become progressively mesocumulate to orthocumulate in texture. Plagioclase and clinopyroxene typically form well-developed and preserved poikilitic textures, enclosing olivine crystals, which are relatively fresh. In other places within the layered rocks, poikilitic pyroxene crystals up to a few centimetres in diameter occur in a weakly deformed gabbro or olivine gabbro (Plate 13). In other locations within the Lower Series, varitextured melagabbro has been observed, although, due to the poor outcrop exposure in the map area, the lateral extent is indeterminable.

Plate 12. *Well-developed magmatic layering in olivine gabbro from the central portion of the intrusion, close to the Upper–Lower series contact. Layers grade upward toward the top of the image. Layers are defined by relative abundance of olivine and plagioclase.*

Within the Upper Series, textures are more restricted because the rocks are generally massive, and cut by late fractures or joints. In some places, a weak tectonic fabric is developed, causing a weak mineral lineation. The Upper Series is characterized by a relative abundance of biotite, which occurs as glomeroporphyrocrysts and as discrete, irregular grains. Biotite varies from 1 to 10 percent and appears to be controlled, at least partially, by proximity to biotite-bearing xenoliths, which are discussed below.

In the eastern portion of the RCLIS, a massive to weakly layered mafic-ultramafic facies occurs with an approximately pyroxenite composition. This zone, which occurs

Plate 13. *Coarse-grained subophitic pyroxene crystals in a weakly foliated olivine gabbro.*

within 1 km of the basal contact, is heavily contaminated by biotite schist and quartzofeldspathic gneiss xenoliths of variable size. In these rocks, the crystals are usually massive to interlocking, and the rock varies from medium to coarse grained. This unit is relatively homogeneous on an outcrop scale, but does have compositional layering over several tens of metres horizontally.

One of the main features of the RLCIS that has not been discussed in any detail by previous authors (e.g., Kean, 1977; Nuri, 1980; Barbour, 1998) is the abundance of xenoliths, and their distribution throughout the complex. Xenoliths are widespread in the RCLIS, but their distribution is restricted, for the most part, to the Upper Series. In the Lower Series, xenoliths are uncommon and then only occur proximal to the basal contact with country rocks.

Xenoliths in the RCLIS occur in three main groups. The most common mode of occurrence is in the Upper Series, as sheared, belts that range in thickness from one up to nearly 10 m. These xenolith belts are approximately parallel to the local layering in the Upper and Lower series. The belts locally comprise approximately 90 percent heterolithic xenoliths, although the average xenolith content is about 25 percent, and the matrix to the xenoliths ranges from biotite gabbro and anorthositic gabbro and granitic pegmatite (Plate 14). The composition of the xenoliths is dominated by biotite paragneiss or schist, and to a lesser extent, quartzofeldspathic orthogneiss. Xenolith sizes range from a few centimetres up to 50 cm long. Some of these belts contain rare, ultramafic olivine–plagioclase–magnetite-layered cumulate xenoliths. This rock type was not observed anywhere in the RCLIS, and thus may represent a facies from greater depth, or closer to the basal contact, which is obscured everywhere by overburden and vegetation. Every xenolith belt in the Upper Series is spatially associated with

Plate 14. *An example of a xenolith belt that does not exhibit a strong fabric; note random orientation of xenoliths and pegmatitic or hydrothermal matrix. This undeformed zone grades into a strongly deformed margin within 20 m to the north (to right side of image). Xenoliths in this outcrop are predominantly biotite gneiss, but also comprise quartzofeldspathic gneiss and cumulate ultramafic rocks.*

dendritic to wispy veins or pegmatites, probably the result of fluids released during melting of the xenoliths, which often appear to have been partially melted or assimilated. In some cases, pegmatite pipes are present, but are not always directly linked with xenoliths, as they are proximal to the xenolith zones (Plate 15). The xenoliths in these belts are aligned parallel to the shear zones and do not appear to have been deformed in the shear zones.

The second most common xenolith type is found in small zones of small, heterolithic xenoliths composed mainly of quartzofeldspathic gneiss, with subordinate amounts of biotite schist. They are most common near the basal contact of the RCLIS in the southeast. The xenoliths are locally sheared and individual xenoliths are subrounded to subangular and smaller than in other xenolith zones, averaging <5 cm and comprising <5 percent of the total rock volume. These zones are not spatially extensive, have variable orientation relative to magmatic layering and appear to form a

Plate 15. *An example of an irregular pegmatite pipe. In some locations, the fluids emanate directly from the xenolith-rich zone whereas in others it occurs more distal to the xenoliths.*

xenolith belt of sorts. Due to poor outcrop exposure, however, it is difficult to estimate their lateral continuity or overall distribution.

The final, and least common xenolith mode is a large raft that measures at least 50 m^2 in outcrop. This large raft was observed in the southeast portion of the suite, where there is good exposure along a small river. This raft is composed of quartzofeldspathic gneiss, which might explain its larger size, as perhaps it was more difficult for a small pluton to digest.

It is possible that these parallel shear zones and xenoliths mark boundaries where extensive stoping of wall rock occurred during emplacement of the RCLIS. This hypothesis is supported by the apparent contrast in composition to the north and south of the major xenolith belts, implying that the intrusion was emplaced as pulses of magma with variable composition.

The RCLIS hosts minor amounts of sulphide mineralization, which occur primarily in the Lower Series ultramafic rocks, particularly in troctolite and melatroctolite of the southwestern region, as well as in association with small gabbroic pegmatite veins. Sulphide occurs in weakly developed net-textures, but more commonly in fine- to medium-grained irregular blebs that are interstitial to silicate grains and constitute up to 2 percent of the rock. These textures indicate the presence of an immiscible sulphide liquid, which has crystallized as droplets and are characteristic of primary magmatic sulphides. Typically, it was not possible to directly observe sulphides in the outcrop, because surfaces are weathered, although where fresh bedrock was exposed, the presence of sulphides is apparent. They were noted by discrete rusty patches on an otherwise clean-looking outcrop. Where coarse enough to discern, the sulphide mineral assemblage includes pyrite, pyrrhotite, and chalcopyrite. Barbour (1998) described the presence of pentlandite, and indicated that sulphides had a high Ni tenor; values up to ~2300 ppm Ni having been reported in samples from the Lower Series (Barbour, *op. cit.*). Petrographic work as part of the present project has recorded the preserve of pentlandite within pyrohotite grains. Rocks in the Upper Series are devoid of sulphides, although rare sulphides occur in the xenolith belts in association with rusty xenoliths, where it is likely that there are remobilized sedimentary sulphides. In some weakly layered, vari-textured gabbro of the upper part of the upper Lower Series, sulphides are concentrated at the base of layers.

SUMMARY

The RCLIS is far more heterogeneous than previous work has indicated. Heterogeneities are mainly reflected by the widely distributed zones of xenolith belts, which occupy shear zones oriented parallel to Lower Series layering. Layering in the RCLIS has a consistent east–west orientation, which is consistent with that defined in previous work (Kean, 1977) and has variable composition. There is a major overall compositional change from the southwest corner of the RCLIS, which exhibits the most mafic composition, toward the north, where the complex has a biotite gabbro composition. This change occurs over a relatively short distance of less than 200 m in some locations. It appears at first glance that the east–west parallel xenolith belts bound units of distinctive composition in the Upper Series. This will require geochemical data to confirm and if it is the case, will have implications for the overall geometry of the complex, and the mode of emplacement.

Xenoliths, especially those with sulphides, (e.g., some of the less-altered biotite schists), can play a potentially important role in the formation of Ni–Cu–PGE sulphide concentrations because they can provide an external source of sulphur and silica, both of which can affect sulphide saturation, and thus control the rate, relative timing, and abundance of sulphide formation. As well, it is possible that the presence of abundant biotite gneiss xenoliths has altered the composition of the magma. There is a weak positive correlation between the abundance of xenoliths and the presence of biotite in the gabbro. This also requires more investigation using geochemical data to fully characterize the degree of contamination in the RCLIS.

The presence of Ni and Cu sulphides within the layered mafic to ultramafic units of the RCLIS is significant, especially given the presence of xenolith contamination. Further investigation of mineral and bulk rock geochemistry will help to elucidate the origin of sulphur in these rocks and aid in calculating the Ni and PGE tenor of the sulphides. Preliminary petrographic analysis has clearly indicated the presence of pentlandite in the metatroctolites.

CONCLUSIONS

The contact relationships and internal igneous stratigraphies of three mafic to ultramafic intrusions in central and western Newfoundland were mapped. The intrusions were also extensively sampled in order to evaluate their respective potential to host Ni–Cu–PGE mineralization. Geochemical and petrographical work on these samples is in progress.

The SMA hosts several magnetite occurrences, which are locally associated with norite bodies. The norite map units proved to be smaller than previously defined. A series of diabase dykes that intrude the anorthosite were also identified.

The TBGS ranges from gabbro to ferrogabbro in the south, to pegmatitic gabbro in the north. The intrusion is heterogeneous in terms of texture, xenolith content and the presence or absence of later felsic intrusions. Igneous layering dips toward the centre of the south intrusion. There is a general lack of sulphide mineralization, except for local sulphide mineralization in brittle fracture systems, hosted by melagabbro to pyroxenite. Mineralization potential is suggested by regional lake-sediment and lithogeochemical Ni anomalies. The south intrusion exhibits evidence for mixing of mafic and felsic magmas. Three generations of mafic dykes have been defined in the TBGS, the oldest which appears to have intruded before final crystallization.

The RCLIS exhibits well-developed layering from melatroctolite, feldspathic peridotite, troctolite and olivine gabbro in the southwest, to biotite gabbro in the north. The layering includes cumulate textures with gradational layering of olivine and plagioclase. The intrusion has been subdivided into the Lower Series layered ultramafic to mafic rocks and the Upper Series, which consists predominantly of biotite gabbro. Heterogeneities include widely distributed, layer-parallel belts consisting of 25 to 85 percent heterolithic xenoliths that locally resemble intrusion or hydrothermal breccia. These belts are located along basal contacts and, more commonly, in the centre of the intrusion. Sulphides up to a few percent are present throughout the most mafic basal units, and comprise pyrrhotite, pyrite, chalcopyrite and pentlandite. Previous work (Barbour, 1998) indicates sulphides have a high Ni tenor. The potential for sulphides (or other minerals) to host PGE's will be investigated. The less-altered biotite schists xenoliths also contain abundant sulphides.

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