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STRUCTURAL EVOLUTION AND EMPLACEMENT OF THE NAIN PLUTONIC SUITE IN THE DOG ISLAND AREA

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ABSTRACT

Fieldwork was carried out in the Dog Island area near Nain, Labrador, during the summer of 1994. The area consists of Archean quartzofeldspathic gneisses, intercalated with mafic banded gneisses and paragneisses that have been intruded by the Mesoproterozoic Nain Plutonic Suite (NPS). The objective of the 1994 fieldwork was to elucidate the structural effects of the emplacement of the NPS on the country-rock, and to evaluate the setting of the plutons in this area relative to others in the NPS. It appears that the emplacement of the NPS had negligible structural imprint on the country-rock in the Dog Island area, contact metamorphism being the main manifestation of the arrival of the plutons at this crustal level. Differences in the mode of emplacement of the NPS can be used to group its constituent anorthositic plutons into two types: the diapiric type and the passive type. It is proposed that the former represents bodies emplaced mainly in the solid state from a deeper crustal level, whereas the latter crystallized in situ *in magma chambers at the present level of erosion.*

INTRODUCTION

The myriad of islands in the archipelago centred on Dog Island, located about 30 km northeast of Nain, is underlain mostly by i) Archean quartzofeldspathic gneiss intercalated with earlier metasedimentary and mafic gneiss and ii) the Mesoproterozoic Nain Plutonic Suite (NPS) consisting of anorthosite, norite, troctolite, diorite and granite. The Archean gneisses were collectively termed the Ford Harbour Formation by de Waard (1971), but this nomenclature is no longer considered valid for these rocks because of the definition of 'formation' under the stratigraphic code (see Ryan, 1991).

E.P. Wheeler (from 1926 to 1974) was the first to examine the area in any detail. His pioneering work provided the basis for surveys by S.A. Morse and colleagues under the Nain Anorthosite Project (NAP) between 1971 and 1981 (see Morse, 1971-1983), which focused on the genesis of the Nain anorthosite and associated plutonic rocks now referred to as the Nain Plutonic Suite (NPS). Wheeler's work and the NAP revealed the diverse nature of the NPS, showing it to comprise predominantly anorthosite, norite, troctolite, diorite and granite. Morse (1982) and Berg *et al.* (1994) have cited the NPS as a classic example of Mesoproterozoic anorogenic magmatism.

The gneissic country-rock to the NPS has received considerably less attention than the plutons themselves. Wheeler's earliest mapping of the Nain region provided data for the first descriptions of the gneisses (cf. Wheeler, 1942). Later, Taylor (1979), among others, presented a more detailed description of the gneisses of the Nain area as part of an overview of all the Labrador gneisses. More restricted areas on some of the islands east of Nain were examined by de Waard (1971) and Bridgwater *et al.* (1990). Ryan (1991, 1992) has presented results of a regional examination of the gneisses between Port Manvers Run and the Seniartlit Islands, resulting from a two-field-season mapping program in the area.

Within the context of the regional geology of Labrador, the Archean rocks of the Nain area fall midway between the Saglek and Hopedale blocks of Nain Province, but their structural and lithological affinity with either has not been definitely determined because the continuity between the two blocks is disrupted by the igneous rocks of the NPS. Speculation regarding the evolutionary history of the Nain area gneisses has been given elsewhere (Ryan, 1991, 1992; Connelly and Dunning, 1990; Bridgwater *et al.*, 1990; Connelly and Ryan, 1994) and studies are continuing to refine the important events so far identified. As part of the continuing investigations of the Nain gneisses and plutonic rocks, further field mapping and structural analysis of part of the archipelago east of Nain were carried out by the first author in the summer of 1994. This program concentrated on the area around Dog, Carey and Moskie islands (Figure 1), and is a continuation of a Ph.D. project begun in the Nukasusutok Island area in 1993 (Royse *et al.*, 1994). A short visit was made to the Mount Lister intrusion north of Nain at the end of the field season in order to compare this anorthositic body with those examined on the islands to the east.

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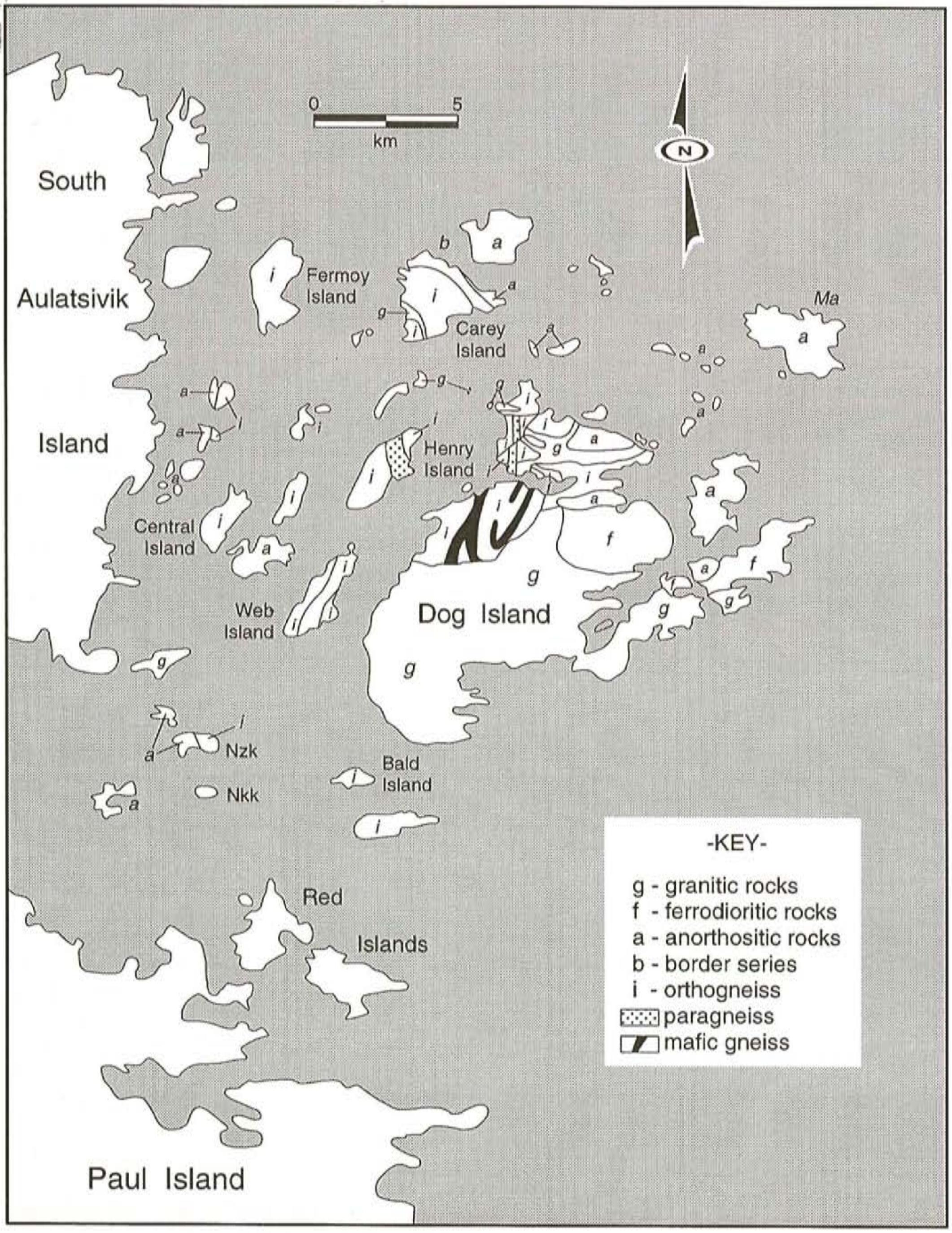

Figure 1. *Geological sketch map of the area around Dog Island (Nzk–Noazunaluk Island, Nkk–Noazunakuluk Island, Mo–Moskie Island, Ma–Marshall Island, S–Spruce Island, D–Dumbell Island.*

ROCK UNIT DESCRIPTIONS

Gneissic Rocks

Several types of gneiss have been outlined by Ryan (1991, 1992) within the Archean complex northeast of Nain, viz. layered and foliated orthogneisses, paragneiss and mafic gneiss. The quartzofeldspathic orthogneisses, which are by far the largest group, can be further divided into two distinct subgroups–a migmatitic gneiss and a schlieric, foliated granite.

Migmatized Tonalitic to Granodioritic Gneiss

These gneisses are the dominant rock type forming the bulk of Dog, Spruce and Carey islands. They weather a brown to grey or pink, mainly dependent on their grade of metamorphism, the brown ones represent granulite facies whereas the grey and pink ones reflect varying degrees of retrogression from this high-grade condition. Granodioritic to quartz-dioritic variants within the gneisses, such as on Fermoy Island, tend to weather a dark grey because of their higher content of mafic minerals. Within the quartzofeldspathic orthogneisses, locally, are isolated to abundant lenses and pods of ultramafic, mafic, and metasedimentary rock. Migmatization takes the form of agmatitic, schollen, and stromatic varieties. In some parts of the gneiss complex, such as on the south shore of Carey Island, ductile shear zones overprint the migmatites giving rise to discrete domains in which the rocks are converted to protomylonite.

Schlieric Granitoid Gneiss

Schlieric to diffusely banded granitoid gneiss derived from intrusions that postdate the migmatites are best developed on Dumbell Island and Misfit Island (Ryan, 1991), where inclusions of the older migmatitic rocks clearly indicate the relative age of the two gneiss units. These younger intrusions were emplaced at 2578 ± 3 Ma (Connelly and Ryan, 1994). On the above mentioned islands, the granitoids are the dominant rocks, but elsewhere the granites occur as sheets both parallel and slightly oblique to the layering in the older migmatized gneisses. Hornblende and biotite, locally defining a strong L-fabric, are the dominant mafic minerals in these rocks, in contrast to the granulite-facies assemblages of the surrounding older migmatites. In places, relicts of potassium feldspar phenocrysts give rise to a porphyroclastic (augen) texture in outcrop.

Paragneiss

The paragneisses are mostly found intercalated as distinct units within the migmatized quartzofeldspathic orthogneisses. Lesser amounts are also associated with the mafic gneisses in the area. The largest units of paragneiss occur on Dog and Henry islands. The paragneisses are dominated by pelitic and semipelitic compositions, but siliceous units derived from quartzite or chert occur locally. A variety of regional and contact metamorphic minerals can be identified in outcrop. The regional metamorphic assemblage contains garnet, sillimanite, cordierite and orthopyroxene; contact minerals include second-generation cordierite and orthopyroxene as a replacement of garnet, and cordierite and spinel as a replacement of sillimanite. These pseudomorphics assemblages indicate pyroxene hornfels metamorphism, and compares with contact metamorphic conditions evident elsewhere adjacent to the NPS (cf. Berg, 1977). Garnet and sillimanite replacement textures indicate that no regional deformation was associated with the contact metamorphic overprinting (Ryan, 1991).

Leucocratic Granites

Leucocratic granites are a discrete member of the gneiss complex on the northern part of Dog Island, where they occur as sheets within the mafic gneiss, paragneiss, and quartzofeldspathic migmatites. On Hayes Cone, at the northern end of Dog Island, there are numerous sheets of such leucocratic granite. The attitude of the gneissic foliation within this area is very erratic, suggesting reorientation of the older rocks above a near-surface larger body of the leucocratic granite.

Mafic Gneiss

Mafic gneisses are found as metre- to kilometre-scale units throughout the study area. They vary in texture in outcrop from massive granular rocks having no planar fabric to well-layered and migmatized gneisses having a strong preferred orientation to their constituent minerals. Locally, they contain concentrations of stubby black hornblende that gives them a spotted appearance. Ryan (1991) pointed out that two types of gneissic mafic rocks could be identified in the area, one characterized by hornblende and biotite, and a second by olivine. The latter type is preferentially developed adjacent to some of the mafic plutons and Ryan (1991, 1992) surmized that there may be a genetic connection between the two. In this paper, the position is adopted that the second group of mafic gneisses is, indeed, part of the NPS and is dealt with in a subsequent section.

The regionally developed mafic gneisses are well-exposed on Dog, Noazunakuluk, Web and West Red islands. Mafic gneiss on the east side of Noazunakuluk Island is one of the largest units in the area, and is representative of such rocks. It is a weakly layered granulite, having a granular texture and a locally developed spotted appearance. It is intruded by many slightly transgressive sheets of pink granite that may be equivalent to the Red Cliff granite to the south (Ryan, 1991) and the Loon Island granite to the north (Ryan, 1992). A peculiar feature to the mafic granulite here is a foliated, saccharoidal-textured, biotite-bearing anorthosite sheet on its western margin. Other mafic granulites occur on Dog Island, where some contain podiform ultramafic units. In this respect, these latter mafic gneisses are similar to those of the Paul Island—Nukasusutok Island sector (Royse et al., 1994).

Deformed and Recrystallized Mafic Dykes

All the rock units described above are intruded by a multi-generation assemblage of mafic dykes (cf. Ryan, 1991, 1992; Cadman *et al.*, 1993; Cadman and Ryan, 1994). They vary texturally from diabasic to granular to strongly foliated; massive to porphyritic types are present among all three varieties. Most dykes are continuous planar intrusions that can be traced for hundreds of metres along strike, but others are podiform or sheared and folded. Some of these dykes are Late Archean (Connelly and Ryan, 1994) but others are quite probably related to the initial phases of mafic magmatism that gave rise to the NPS. The dykes are somewhat enigmatic because, in many cases, there is difficulty in deciding if their granular texture is a result of contact metamorphism or if it is primary igneous structure.

Anorthosite, Norite and Troctolite

Anorthosite, norite and troctolite constitute the predominant basic rocks in the NPS. The general characteristics of these rocks have been outlined by Wheeler (1942), Emslie (1980) and Morse (1982). Troctolitic to anorthositic rocks are present on Carey, North Carey, Marshall, Myrtle, Mary, and Moskie islands and on the small islands just off the north shore of Dog Island. Leuconorite and norite occur on Noazunakuluk Island, West Red Island and on the Pat Rocks. All these rocks contain inclusions of older mafic plutonic material that may differ from their host in being coarser, darker, or more saccharoidal. The basic rocks exposed on Club Island are more melanocratic than most of the other plutonic rocks in the area and contain appreciable amounts of hornblende and biotite. The Club Island body may represent a small pluton that predates the NPS.

Some of the noritic and troctolitic plutons of the NPS are bordered by layered rocks ('mafic granulites') that commonly contain olivine and two pyroxenes but little or no hornblende (Ryan, 1991). Such rocks here and elsewhere in the NPS (cf. Morse, 1969) have proven to be an enigmatic group, exhibiting characteristics in common with both the regional mafic gneisses and the plutons. In keeping with a notion expressed by Ryan (1991), these mafic rocks in the study area are herein referred to as a 'border series' to the plutons they abut. These border rocks are particularly well developed on the eastern shore of Carey Island, where they separate granulite-facies country-rock from massive olivine norite of the Jonathon Island intrusion. Within the border series, there are elongate inclusions and rafts of paragneisses, quartzofeldspathic rocks and older mafic granulite. Anorthositic layers are locally present, and noritic to anorthositic veins and sheets give rise to a migmatitic rock in some places.

Rapakivi Granites and Ferrodiorite

Granites are found on Dog Island, Natsutuk Island, Koliktalik Island and a small cluster of islands near Dog Island known as Red Rocks. The granites on Dog Island were initially described and named by de Waard (1973) as the Alagaiai adamellite (in the north) and the Iviksuak adamellite (in the south). These rocks are here referred to as granites (s. l.) rather than adamellite. Both intrusions have sharp contacts against the older rocks; agmatitic structure and pegmatite dykes are characteristic of some contacts against anorthosite.

The Alagaiai granite is disposed as several large dykes that crosscut both the gneisses and anorthosite (Ryan, 1991). It tends to be a hypidiomorphic-textured hornblende-granodiorite over most of its outcrop area, the amphibole locally containing cores of augite or olivine; in some of the dykes, the amphibole exhibits a weakly developed lineation. The Iviksuak granite, on the other hand, has well-developed rapakivi feldspars and ovoid quartz, and is an olivine-bearing rock that for the most part is quartz monzonitic in composition.

Medium- to fine-grained melanocratic rocks, referred to as ferrodiorite, occur along the interface between the northern margin of the Iviksuak granite and the abutting anorthosite (de Waard, 1973). These vary from massive to well-layered (Plate 1), and locally contain xenocrysts from the adjacent anorthosite. Such rocks are absent from the Alagaiai granite dykes. The contact between the Iviksuak granite and the ferrodiorite is diffuse in many places, being a transitional interface of hybrid rocks in which pillows of the mafic rocks occur within the granite, and stringers and isolated feldspar crystals from the granite occur within the ferrodiorite. Such features are well developed through the central part of Dog Island, and have been cited elsewhere as evidence that the two rocks were both magmas when they came in contact with each other (cf. Wiebe, 1979). A foliation is present in ferrodiorite at the northern contact with gneisses on the coast of the east–west bay of central Dog Island, and a lineation is present within these rocks on parts of Koliktalik Island where it separates anorthosite from granite.

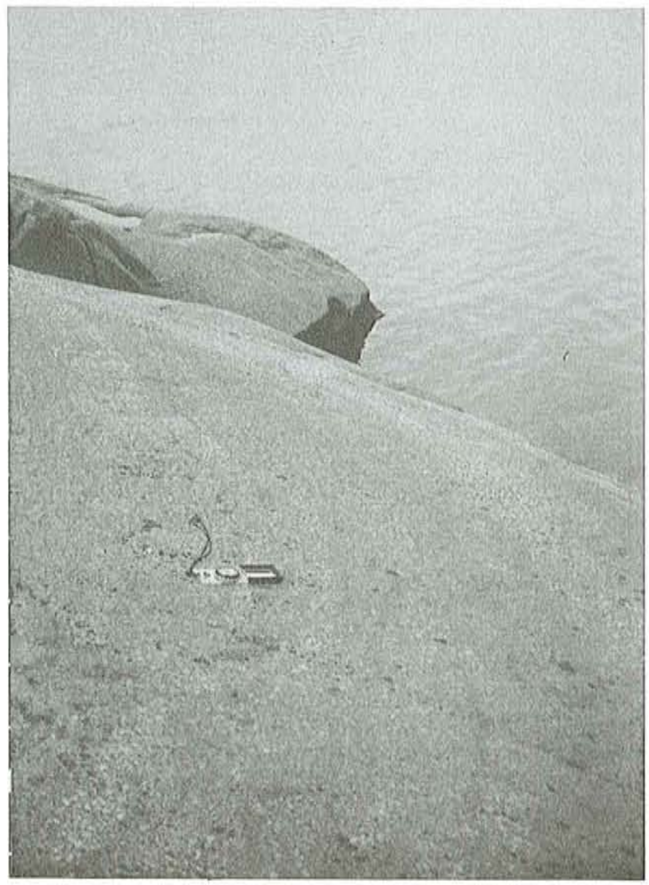

Plate 1. *Layering defined by varying comcentrations of feldspar and quartz xenocrysts within ferrodiorite on Dog Island.*

STRUCTURAL FEATURES

The gneissic foliation in the area strikes northeast–southwest and dips predominantly to the east at between 50 to 90° (Figure 2), but variations due to earlier

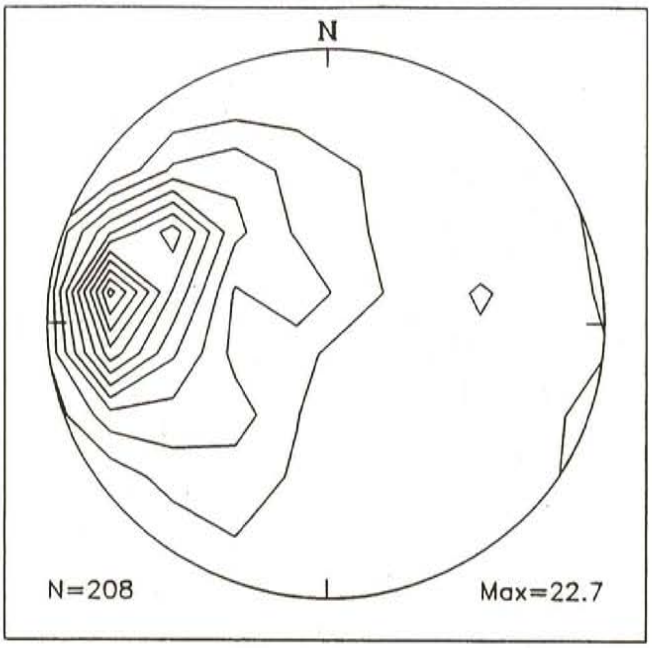

Figure 2. *Contoured equal-area stereoplot of the poles to layering for the migmatitic gneisses (contours per 2 percent area; maximum 22.7 percent).*

deformational events complicate this pattern locally. It is clear from mesoscopic structures that the gneisses have undergone a complex polyphase deformational history, the schlieric granitoid gneisses showing only part of this history. The following is a brief description of the main small-scale structural features that can be seen in the gneisses of the Dog Island area as determined by the first author.

The migmatized gneisses display a composite transpositional S_0-S_1 foliation within which are intrafolial B_{s2} folds. This transposed foliation has enhanced the gneissic layering through the attenuation and repetition of differing compositional components within the earlier rocks. The layering has been regionally folded by isoclinal northeast-trending folds (B_{s2}); an axial-planar foliation is developed locally. The B_{s2} folds have refolded and tightened earlier structures; refolding of earlier folds has resulted in the development of type one and type three interference structures (Plate 2). Overturned B_{s2} folds can be found within the mafic gneiss on the southern side of Dog Island and within the quartzofeldspathic gneisses of Nest, Moskie and Spruce islands (Figure 3). Higher strain zones in the gneisses, postdating the migmatization, locally give rise to metre-scale belts, in which the banding has a mylonitic and finely laminated aspect. Such zones have been identified on the south coast of Carey Island and the north coast of Dog Island.

The migmatized gneisses are intruded by schlieric granitoid gneiss that does not display the same complex history as the older rocks. It is characterized by a single northeast-trending mineral foliation and a strong mineral lineation, and lacks the pervasive migmatization seen in the

Plate 2. *Dome-and-basin interference structures within grey migmatite on Carey Island.*

older rock. The foliation appears to be folded on a regional scale by B_{s2} folds (Figure 4) but the variations in foliation orientation evident in this unit could be a result of perturbations caused by broad ways of the layering because no small-scale structures or fold closures have been identified. The mineral lineation in these rocks is not parallel to the regional fold axis.

Shear zones, as noted above, have been locally impressed on the gneisses. Their orientation varies within the area, and they may not all be the same age. For instance, a shear zone on the south shore of Carey Island is east–west trending, and dips gently to the north. At Dumbell Island, some vertical shear zones striking northeast are crosscut by recrystallized basic dykes, yet other shears with the same orientation offset the dykes.

Structures that appear to postdate the NPS include faults, late brittle fractures, and conjugate kink bands (Plate 3). The orientation of the majority of these structures imply that the maximum compression during their development was oriented northeast–southwest.

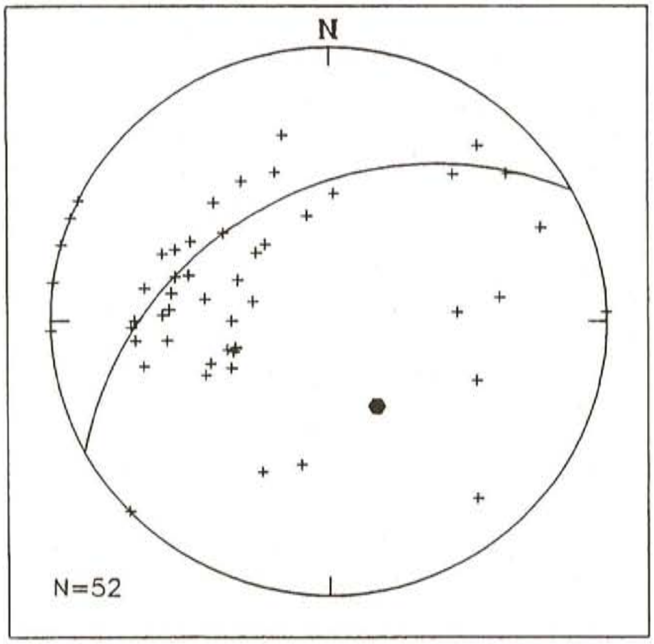

Figure 3. *Stereographic projection of layering orientation from migmatitic gneisses in an overturned fold around Moskie, Nest and Spruce islands.*

EMPLACEMENT STYLES WITHIN THE NAIN PLUTONIC SUITE

The anorthositic rocks within the NPS exhibit two radically different types of contact with their country rock, a feature noted by Ryan (1991, 1992) as a result of work on the coast and inland in 1990 and 1991. Some anorthosites, especially those found inland, are characterized by strongly foliated margins, for example the Mount Lister intrusion, Kingurutik Lake area, and the Pearly Gates intrusion (cf. Emslie *et al.*, 1972; Ryan, 1991, 1992). Other anorthositic intrusions, such as the Jonathon intrusion and the anorthositic rocks of the Noazunakuluk Island area, show no deformation along the pluton–gneiss interface. The intrusive style of the plutons thus seems to be compound, including both passive and forceful intrusions, the former within "*in situ*" magma chambers, the latter probably as solid-state diapirs (Ryan, 1993). These differences in the mode of emplacement of the NPS anorthositic plutons are used to group them into two types: the 'diapiric type' (of which only one example was examined, the Lister massif) and the 'passive type' (of which two main examples were studied, the Jonathan Island intrusion and Noazunakuluk Island pluton).

The diapiric type is composed mostly of coarse- to very coarse-grained anorthosite and leuconorite. These intrusions have foliated to gneissic margins (Plate 4) and less-deformed anorthositic and noritic rocks within their interior parts (Ryan, 1991, 1992), features that were used by Ryan (1992, 1993) to compare them with the Rogaland anorthosites of Norway. The marginal gneissosity is enhanced by the presence of a primary layering and deformed anorthositic rafts that are attenuated within the foliation. The characteristic rock of the deformed margins is one in which recrystallized, saccharoidal-textured plagioclase and elongate aggregates of orthopyroxene surround relicts of dark-grey primary igneous plagioclase. The only example of this type of intrusion examined during the 1994 season is the Mount Lister intrusion, where it is exposed in shoreline outcrop along the west side of Webb Bay. The Mount Lister intrusion, in the region examined, also

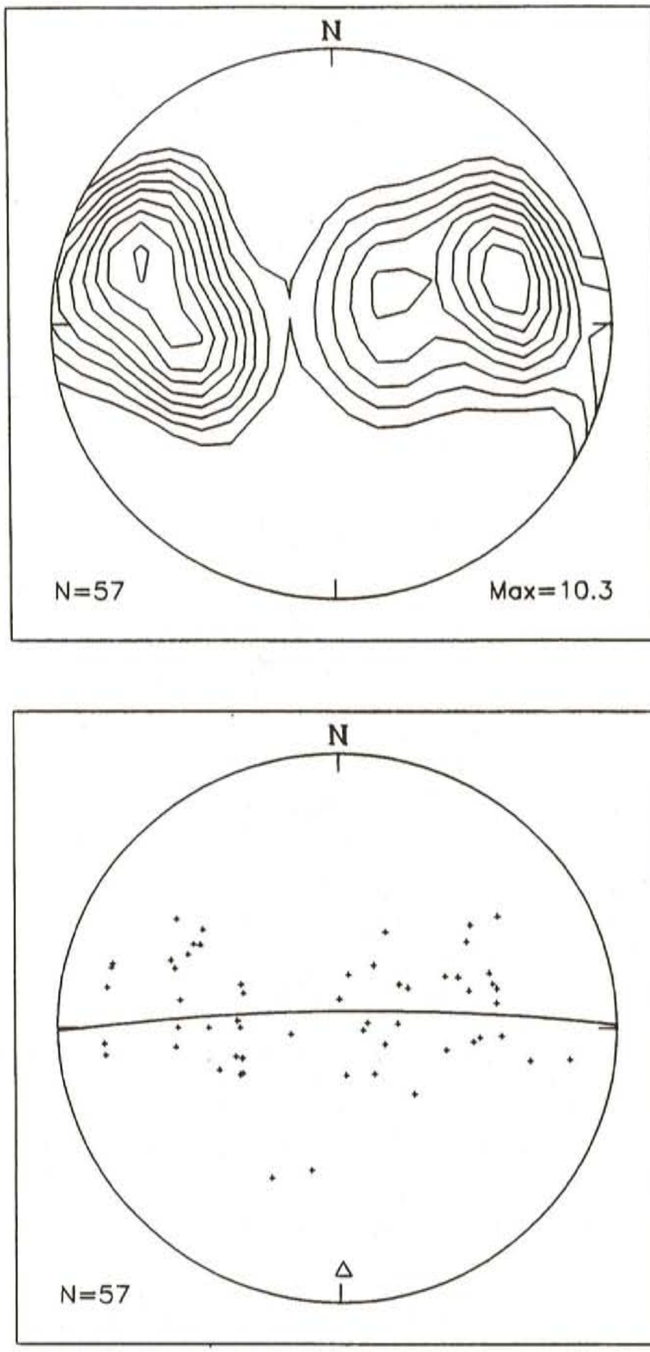

Figure 4. *Equal-area stereoplot of the foliation in the granitoid gneiss. Upper diagram shows a contoured equal-area plot of poles to layering (contours per 1 percent area; maximum 10.7 percent); lower diagram displays a π-diagram of poles to layering, showing position of the regional* F_2 *fold axis.*

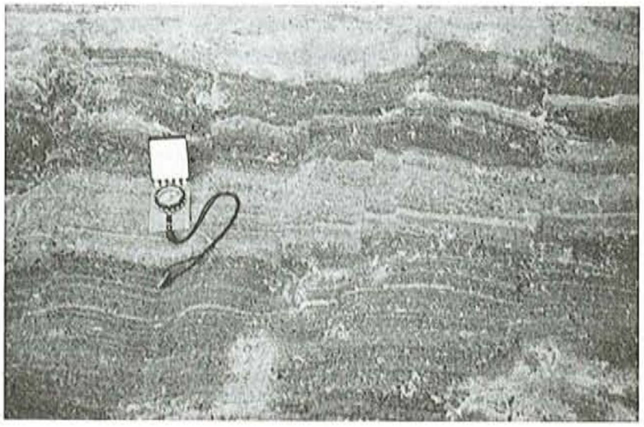

Plate 3. *Closely spaced brittle fractures indicating sinistral offset, Dog Island.*

Plate 4. *Foliated gneissic leuconorite from the marginal zone of the Mount Lister intrusion, Webb Bay, containing recrystallized saccharoidal-textured plagioclase surrounding augen of primary plagioclase. Orthopyroxene occurs as lozenge-shaped grains and aggregate trains that define the foliation.*

includes a foliated monzonite that forms a thin discontinuous sheath separating the anorthosite and norite from Archean granulite-facies gneisses (Ryan, 1993).

The presence of highly strained foliated margins, unrelated to any post-NPS deformation, is taken to indicate that these anorthositic plutons have been diapirically emplaced. Saccharoidal-textured, recrystallized anorthosite surrounding remnants of primary plagioclase megacrysts indicates that the material was emplaced when already in the solid state (at least partially), which is consistent with the high melting point monomineralic nature of anorthosites. Ramberg (1981) stated that solid-state diapirs should contain radial upright buckle folds. Due to a lack of detailed mapping and paucity of structural data on the diapiric intrusions, it has yet not been determined if this structural configuration exists in the Nain plutons.

The margin of the Mount Lister intrusion exposed on the shore of Webb Bay is noteworthy in having a shallow- to moderate-plunging lineation that indicates an oblique-slip to strike-slip movement sense. This appears at odds with a vertical emplacement model, but, depending on where the lineation is taken in respect to the shape of diapirs (Dixon, 1975), and the type of diapir, (e.g., sheet, forehead, or mushroom: Haller, 1955, 1971) a strike-slip lineation may be produced. Models put forward for the emplacement of basic material from the mantle by Yoder (1978), are consistent with the concept that, under favourable conditions, systems of hot plastic solid matter plus magmatic melt could be emplaced in the uppermost levels of the crust. The Konder pluton in Siberia is a manifestation of such a process (Lazarenkov and Landa, 1992).

Plutons that have crystallized passively *in situ* are composed of unfoliated anorthosite and leuconorite. The margins of the intrusions examined during this study are variable. For instance, on Noazunakuluk Island the contact between the pluton and the adjacent mafic gneiss is marked by a zone of fine-grained feldspar porphyry. On Carey Island, however, the contact between the olivine norite pluton and the quartzofeldspathic granulites is defined by a belt of 'mafic granulite' that is here considered to represent early layered rocks of the floor or walls to the magma chamber that ultimately housed the main plutonic mass (Plate 5). These

Plate 5. *Layered rocks forming the border zone to the Jonathon Island intrusion, Carey Island. Light-coloured veining is anorthositic in composition.*

rocks exhibit evidence of solid state boudinage and folding, but they lack the intense and pervasive mineral foliation that characterizes the margin of the diapiric intrusions. The general lack of a penetrative deformational fabric within these coastal anorthosites suggests that emplacement and crystallization were probably *in situ* at the crustal level that these intrusions now occupy. Anorthositic layers, folding, and orthopyroxenite to noritic veins and dykes that crosscut and engulf the marginal layered sequence on Carey Island (Plate 6), indicate the edge of the magma chamber was repeatedly injected by younger magma as the chamber evolved, causing the earlier formed material to become unstable and deformed. Similar features have been observed in some other basic intrusions, e.g., the Klokken intrusion (Parsons and Becker, 1987) and the Duke Island ultramafic intrusion, where Irvine (1987) attributes them to the collapse, stoping and crumbling of layers, within a highly turbulent convecting system. The outer border zone of the Kiglapait intrusion has many features in common with the marginal layered rocks around the Jonathan Island intrusion (e.g., mafic, granular, banded, and containing mafic xenoliths). Although there has been some debate about its origin, Morse (1969) considered the outer border zone as part of the Kiglapait intrusion, noting that such mafic rocks are commonly seen in border zones of many large gabbroic intrusions.

Plate 6. *Noritic and orthopyroxenite dykes crosscutting banding within the marginal layered gabbro of the Jonathan Island intrusion, Carey Island.*

CONCLUSIONS

The Archean gneisses of the Nain area comprise an assemblage of plutonic and supracrustal rocks that exhibit a polyphase deformational history. Ductile deformation is manifested in composite mineral foliations, lineations, shear zones and folds. Brittle features in the area include faults and fractures. Some of the ductile shear zones within the area may have been reactivated during emplacement of some of the plutons of the NPS, but apart from contact metamorphic overprint on the country-rock, there was negligible effect from the intrusions on the Nain gneisses. The anorthositic plutons of the NPS can be categorized into two subgroups on the basis of their structural features. Some were emplaced as solid-state diapirs following initial crystallization at a deeper level, whereas others crystallized and remained at their present level of exposure.

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