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AN INVESTIGATION OF SOME METAMORPHOSED MAFIC DYKES OF THE NAIN AREA, LABRADOR: PART 1

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ABSTRACT

Archean gneisses of the Nain area of Labrador contain a multi-generation assemblage of mafic dykes that exhibit variable trend, metamorphic grade and mineralogy. Preliminary structural studies show that some dykes were injected via a mechanism of pure tensile failure whereas others seem to have been emplaced during shear-style deformation. In many cases, the timing of deformation relative to emplacement is difficult to establish because solidified dykes may act as rheologically weak, incompetent layers at high-metamorphic grades.

Some dykes having similar orientation have strongly opposing senses of shear. A model is presented, which suggests that opposing shear senses are caused by local variations in principal stress directions associated with the emplacement of Nain Plutonic Suite intrusions.

INTRODUCTION

In recent years, much progress has been made in the understanding of dyke swarms and their relative importance to the geological record. In many cases, episodes of dyke emplacement have been linked, spatially, temporally and chemically, to Continental Flood Basalt(CFB)-type magmatism (e.g., LeCheminant and Heaman, 1989). Large continental dyke swarms are interpreted as forming the root zones to CFB provinces, and consequently are best exposed in exhumed terranes of mainly Proterozoic age. Continental flood basalts and continental dyke swarms are considered to be associated with the formation of continental rift zones, which themselves represent precursors to the development of oceanic or back-arc basins (e.g., Fahrig, 1987; Smith, 1992).

The eastern Canadian Shield in Labrador has been intruded by several prominent swarms of mafic dykes (cf. Fahrig and West, 1986) of diverse ages and compositions. Dykes are especially abundant in the Archean Nain Province, where studies in the Saglek and Hopedale blocks (Figure 1) have identified at least two major swarms (cf. Morgan, 1975; Ryan, 1990a; Ermanovics, *in press*; Cadman *et al.*, 1992), one of Early Proterozoic and one of Middle Proterozoic age, and a less extensive suite of mid-Archean dykes (see below).

Recent studies in the Nain area (Ryan, 1991, 1992) have shown that the region has been injected by at least six generations of mafic dykes (Ryan, unpublished data). Four of these dyke generations, the subject of this paper, have textures and a mineralogy that indicate metamorphic

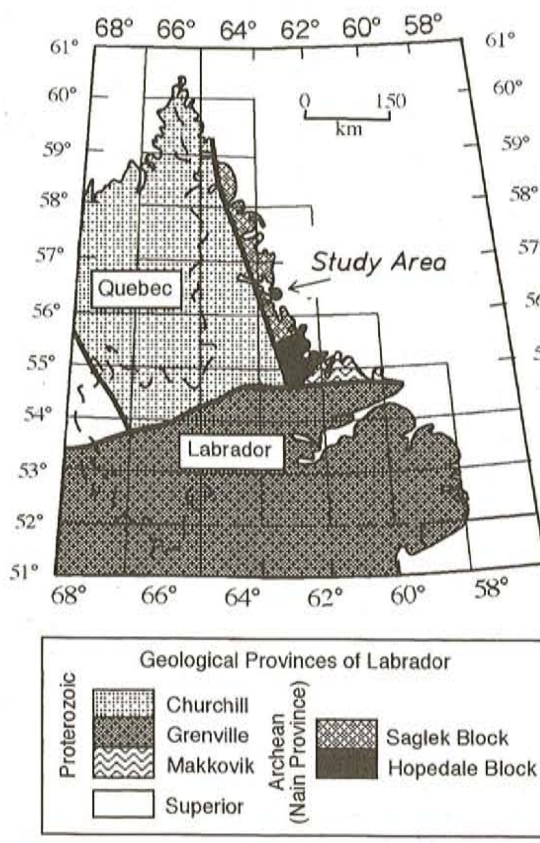

Figure 1. *Location of the study area in relation to the regional tectonic framework of Labrador.*

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recrystallization at amphibolite and granulite facies; some are demonstrably intruded into ductile country rocks and were subjected to shear deformation. This study of the Nain area dykes was undertaken to determine the significance of the recrystallized dykes and to ascertain if correlations could be established between any of these dykes and those of the Saglek and Hopedale blocks. Regional observations on the dykes by Ryan (1991, 1992) had indicated some unique morphological features, and a geochronological investigation of one dyke demonstrated a Late Archean age (Connelly *et al.*, 1992). Therefore, a number of questions regarding these deformed and recrystallized intrusions may be asked: 1) how many of the dykes are Archean or Early Proterozoic? 2) how many of the dykes are related to emplacement of the Middle Proterozoic Nain Plutonic Suite (NPS), an anorogenic igneous assemblage in the Nain area that contains an abundance of basic rocks? 3) is dyke deformation related to emplacement of the NPS? 4) how does each dyke episode compare to dyke swarms generated during established CFB-type magmatic events, and 5) what can this prolonged period of basic magmatism tell us about the way the Nain area has evolved throughout geological time?

PREVIOUS WORK

Much of the pioneering regional mapping of the rocks of the Nain area was carried out by E.P. Wheeler in an extensive research program starting in 1926 and lasting until 1974 (Wheeler, 1942, 1960). The anorthosites and associated rocks of the NPS were studied in detail during the ten-year (1971-1981) Nain Anorthosite Project under the co-ordination of S.A. Morse (cf. Morse, 1983). Mapping of the gneissic country rocks was carried out by de Waard (1971), Taylor (1979) and more recently by Bridgwater *et al.* (1990) and Ryan (1991, 1992). A suite of diabase dykes that postdates the ca. 1.30 Ga anorthositic rocks near Nain has been described by Wiebe (1985). The dykes of the Nain area that are the focus of this paper, although noted by earlier workers such as Upton (1971, 1974), have largely been ignored. Their characteristics and potential significance remained unknown until Ryan (1991, 1992) undertook a mapping survey of Archean rocks on the islands east of Nain in 1990 and 1991.

GEOLOGICAL SETTING OF THE NAIN AREA

The Archean Nain Province (Figure 1) comprises metamorphic and igneous rocks that are superbly exposed along the northern and central Labrador coastal area. The province is subdivided into two distinct crustal blocks. The older Saglek block occupies the northern half of the province; its major rock units range in age between 3900 to 2500 Ma (Bridgwater and Schiøtte, 1991). Rocks of Early- and Mid-Archean age are dominant, including migmatized layered tonalites and granodioritic gneisses, minor quartz monzonites, Fe-rich granodiorites and metagabbros, and basic supracrustal and intrusive units. Bridgwater and Schiøtte (1991) suggest that tectonic intercalation of Early and Mid-Archean gneisses occurred around 2700 Ma and that this event correlates with a terrane amalgamation episode postulated for the Archean rocks of west Greenland (Friend *et al.*, 1987, 1988; Nutman *et al.*, 1989). At least two generations of mafic dykes intrude the Saglek block; the Saglek dykes of Mid-Archean age (Bridgwater and Schiøtte, 1991), and the Early Proterozoic Domes/Napatok swarms (Ryan, 1990a; Ermanovics and Van Kranendonk, 1990).

The southern part of the Nain Province, the Hopedale block, comprises polydeformed gneisses of predominantly granodioritic to tonalitic composition, ranging in age between 3200 and 2800 Ma. The gneisses have a predominantly northeast–southwest (Fiordian) trend interpreted by Ermanovics *et al.* (1982) as Late Archean. This foliation overprints an earlier (Hopedalian) northwest–southeast-oriented gneissic layering dated at 3100 Ma (Grant *et al.*, 1983). Earlier events, around 3300 to 3250 Ma (ages derived from U–Pb zircon; Loveridge *et al.*, 1987), were largely erased by the Hopedalian event (Ermanovics *et al.*, 1982). The Hopedale block is intruded by three generations of mafic dykes: the Mid-Archaean Hopedale dykes, the Early Proterozoic Kikkertavak dykes and the Mid-Proterozoic Harp dykes. The U–Pb geochronological studies yield ages of 2235 $\pm$ 2 Ma and 1273 $\pm$ 1 Ma for the Kikkertavak and Harp dyke swarms, respectively (A. Cadman, unpublished data).

The Nain Province is bounded to the west and south by the Lower Proterozoic Churchill and Makkovik provinces, respectively. Metamorphism associated with the accretion of these terranes, dated at ca. 1.8 Ga (Wardle *et al.*, 1990; Ermanovics and Ryan, 1990), variably overprints Archean rocks of the Nain Province.

The study region near Nain village, lies in an area intermediate between the Saglek and Hopedale blocks, and has been the site of intrusion of voluminous Mid-Proterozoic plutonic rocks. These intrusions are collectively known as the Nain Plutonic Suite and consist primarily of anorthositic, noritic, troctolitic and granitic rocks (Ryan, 1990b). The Archean country rocks in this region have not been studied in detail until recently. Bridgwater *et al.* (1990) attempted to correlate them with units present within the Saglek and Hopedale blocks. Ryan (1991) subdivided the rocks into four main lithological subdivisions but could correlate none of these directly with rocks from the Saglek and Hopedale areas. The major components of the gneiss terrane are:

1) quartzofeldspathic gneisses and foliated granitic rocks, including migmatized tonalites and granodiorites, wispy gneissose granitoid rocks, foliated granitoid rocks and aplite sheets; some of the wispy granitoid gneiss has been dated ca. 2580 Ma (Connelly *et al.*, 1992);

2) granulite-grade quartzofelspathic gneiss; in some cases higher grade equivalents of (1);

3) metasedimentary gneisses; and

4) mafic gneisses, including two types of well-layered, mafic granulites, one of which may be related to NPS magmatism.

Table 1. Summary of crosscutting relationships between dyke generations on various islands in the Nain archipelago. Data taken from this study, Ryan (1991) and Ryan (unpublished data collected during 1990 and 1991). Dykes within each column crosscut at least the dyke listed immediately above it

	Dumbell Is.	Trend	Fermoy Is.	Trend	Turnagain Is.	Trend	Sculpin Is.	Trend
1	Amphibolite*	080°	Amphibolite	160°	Granulite	160°	Granulite	106°
2	Granulite	160°	Amphiboite+	080°	Granulite	080°	Granulite	090°
3	Amphibolite	020°	Amphibolite	160°	Granulite*	020°		
4	Granulite	097°						
5	Gabbro	060°						

* field name; mineralogy not verified by thin section
\+ retains primary, radiating, plagioclase aggregates

DYKE RELATIONSHIPS IN GNEISSES NEAR NAIN

Ryan (1991, 1992) recognized, on the basis of crosscutting relationships, the existence of at least four generations of metamorphosed dykes. The relative ages of each of these sets, however, is difficult to discern. Each set may represent a discrete magmatic event or two highly discordant dykes may be coeval or near-coeval and represent intrusion controlled by a conjugate fracture system. In this respect, Ryan (1991) has noted that where crosscutting relationships have been observed in widely separated outcrops, there is no clear relationship between dyke trend and order of emplacement. In addition, dykes with apparently similar morphology and mineralogy also have markedly different trends from one locality to another. Consequently, distant from the localities where definite crosscutting relationships are present, dykes cannot be subdivided into discrete generations or swarms on the basis of field characteristics. In the absence of any discernible subdivision, the intrusions in the Nain area are referred to as constituting a 'dyke assemblage'. Some examples of observed crosscutting relationships in this dyke assemblage are given in Table 1, and a description of one outcrop example is given below.

One of the best exposures of crosscutting dykes is situated on the northeast coast of Dumbell Island (Figure 2), where four generations of mafic dykes are in evidence. The oldest generation comprises thin (0.1 to 0.2 m), white plagioclase-bearing, black, melanocratic dykes having highly lobate margins trending east-west (generation 1; Figure 3a,b). These are in turn crosscut by relatively thick (0.7–0.9 m), 170°-trending, green, two-pyroxene (granulite) dykes (generation 2; Figure 3) having margin-parallel foliations. Both sets of dykes crosscut a north-northeast-trending high-grade shear zone (Figure 3a). In turn, the same dykes are displaced laterally along other north-northeast-trending greenschist-facies dextral shears (Figure 3a; Plate 1). There is also some evidence that the second generation of dykes was injected into shear zones: the gneissic foliation appears to bend into parallelism with the trend of a generation 2 dyke approaching the dyke margins (Figure 3a), indicating a sinistral sense of displacement along these margins. The dykes are also 'necked' within the shears, and, at one location, a dyke margin is folded by small-scale folds that are confined to the shears; this implies dyke injection into a developing shear zone that formed by episodic movement. Another generation 2 dyke (Figure 3b) splits into two branches, which may be interpreted as intrusion along conjugate shear fractures. However, offset criteria at this outcrop, such as bayonets and steps on the dyke margins or distinctive bands in the gneissic country rocks, are uncommonly sparse; therefore, the information present is not enough to point

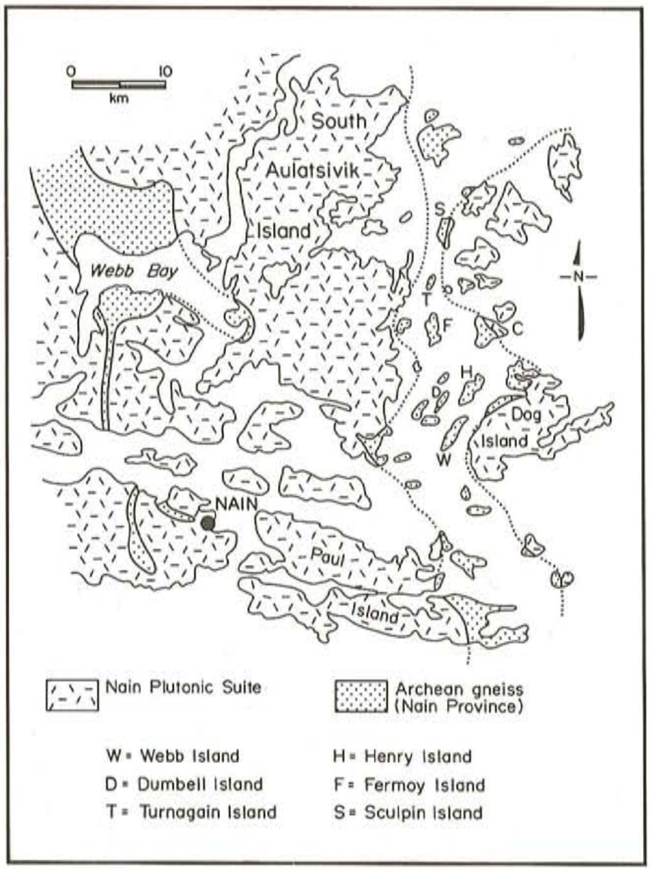

Figure 2. *General geology of the archipelago east of Nain (after Ryan, 1990b), showing islands mentioned in the text.*

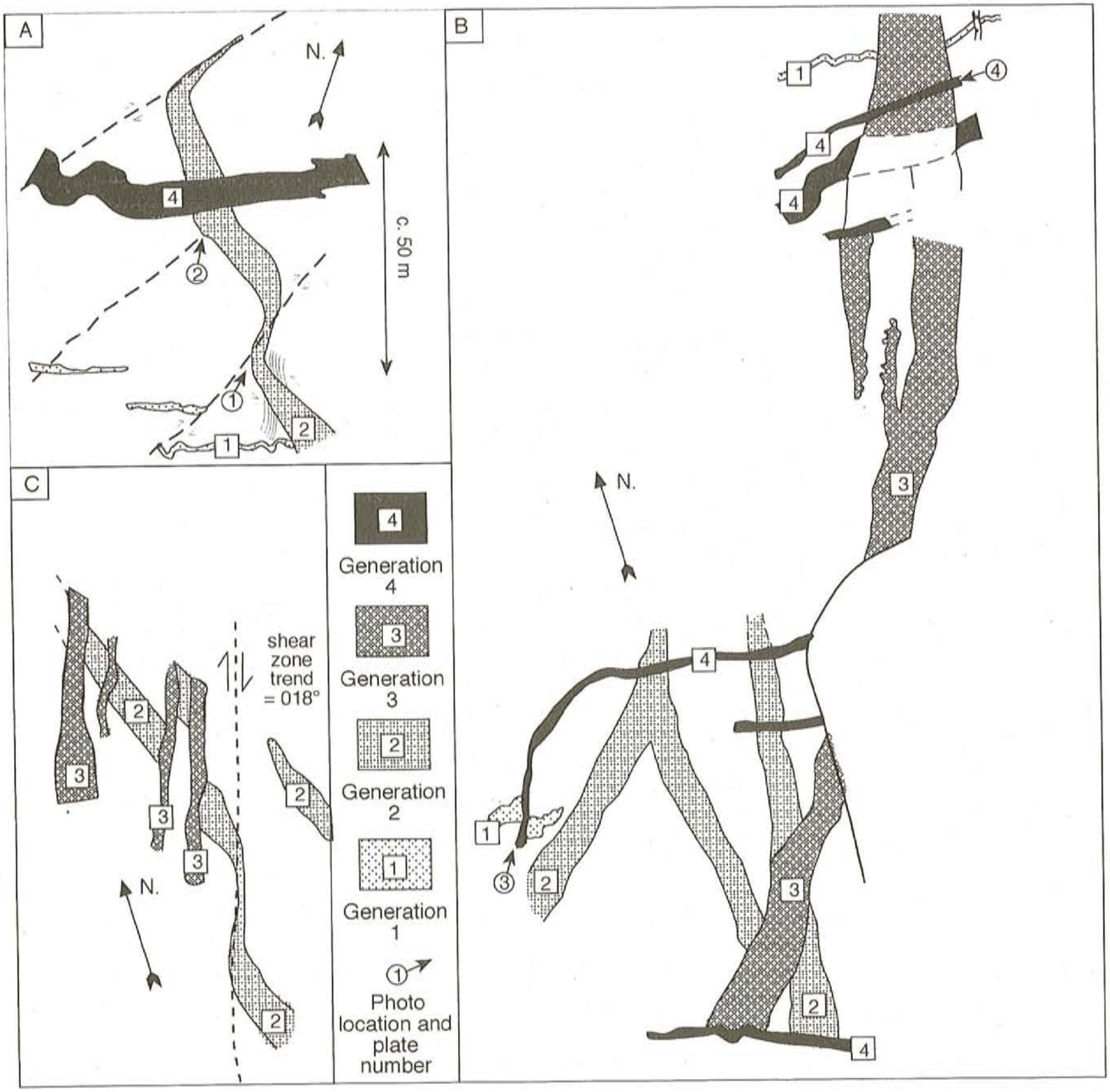

Figure 3. *Schematic diagram of crosscutting relationships between four dyke generations in several outcrops on the northeast coast of Dumbell Island. (See text for full explanation).*

unequivocally to a shear-zone environment of intrusion for the green granulite dykes.

Following emplacement and subsequent displacement of the green granulite dykes, melanocratic amphibolite dykes were injected along a trend of 020°. At one point, offshoots from one of these third-generation dykes are clearly emplaced along the low-grade shear zones, which displace the green granulite dykes (Figure 3c). At the northern tip of the island, the black amphibolite dykes splay to form a series of anastomosing and interconnecting intrusions which may be indicative of conjugate fracture-controlled emplacement. The black amphibolite dykes are locally characterized by a weak marginal foliation or fissile parting. Fourth-generation dykes on Dumbell Island consist of east–west-trending intrusions, which crosscut all previous dyke generations and both high- and low-grade shear zones (Figure 3; Plates 2, 3 and 4). At least one such dyke is diffusely layered and is openly folded. Mesoscopically, they appear mineralogically indistinguishable from the north-northeast-trending melanocratic dykes but are, in fact, orthopyroxene-bearing. An even younger, fresh, northeast-striking, granular, biotite-bearing gabbroic dyke,

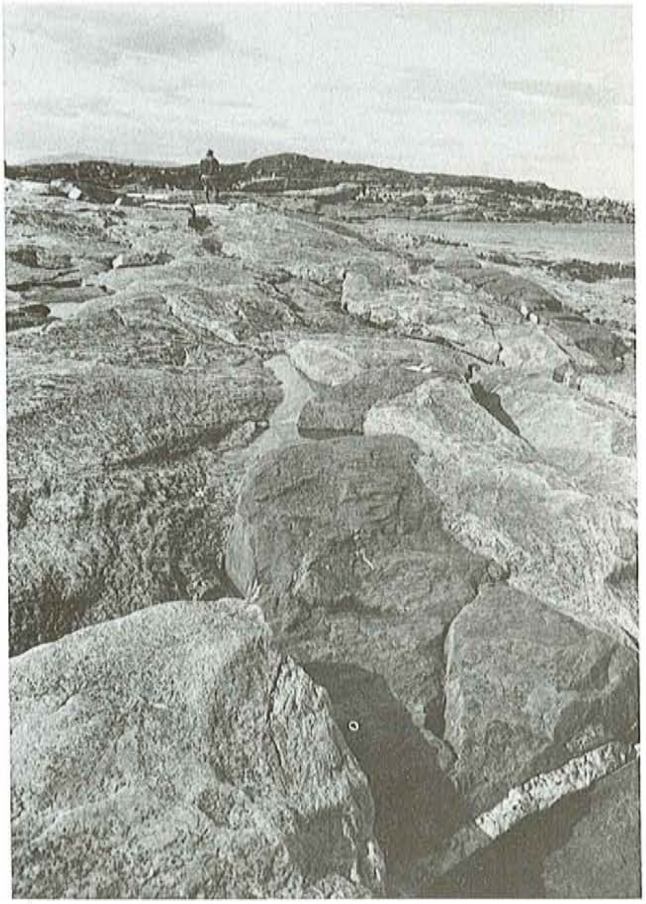

Plate 1. *Green-coloured dyke displaced by a low-grade shear zone, north Dumbell Island. Locally this dyke represents the second generation of dyke emplacement.*

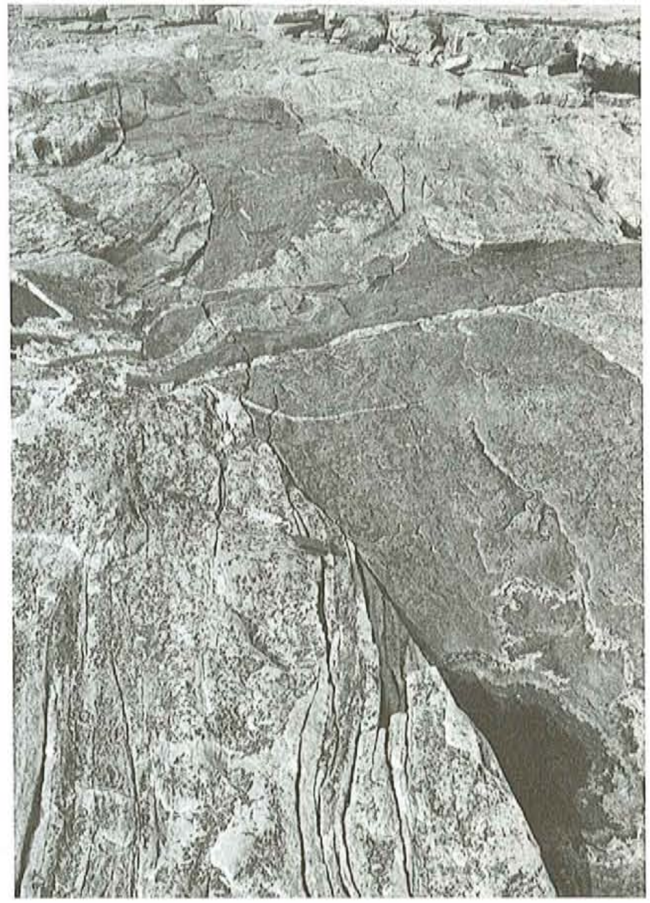

Plate 2. *Crosscutting relationship between second- and fourth-generation dykes on Dumbell Island. Note that both dykes crosscut a high-grade shear zone.*

characterized by pilotaxitic texture and dark-grey plagioclase xenocrysts, postdates all the above dykes at the northern tip of the island.

AGES OF DYKES IN THE NAIN AREA

Two age determinations are available for dykes in the Nain area. A preliminary U–Pb date of ca. 2.55 Ga has been obtained from one of the second-generation green granulite dykes from Dumbell Island (Connelly *et al.*, 1992). This age is comparable to that of the host rock, possibly indicating coeval intrusion of the two units. A U–Pb upper intercept age of 2100 ± 100 Ma obtained from an amphibolite dyke on the mainland south of Nain may represent a younger episode of dyke emplacement (Ryan *et al.*, 1991). A number of deformed basic dykes also intrude a ca. 2.0 Ga monzonite intrusion near Nain (J. Connelly, personal communication, 1992). Thus, based on geochronological data, the metamorphosed dykes span the Late Archean to Early Proterozoic. In addition, many Nain dykes contain plagioclase aggregates with 'snowflake' morphology, similar to spherulites in some troctolitic rocks of the Middle Proterozoic NPS described by Berg (1980). Other dykes contain black or grey phenocrysts, which are also reminiscent of NPS intrusions described by Wheeler (1942). On the basis of textural and mineralogical similarity to NPS intrusions, Ryan (1991, 1992) suggested that elements of the dyke assemblage may be comagmatic with NPS intrusion. During this study, several dykes containing either snowflake plagioclase aggregates or black plagioclase phenocrysts were noted on northern Dog Island, near the margin of a troctolitic NPS intrusion. Furthermore, a 'granulite' dyke was found on the north coast of the island containing about 50 percent xenolithic gabbroic blocks and having subophitic igneous textures (Plate 5). It is postulated here that these xenoliths may represent the cognate material from the nearby NPS intrusion.

In addition to the dykes described above, two sets of Mid-Proterozoic fresh basic dykes intrude the Nain area. The first set consists of thick olivine gabbronorite dykes that intrude the Archean gneisses on Dog Island and adjacent Carey Island (Ryan, 1991). The second consists of east–west and north–south striking intrusions, which crosscut the Archean gneisses and also members of the NPS. This second set has been subdivided on the basis of its chemistry into Nain LP (low phosphorus) and Nain HP (high phosphorus) types (Wiebe, 1985). The K–Ar dates of 977 ± 44 Ma and 1042 ± 54 Ma that have been obtained from the Nain LP and HP dykes, respectively, are considered by Wiebe (1985) to

Plate 3. *Fourth-generation melanocratic dyke crosscutting first-generation dykes on Dumbell Island. Note the well-developed cuspate margins on the first-generation intrusions.*

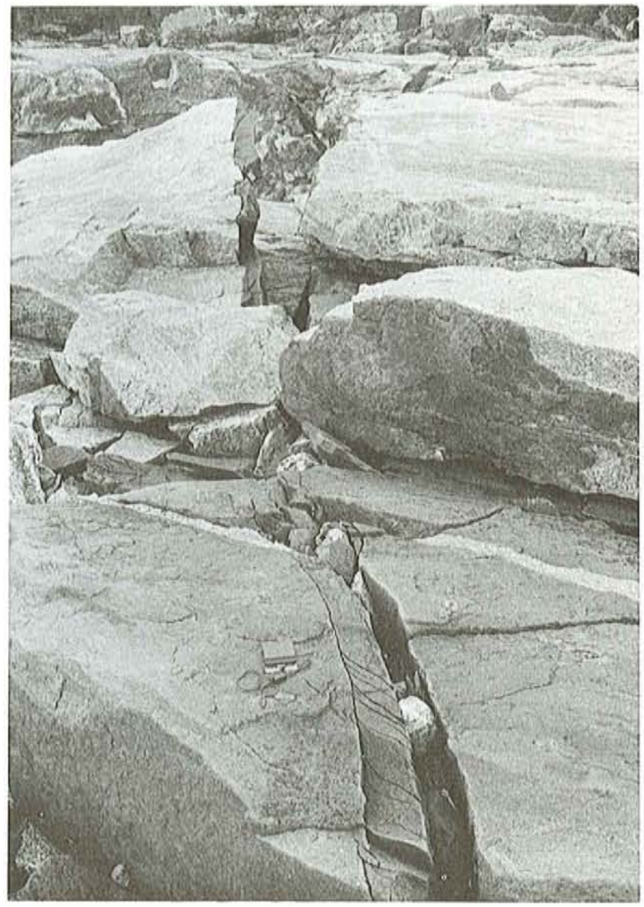

Plate 4. *Fourth-generation melanocratic dykes crosscutting a mesoscopically similar third-generation dyke on Dumbell Island.*

represent minimum ages for these intrusions. A further Rb–Sr age of 1276 ± 23 Ma has been obtained from a Nain HP dyke (Wiebe *in* Gower *et al.*, 1990). Both sets of these later intrusions are clearly distinct from the dykes in the Nain area that are the focus of this paper and are not considered further within this report.

STRUCTURE AND MORPHOLOGICAL CHARACTERISTICS OF DYKES IN THE GNEISSES

During the 1992 field season, examination of the Nain dykes in the Archean gneisses was geographically restricted to the archipelago immediately west and southwest of Dog Island (Figure 2). The orientations and widths of a total of 115 dykes were measured and, where good kinematic indicators were present on the margins of intrusions (e.g., dyke offsets, distinctive gneissic banding), the dilation direction of the dyke (in the horizontal plane) was also noted. The data set shows that east to east–northeast dyke orientations predominate, with a few intrusions having trends varying between north-northwest and north-northeast (Figure 4a). East–west-trending dykes predominate within local areas, although dyke trends are quite variable over the Nain area as a whole (B. Ryan, unpublished data). Dykes are generally thin, with over two-thirds of intrusions examined in the Dog Island area being under 1.25 m wide (Figure 4b). Dilation directions show considerable variability, with north-northwest–north-northeast directions dominant, but with a substantial minority of intrusions dilating in east–west and east-southeast directions (Figure 4c).

Plate 5. *Dyke containing abundant (cognate?) xenolith material of igneous origin, north Dog Island.*

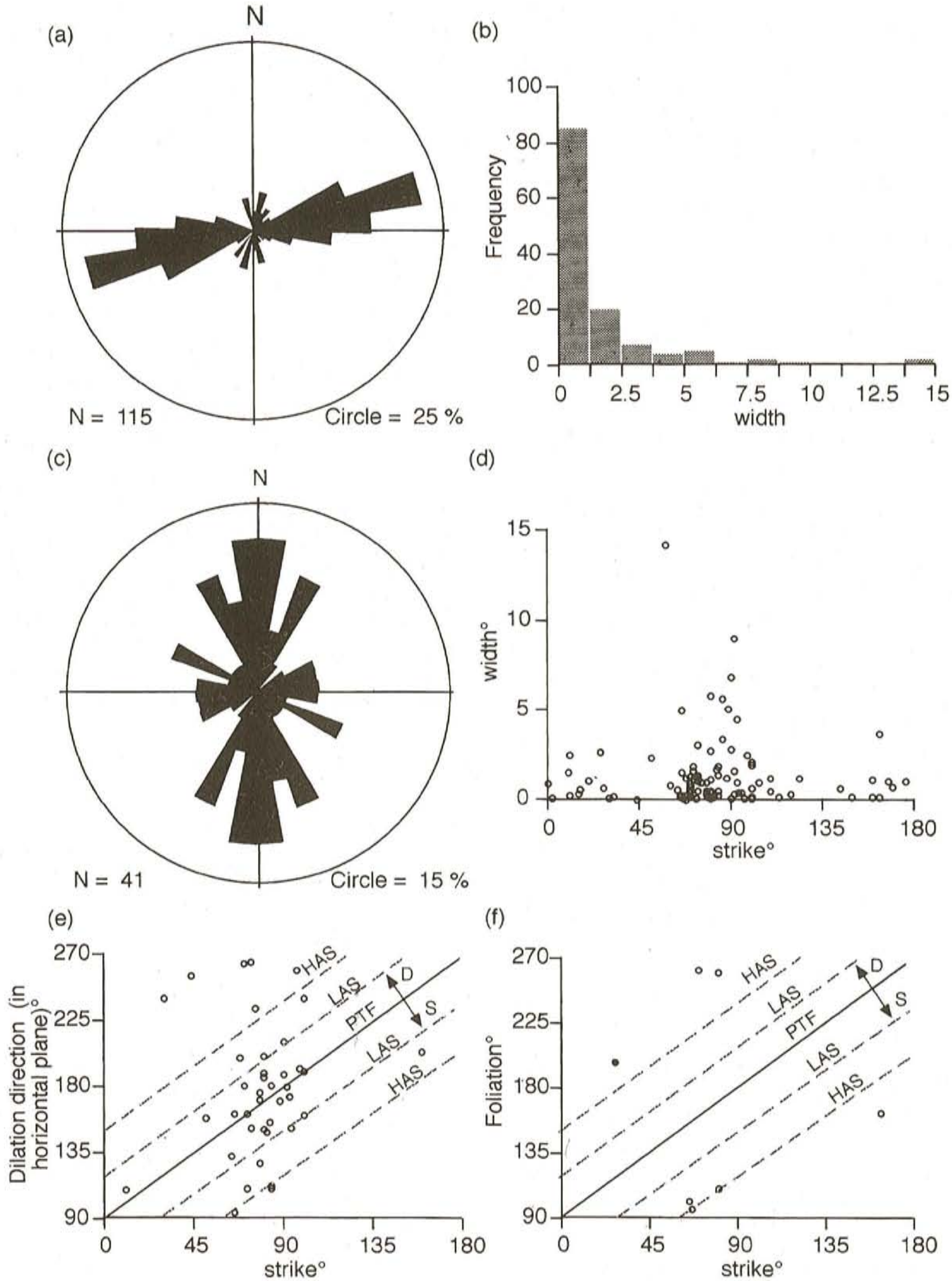

Figure 4. *Preliminary structural data for the Nain dyke assemblage: (a) dyke orientations. N = number of measurements, circle = X% describes the percentage of the total data set that would lie on a line of equal length to the circle diameter; (b) dyke widths; (c) dyke dilation directions measured in the horizontal plane. Labels as for (a); (d) dyke widths vs. strike; (e) dilation direction vs. strike. LAS = low-angle shear plane; HAS = high-angle shear plane; PTF = pure tensile failure plane; D = dextral shear; S = sinistral shear; (f) trend of dyke internal foliation vs. dyke strike. Labels as for (e).*

The relationship between dyke orientation, width and dilation direction is worth considering further. When plotted against strike, dyke widths clearly show that all relatively wide dykes (> 5 m) have approximately east to east-northeast orientations (Figure 4d). When the relationship between dyke orientation and dilation direction is considered, it shows that many intrusions of approximately east–west strike, plot closely to the line of pure tensile failure, i.e., their dilation direction is approximately north–south (180°; Figure 4e) orthogonal to their orientation. Measured dilation directions are unfortunately sparse for the dykes over 5 m wide, but one 6.8-m-wide dyke records a strike of 090° and a dilation direction of 188°. The widest intrusions in a swarm are clearly likely to be those that opened perpendicular to their strike. If this intrusion is typical, then these lines of evidence suggest that many of the Nain intrusions were intruded along east-northeast- to east-trending tensile fractures. Whether these intrusions comprise a single swarm or represent more than one episode of dyke emplacement is unknown.

Many intrusions in the Nain dyke assemblage have dilation directions oblique, rather than orthogonal to their strike orientations. Therefore, either these intrusions opened by a mechanism that includes a component of shear parallel to their margins, or the dykes acted as loci for shear displacement after their emplacement. Some dykes both crosscut and are crosscut by shear zones (cf. Figure 3), whereas other dykes are confined to shears and may have been intruded along such zones during or after shear deformation. Other intrusions are demonstrably affected by post-emplacement margin-parallel shearing along the length of the dyke. Both sinistral and dextral senses of displacement are recorded, and for both senses the apparent opening direction of the dyke is locally exceptionally oblique, being near-parallel to the orientation of the dyke margins (Figure 4e). On Dog Island, some thin (< 10 cm) east-northeast-trending intrusions show a consistent sense of stepping (Plate 6). This feature has been previously observed in dykes intruded along shear fractures in the Kangâmiut swarm in Greenland (Escher *et al.*, 1976).

Many Nain dykes also exhibit internal foliations, which may give additional strain information, particularly in the absence of other offset criteria (Berger, 1971). Foliations vary from weak mineral alignments to penetrative fabrics, which preserve both planar and sigmoidal geometries (Ryan, 1991, 1992). A striking feature of these internal structures is the often complete lack of complementary features in the intruded country rock. In most cases, there is no evidence that deformation has occurred in the gneisses marginal to the intrusions, despite significant offsets across the dykes and foliations within the dykes themselves (Ryan 1991; Plate 7). In some cases, foliations are defined by minerals, in others, by the presence of felsic mineral segregations. Where internal foliations define planar geometries, the trend of the foliation is in some cases subparallel to the dilation direction defined by kinematic indicators. Where sigmoidal foliations are present on horizontal surfaces, the sense of displacement indicated by the fabric (i.e., 'Z' shape–sinistral shear; 'S' shape–dextral shear) is in agreement with the sense of displacement indicated by dyke margin kinematic indicators. It should be noted, however, that in this latter case the kinematic indicators clearly preserve the final sense of offset and not the incremental strain that accompanied initial dilation during intrusion.

Plate 6. *Thin dyke showing consistent sense of offset, northwest Dog Island.*

A good example of the relationship between dyke marginal kinematic indictors and internal foliations is present in a 1-m-wide, 074°-trending dyke on the north coast of Henry Island. Kinematic indicators clearly show an apparent 'dilation direction' of 085° (Plate 7). The internal foliation within the dyke is defined by felsic mineral segregations. These segregations do not define a good planar fabric but near the margins of the dyke show a general alignment oblique to dyke margins and trend in the same orientation as the 'dilation direction'. However, within the centre of the intrusion, segregations are blotchy and locally randomly oriented. Both types of segregation are crosscut by shear fractures infilled by felsic material that have the correct orientation for Reidel shears (Plate 8, Figure 5). At some points along the dyke, the foliation appears to bend into parallelism with the dyke plane toward the dyke centre (Plate 8).

A further major feature of the Nain dyke assemblage is the variability of contact relationships between the dykes and

Plate 7. *Dyke with highly oblique dilation direction and intense mineral segregation foliation, north Henry Island. Note that despite the pronounced offset the host gneisses show no sign of similar deformation.*

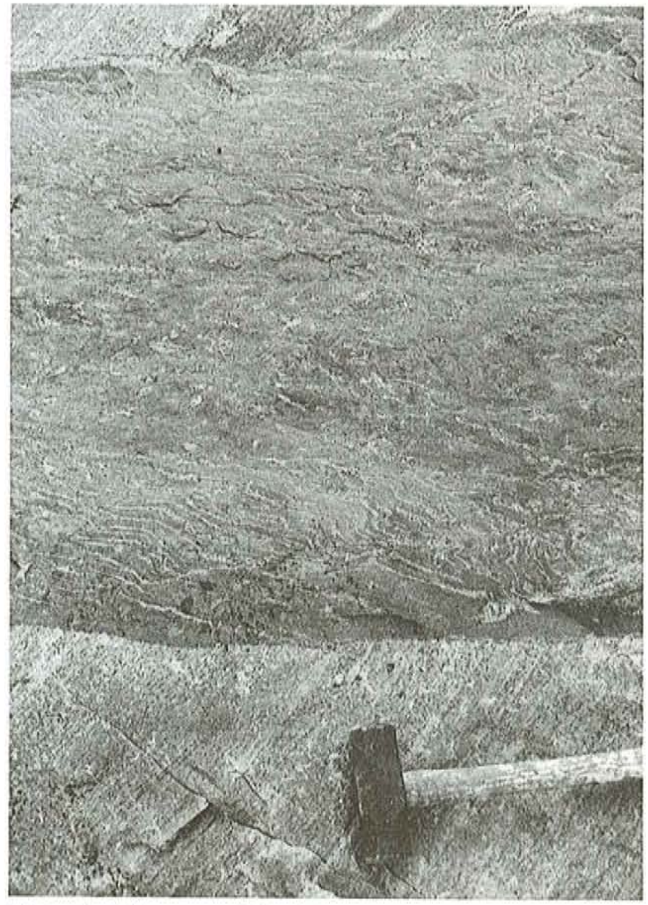

Plate 8. *Close-up of the dyke shown in Plate 7. Note that the internal foliation is much more highly ordered on the dyke margins than at the dyke centre; note, also, the sharp contact between gneiss and dyke, and the absence of a foliation in the gneiss to complement that in the dyke.*

the host gneisses. Although most intrusions have planar margins and are strike continuous, many dykes have cusp-and-lobe structures on their margins (Ryan, 1991, 1992). The development of cusps and lobes is often strikingly variable, with pronounced asymmetry between the two sides of the dyke. In the most extreme cases, one margin of the dyke exhibits lobate structures whereas the other is planar. The cusps are occupied by the dyke and the lobes by the host gneisses, indicating that the dyke was less competent than the surrounding gneiss. Similar variation in margin morphology was noted along-strike in a few intrusions. In some cases, dyke width is variable, with podiform, or in extreme cases, amoeboid structures being developed. These latter forms were only observed in thin intrusions and in most cases these appear to be primary structures and not due to later deformation.

CORRELATION OF THE RECRYSTALLIZED DYKES WITH OTHER MAGMATIC EVENTS

As previously noted, attempts have been made to correlate the gneissic rocks of the Nain area with those to the north and south in the Saglek and Hopedale blocks. Similarly, correlations between the dykes of the Nain area and those in neighbouring terranes may be attempted. To the south, the Kikkertavak and Harp dyke swarms intrude the Hopedale block. Both swarms consist of diabase and gabbro intrusions up to 400 m in width. U–Pb age dating has yielded emplacement ages of 2235 $\pm$ 2 Ma for a Kikkertavak dyke and 1273 $\pm$ 1 Ma for a Harp intrusion (A. Cadman, unpublished data). Kikkertavak dykes consist mainly of a simple gabbroic mineralogy of plagioclase, augite and opaque oxides with accessory olivine, hornblende and apatite (Ermanovics, *in press*). A few Kikkertavak intrusions are plagioclase megaphyric, containing phenocrysts of up to 15 cm in length, which are commonly highly differentiated across the dyke (Cadman *et al.*, 1990). Approaching the Proterozoic Makkovik and Churchill provinces, Kikkertavak intrusions become increasingly altered to greenschist and lower amphibolite facies (Ermanovics, *in press*; Cadman *et al.*, *1992).* In comparison, dykes of the Harp swarm consist mainly of olivine, plagioclase, Ti-rich augite and opaque phases (Ermanovics, *in press*). Intrusion of this swarm postdates Early Proterozoic tectonothermal events in the Churchill and Makkovik provinces and Harp dykes are unaltered within the Hopedale block.

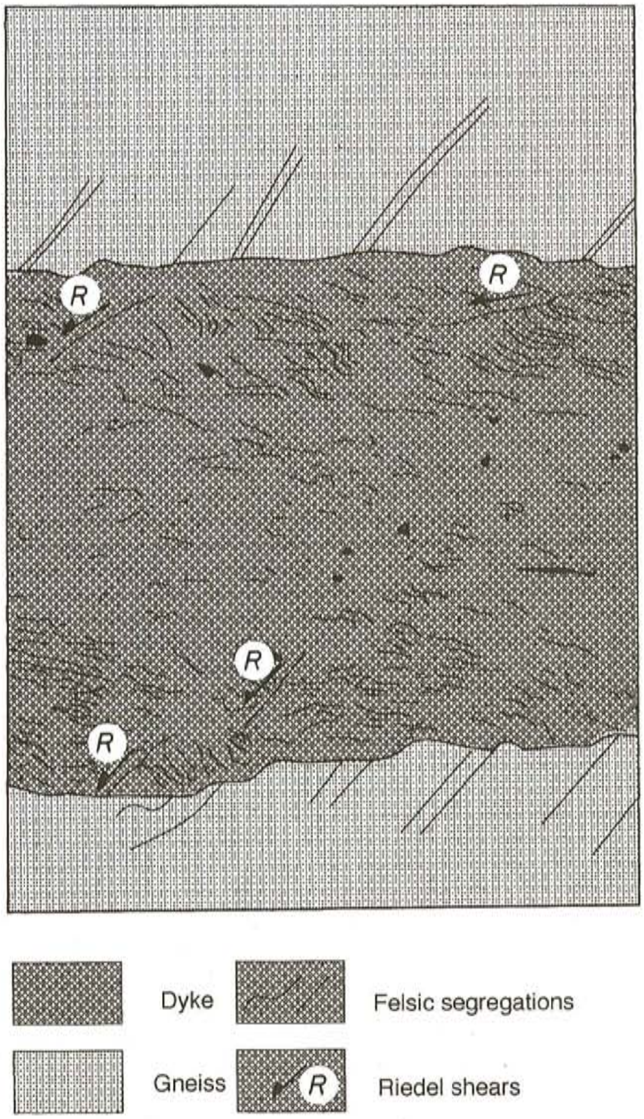

Figure 5. *Sketch of relationships seen in Plate 8 and their interpretation for a dyke with a pronounced internal foliation defined by mineral segregations on northern Henry Island.*

Within the Saglek block, at least one Early Proterozoic set of basic dykes is emplaced. These are termed the Domes (Ryan, 1990a) or Napaktok (Ermanovics and Van Kranendonk, 1990) dykes and are thought to have been intruded between 2.4 and 2.2 Ga (Korstgård *et al.*, 1987). They consist of simple gabbroic mineralogy similar to the Kikkertavak dykes. Dykes with fresh mineralogy akin to Kikkertavak and Domes/Napaktok dykes are not present in the Nain area, but some of the least metamorphosed dykes have relicts of a comparable mineral assemblage (B. Ryan, unpublished data).

Clearly, the Early Proterozoic intrusions within both the Saglek and Hopedale blocks cannot be correlated with either of the U–Pb dated examples of the Nain dyke assemblage noted earlier, or with those dykes that are known to postdate the 2.0 Ga monzonite. However, correlation of Domes–Napaktok or Kikkertavak dykes with other members of the Nain dyke assemblage cannot be unequivocally ruled out at present.

Several Proterozoic dyke swarms intrude the Archean craton of southwestern Greenland and a correlation between some of the Nain assemblage and Greenlandic dykes may be possible. The central section of the craton is intruded by a metadolerite (MD) dyke swarm, which consists of at least three generations; MD1, MD2 and MD3 having respective trends of north–south, northeast–southwest and east-southeast–west-northwest. The three generations are considered to be intruded within the same event and yield a pooled, weighted mean Rb–Sr age of 2130 ± 65 Ma (Kalsbeek and Taylor, 1985). This age is within error of the 2100 ± 100 Ma U–Pb date noted earlier from an amphibolite dyke south of Nain. However, the MD dykes generally contain olivine or primary (igneous) hypersthene and are, therefore, mineralogically dissimilar to even the least altered of the Nain dyke assemblage. Hence, although it may be considered possible that MD series dykes also occur within the Nain craton of Labrador, they cannot as yet be definitely correlated with any elements within the Nain dyke assemblage.

DISCUSSION

This section presents a short commentary on possible models for the emplacement of the Nain dyke assemblage and outlines outstanding problems. Given the weak geochronological constraints and the lack of clearly definable swarms within the assemblage, the ideas presented are hypotheses only.

(1) Emplacement of dykes and their relationship to shear deformation

The structural relationships described for many Nain area dykes show unequivocally that, in many cases, dykes and shear deformation are intimately linked. However, many intrusions also clearly show a more classical 'pure tensile' mode of opening, with dilation directions roughly orthogonal to their strike. Therefore, a question to be addressed is: were individual dykes originally emplaced along shear fractures or were dykes that were originally emplaced by pure tensile fracture subsequently used as loci of shear?

A syn-shear emplacement environment appears probable for some dykes, although for others, post-emplacement shearing could equally result in the observed field relationships. If dykes are emplaced along shear fractures, then the orientation of the maximum compressive stress may be expected to be 30° from the plane of shear (in this case, the plane of the dyke margin). It follows that the dilation direction, which should parallel the least compressive stress, should form an angle of 60° with the dyke margin. Assuming that the maximum and minimum compressive stresses lie approximately within the horizontal plane, then the measured dilation directions should be no more than 60° if the dykes are emplaced during shearing and are not subsequently deformed. (As the dyke margin kinematic indicators used during this study to measure dilation directions were subvertical features, movement in the vertical plane is unlikely to result in erroneously highly oblique dilation direction being recorded on horizontal surfaces. Instead, if anything, vertical movement is likely to decrease the obliquity of apparent dilation directions in the horizontal plane.) Figure 4e shows that some dykes do indeed have this relationship between strike and dilation direction.

Previous studies of the Kangâmiut dyke swarm in southwestern Greenland have documented features similar to those found in the Nain dyke assemblage, including complex crosscutting relationships involving conjugate dyke sets intruded along shear planes (e.g., Escher *et al.*, 1976). Particularly worthy of note from the Escher *et al.* (1976) study is that analysis of the dilation directions of conjugate Kangâmiut intrusions show that the maximum principal stress bisects the 120°, rather than 60° angle, between the conjugate sets of dykes. Escher *et al.* (1976) and Wilson *et al.* (1992) suggest that such high-angle shear zones may be generated at depth, whereas low-angle conjugate sets are generated at higher crustal levels. If a variety of crustal levels are exposed within the Nain area, then intrusion along high-angle shear planes may explain why some dykes have more oblique dilation directions, opening at angles approximately 30° from the orientation of the dyke. However, this hypothesis cannot apply to any intrusions that may be coeval with NPS emplacement, as the NPS was emplaced at a relatively high crustal level throughout the Nain area (6 to 14 km; Berg, 1979). Hence, if any dykes are emplaced along high-angle shear planes, then they are likely to belong to earlier episodes of magmatism.

A third mechanism of syn-shear emplacement may also be considered: shear displacement can also occur along secondary shear planes as well as, or instead of, on the primary displacement plane (e.g., Gamond, 1987). These are termed Riedel (R) and P (or thrust) shears. Figure 6 shows the relationship between these two secondary shear types and the main sense of shear displacement. Shear movement along coupled P and R shears results in shortening along the P fracture and dilation along the R fracture. Examination of Plate 6 shows that the consistent sense of offset of this thin dyke may be caused by this process. The dyke is intruded in the dilational segments (R shears) and is offset along P shears. It is possible that some of the thin amoeboid dykes having variable widths that occur in the Nain area were intruded by this process under more ductile conditions.

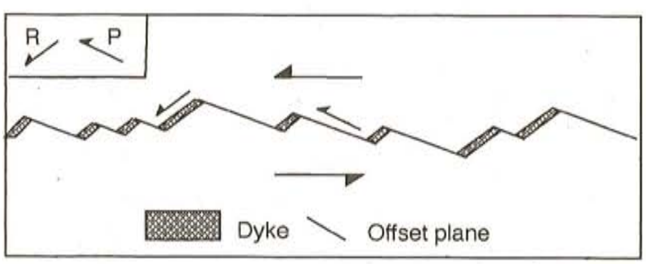

Figure 6. *Diagram showing the possible relationships between secondary shear planes (Riedel and P shears) to produce offsets during dyke emplacement.*

Many of the relationships observed within the Nain dykes can, however, only be the result of post-emplacement shearing: a minority of dykes have dilation directions so highly oblique to their orientation that even intrusion along lower crustal high-angle shear planes is not a viable explanation. At the very least these intrusions must have undergone some post-emplacement deformation, and may have been originally intruded along shear or pure tensile fractures. Similarly, dykes having less-oblique dilation direction may also have been intruded during pure tensile failure and subsequently sheared. Davidson and Park (1978), Talbot (1982) and Talbot and Sokoutis (1992) state that mafic sheets are often the weakest part of a deforming block, i.e., the mafic sheets are less competent than the surrounding host rocks. The relative competence of the dyke and the surrounding host rock depends largely on their respective mineral content, strain rate and metamorphic grade during deformation (Talbot and Sokoutis, 1992; R.G. Park, personal communication, 1992). Consequently, mafic sheets commonly preserve foliations not present in the country rock and act as loci for shear deformation. Talbot (1982) further states that the incompetence of mafic sheets may lead to marginal shearing during rotation of the sheets and the antithetic rotation of internal sheet foliations. A significant feature of Talbot's analysis is that it is not necessary for mafic bodies to deform prior to complete solidification in order that they behave less competently than the surrounding material. Therefore, the development of sheared intrusions with internal foliations, and also the production of some cusp-and-lobe structures on the dyke margins, may have been induced by post-emplacement stress fields.

2) A model for the intrusion and deformation of dykes and the possible relationship with NPS magmatism

The mineralogy of the dyke assemblage suggests that some of the Nain dyke assemblage may be related to NPS magmatism. This setting may give clues to the apparent lack of correlation between dyke trend, metamorphic grade and emplacement style, thus constituting the biggest problem in unravelling the history of dyke emplacement in the Nain area. Berg (1977) concluded from detailed geobarometry work that the Nain area had experienced a polymetamorphic history, as a result of the multiple intrusion of NPS bodies over perhaps a minimum period of 30 to 40 million years (cf. Emslie and Loveridge, 1992, p. 106). If some of the dykes represent leaks from the subcrustal magma source of the NPS (Ryan, 1991), then the stress field controlling dyke emplacement will be governed by two components: (1) the long range regional stress field, and (2) the short range local stress fields around individual NPS plutons. Berg (1977), following Stephenson (1974), suggested that the NPS was emplaced in an east–west graben structure that was subsequently isostatically uplifted. The Nain study area lies to the north of the Grenville Province of North America (Figure 1). Windley (1989) suggested that prior to the Grenville orogeny, the lithosphere both north and within the subsequently formed Grenville belt extended by a mechanism of heterogeneous simple shear (e.g., Wernicke, 1985). A feature of heterogeneous simple shear models is that basin-parallel detachment faults are cut perpendicularly by transfer faults (Lister *et al.*, 1986). Mimicking of this basin architecture by dyke emplacement patterns may explain the near perpendicular nature of many dyke crosscutting relationships shown in Table 1. The predominance of east-northeast–west-southwest trends for dykes within parts of the Nain area may reflect dyke intrusion parallel or along detachment faults, with the fewer more northerly trending dykes paralleling transfer fault orientations.

The lack of obvious regional coherence between dyke orientation and the grade of metamorphic recrystallization may similarly reflect factors associated with local pluton emplacement. The overall mineralogy of many dykes at similar metamorphic grades is remarkably variable over short distances; it may simply be related to different episodes of NPS magmatism.

Perhaps the most intriguing aspect of the structural data collected from the Dog Island area is the relatively constrained orientation of dykes compared to the variety of dilation directions and senses of shear displacement recorded; intrusions with roughly east–west strikes show either sinistral or dextral shear. Assuming that the opposing shear senses were not generated in temporally separated events (although this cannot be ruled out with any certainty), then the orientation of principal stresses during deformation must have been subject to considerable local deviation. The most likely cause of such deviation is that the stress field was locally controlled by the diapiric emplacement of NPS bodies. Previous studies have shown that the emplacement of diapirs results in the local reorientation of the maximum compressive stress perpendicular to the margin of the intrusion (e.g., Odé, 1957). Structures observed in the Nain area also suggest that at least some NPS bodies were emplaced diapirically (Wiebe, 1991).

The preceding discussion highlights the fact that in many cases it is not as yet possible to state with certainty whether shear deformation of the Nain dyke assemblage occurred while the dykes were still hot from intrusion or whether it occurred after cooling and solidification. Indeed, the multi-generation nature of the assemblage means that both syn- and post-emplacement deformation processes could occur. Dykes, which were injected during the Late Archean or Early Proterozoic, may be reheated during later granulite-facies metamorphism during NPS emplacement and act as loci for later shear. Alternatively, deformation of dykes intruded as precursors to NPS magmatism may take place either when the dykes are semi-liquid or after solidification during low pressure–high temperature metamorphism: in both cases the dykes would act as incompetent bodies. Intrusion of NPS diapirs could cause shear displacement along the dykes as the local stress field was reoriented. The sense of displacement would depend on the relative orientations and positions of the dykes with regard to the intruding pluton (Figure 7).

It must not be forgotten, however, that some of the dyke assemblage undoubtedly substantially predates NPS emplacement. Therefore, the observed complexity could equally be produced by the intrusion of several dyke swarms, interspersed with Archean and Proterozoic tectonothermal events, over an interval of perhaps more than 1 Ga.

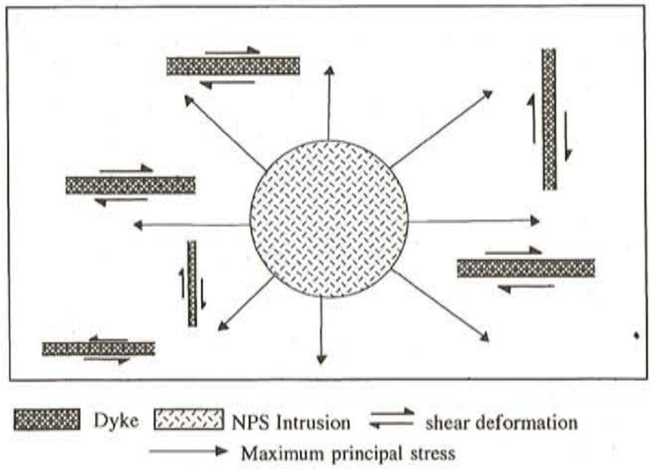

Figure 7. *Diagram showing the possible cause of opposing shear senses in basic dykes due to local variation in principal stresses associated with NPS intrusion.*

FUTURE WORK

Future work will involve extensive bulk geochemical analysis in order to identify chemical signatures that may correlate with other characteristics exhibited by the dykes. It is hoped that this work will arrive at a coherent classification of the multiple generations in the Nain dyke assemblage. Petrographic and structural work will concentrate on examination of the internal foliations of the dykes with a view to understanding the genesis of these fabrics. Lastly, a more regional outlook will seek to understand the processes at work during petrogenesis of the Nain dyke assemblage and to compare these processes with other areas of mafic continental magmatism.

CONCLUSIONS

Examination of the Nain dyke assemblage shows that some dykes were intruded during episodes of pure tensile fracture, whereas others may have been intruded during periods of shear deformation. Alternatively, many of the sheared dykes may have acted as incompetent layers and served as loci for later shear deformation. It is postulated that shear deformation of dykes occurred both substantially and immediately predating NPS magmatism.

Correlation of the Nain dyke assemblage with other Proterozoic swarms in the North Atlantic Craton suggests that elements of the Nain dyke assemblage may correlate with the Greenland MD swarm. There is, as yet, less positive evidence to correlate dykes in the Nain area with Proterozoic swarms intruding adjacent areas in Labrador.

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