U–Pb ages of syndeformational dykes associated with the Mesoproterozoic Nain Plutonic Suite, Labrador[1]

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Abstract: Field and U–Pb zircon geochronological studies in a suite of crosscutting, deformed, and metamorphosed basic dykes show that they were emplaced in a syndeformational environment between 1328 ± 2 and 1316.5 ± 1.6 Ma. Earlier dykes in the suite are granulitic, commonly folded along north–south axes or strongly rotated into north–south-trending shear zones. Later dykes are metamorphosed to amphibolite grade. These sometimes retain igneous porphyritic textures and occasionally crosscut the granulite dykes. The amphibolite dykes were emplaced in a less ductile crustal environment and a structural environment less dominated by shear deformation. Both granulitic and to a lesser extent amphibolite dykes show evidence of synshear emplacement. The episode of emplacement is broadly coeval with the injection of the mid-Proterozoic Nain Plutonic Suite (NPS) and suggests that the dykes were injected as a series of leaks from NPS feeder chambers. If so, the granulite dykes may represent leaks intruded near the culmination of NPS activity, whereas the amphibolite dykes were probably injected during the waning phase of tectono-thermal conditions.

Résumé : Les études sur le terrain et les analyses géochronologiques U–Pb sur zircon d'une suite de dykes basiques intersectants, déformés et métamorphisés indiquent une mise en place dans un contexte structural de déformation, échelonnée entre 1328 ± 2 et 1316 ± 1,6 Ma. Les dykes précoces de la suite sont granulitiques, généralement plissés le long d'axes nord–sud ou fortement pivotés à l'intérieur de zones de cisaillement orientées nord–sud. Les dykes tardifs ont été métamorphisés sous faciès des amphibolites. Ceux-ci conservent parfois leurs textures ignées porphyriques et occasionnellement ils recoupent les dykes granulitiques. Les dykes amphibolitiques furent mis en place en milieu crustal moins ductile et sous un régime tectonique moins influencé par la déformation cisaillante. Les dykes granulitiques, et à un moindre degré les dykes amphibolitiques, montrent des indices qui reflètent une mise en place contemporaine du cisaillement. La période de mise en place est, en général, contemporaine de l'injection de la Suite plutonique de Nain, au Protérozoïque moyen, et on suggère que les dykes furent injectés sous forme d'une série de fuites issues des chambres qui alimentaient la Suite plutonique de Nain. Si c'est le cas, alors les dykes granulitiques pourraient représenter des fuites qui ont fait intrusion durant la phase d'activité culminante de la Suite plutonique de Nain, tandis que les dykes amphibolitiques furent probablement injectés durant la phase de décroissance des conditions tectono-thermiques.

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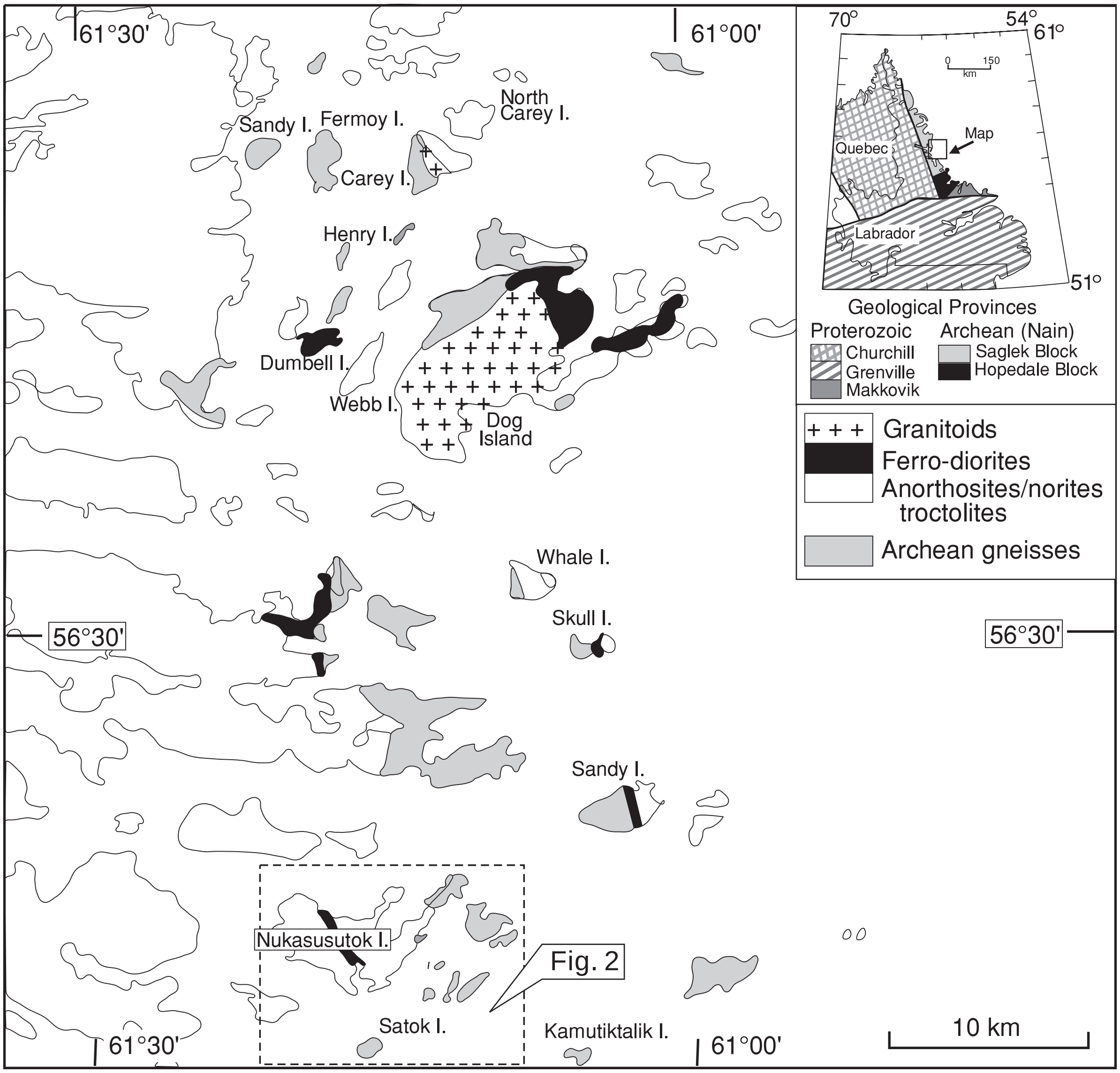
Introduction and geologic setting

Dyke swarms are mostly associated with tectonically extensional terranes. Field evidence suggests that some dyke swarms were emplaced into crustal regions undergoing shear deformation (Bridgwater and Myers 1979; Jack 1978; Nash 1979; Myers 1984; Hanmer and Scott 1990). Synshear emplacement is usually deduced from the relative chronology of dyke intrusion with deformation structures within the dykes and the surrounding country rocks. The absolute time of intrusion and its relationship to shear deformation are often unknown and represent a particularly intractable problem in ancient shield areas where the country rocks may have undergone many cycles of deformation, metamorphism, and dyke injection. In this study we seek to prove using U–Pb geochronological analysis and relative field chronology that a metadyke assemblage in the Nain region, Labrador, was injected into a synshear environment associated with em-

Fig. 1. Geological map of the Nain area, east-central Labrador. The inset map shows the main geological provinces of Labrador.



placement of the Mesoproterozoic Nain Plutonic Suite (NPS). The aim of the study is to help validate the field criteria currently used to ascertain tectonic environments of dyke injection and also the relationship between dyke magmatism and plutonic emplacement.

The NPS (Fig. 1) consists of four main petrological components, anorthosite, ferrodiorite, granite, and troctolite, and is a world-famous type locality for anorogenic magmatism. Recent U–Pb geochronological studies have shown that the NPS was injected between 1.35 and 1.29 Ga (Ryan et al. 1991; Connelly in Ryan and Emslie 1994; J.C. Roddick, personal communication, in Ryan and Emslie 1994). The intrusions are emplaced into a narrow septum of gneisses which lie between the Archean Saglek (~3.8–2.8 Ma) and Hopedale blocks (3.3–2.8 Ma) to the north and south, respectively (Bridgwater and Schiøtte 1991). These gneisses of the Nain Province were subdivided by Ryan (1991) into granitic, quartzofeldspathic, metasedimentary, and mafic gneiss types. Metamorphic grade varies between amphibolite and granulite. Of course, noritic and anorthositic rocks can crystallize directly to a two-pyroxene–plagioclase assemblage (cf. Fram and Longhi 1992), and hence there is the possibility that some granulite dykes may be primary igneous rocks. Likewise, some dykes may have crystallized with primary amphibolite-facies mineral assemblages.

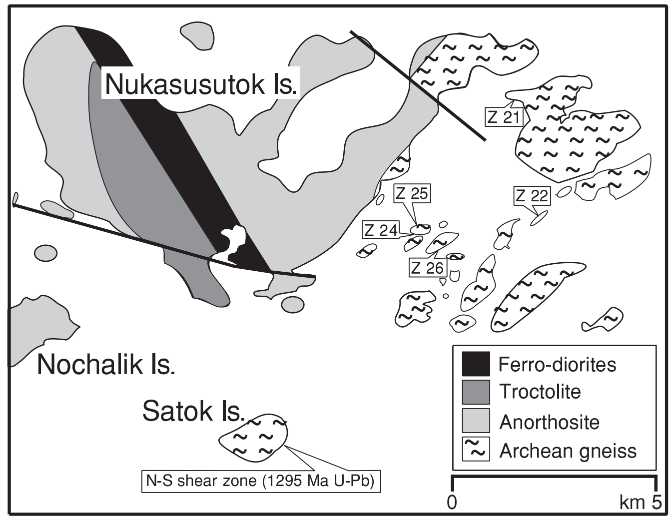
Metamorphosed dykes intrude all the gneiss types with the exception of some of the mafic granulite rocks, which occur as marginal zones to the NPS troctolitic and noritic plutons (Ryan 1995). The concentration of dykes within the host gneisses is highly variable, where they occur as thin (0.1–20 m wide) intrusions that can be traced along strike for up to 2 km. The dykes are ubiquitous but constitute <1% of the Nain region crust due to their small size. The Nain dykes contrast with most major Proterozoic dyke swarms in that the latter are typically composed of intrusions with widths on the order of several tens of metres and lengths of many kilometres. Metamorphic grade in both gneisses and dykes ranges from amphibolite to granulite, but there is no apparent correlation between the metamorphic grade exhibited by the dykes, their trend, style of deformation, and the metamorphic grade of the host rocks they intrude (Ryan 1991).

The time of dyke emplacement has hitherto been poorly constrained by U–Pb geochronology: Connelly and Ryan (1994) dated a sheared green granulite at 2560 ± 10 Ma. Chemical analysis of this dyke and petrographically similar ones shows them to be alkaline basaltic in composition. In addition, some of the basaltic dykes intrude the Loon Island granite (minimum age ~2.05 Ga; Connelly and Ryan 1993) and are intruded by granite dykes dated at ~1.31 Ga (Connelly et al. 1992). Titanite U–Pb ages on the 2.0 Ga lamprophyres in one such north–south-trending sinistral zone on Satok Island (see Figs. 1, 2) suggest that the last major phase of movement along the zone occurred at ~1295 Ma.[4] Hence it is apparent from these data that at least two episodes of basaltic dyke intrusion occurred prior to the cessation of Mesoproterozoic thermotectonic events. A third component of the assemblage consists of grey and black, sheared and deformed, tholeiitic to transitional alkaline intrusions of unknown age. At one locality these are seen to crosscut the dated late Archean granulite dyke.

Hence this dyke assemblage comprises at least three generations of mafic dyke emplacement. After the intrusion of this assemblage and the cessation of the tectono-thermal events responsible for their metamorphism, a number of unmetamorphosed, undeformed dykes swarms crosscut both the NPS and their host-rock gneisses. Examples of these intrusions have yielded the post-NPS ages of 1276 ± 23 Ma (Wiebe, in Gower et al. 1990) and 1267 Ma (J.C. Roddick personal communication, 1993). These are not considered further in this study.

In terms of the individual components, the first two episodes combined constitute <20% of the metadyke assemblage. These dykes were not included in this study because they considerably predate NPS emplacement; much of their original structural and metamorphic characteristics are likely to be strongly overprinted by NPS emplacement-related tectono-thermal events. In contrast, field evidence (described below) suggests that at least some of the tholeiitic–transitional alkaline dykes are associated with NPS emplacement. Additionally some dykes contain "snowflake" plagioclase textures similar to the textures described by Berg (1980) for the NPS Hettasch intrusion, although Ryan (1995) considers these unlikely to be directly related on petrological grounds. Similarly, anorthositic xenoliths were found in one otherwise granular-textured dyke on the north coast of Dog Island, marginal to the Jonathon Island intrusion (Cadman et al. 1993). Geochemical studies[5] also show that the trace element chemistry of these tholeiitic dykes bears a strong similarity to the signature of local NPS intrusions.

Fig. 2. Map showing geological detail of sampling regions, east of Nukasusutok Island.



Field relationships

Deformation patterns within the dyke assemblage clearly show that many dykes were subjected to compressional stresses oblique to their strike directions: many dykes contain sigmoidal, oblique, or margin-parallel internal foliations. These internal foliations are commonly defined by biotite, and rarely by quartz-rich segregations or pressure-solution shadows at the margins of black plagioclase phenocrysts. They are usually most strongly developed at dyke margins, but are rarely mirrored by external structures in the gneissic host rocks which the dykes intrude (Ryan 1993, 1995): instead, the regional gneissic foliation is commonly disturbed and reoriented into parallelism with the dyke trend as one or both margins of the dykes are approached. In other cases, dykes are found within discrete discordant mylonitic zones or high-strain zones (straight belts) which follow the regional gneissic trend in a particular area and vary from a few centimetres to hundreds of metres in width (Ryan 1995). Where both are present, structures internal and external to the dyke almost always give a coherent sense of shear direction. The interface between some dykes and their enclosing gneisses is also notable for the development of "cusp and lobe" structures associated with competence contrast.

Figure 3 shows the orientations of internal foliations and offset directions for the dykes in question. Most internal foliations are margin parallel but the orientation of oblique foliations indicates a broadly consistent sense of displacement, with the majority of northeast–southwest-trending intrusions showing dextral displacement, and northwest–southeast-trending intrusions showing a sinistral sense of displacement. However, there are also a significant number of north–south dykes showing no consistent sense of shear. Dyke offset directions are most commonly indicated by bayonet and step features on the margins of dykes, and mostly show pure shear – tensile failure emplacement. These dykes have predominantly east-northeast–west-southwest to east–west trends and rarely contain internal foliations or have cuspate margins. The orientations of the dykes are consistent with emplacement in a stress field where the orientation of

[4] Noble, S.R., Cadman, A.C., Tarney, J., and Ryan, B. U–Pb geochronology and regional significance of ca. 2 Ga mafic dikes, Nain Province, Canada. In preparation.
[5] A.C. Cadman et al. In preparation.

Fig. 3. Foliation and offset directions against dyke strike in the metadyke assemblage.

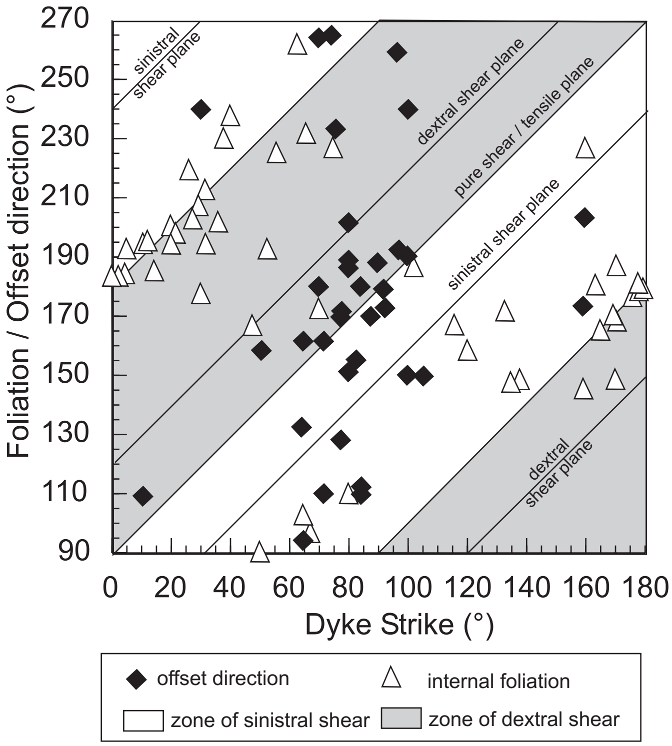
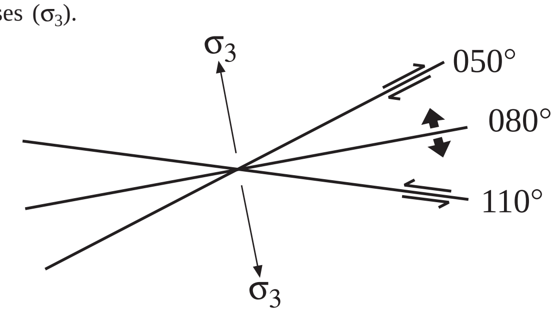


Fig. 4. Sketch showing the orientations of dykes associated with the Nain Plutonic Suite and their relationship to regional tectonic stresses (σ_3).



the principal stresses has remained approximately constant but the relative magnitudes of the stresses have changed from conditions favouring tensile failure to those favouring shear failure or vice versa (Fig. 4).

The dykes under discussion can be divided in the field into three main types. Type A consists of black, two-pyroxene–hornblende dykes; type B comprises grey granulitic dykes; and type C is composed of black amphibolitic dykes. The relationship of these dyke types to each other and to the shear zones is illustrated in Figs. 5–7, all taken from the same group of small islands (see Fig. 2). No crosscutting relationships are seen between dykes of type A and those of type B, but both of the latter are clearly cut by dykes of type C (Figs. 6, 7). One folded type A dyke lies within a major north–south-trending shear zone and contains leucocratic segregations, which define a margin-parallel foliation. Grey granulitic dykes of type B are demonstrably synshear. Figure 5 shows two of these dykes cut by northeast–southwest shears, whereas a thin undeformed apophysis (see sample Z22) is intruded along one of the shears. Elsewhere, thin (<1.4 m) type B dykes are rotated into parallelism with the major north–south to north-northwest–south-southeast shear zone which has caused a pronounced margin-parallel fabric in the dyke (Figs. 6*a*, 6*b*).

Thin black type C dykes cut both A- and B-type dykes (Figs. 6, 7) and are folded and foliated within the north–south shear zone. One of these type C dykes (shown in Fig. 6*a*) from which sample Z25 is taken cuts a deformed type B dyke, but possesses a poorly developed marginal foliation. The margins of these type C dykes have a well-developed cusp-and-lobe morphology, indicating that the dykes were less competent than the host gneisses at the time of their formation. In places the gneissose foliation bends into parallelism with the dyke margin in a dextral sense (e.g., Fig. 7). The type C dyke shown in Fig. 7 was emplaced as two en-echelon segments which are rotated anticlockwise as they approach the older type A dyke, indicating that sinistral shear continued during the emplacement of the type C dyke. Evidence of lower grade retrogressive shearing is seen in one thick, folded type A dyke on the south coast of this island where a thin north–south shear containing epidote and haematite cuts the dyke within and parallel to the main shear zone. The dyke is folded around an axis of 014° and contains a north–south lineation. However, the age of this retrogressive shearing relative to the younger type C dykes is not known.

At another locality, a 0.6 m wide north–south-foliated type C intrusion is intruded concordantly both to the Archean gneissic foliation along a strike of 043° and along a small-scale shear plane trending 171°. In places, a parallel north–south shear displaces one margin of a northeast-trending discordant branch of the dyke but not the other, proving that shear displacement occurred when the dyke was still liquid.

Hence the field relationships indicate that dyke emplacement occurred coeval with shear-zone deformation and spanned a period during which country rock temperatures appear to have declined.

U–Pb geochronology

Analytical techniques

All analytical work was done at the NERC Isotope Geosciences Laboratory, Nottingham, U.K. Samples weighing 10–20 kg were jaw-crushed and disk-milled to <420 mm. Heavy minerals were concentrated using a Gemini table, a Magstream 100 separator, and a Frantz LB-1 separator. Zircon separates were hand-picked under alcohol, abraded following Krogh (1982) to improve concordance, and washed in warm distilled 4N HNO_3 and H_2O prior to dissolution. Samples were then weighed on a microbalance and spiked with a mixed $^{205}Pb/^{235}U$ tracer solution prior to digestion. Miniaturized versions of the dissolution and chemical separation techniques of Krogh (1973) were employed. Procedural blanks for Pb and U ranged from 6.5 to 0.8 pg and <0.5 pg, respectively, during the course of this study.

Data were obtained on a VG Isotopes 354 mass spectrometer with an ion-counting Daly detector following Noble et

Fig. 5. Field relationships between grey granulite dykes (type B), shear zones, and Nain LP dyke. Note location of sample Z22.

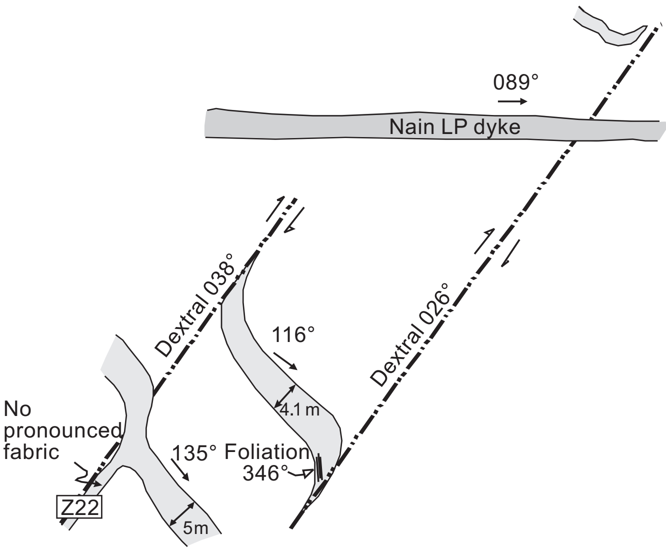
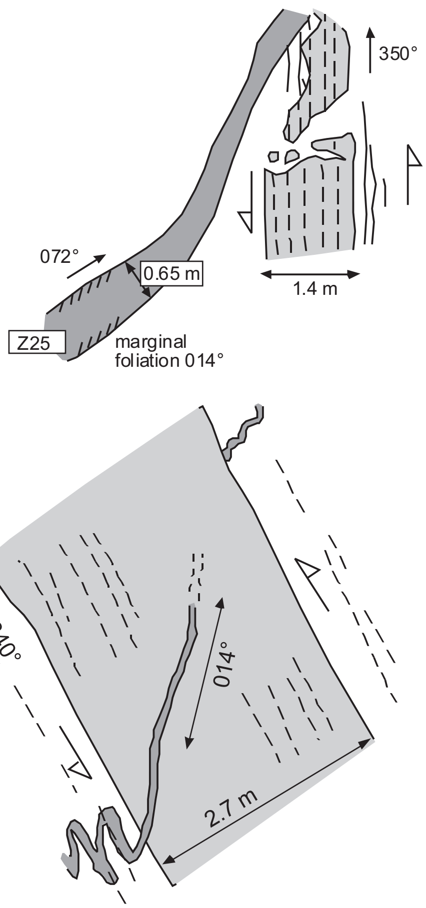
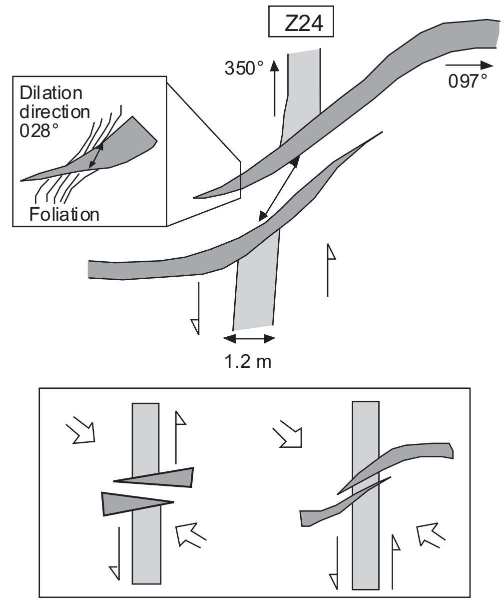


Fig. 6. Field relationships between grey granulite dykes (type B), shear zones, and later black (amphibolite) dykes (type C).



al. (1993). The decay constants of Jaffey et al. (1971) were used in data-reduction calculations. Uncertainties for isotope ratios, ages, and error ellipses on concordia plots throughout the paper are quoted at the 2σ level and were calculated following Ludwig (1980).

Fig. 7. Field relationships between two-pyroxene hornblende-granulite dyke (type A), shear zones, and crosscutting black dyke (type C). The enlargement shows the postulated mode of formation.



Sample descriptions and results

U–Pb isotope data were obtained for zircons recovered from five mafic dykes to place absolute age constraints on deformation and dyke emplacement. Zircon was the only suitable mineral present and, despite a careful search, no baddeleyite was encountered. Three of the samples are type B grey granulites, while the remaining two are from the types A and C groups. In most of the dykes, the zircons recovered are limpid and generally free from inclusions. Grains with cores were noted in some samples and were excluded from the analysed fractions, given that the primary focus of this study is to investigate the timing of dyke emplacement. Most zircons are colourless, pale brown, or pale pink and have smooth, poorly faceted surfaces. Ages quoted below are based on the most concordant analyses and, where data are virtually concordant, are calculated using the weighted mean $^{207}Pb/^{206}Pb$ age.

Z21: biotite-bearing granulite-facies tholeiitic dyke

Sample Z21 is a 3.2 m wide, north-striking (014° north) type B granulite dyke containing abundant secondary biotite. Most zircons in Z21 are <100 mm long, equant, colourless to pale pink, and free from inclusions, obvious cores, and overgrowths. Some very large and complex zircons, with irregular shapes and maximum dimensions >100 mm, are also present. The complex grains are comprised of colourless to pink cores with colourless to pink overgrowths, or are composite grains where a number of cores are welded together with colourless overgrowths. The dominant population of equant <100 mm zircons is interpreted here as being the most likely to have crystallized from the dyke magma on the basis of their relative abundance, textural uniformity, and apparent lack of complex zonation, and were therefore ana-

Table 1. Nain dykes U–Pb data.

Fractions[a]	Wt. (mg)	Concentrations[b] U (ppm)	Pb (ppm)	Common Pb (pg)	Atomic ratios $\frac{^{206}Pb}{^{204}Pb}$ [c]	$\frac{^{208}Pb}{^{206}Pb}$ [d]	$\frac{^{206}Pb}{^{238}U}$ [d]	$\frac{^{207}Pb}{^{235}U}$ [d]	$\frac{^{207}Pb}{^{206}Pb}$ [d]	$\frac{^{207}Pb}{^{206}Pb}$ age (Ma)	ρ[e]
Z21: Nain type B tholeiitic dyke (grid reference 116 491)											
1. eq, cl, 70, 5	0.0064	147.4	36.65	4.0	3 254	0.1852	0.2260±0.25	2.665±0.30	0.08553±0.16	1327.6±3.1	0.84
2. eq, cl, 60–90, 6	0.0264	213.6	56.53	2.2	34 569	0.2629	0.2278±0.71	2.687±0.72	0.08553±0.15	1328.1±2.8	0.98
3. eq, cl, 60–70, 8	0.0151	185.5	45.69	5.6	6 917	0.1846	0.2252±0.30	2.644±0.32	0.08514±0.12	1318.8±2.4	0.92
Z22: Nain type B tholeiitic dyke (grid reference 121 467)											
4. eq, cl, 60, 4	0.0040	298.8	71.83	4.5	3 604	0.1511	0.2244±0.26	2.641±0.31	0.08537±0.17	1323.9±3.4	0.83
5. eq, cl, <60, 20	0.0073	306.3	72.55	3.3	9 347	0.1486	0.2228±0.25	2.611±0.27	0.08499±0.11	1315.2±2.1	0.92
6. eq, cl, <60, 40	0.0167	159.7	38.06	1.8	20 137	0.1492	0.2242±0.30	2.626±0.32	0.08496±0.11	1314.5±2.1	0.94
Z24: Nain type A tholeiitic dyke (grid reference 099 464)											
7. fr, br, 80–100, 3	0.1045	19.74	4.514	11	2 781	0.0831	0.2274±0.25	2.668±0.29	0.08507±0.14	1317.1±2.8	0.87
8. fr, br, 70, 5	0.0646	11.94	2.757	4.2	2 586	0.0865	0.2270±0.34	2.661±0.37	0.08502±0.14	1316.1±2.8	0.92
9. fr, br, 60, 9	0.0579	11.29	2.617	6.2	1 880	0.0957	0.2265±0.35	2.656±0.39	0.08504±0.16	1316.4±3.0	0.92
Z25: Nain type C tholeiitic dyke (grid reference 096 464)											
10. eq, cl, 50, 10	0.0387	36.20	9.896	7.6	2 492	0.1748	0.2208±0.41	2.589±0.43	0.08507±0.14	1317.0±2.6	0.95
11. fr, pk, 70–100, 5	0.0181	4.393	1.162	1.8	615	0.2264	0.2274±0.74	2.707±1.04	0.08633±0.73	1345.6±14	0.72
12. eq, cl, 70, 4	0.0120	84.61	20.86	7.5	1 879	0.1748	0.2250±0.40	2.646±0.47	0.08527±0.26	1321.6±4.9	0.84
Z26: Nain type B tholeiitic dyke (grid reference 102 461)											
13. el, pk, 60–80, 3	0.0370	10.88	2.566	7.2	789	0.0965	0.2266±0.94	2.679±0.99	0.08578±0.29	1333.2±5.6	0.96
14. eq, pk, 60, 10	0.0403	19.62	4.671	9.7	1 144	0.1059	0.2266±0.32	2.666±0.36	0.08534±0.15	1323.4±3.0	0.91
15. eq, pk, 70, 6	0.0471	13.13	3.044	6.1	1 423	0.0966	0.2263±0.49	2.672±0.53	0.08565±0.19	1330.3±3.7	0.93
16. fr, br, 100, 5	0.0479	13.27	3.071	5.1	1 758	0.0981	0.2273±0.38	2.675±0.42	0.08536±0.16	1323.8±3.0	0.93
17. fr, br, 120, 7	0.2100	16.22	3.785	7.9	5 968	0.1072	0.2267±0.19	2.668±0.22	0.08536±0.11	1323.7±2.1	0.86
18. eq, br, <60, 40	0.1853	18.53	4.328	18	2 614	0.0955	0.2276±0.21	2.677±0.24	0.08531±0.12	1322.5±2.3	0.87

[a] All grains separated from the least magnetic fraction separated on a Frantz LB-1 separator at 1.7 A. br, brown; pk, pink; cl, colourless limpid; fr, fragments; eq, equant (1:1–2:1 aspect ratio); el, elongate (3:1–10:1 aspect ratio). Lengths of grains are given in micrometres; the last value is the number of grains analyzed.

[b] Maximum errors are ±20%. Weights were measured on a Cahn C32 microbalance.

[c] Measured ratio corrected for fractionation and common Pb in the spike.

[d] Corrected for fractionation, spike, laboratory blank Pb and U, and initial common Pb (Stacey and Kramers 1975). The laboratory blank Pb composition is $^{206}Pb/^{204}Pb : ^{207}Pb/^{204}Pb : ^{208}Pb/^{204}Pb$ = 17.46 : 15.55 : 37.32. Quoted errors are 2σ (% for atomic ratios, absolute for ages).

[e] $^{207}Pb/^{235}U–^{206}Pb/^{238}U$ error correlation coefficient calculated following Ludwig (1980).

Fig. 8. U–Pb isotope data for Nain dykes Z21, Z22, and Z24. Data for Z22 do not constrain the age of the dyke. The Z22 data show Pb loss, probably occurring during the emplacement of the NPS, with superimposed more recent loss. The 1316–0 Ma and 1328–0 Ma reference lines illustrate recent Pb-loss trajectories.

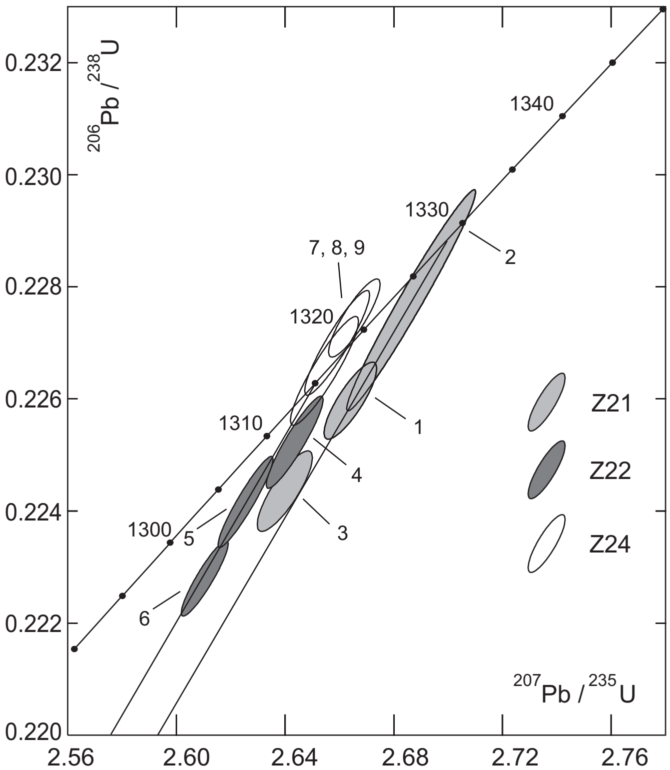
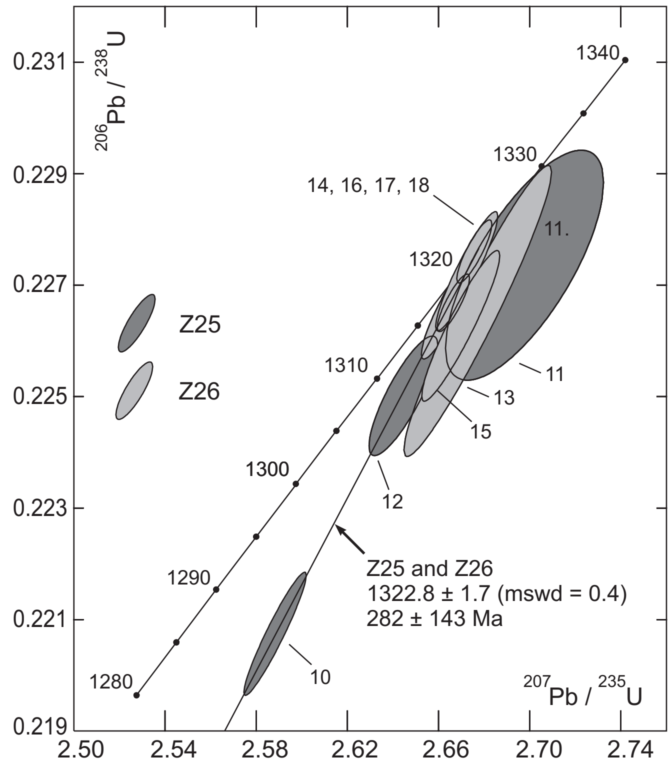


Fig. 9. U–Pb isotope data for Z25 and Z26. Age for Z26 is given by concordant grains. Pinkish zircons (analyses 11, 13, 15) for the two dykes are inherited. The 1322.8 Ma regression line is based on Z25 analyses 10 and 12 and Z26 analyses 14, 16, 17, and 18. mswd, mean square of weighted deviates.



lysed. The complex grains were not analysed on the basis that they represented obvious inheritance. An age of 1328 ± 2 Ma is assigned to Z21, defined by the weighted mean $^{207}Pb/^{206}Pb$ age for the two overlapping concordant and nearly concordant analyses, and is confirmed by the upper intercept of a regression through the two points (Table 1; Fig. 9), forced through a lower intercept of 0 ± 10 Ma. The coarsest zircons were the most concordant, and a third analysis of the smallest (approx. 60 mm) crystals plots to the right of the 1327 Ma discordia line.

Z22: grey granulite-facies tholeiitic dyke

Sample Z22 was collected from a thin, undeformed apophyse of a type B granulite dyke (Fig. 5). Zircons recovered from Z22 are predominantly limpid and equant, all of which are <60 mm long. A very small proportion of the zircons in the dyke have teardrop shapes, colourless to pale pink cores, and thin colourless overgrowths. Three multigrain analyses of abraded, apparently core-free equant zircons were obtained in an attempt to determine the crystallization age of the dyke. The zircons in Z22 have the highest uranium contents encountered for any of the dykes analysed and are among the most discordant. The analyses yield $^{207}Pb/^{206}Pb$ ages that range from 1314 to 1324 Ma (see Fig. 8), with the smallest zircons giving the youngest $^{207}Pb/^{206}Pb$ ages, as was observed for zircons in Z21. The data do not provide a precise age but do support an argument for the dyke being coeval with the overall emplacement period for the Nain plutonic suite.

Z24: black granulite-facies tholeiitic dyke

Sample Z24 is an 18 m wide type A granulite dyke. The dyke has an internal foliation of 006° north and is folded about a 014° north axis, but has an overall northwest–southeast strike. Virtually all of the zircons recovered from Z24 are clear brown fragments of very large (>200 mm) zircons, or 80–120 mm long grains with aspect ratios between 2:1 and 3:1. Prism faces are present but well-defined pyramid faces are absent. Zircons analysed from Z24 were flawless, low-uranium (<20 mg/g U; Table 1) fragments of larger grains. All three analyses are concordant and overlap with each other (Fig. 8). An age of 1316.0 ± 1.5 Ma is assigned to this dyke based on a weighted mean $^{207}Pb/^{206}Pb$ age of all three analyses.

Z25: black amphibolite-facies tholeiitic dyke

The dyke from which sample Z25 was collected unequivocally crosscuts types A and B granulite dykes, including the dyke from which sample Z24 was collected. Z25 is an amphibolite-facies type C tholeiitic dyke and, perhaps significantly, it is the thinnest of all dykes sampled in this study. The zircons recovered from Z25 are the most texturally varied of all the separates recovered from the Nain tholeiitic dykes. The dominant morphological group in Z25 is <70 mm long ellipsoidal grains ranging from colourless to pale pink. In addition to this main group, there are three other subordinate groups of zircons and include >70 mm brownish pink zircon fragments, obvious xenocrysts that are elongate, clear to turbid brown grains, in some cases overgrown with pale pink neocrystalline zircon, and composite grains composed of several rounded grains welded together by pink overgrowths. Of the above zircon types, the elongate clear to turbid grains are unique to Z25 and are similar to zircons typically found in Archaean tonalites and trondhjemites. Data from the colourless to pale pink ellipsoidal zircons were obtained to date the dyke on the basis that the most common zircons were the most likely to be related to dyke crystallization. An analysis of pale pink zircons shows that they have very low uranium contents (~4 ppm) and yield a nearly concordant but imprecise age of 1346 ± 14 Ma. Two more precise analyses, albeit more discordant, of higher U (36–84 ppm) colourless zircons yield a discordia upper intercept age of 1324 ± 13 Ma similar to the age of colourless zircons in Z26 (see below), as highlighted by a 1322.8 ± 1.7 Ma regression obtained for Z25 and Z26 data (Fig. 9). In light of the extremely varied range of zircon morphologies, the range of ages obtained for the elliptical zircons, and the field data for Z25 which indicate post-Z24 intrusion, we conclude that the zircons analysed here are inherited and do not date dyke crystallization.

Z26: grey granulite-facies tholeiitic dyke

Sample Z26 was collected from a 2.3 m wide deformed type B dyke. The dyke is particularly notable for its cusp and lobate margins. The cusps cut the dyke, therefore indicating that the dyke was more competent than the host gneisses at the time of their formation. Z26 contains poorly faceted, equant, pale pink to pale brown zircons. In addition to the equant grains, a very small proportion of zircons recovered from this sample were pale pink–brown elongate cores with pale pink overgrowths or >100 mm grain fragments. Four analyses of the pale brown grains, together with an analysis of pale pink grains, yield an age of 1323.0 ± 1.5 Ma (Fig. 9). Two analyses of the pale pink zircons have $^{207}Pb/^{206}Pb$ ages of 1329 and 1332 Ma, indicating that some of the pink grains contain a minor inherited component not identified during picking.

Discussion

Within the Nain Plutonic Suite, zircon and baddeleyite isotope data are generally simple, and zircons appear to record reliably the crystallization ages of both anorthositic and related ferrodioritic rocks, and NPS-related anorogenic granitoids: according to Hamilton (1994), Hamilton et al. (1994), and others (J. Connelly, personal communication, 1994), metamorphic growth of zircon is not recorded, and so NPS data are typically concordant or nearly concordant with only minor amounts of Pb loss. The data presented here show, however, that the zircons in the ca. 1300 Ma Nain tholeiitic metabasic dykes are more complex.

All of the data obtained in this study plot in a region bounded between a lower 1316–0 Ma reference line through data for Z22 and Z24 data and 1346 Ma as constrained by the analysis of pink zircon in Z25. Interpretation of the data array is not straightforward. The paucity of zircons in the dikes has thus far frustrated attempts to observe the zircons in their petrographic context and hence unequivocal evidence for or against a primary origin for some of the zircons is absent. Samples Z21, Z24, and Z26 appear to have the least complicated zircon populations and are more typical of main NPS intrusives. In these samples there is a predominant group of relatively coarse grained zircons with only minor inheritance and trace development of overgrowths, coupled with the highest degree of data concordance. In the absence of evidence to the contrary, the coarse-grained zircons are interpreted to be primary. The rest of the data array is thus interpreted as resulting from some inheritance, primary magmatic growth, Pb loss, and (or) new zircon growth during deformation and metamorphism associated with NPS emplacement. Clearly, if the dominant group of zircons in Z21, Z24, and Z26 is in the future shown to be other than primary, then the interpretation of the age of emplacement and importance of inheritance and metamorphism for the entire sample suite would require reevaluation.

Given that the field observations on the islands southeast of Nukasusutok indicate dyke emplacement within active shear zones, the ages obtained from dykes on these islands are interpreted as reliably recording dyke emplacement and deformation within shear zones spanning at least 11.5 ± 3.6 Ma, between ca. 1328 ± 2 Ma and ca. 1316 ± 1.6 Ma. This time interval is well within the time period covering the intrusion of many of the Nain anorthosites and ferrodiorites. The reversal of competence contrast from types A and B dykes to type C dykes suggests that the metamorphic grade of the host gneisses may have decreased during this time period, causing the gneisses to become more competent by the time the younger C dykes were intruded. (Additionally, dykes of low amphibolite grade in the Dog Island area, to the north, which are intruded by brittle crack failure and have no shear component, may be interpreted as the last dyke intrusions to have been injected during NPS thermotectonic events.)

The Pb-loss patterns of the data suggest that some Pb loss occurred at an early time, probably during post-dyke emplacement deformation within the shear zones, or in association with the emplacement and cooling of the NPS as a whole. The most discordant data are from the smallest zircons, particularly those which have high uranium contents. Integrated Pb loss leading to trajectories trending to 0 Ma is apparent, but older Pb loss must be present to explain the fact that as Pb loss becomes more pronounced for many of the dykes (e.g., Z21, Z22, or Z25), the $^{207}Pb/^{206}Pb$ ages of the data decrease.

Inheritance in major NPS intrusions is generally not recorded, with the exception of the Satosuakuluk ferrodioritic megadyke where 1315 Ma zircons were inherited within a magma which crystallized at 1301 Ma as constrained by baddeleyite (Hamilton 1994). In contrast, there is good evidence for inheritance in the Nain metabasic dykes. The case for inheritance is strongest for Z25 and Z26, where there are differences in colour or U concentrations between groups of zircons, and there is field evidence indicating that dykes with 1316 Ma concordant zircons are crosscut by dykes containing older zircons. The grey granulite dyke Z26 was emplaced under granulite-facies conditions and contains brownish and pinkish zircons, with the pinkish grains tending to be more discordant and slightly older. Z25 is part of a suite of black amphibolite-facies dykes which locally, i.e., proximal to Z24, systematically crosscuts the grey granulite dykes. The zircons in Z25 show greater morphological variation than encountered in any of the other Nain dyke samples. Analyses of some of these zircons showed a wide range of uranium contents and $^{207}Pb/^{206}Pb$ ages, consistent with a scenario where most or all of the zircons in Z25 are inherited. A variety of sources are probably contributing xenocrysts to the type C dyke Z25, and one of the sources is very likely some early component of the NPS. The best evidence for this is the 1346 ± 14 Ma zircons that overlap in age with zircons from the structurally older dykes Z26 and the oldest dated members of the NPS (Hamilton 1994) coupled with the 4 ppm U concentration of these zircons, which would be very low for zircons from potential crustal contaminants possessing typical intermediate to felsic chemical characteristics.

It is now worth considering the precise relationship between the U–Pb zircon age data and the structural characteristics of the dykes. The best possible evidence that the U–Pb dates could provide for dyke emplacement into an active thermo-tectonic environment would be if the variation of concordant or near-concordant dates within individual intrusions approached the variation present in the entire dyke assemblage. Whereas the oldest date in a particular intrusion would reflect the timing of emplacement, the youngest would affect the final episode of recrystallization and would be the same in all intrusions. In practice, only the data for dyke sample Z22 approaches this criterion: although later Pb loss has made the data slightly discordant, the evidence for earlier Pb loss suggests that two distinct ages of crystallization or recrystallization have occurred within the time envelope of Nain events. The excellent field evidence for synshear intrusion at this sample locality (Fig. 5) strongly suggests that the dyke was injected into a hot, mobile environment.

Samples Z21, Z24, and Z26 do not give a single distinct age for crystallization, which by themselves do not lend support for a synmetamorphic and syndeformational environment of emplacement. However, taken together, all the ages falling within the time frame of Nain events strongly support the hypothesis that dyke injection was coeval with metamorphism and tectonism associated with NPS magmatism. The alternative hypothesis, that the dykes were injected prior to NPS magmatism, possibly in several magmatic episodes, and were then strongly recrystallized, can be regarded as improbable on several grounds. None of the dyke samples gave zircon ages older than NPS-related events. Concordant metamorphic ages of the type noted in this study could be produced by strong recrystallization of older material during NPS magmatism, but many dykes at amphibolite grade retain remnant igneous textures, showing that complete recrystallization did not occur. The presence of east–west-trending dykes (now amphibolite), with brittle emplacement structures, near to strongly recrystallized and deformed (granulite) dykes in the Dog Island area, and demonstrably crosscutting grey granulite dykes on the islands southeast of Nukasusutok island, clearly indicates that granulite recrystallization did not predate the emplacement of the entire dyke assemblage. Clearly, if the injection of the amphibolite-grade dykes predated Nain tectono-thermal events, then peak metamorphic conditions within the Nain could not have attained the high metamorphic grades necessary for the complete recrystallization of the dykes and the resetting of their zircon U–Pb systematics. The implication is that at least the amphibolite dykes cannot be older than Nain tectono-thermal events.

Furthermore, even if zircon recrystallization was extensive during high-grade Nain metamorphism, then this argument would have to be applied equally to all Nain intrusions, in which case all Nain ages would have to be interpreted as being metamorphic in origin. In fact, most of the Pb loss within the Nain metadyke assemblage is trending towards 0 Ma, possibly because of diffusion and U-decay damage. If there were high levels of Pb diffusion during Nain events, then a subparallel array of data over the time period between intrusion of the dykes and the end of their exposure to granulite temperatures should be observed. Additionally, if all dykes were pre-NPS, then the zircons analysed should show a positive correlation between levels of Pb loss and U contents. Given that the dykes come from a relatively small area when compared with the size of Nain intrusions, it is unlikely that the metamorphic history of each dyke would be significantly different. In practice, no such correlation is observed.

The emplacement of east–west-trending amphibolite dykes in the Dog Island area, with brittle emplacement structures near to strongly recrystallized and deformed granulite dykes, clearly indicates that granulite recrystallization did not predate the emplacement of the entire metadyke assemblage.

The most likely explanation for the emplacement of the dyke assemblage is that the dykes represent leaks from underlying magma bodies (Ryan 1995), which also gave rise to the voluminous NPS magmatism. We can more rigorously test this hypothesis geochemically (see footnote 5), but the age correspondence is confirmed. The earlier granulite dykes were injected into a hot, ductile crustal environment in a compressive shear regime. They were consequently strongly affected by shear deformation and high-grade metamorphism. The later amphibolite dykes were injected into a less ductile crustal environment under lower grade metamorphic conditions. The waning thermal conditions were matched by a stress regime which became less compressive, as shown by the fact that they are often only weakly sheared or were emplaced by tensile failure of the gneissic host rocks rather than by simple shear.

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References

Berg, J.H. 1980. Snowflake troctolite in the Hettasch intrusion, Labrador: evidence for magma-mixing and supercooling in a plutonic environment. Contributions to Mineralogy and Petrology, **72**: 339–351.

Bridgwater, D., and Myers, J.S. 1979. Outline of the Nagssugtoqidian mobile belt of East Greenland. Rapport Grønlands Geologiske Undersøgelse, **89**: 9–18.

Bridgwater, D., and Schiøtte, L. 1991. The Archaean gneiss complex of northern Labrador: preview of current results, ideas and problems. Bulletin of the Geological Society of Denmark, **39**: 153–166.

Cadman, A.C., Harris, D., and Ryan, B. 1993. An investigation of some metamorphosed mafic dykes of the Nain area, Labrador, Part 1. *In* Current research. Geological Survey Branch, Newfoundland Department of Mines and Energy, Report 93-1, pp. 1–15.

Connelly, J., and Ryan, B. 1993. U–Pb constraints on the thermotectonic history of the Nain area. *In* Eastern Canada Onshore–Offshore Transect (ECSOOT). *Edited by* J. Hall and R.J. Wardle. Report 32, Lithoprobe Secretariat, University of British Colombia, Vancouver, pp. 137–144.

Connelly, J.N., and Ryan, B. 1994. Late Archean and Proterozoic events in the central Nain craton. *In* Eastern Canada Onshore–Offshore Transect (ECSOOT). *Edited by* J. Hall and R.J. Wardle. Report 36, Lithoprobe Secretariat, University of British Colombia, Vancouver, pp. 53–61.

Connelly, J.N., Ryan, B., and Dunning, G.R. 1992. U–Pb geochronology from the Nain archipelago area, Labrador. *In* Eastern Canadian Shield Onshore–Offshore Transect (ECSOOT). Report 27, Lithoprobe Secretariat, Vancouver, pp. 72–75.

Fram, M.S., and Longhi, J. 1992. Phase equilibria of dikes associated with Proterozoic anorthosite complexes. American Mineralogist, **77**: 605–616.

Gower, C.F., Rivers, T., and Brewer, T.S. 1990. Middle Proterozoic mafic magmatism in Labrador, eastern Canada. *In* Mid-Proterozoic Laurentia–Baltica. *Edited by* C.F. Gower, T. Rivers, and B. Ryan. Geological Association of Canada, Special Paper 38, pp. 485–506.

Hamilton, M.A. 1994. Review of isotopic data for the Nain Plutonic Suite in anorthositic, granitoid and related rocks of the Nain Plutonic Suite. Field excursion to the Nain area, 4–10 Aug. 1994. International Geological Correlation Programme, IGCP Projects 290 and 315.

Hamilton, M.A., Emslie, R.F., and Roddick, J.C. 1994. Detailed emplacement chronology of basic magmas of the mid-Proterozoic Nain Plutonic Suite, Labrador: insights from U–Pb systematics in zircon and baddeleyite. *In* Proceedings of the 8th International Conference on Geochronology, Cosmochronology, and Isotope Geology (Program Abstracts). U.S. Geological Survey, Circular 1107, p. 124.

Hanmer, S., and Scott, D.J. 1990. Structural observations in the Gilbert River belt, Grenville Province, southeastern Labrador. *In* Current research, part C. Geological Survey of Canada, Paper 90-1C, pp. 1–12.

Jack, S.M.B. 1978. The North Atlantic Proterozoic dyke swarm. Ph.D. thesis, University of Liverpool, Liverpool, U.K.

Jaffey, A.J., Flynn, K.F., Glendenin, L.E., Bentley, W.C., and Essing, A.M. 1971. Precision measurements of half-lives and specific activities of ^{235}U and ^{238}U. Physical Review C: Nuclear Physics, **4**: 1889–1906.

Krogh, T.E. 1973. A low contamination method for the hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations. Geochimica et Cosmochimica Acta, **37**: 485–494.

Krogh, T.E. 1982. Improved accuracy of U–Pb zircon ages by the creation of more concordant systems using an air-abrasion technique. Geochimica et Cosmochimica Acta, **46**: 637–649.

Ludwig, K.R. 1980. Calculation of uncertainties of U–Pb isotope data. Earth and Planetary Science Letters, **46**: 212–220.

Myers, J.S. 1984. The Nagssugtoqidian mobile belt of Greenland. *In* Precambrian tectonics illustrated. *Edited by* A. Kroner and R. Greiling. Schweizerbart'sche Verlagsbuchhandlung, Stuttgart, pp. 237–250.

Nash, D. 1979. An interpretation of irregular dyke forms in the Itivdleq shear zone, West Greenland. Rapport Grønlands Geologiske Undersøgelse, **89**: 77–83.

Noble, S.R., Tucker, R.D., and Pharaoh, T.C. 1993. Lower Palaeozoic and Precambrian igneous rocks from eastern England, and their bearing on late Ordovician closure of the Tornquist Sea: constraints from U–Pb and Nd isotopes. Geological Magazine, **130**: 835–846.

Ryan, B. 1991. New perspectives on the Nain Plutonic Suite and its country rocks. *In* Current research. Geological Survey Branch, Newfoundland Department of Mines and Energy, Report 91-1, pp. 231–255.

Ryan, B. 1993. Further results of mapping gneissic and plutonic rock of the Nain Bay area, Labrador. *In* Current research. Geological Survey Branch, Newfoundland Department of Mines and Energy, Report 92-1, pp. 61–75.

Ryan, B. 1995. Morphological features of multigeneration basic dykes near Nain, Labrador: clues to the original emplacement mechanisms and subsequent deformation. Precambrian Research, **75**: 91–118.

Ryan, A.B., and Emslie, R.F. 1994. Pre-Elsonian mafic magmatism in the Nain igneous complex, Labrador: the Bridges layered intrusion – comment. Precambrian Research, **68**: 179–181.

Ryan, B., Krogh, T.E., Heaman, L., Schärer, U., Phillippe, S., and Oliver, G. 1991. On recent geochronological studies in the Nain Province, Churchill Province, and the Nain Plutonic Suite, north-central Labrador. *In* Current research. Geological Survey Branch, Newfoundland Department of Mines and Energy, Report 91-1, pp. 257–261.

Stacey, J.S., and Kramers, J.D. 1975. Approximation of terrestrial lead isotope evolution by a two-stage model. Earth and Planetary Science Letters, **26**: 207–221.