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AN INVESTIGATION OF SOME METAMORPHOSED DYKES OF THE NAIN AREA: PART 3–GEOCHEMISTRY AND STRUCTURAL RELATIONSHIPS OF DYKES IN THE NUKASUSUTOK ISLAND AREA

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ABSTRACT

Massive to foliated mafic dykes of the Nukasusutok Island area are part of an assemblage regionally developed within Archean gneisses of the Nain Province east of Nain. Several chemically distinct groups are apparent from whole-rock analyses, most classified as transitional tholeiites having predominently 'within-plate' affinities. Lamprophyric and alkali-basaltic dykes form distinct intrusions in the area as well. The deformation and recrystallization of the dykes has had little effect on the element distribution in most dykes, but some have trace-element patterns indicative of interaction between the mafic magma and a local crustal melt. A folded dyke, unclassified in the present chemical grouping of other dykes, yields a U–Pb zircon age of 1317 ± 4 Ma; the significance of this dyke and the geochronological results are not yet understood, but the age falls within the event window of the Nain Plutonic Suite. Establishing the precise age of the differing chemical subgroups may prove to be the only means by which dyke emplacement within the Nain Province can be linked to mantle evolution beneath it.

INTRODUCTION

In recent years, much progress has been made in the understanding of dyke swarms and their importance to the geological record. Episodes of dyke emplacement have been linked, spatially, temporally and chemically, to Continental-Flood-Basalt-type (CFB) 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. However, fundamental challenges still exist in understanding the relative influence different petrogenetic processes have in the generation of continental basaltic magmas. One reason for the continuing controversy is that the precise chronological and petrological relationships between the large plutons, dyke swarms and flood basalts that make up these igneous suites are still, in many cases, poorly understood. The degree to which secular evolution of the mantle may have affected magma chemistry with time is also in need of resolution.

The Dog Island–Nukasusutok Island region east of Nain, Labrador (Figures 1 and 2) is an excellent area to study the relationships between dykes and adjacent plutonic rocks because the region is host to voluminous, Mesoproterozoic plutonic complexes, consisting predominantly of massive anorthosites, norites, troctolites and granitoids, collectively termed the Nain Plutonic Suite (NPS). Recent studies in the Nain area (Ryan, 1991, 1992, *in press;* Ryan *et al.*, 1991; Connelly and Ryan, 1993; Cadman *et al.*, 1993a; Cadman and Ryan, 1994) have also shown that the region has been injected by at least six generations of mafic dykes, ranging in age from ca. 2.5 to 1.27 Ga (Ryan, *in press*) thus allowing glimpses into changing source-region conditions over a prolonged period. At least four generations of these dykes are considered to predate the peak of NPS magmatism in the Nain area.* These intrusions, the subject of this paper, have textures and a mineralogy that indicate crystallization or recystallization at conditions of granulite facies; some are demonstrably intruded into ductile country rocks and were subjected to shear deformation. Examination of the Nain dyke assemblage was undertaken between 1992 and 1994 in an attempt to define their chemical, structural and geochronological relationship to the presently defined history of the Nain area, especially to ascertain whether there is a connection between the dykes and the development of the Mesoproterozoic NPS.

Many dyke samples were collected in the region around Dog Island, northeast of Nain village (Figure 2) during July and August of 1992. These have since been chemically analyzed for major and trace elements. The resulting chemical and structural data were in part reported by Cadman and Ryan (1994). In the subsequent 1993 field season, a correspondingly

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* The use of the term "Akkuneq dykes" for these intrusions (Cadman and Ryan, 1994) has now been discontinued.

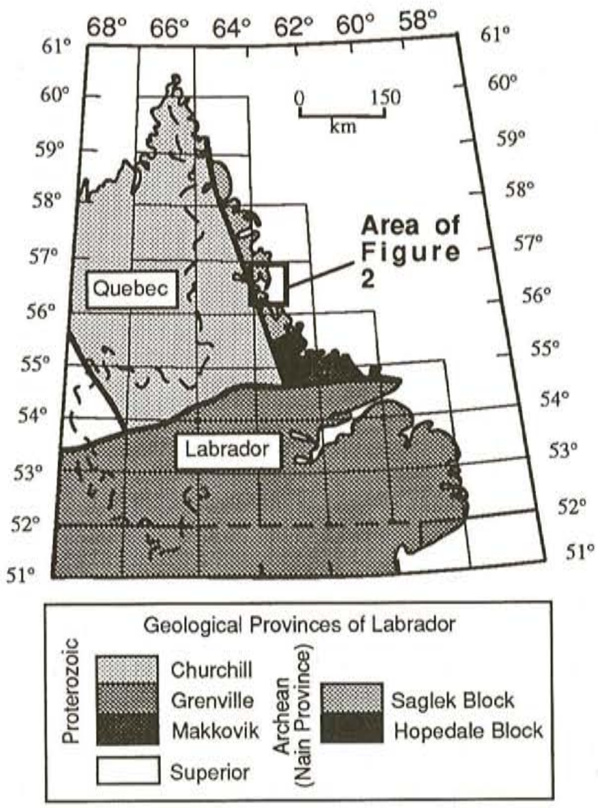

Figure 1. *Location of study area, Labrador.*

large chemical and structural investigation of the dykes within the Nukasusutok Island region was undertaken (Figure 2). The purpose of this paper is primarily to report these new data and to compare them to the Dog Island area dataset. By combining the data from the two areas, more accurate conclusions can be made concerning the timing of dyke emplacement and its broader relationship to the geological development of the Nain Province.

PREVIOUS WORK

Much of the pioneering work on 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 (e.g., Wheeler, 1942, 1960). Subsequently, a number of studies have focused on more specific topics and problems: the anorthosites and associated rocks of the NPS were studied during the ten-year (1971-1981) Nain Anorthosite Project under the co-ordination of S.A. Morse (cf. Morse, 1983). Studies of the gneissic country rocks were carried out by de Waard (1971), Taylor (1979) and more recently by Bridgwater *et al.* (1990) and Ryan (1991, 1992).

Compared to the gneissic host rocks, the dykes of the Nain area, although noted by earlier workers such as Upton (1971, 1974), have until recently been neglected. Consequently, their characteristics and potential significance to understanding crust and mantle evolution remained largely unknown until re-examination by Ryan (1991, 1992) during remapping of the Nain area between 1990 and 1992.

GEOLOGICAL SETTING

The Archean Nain Province comprises a superbly exposed sequence of metamorphic and igneous rocks along the northern and central segments of the Labrador coast (Figure 1). 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 at about 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). Recent age-dating in the Nain area further suggests a late Archean terrane amalgamation of the Saglek and Hopedale blocks (Connelly and Ryan, 1993). At least three generations of mafic dykes intrude the Saglek block; the mid-Archean porphyritic Saglek dykes and a late Archean swarm, perhaps correlative with the Hopedale dykes in the Hopedale block (Bridgwater and Schiøtte, 1991), and the Paleoproterozoic Domes–Napatok swarms (Ryan 1990; Ermanovics and Van Kranendonk, 1990). The southern 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 trend interpreted by Ermanovics *et al.* (1982) to be Late Archean. This foliation overprints an earlier northwest–southeast foliation termed the Hopedalian trend dated at 3100 Ma (Grant *et al.*, 1983). Earlier events, at about 3300 to 3250 Ma (U–Pb zircon data; Loveridge *et al.*, 1987), were mostly erased by the Hopedalian event (Ermanovics *et al.*, 1982). The Nain Province is bounded to the west and south by the Paleoproterozoic Churchill and Makkovik provinces, respectively. Metamorphism associated with the accretion of these terranes dated at about 1.8 Ga (Wardle *et al.*, 1990; Ermanovics and Ryan, 1990) variably overprints Archean rocks of the Nain Province. The Hopedale block is intruded by three generations of mafic dykes: the Late Archean Hopedale dykes, the Paleoproterozoic Kikkertavak dykes and the Mesoproterozoic Harp dykes. U–Pb geochronological studies yield emplacement ages of 2235 $\pm$ 2 and 1274 $\pm$ 1 Ma for the Kikkertavak and Harp dyke swarms respectively (Cadman *et al.*, 1993b).

The gneisses of the Nain region, which host the dykes that are the focus of this study, occupy a narrow north-trending septum between NPS intrusions in an area that lies approximately midway between the Hopedale and Saglek blocks. The Archean gneissic rocks in this region have not been previously studied in detail until recently: Bridgwater

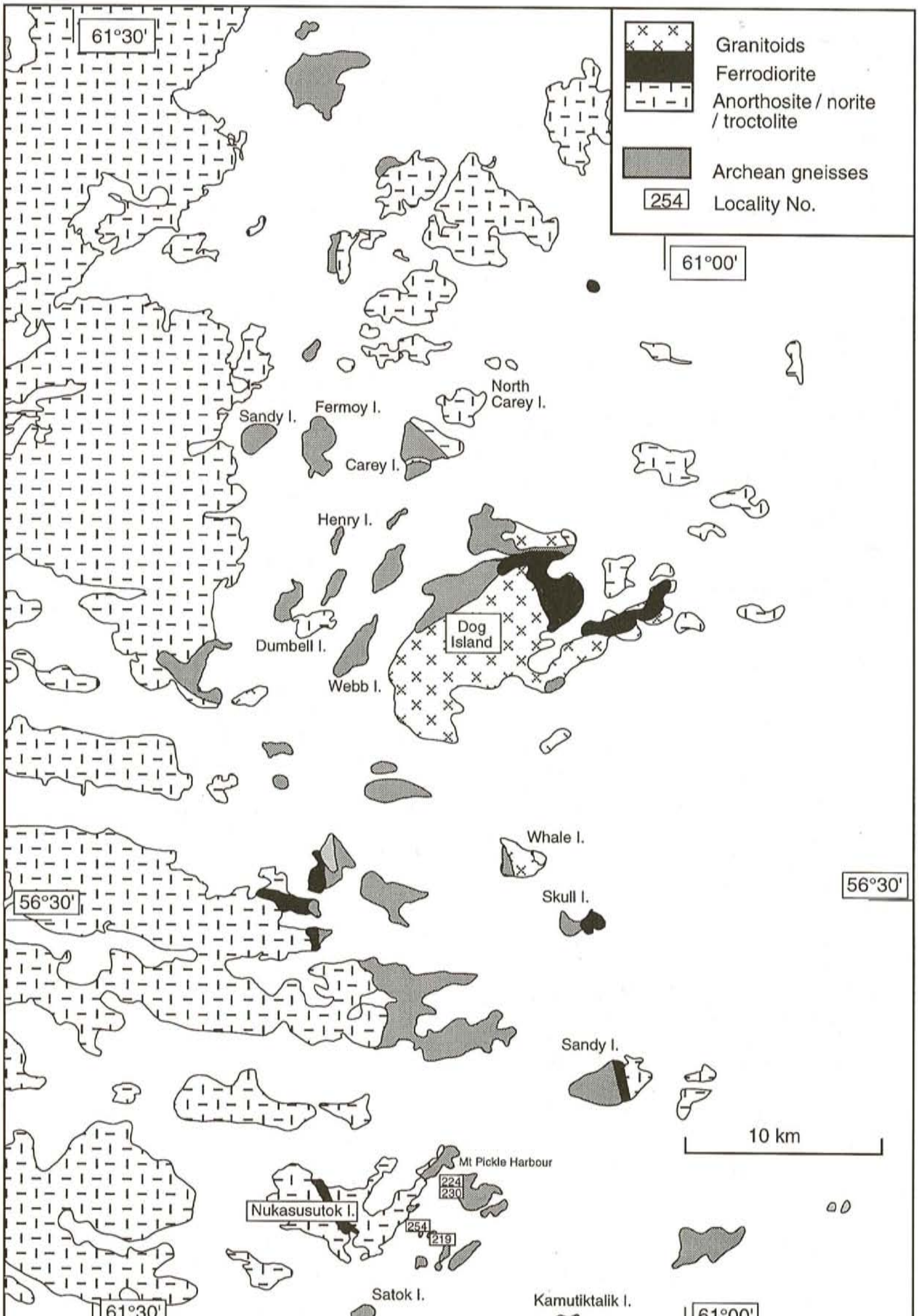

Figure 2. *Map of coastal area east of Nain village.*

et al. (1990) attempted to correlate them with units present within the Saglek and Hopedale blocks, and Ryan (1991) subdivided the rocks into four main lithological subdivisions, which are in turn divisible into a number of distinct units of quartzofelspathic, metasedimentary and mafic gneisses. Metamorphic grade varies between amphibolite and granulite.

The dykes reported on here intrude all the above rock types, with the possible exception of some enigmatic 'mafic granulites' that occur marginal to the NPS troctolitic and noritic plutons (see Ryan, 1991).

RESULTS

MINERALOGY AND PETROGRAPHY

Only a brief summary of the mesoscopic and microscopic features of the dykes is given here, and the reader is referred to Ryan (*in press*) for a more detailed account. The dykes in the Nukasusutok region show a similar complex and diverse mineralogy to those of the Dog Island region, although on a mesoscopic scale some differences are apparent.

In both areas, the primary mineralogy and texture of most dykes have been overprinted by granulite- or amphibolite-grade metamorphism. Where igneous textures are preserved, subophitically intergrown plagioclase and clinopyroxene and accessory oxide are the dominant crystal phases. In the Dog Island region, plagioclase phenocrysts are in some cases black or grey, similar to the plagioclase crystals observed in 'dark facies' members of the NPS described by Wheeler (1942). In other cases, white laths of plagioclase, a few millimetres in length, form radial aggregates that superficially resemble spherulitic textures within some troctolitic NPS rocks described by Berg (1980). Phyric plagioclase is, however, much less evident in dykes around Nukasusutok. Black–grey plagioclase crystals are found in shallowly dipping intrusions on Kamutikalik Island (Figure 2) and smaller islands nearby; steeply dipping porphyritic dykes occur north of Mount Pickle Harbour and on the smaller of two islands immediately to the southeast.

The primary groundmass of basaltic dykes is dominated by plagioclase and clinopyroxene. However, in the majority of intrusions the groundmass assemblage has been recrystallized as polygonal crystals of plagioclase and secondary brown or green amphibole (replacing pyroxene), although original plagioclase phenocrysts are often recognizably preserved (Ryan, *in press*). Biotite and granular orthopyroxene are also common secondary minerals. The proportions of secondary minerals, both to primary phases and to each other, vary substantially between individual intrusions.

In both the Dog Island and Nukasusutok areas, secondary biotite crystals commonly show good alignment and define a foliation. Rarely, dykes that have demonstrably undergone shear deformation contain leucocratic 'sweats' that define a foliation. In the Nukasusutok region, this feature is particularly well preserved in a thick (6.5 m), north-trending dyke exposed on islands southeast of Nukasusutok Island (Figure 2). In this case, the leucocratic patches contain plagioclase and three mafic phases (two pyroxenes and hornblende), a mineralogy that is similar to that of the dyke groundmass.

A distinct group of dykes, which occurs in the extreme south of the area studied, is a set of lamprophyric intrusions clearly identifiable on the basis of their dark colour and ultramafic composition. Ryan (*in press*) suggested that these dykes are not an integral part of the regional dyke assemblage because they are parochial to Satok Island (Figure 2) and Nuasurnak Island (not shown). However, they are included in this record for completeness.

GEOCHEMISTRY

The chemistry of the dykes in the Nukasusutok Island region shows some striking differences from dykes in the Dog Island region that were classified by Cadman and Ryan (1994) into four distinct chemical groups of basaltic composition (A to D). The general chemical features of these rocks are presented in Cadman and Ryan (1994) and are not repeated here. All these chemical groups are also present in the Nukasusutok dyke assemblage, but the relative importance of each group is very different. Whereas the Dog Island assemblage is dominated by dykes having Zr/Nb > 8 (Groups B to D), the Nukasusutok assemblage is dominated by intrusions having Zr/Nb < 8 (A group). The expanded dataset clearly reinforces the validity of subdividing the dykes using Zr/Nb ratio (Figures 3 and 4). However, the combined dataset also shows a smoother change in Ba/Rb ratio, particularly in dykes having Zr/Nb < 8.

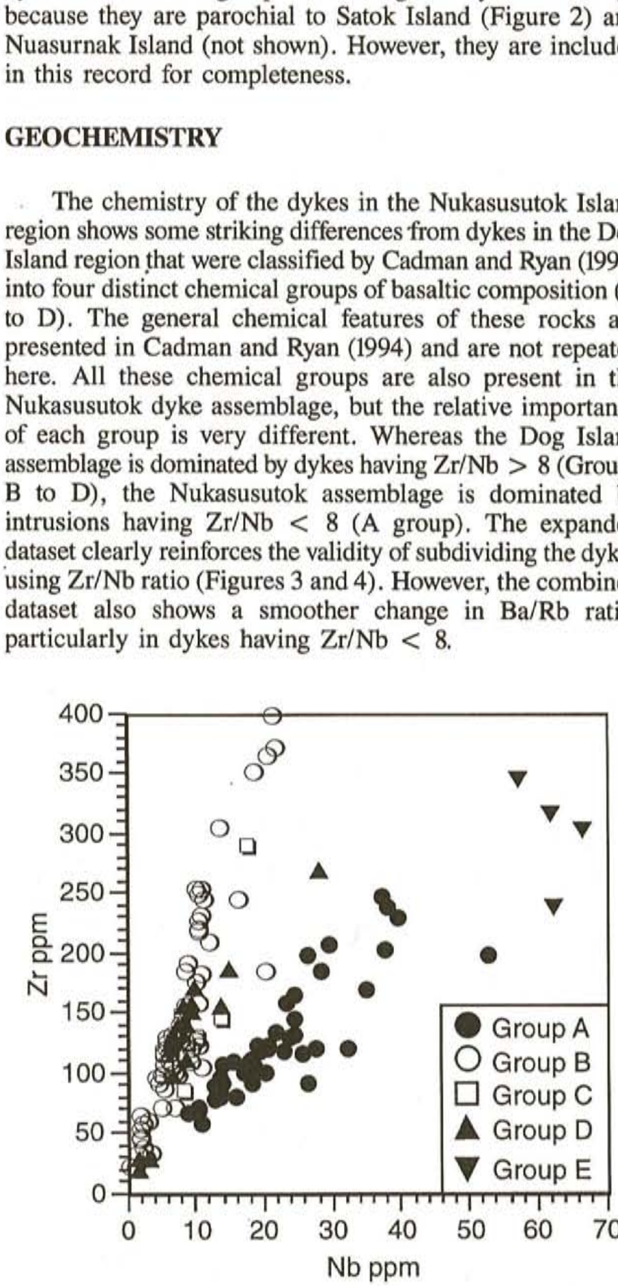

Figure 3. *Plot of Zr vs Nb, for all basaltic dykes.*

Plots of these chemical groups on discrimination diagrams (Figure 5a,b) clearly show that the A to D chemical

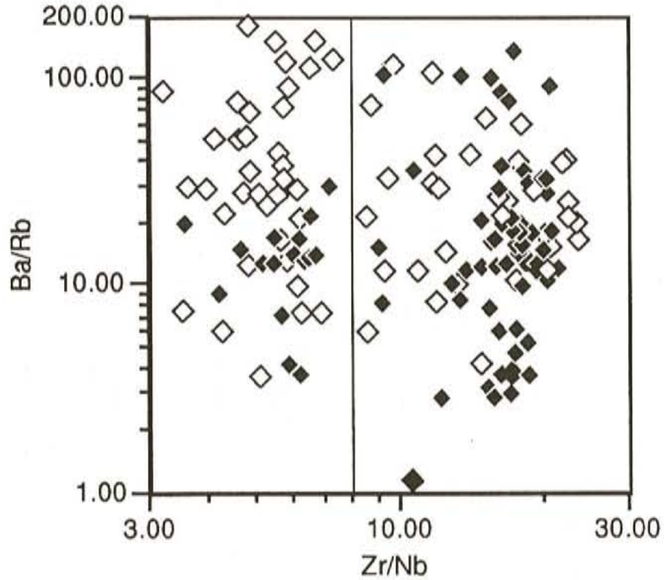

Figure 4. *Plot of Ba/Rb vs Zr/Nb for samples taken from the Dog Island region (filled diamonds) and the Nukasusutok Island region (open diamonds). The plot clearly shows the differences in geochemical variation between the two areas.*

groups can all be classified as transitional tholeiites, straddling the boundary between tholeiitic and alkaline rocks as defined by Irvine and Baragar (1971). The importance of fractional crystallization in the petrogenesis of the B group (see Cadman and Ryan, 1994), is underlined by the fact that a few samples plot within the basaltic andesite field as defined by Le Bas *et al.* (1986). Using the alternative basalt classification of Meschede (1986), the A group is clearly more alkaline in character than the other chemical groups (Figure 5c). The B group samples plot mostly within the 'within-plate' fields or MORB fields, whereas the C and D groups fall almost entirely in the 'within-plate' fields (Figure 5c,d).

The Nukasusutok region is also host to two more chemical groups unrecorded in the Dog Island area—Group E and lamprophyres (Group L). Both groups have similar spidergram patterns with very high concentrations of incompatible elements and positive niobium anomalies (Figure 6). The E group has similar Zr/Nb ratios to the A group but with markedly higher abundances (Table 1). The combined Le Bas and Meschede plots clearly show that samples within this group should be classified as alkaline basalts (Figure 5b,d). The second group, the lamprophyric intrusions, is silica undersaturated (SiO_2 = 35 to 42 percent) and iron- and magnesium-rich (see Table 1).

A striking feature seen in one dyke of alkaline basaltic composition (locality 230; Figure 2) is the remelting and digestion of gneissic country rock. Diffusion of gneissic material into the north-trending 5.6-m-wide intrusion is evident both at the dyke margins and in xenoliths entrained within the centre of the dyke. Evidence of elevated host-rock temperatures during dyke intrusion is common throughout the Nain region. For example, the marginal morphology of some dykes shows that the host gneisses were highly ductile (Ryan, *in press*). In other intrusions, rheomorphic back-veining by mobilized gneissic material is evident. (In contrast, many dykes do not possess these features and may have been intruded into colder country rock.) Intrusions displaying such rheomorphism and host-rock digestion clearly indicate that crustal contamination processes have locally been active in these dykes.

A number of (xenolith-free) samples were taken from the dyke and also of the remelted—unmelted gneissic country rocks to examine the degree of contamination in the above dyke. The spidergram patterns show a surprisingly limited variation in incompatible trace elements within the dyke (Figure 7a). Most elements show no evidence of bulk mixing between the dyke and the gneiss, although this is visibly the case. The reason for this unusual anomaly is that the alkali basalt chemistry of the dyke has markedly higher abundances of most trace elements than the gneiss, and it is therefore insensitive to the addition of gneissic material except in very large quantities. The gneiss has only similar or higher abundances of LIL-elements Rb, Ba and K, so ratios using these trace elements do show unequivocal evidence of mixing processes (Figure 7b).

STRUCTURAL RELATIONSHIPS

Orientation

The combined dataset for the Dog Island and Nukasusutok Island areas clearly show different primary orientations for the A and B chemical groups. The A group dykes are predominantly north-trending and on average thinner than the east—west-trending B group dykes (Figure 8a,b). However, a close inspection of the dataset suggests that the trends of the dykes are mainly controlled by the region into which they were injected rather than by chemical group. The majority of B group dykes within the Dog Island region strike between 60 and 120° (see Cadman and Ryan, 1994), whereas north—south orientations are more common within this group in the Nukasusutok region. Therefore, dyke trends cannot be used as a likely discriminant of geochemical type. Alkali basalts and lamprophyres in the Nukasusutok Island area also have dominantly north—south trends (Figure 8c).

Crosscutting Relationships

The problems with constructing a relative chronology based on dyke trend or morphology may be partially resolved by examining the chemical signature of crosscutting intrusions. During field work within the Dog Island and Nukasusutok areas, five sets of crosscutting dykes were sampled for chemical analyses (Figure 9). All the crosscutting relationships observed are between tholeiitic dyke types. On Dumbell Island (Figure 2), a multitude of crosscutting relationships were observed between different generations of dykes (see Cadman *et al.*, 1993a). A 0.7-m-wide north-northeast-striking green granulite dyke dated at 2560 ± 10

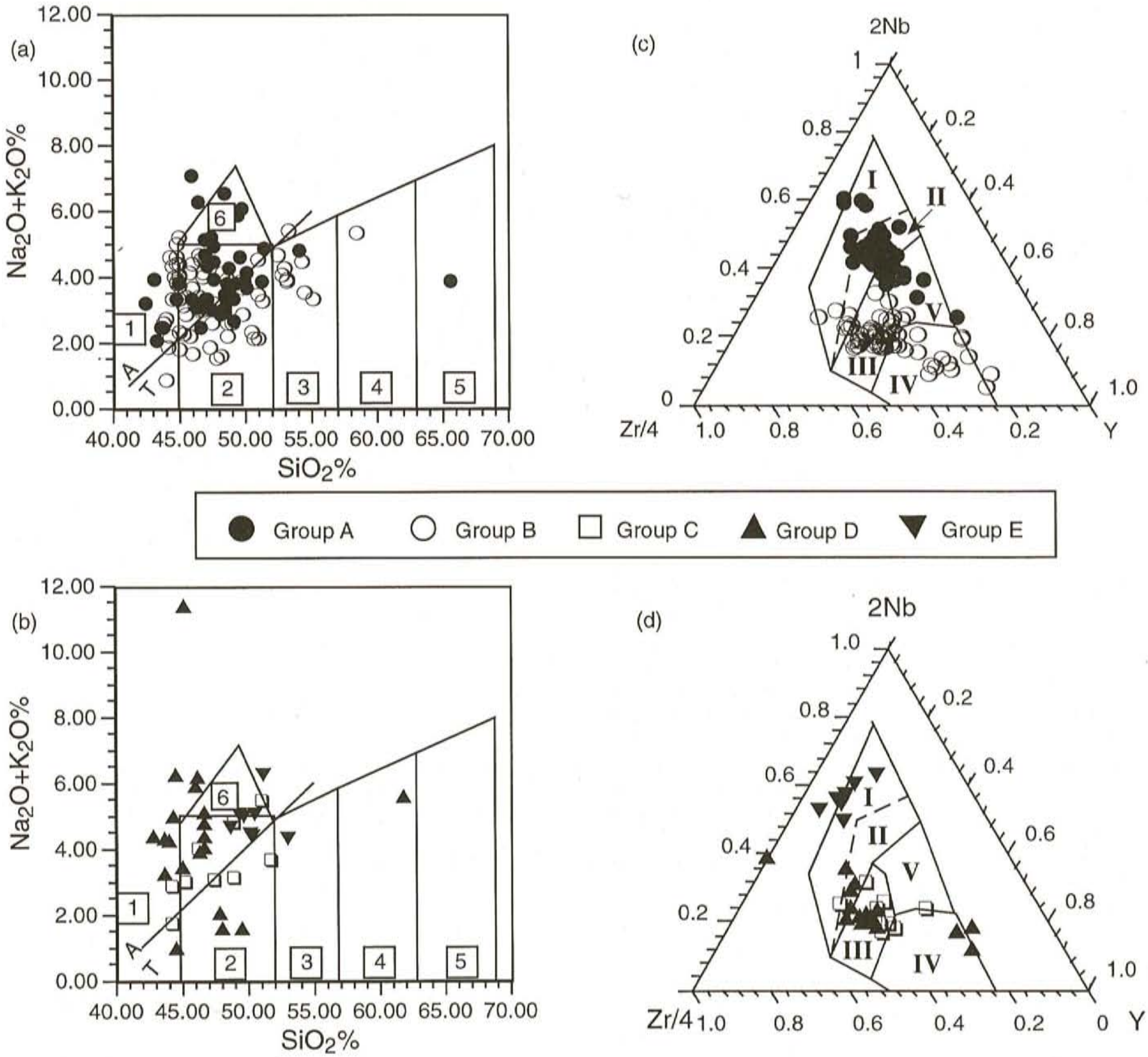

Figure 5. *Discrimination diagrams showing the chemical variation present in members of the dyke assemblage. Plots a and b: classification of dykes according to Irvine and Baragar (1971) and Le Bas* et al. *(1986). A = alkaline basalt; T = tholeiitic basalt; field nos.: 1—foidite; 2—basalt, 3—basaltic andesite, 4—andesite, 5—dacite, 6—trachy-basalt. Plots c and d: classification according to Meschede (1986). Within-plate alkali basalts plot in fields I and II. Within-plate tholeiitic basalts plot in fields II and III. MORB basalts plot in field IV. Volcanic arc basalts plot in fields III and IV. Plume-type mid-ocean ridge basalts plot in field V. Lamprophyric dykes not shown.*

Ma (Connelly and Ryan, 1993) is sheared and crosscut by a folded black dyke striking 080°. Chemically, the green granulite dykes (N91-92) belong to tholeiite group A, whereas the crosscutting 080° black dykes (N93-92) belong to Group D (Figure 9a). Farther along the shore, green granulite dykes are also crosscut by northeast-striking black dykes. Both sets of these intrusions are crosscut by the 080°-striking black dykes (see Figure 3 in Cadman *et al.*, 1993a). The two sets of black dykes appear mesoscopically similar, and of lower metamorphic (amphibolite?) grade than the green granulite dykes. Chemical analyses of these dykes show that both the green granulite dyke and the northeast-striking black dykes belong to Group A (Figure 9b), despite their apparent differences in metamorphic grade. The 080° black dyke (not shown on Figure 9b) is geochemically similar to the dyke referred to above having D group chemistry.

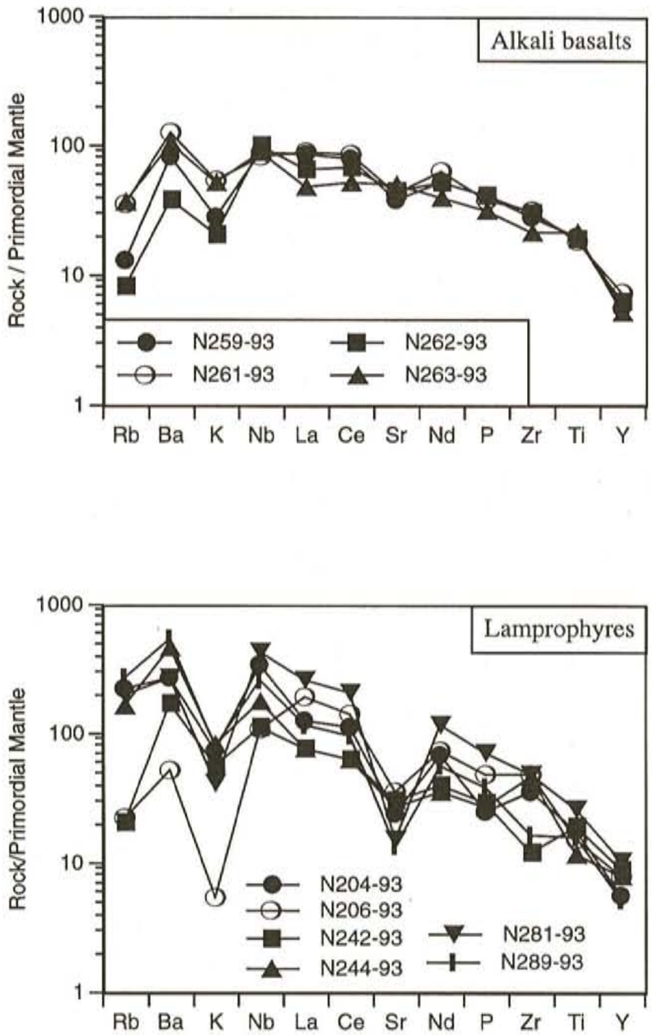

Figure 6. *Incompatible-element-spidergram patterns of alkali basalts and lamprophyric dykes.*

At locality 219 in the Nukasusutok area (Figure 2), a folded, 18-m-wide two-pyroxene + hornblende dyke striking 103° is crosscut by a fresh diabase dyke very likely to belong to the Nain LP (low phosphorus) swarm of Wiebe (1985). The two-pyroxene + hornblende-bearing intrusion has a peculiar spidergram pattern that may have resulted from metamorphic overprinting (Figure 9c). The trace-element signature of the Nain LP dyke is similar to many earlier A group intrusions, but its pristine nature clearly shows that it is younger in age.

A 7-m-wide dyke having a similarly peculiar chemical signature is found situated on a broad north–south-striking shear zone on the island immediately southeast of Mt. Pickle Harbour (locality 224; Figure 2). This dyke has a strike of 358°, concordant to the zone, and is intruded by a thin tholeiitic (Group A; Figure 9d) dyke moderately discordant to the zone. Outside the zone, the younger dyke strikes 083°, is 2 m wide and appears to have locally preserved its primary igneous texture. Within the zone, however, the dyke veers to the north (strike 012°), contains a large amount of biotite and is attenuated to 0.3 m in width. This suggests that the shear zone also affected the younger intrusion, and that for at least part of its history the zone was at amphibolite-metamorphic grade. However, despite the contrast in mineralogy, the younger dyke appears to be chemically unaffected by the shear zone: samples from inside and outside the zone (N230-93; N232-93) have identical incompatible-element-spidergram patterns (Figure 9d).

Another example of crosscutting dykes is seen at locality 254 (Figure 2), where a thin (up to 0.65 m) 097°-striking black dyke (N313-93) crosscuts sheared grey granulitic dykes (N312-93) and the two-pyroxene-bearing dyke described above. The grey granulite dykes are concordant within north-trending shear zones that also appear to attenuate the crosscutting black dykes (see Royse *et al.*, 1994). The black dykes belong to chemical Group D and the grey granulites to chemical Group A (Figure 9e).

Deformation

Superimposed deformation on dykes in the Nukasusutok area is also dominated by north–south-trending structures. Many dykes are clearly rotated by major north–south-striking shear zones and very commonly have internal north-northwest–north-northeast-trending foliations (Figure 10) often defined by secondary biotite. Folding or boudinage structures are less common, but where present have north-northeast to northeast trends, in comparison to the east–west trends noted for folded dykes on the north coast of Dog Island in the previous field season. There are no readily apparent differences in superimposed structural style between the defined chemical groups of dykes.

PRELIMINARY GEOCHRONOLOGY

The keystone to understanding the emplacement and petrogenesis of the dyke suite, and the eventual subdivision of the assemblage into individual swarms, is the analysis of its absolute geochronology. Previous dating work by Ryan *et al.* (1991) and Connelly and Ryan (1993) yielded a date of 2100 ± 100 Ma on a dyke from the mainland north of Voisey Bay, and an age of 2560 ± 10 Ma from a Group A tholeiitic dyke (represented in this study by sample number N105-92; Figure 9). A further seven dykes were sampled during the summer of 1993 for U–Pb mineral work to be carried out at the British Geological Survey, Keyworth. All samples yielded zircon, and a single sample of a Satok Island lamprophyre dyke (Z20) yielded both zircon and titanite. In two of the samples, very rare grains of baddeleyite were thought to be observed during mineral separation but were not recovered during the final stages of processing. At the time of writing, three zircon fractions from a single sample have been run and preparation is well advanced on all others. Over 20 fractions were collected in total and all have been abraded and made ready for mass spectrometer analysis.

The sample run to date (Z24) was taken from the folded and sheared two-pyroxene + hornblende dyke from locality

Table 1. Representative analyses of the alkali basalts (Group E) and lamprophyre (Group L) dykes

Sample no.	N235-93	N259-93	N261-93	N262-93	N263-93	N277-93	N330-93	N204-93	N206-93	N242-93	N244-93	N281-93	N289-93
Chemical Group	E	E	E	E	E	E	E	L	L	L	L	L	L
SiO_2	50.50	50.48	49.47	50.22	49.77	48.74	53.06	40.17	38.82	39.02	42.43	36.04	40.06
TiO_2	3.70	4.24	4.02	4.11	4.52	2.28	4.50	3.87	3.30	4.16	2.54	5.48	3.42
Al_2O_3	14.87	15.05	14.60	15.19	14.41	17.17	15.49	6.35	6.66	11.78	10.02	5.05	7.88
Fe_2O_3	12.79	13.89	13.91	13.76	13.82	14.00	12.46	17.45	17.51	21.58	12.53	21.72	13.51
MnO	0.14	0.16	0.14	0.15	0.15	0.21	0.12	0.29	0.23	0.37	0.22	0.34	0.19
MgO	4.88	4.45	4.64	4.07	4.50	4.94	3.18	15.14	11.99	6.98	12.97	14.58	16.76
CaO	7.51	6.48	7.39	7.22	7.23	7.54	5.86	13.72	20.25	11.64	15.54	13.88	14.85
Na_2O	3.12	3.50	3.27	3.73	3.28	3.63	2.50	0.17	0.04	2.08	0.53	0.11	0.01
K_2O	1.87	0.87	1.71	0.67	1.63	1.00	1.78	2.30	0.17	1.78	2.62	1.28	2.49
P_2O_5	0.604	0.883	0.839	0.883	0.688	0.479	1.054	0.544	1.035	0.629	0.598	1.513	0.826
LOI%	0.65	-0.21	0.30	0.46	0.15	0.40	0.38	0.46	0.33	-0.33	0.47	0.28	0.24
Mg#	47.09	42.76	43.74	40.80	43.16	45.12	37.32	66.92	61.47	42.97	70.70	61.01	74.30
Nb	67	62	57	70	62	70	80	236	76	78	125	301	187
Zr	300	314	343	339	236	194	404	399	528	133	517	541	184
Y	26	25	33	28	23	35	27	25	36	41	36	46	23
Sr	950	802	901	923	1041	578	1216	512	741	631	559	322	284
Rb	36	8	22	5	24	36	75	139	14	13	105	123	172
Ga	29	31	31	31	28	25	32	19	20	24	20	22	13
Zn	152	171	177	174	176	99	141	131	122	188	109	268	132
Ni	88	60	75	68	81	17	59	338	178	36	311	322	398
Sc	13	14	15	13	12	23	12	24	34	44	28	34	32
V	121	105	108	95	110	183	69	376	389	360	266	510	378
Cr	106	53	78	40	61	17	21	859	478	6	545	912	2132
Co	50	42	43	41	46	50	34	75	75	84	64	88	60
Cu		54	50	56	51		22						
Ba	828	571	866	265	729	1133	947	1866	358	1191	3151	1887	3715
La	38	57	59	45	33	48	63	85	130	52	52	175	80
Ce	93	137	152	121	90	96	155	194	243	109	108	357	168
Nd	54	70	86	70	53	44	79	91	100	53	48	156	75

219 (Figure 2; Figure 9c). Two fractions (large- and medium-sized zircon grains) lie 1 percent above concordia, whereas the third (small zircon grains) lies 0.5 percent below concordia. Details of the fractions' ages for each isotopic ratio are given below, errors are shown in brackets:

Fraction	$^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$
1: large zircons	1321.7	1319.8	1316.6
	(0.248%)	(0.276%)	(0.122%)
2: medium zircons	1319.7	1318.1	1315.7
	(0.384%)	(0.402%)	(0.117%)
3: small zircons	1317.7	1318.3	1319.2
	(0.461%)	(0.483%)	(0.145%)

Regression of the data points gives an age of 1317 ± 4 Ma. (Error calculated by overlap of ellipses with concordia.)

DISCUSSION

The accumulation of both relative and absolute geochronology allows some discussion on the relationship between individual dyke chemical groups, their structural deformation, metamorphism and their relationship to other intrusive events within the Nain area. Age data are also highly relevant when considering how the mantle evolved through geological time.

RELATIVE CHRONOLOGY OF DYKE CHEMICAL GROUPS

Two of the dyke crosscutting relationships shown in Figure 9 indicate that Group D dykes crosscut dykes with Group A geochemistry. At both localities, the D group dykes appear as black 'amphibolite' whereas the older A group dykes are green or grey granulites. Thus, it may be tentatively suggested that all Group D dykes are younger than the intrusions in Group A.

However, the diagram (Figure 9b) also shows that dykes with Group A chemistry crosscut the 2560 ± 10 Ma Archean dyke, which also has Group A chemistry. On a mesoscopic scale, these dykes appear to be different: the Archean dyke appears as a 'green granulite', whereas the crosscutting dykes are black. Figure 9 also shows subtle differences in geochemical signature between the older and younger intrusions. This second relationship emphasizes the dangers of relying too heavily on chemical classification, as it is

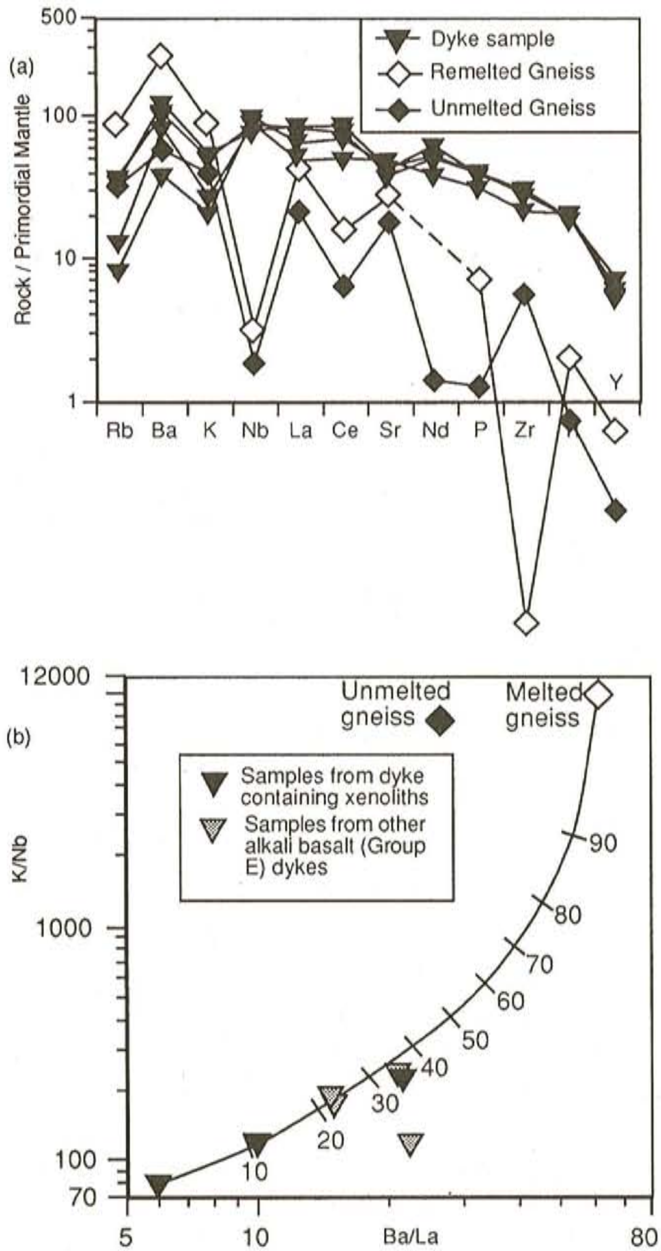

Figure 7. *Crustal contamination of a Group E dyke. (a) Incompatible-element spidergrams show the relationship between gneisses undergoing partial melting and the dyke of alkali-basalt composition. (b) Bulk mixing plot clearly indicating the variation in LIL-element chemistry due to crustal input.*

obvious from the data that dykes classified within the same group are not of the same age.

U–Pb (ABSOLUTE) GEOCHRONOLOGY

The 1317 ± 4 Ma age of the two-pyroxene + hornblende-bearing dyke may either represent an emplacement or metamorphic age. The date puts a maximum age on the unmetamorphosed Nain LP dyke that crosscuts it. Other geochronological studies on similar fresh dykes in Hopedale block and Nain areas (Cadman *et al.*, 1993b; Carlson *et al.*, 1993; Roddick in Cadman *et al.*, 1993b) suggest that the Nain LP swarm may be around 50 Ma younger. The age is within error of 1322 Ma emplacement age of an NPS rapakivi granite and the 1310 ± 5 Ma thermal resetting age of quartzofeldspathic gneisses reported by Ryan *et al.* (1991) and Connelly and Ryan (1993). If the age represents the time of intrusion, then this dyke, and the younger black amphibolite Group D dykes may be chemically linked to the formation of the NPS. Ryan (1991, *in press*) suggested that some of the dyke assemblage may represent leaks from sub-crustal magma chambers during or prior to the emplacement of the NPS to higher crustal levels. However, the spidergram pattern of the two-pyroxene + hornblende-bearing dyke appears to depleted in the mobile large-ion lithophile elements (Rb, Ba, K) relative to the light rare earths (La, Ce, Nd) and high-field-strength elements (P, Zr, Ti and Y). This spidergram pattern may therefore have been modified by fluid flux during metamorphism (see section on Metamorphism).

STRUCTURE

Ryan (1991) noted: '*..there does not seem to be any correlation between particular morphological characteristics and dyke trend. In addition, there is no obvious correlation between dyke trend, relative age, the presence or absence of deformation and the degree of metamorphism.'* Subsequent fieldwork and chemical analysis have largely reinforced this conclusion (Cadman *et al.*, 1993a; Cadman and Ryan, 1994). As noted above, the combined Dog Island–Nukasusutok Island dataset shows that the both primary and secondary dyke trends appear more sensitive to regional structural style than to the chemical group within which they belong. Hence, it would appear that at least one major component of the structural history of the Nain area was superimposed on all the different geochemical groups within the dyke assemblage. The superimpostion of this event may obscure the effects of earlier deformationary episodes that may have occurred prior to the injection of some elements of the dyke assemblage and subsequent to others. Indeed, previous geochronological studies of the Nain dykes show this to be highly likely, as the Archean dyke on Dumbell Island appears to be nearly coeval with its Archean granitic host (Connelly and Ryan, 1993). The production of cusp-and-lobe structures due to competence contrasts, and the rheomorphic veining textures seen in many dykes, may also be the product of more than one event.

On the north coast of the small island, near locality 219 (Figure 2), black amphibolite dykes belonging to chemical Group D intrusions crosscut, but are slightly deflected and attenuated by, north–south shear zones. These zones contain concordant grey granulite dykes and they crosscut the two-pyroxene + hornblende dyke dated at 1317 Ma. All three types of dykes contain north- to north-northeast-trending foliations. The black amphibolite dykes exhibit superb cusp-and-lobe structures, which clearly show that these dykes were less competent at the time of formation than the gneisses. The 1317 Ma age of the two-pyroxene hornblende dyke may therefore give a maximum age for the intrusion of the Group D dykes and also the waning stages of north–south ductile shear deformation. (Alternatively, this age could be due to the static crystallization of zircon during a later metamorphic event, which postdated Group D dyke intrusion and the accompanying tectonothermal event.)

METAMORPHISM

The spidergram patterns in Figure 9 show that in most cases, shear deformation of the various dyke groups was not associated with their depletion in mobile elements. This suggests that the metamorphism resulted in a static overprinting and the development of new textures. Two exceptions to this are worth noting: first is the dated two-pyroxene + hornblende dyke (Figure 9c), and the granulite dyke concordant within the major shear zone due east of locality 224 (Figure 9d). The irregular spidergram pattern of these intrusions strongly suggests some remobilization of elements has occurred. This is especially interesting for the intrusion within the major shear zone (Figure 9d), as the later crosscutting intrusion, also affected by shear movement, shows no sign at all of being affected by chemical mobility. A possible explanation is that the relatively low concentrations of incompatible elements in both of the intrusions having the irregular patterns mean that only a limited amount of remobilization could produce quite significant changes in the chemical signature. The same amount of remobilization would not result in large chemical changes in most of the other spidergram patterns shown in Figure 9.

It has been noted above that the 1317 ± 4 Ma age from the two-pyroxene + hornblende dyke could indicate time of emplacement. Alternatively, it could represent a metamorphic event. If this is a metamorphic age, then zircon growth took place entirely during metamorphism because the zircon fractions give a concordant age, and the Pb concentrations within the zircon population were not disturbed by any subsequent events. If the zircon is of metamorphic origin, it is the first indication of growth of this mineral in the country-rock during the emplacement of the NPS, the usual expression of this thermal event being generation of titanite and monazite. The granular texture and north–south foliation within this intrusion clearly show that at least one episode of recrystallization occurred, although the timing of this event relative to emplacement is uncertain. The crystallization of secondary minerals (such as orthopyroxene and zircon?) may have taken place either a considerable time later than, or very shortly after intrusion. This event seems very likely to be linked to the thermal event associated with NPS emplacement.

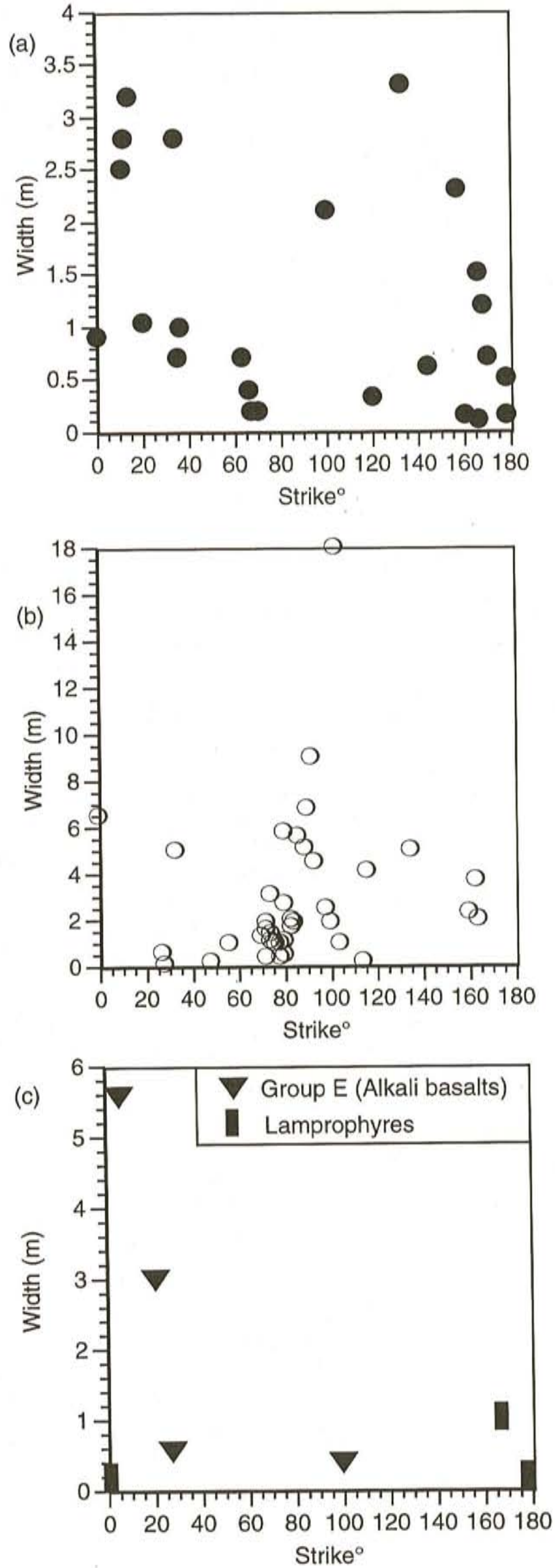

Figure 8. *Orientation of dykes; (a) width versus strike of Group A dykes; (b) width versus strike of Group B dykes; (c) width versus strike of Group E dykes (Alkali basalts) and lamprophyres.*

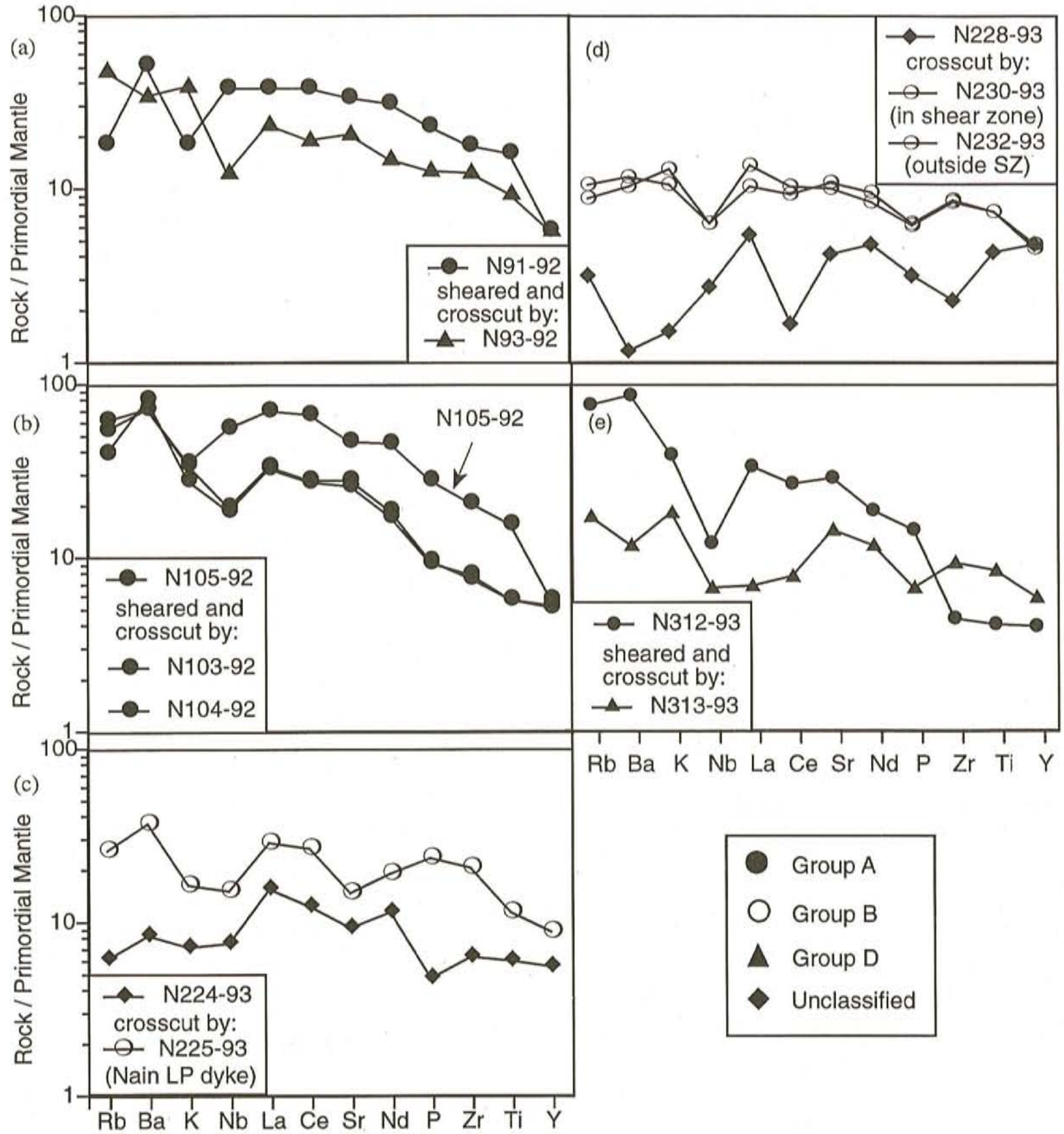

Figure 9. *Incompatible element spidergram patterns showing the chemistry of crosscutting intrusions. See text for full details. The "unclassified" dyke in (C) yielded the U-Pb age of 1317 ± 4 Ma discussed in text.*

GEOCHEMICAL EVOLUTION OF THE NAIN PROVINCE SUBSTRATE

The presence of different generations of crosscutting dykes and distinct geochemical groups suggests that the dyke assemblage in the gneisses at Nain may help to unravel how the mantle underlying the Nain region evolved throughout geological time. Firm conclusions will rely strongly on the U–Pb dating still in progress. However, it is well established that tholeiitic basic magma types occur consistently throughout the geological record, whereas more enriched sources become more important in time (e.g., Gill and Bridgwater, 1976; Tarney, 1992) Continental dyke swarms of transitional to alkaline chemistry first appeared during the Mesoproterozoic (e.g., Condie *et al.*, 1987). Hence, it would appear likely that the alkaline basaltic dykes (Group E) within the Nain Province are Mesoproterozoic. However, when considering the problem of mantle evolution, the presence

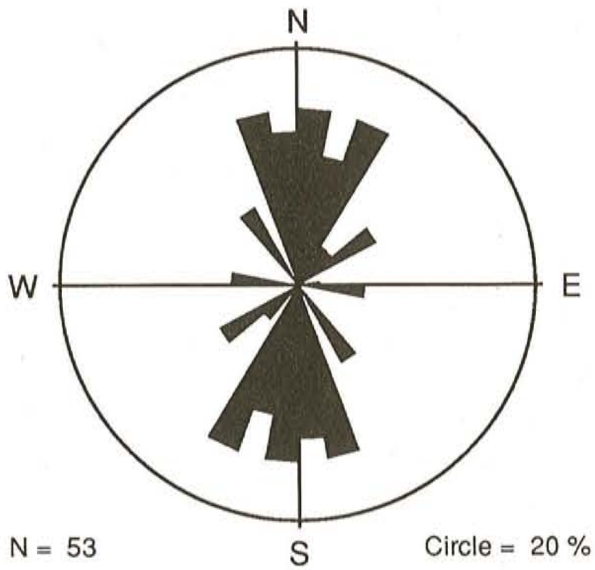

Figure 10. *Internal foliation of all dykes mapped in the Nukasusutok area during the 1993 field season. "Circle = 20 percent" refers to the proportion of data that would form a sector equal in length to the diameter of the circle. N = number of data points collected.*

of crustal contamination must be addressed. Cadman and Ryan (1994) suggested that the geochemical signature of the dykes may be mantle derived. However, on the basis of field evidence presented in this report, the possibility that crustal contamination processes occurred (to some extent) is beyond doubt. It is interesting in this particular case, that it is only selective elements within the contaminated intrusion that are strongly affected by the addition of crustal material. Comprehensive studies of crustal contamination show that it is in fact a high-complex selective process (e.g., see Bilchert-Toft *et al.*, 1992). The main chemical signature of the dykes may therefore indeed be mantle derived, as it is very difficult to see how a positive Nb anomaly (see Figure 7) could be produced by crustal contamination. Future geochemical studies of the dykes will concentrate on determining the relative importance of crustal and mantle processes on the geochemistry. Once the effects of crustal contamination are accounted, then effects of mantle evolution on chemical signature can be studied. Indeed, the fact that some dykes may be contaminated, and others not, may reveal that crust–magma interactions also show secular variations.

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