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THE PETROGENESIS AND EMPLACEMENT OF PROTEROZOIC DYKE SWARMS, PART 3: GEOCHEMISTRY AND MAGMATIC EVOLUTION OF THE MAFIC DYKE SWARMS OF THE HOPEDALE BLOCK, LABRADOR

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ABSTRACT

The Kikkertavak and Harp dykes of the Archean Hopedale block, Labrador, show remarkable similarities in their geochemical evolution, despite some striking differences in petrographic textures and the 1 Ga interlude between the intrusion of the two swarms. The differing textural features and field orientations of the dykes suggest injection of the swarms within different tectonic environments, whereas the geochemical similarities between these and other Proterozoic swarms suggest a cyclicity, unconnected with orogenic crust-forming events in the Hopedale block or elsewhere. Study of these dykes may therefore yield information concerning the formation of dyke swarms in the Proterozoic and the usefulness of Phanerozoic models in contributing to their understanding.

INTRODUCTION

Proterozoic dyke swarms are an important component of Precambrian magmatism. Much debate has focussed on the applicability of Phanerozoic models of intrusion versus arguments that uniquely Precambrian processes are necessary to explain their formation. They provide clues to processes of magma evolution and also the nature of the tapped mantle sources and their secular change, if any, with time. Proterozoic dyke swarms may require more than one mechanism of intrusion, or more than one variant of tectonic style to explain their formation. Examples of such swarms include the Early Proterozoic Kikkertavak and Middle Proterozoic Harp dyke swarms, which intrude the Archean Hopedale block. The existence of these two swarms allow changes and developments in mantle source characteristics, tectonics and magmatic styles to be assessed over the period of their intrusion.

PREVIOUS WORK

In recent years, attempts have been made, as part of IGCP project no. 257, to research Proterozoic dyke swarms in the context of earth evolution. Little detailed research has been done on either of the dyke swarms in the Hopedale block. Previous Kikkertavak data consists solely of analyses undertaken by the Geological Survey of Canada (GSC) during a regional 1:100,000-scale mapping project (Ermanovics, *in press*). However, the Harp swarm has been investigated in the area around the Harp Lake anorthosite–gabbro plutonic complex approximately 100 km west of the Hopedale block by Meyers and Emslie (1977).

The evolutionary history of the Archean gneisses that make up the Hopedale block was studied during the GSC program (Ermanovics, 1979, 1980, 1981a, b, 1984; Ermanovics and Raudsepp, 1979; Ermanovics and Korstgaard, 1981; Ermanovics *et al.*, 1982; Ermanovics, *in press*). Earlier work has also concentrated on structural and metamorphic histories (e.g., Taylor, 1971) and correlation with similar terranes in West Greenland (e.g., Sutton *et al.*, 1972).

GEOLOGICAL SETTING OF THE DYKE SWARMS

The Hopedale block lies in the southern part of the Nain Province, bounded by the Churchill Province in the west and the Makkovik Province in the southeast (Figures 1 and 2). It consists of polydeformed, mainly granodioritic to tonalitic gneisses that have a predominantly northeast-southwest (Fiordian) trend. The Fiordian-trending fabrics are interpreted by Ermanovics *et al.* (1982) to be late Archean and postdate the granitoid rocks of the Kanairiktok Intrusive Suite, dated at about 2830 Ma (U–Pb zircon concordia, Loveridge *et al.*, 1987). The Fiordian trend overprints an earlier northwest-southeast (Hopedalian) trend, which was probably developed between 3250 and 3000 Ma (Grant *et al.*, 1983; Loveridge *et al.*, 1987). Within both the Fiordian and Hopedalian domains, subvertical planar and linear fabrics show strong parallelism, suggesting block-wide, shear-zone deformation in both cases. The Fiordian-trending gneisses, which dominate the study area, are deformed agmatitic gneisses having some amphibolite bands. The gneisses are at amphibolite facies, possibly retrogressed from a granulite-facies assemblage. Any very early Archean structural and metamorphic histories were largely erased by the Hopedalian event (Ermanovics *et al.*, 1982).

Fiordian structural trends are truncated by diabase dykes forming sub-rectiplanar intrusions from 1 cm to 100 m in

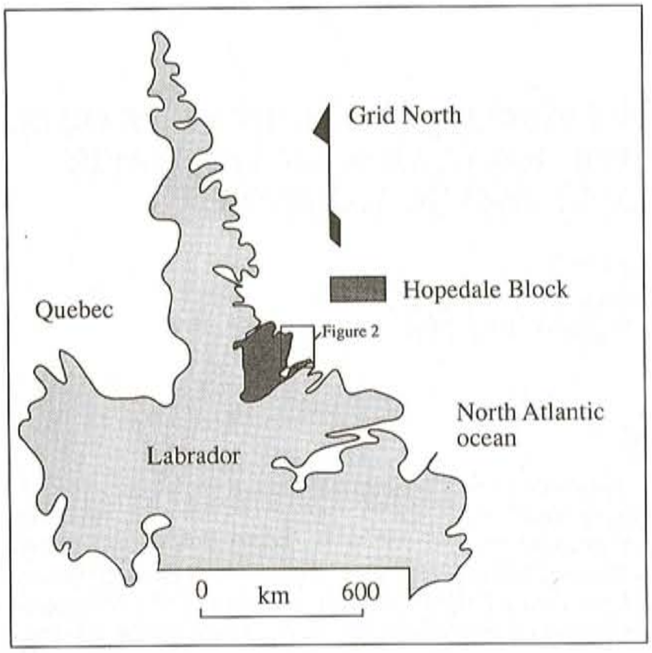

Figure 1. *Location of the Hopedale block, Labrador.*

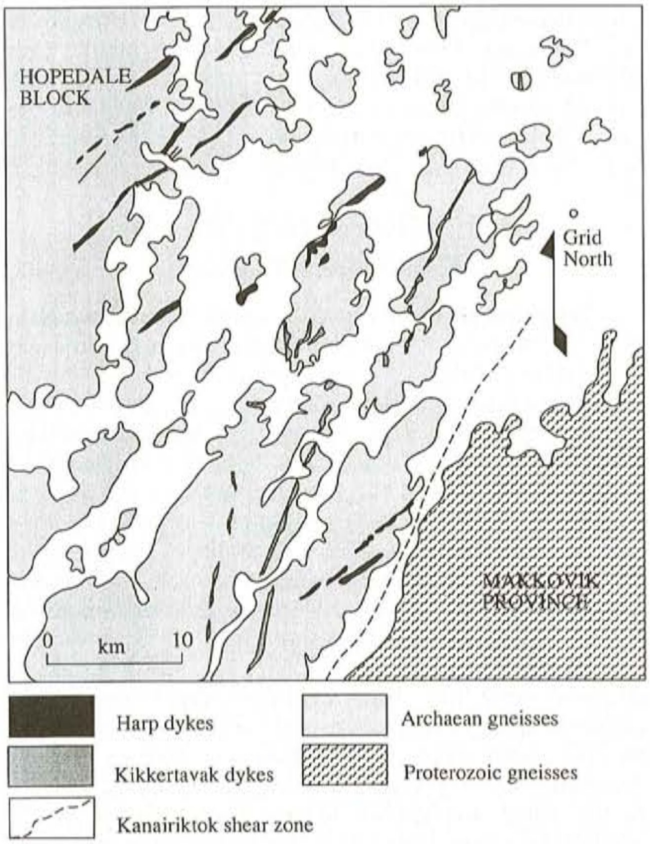

Figure 2. *Map of the coastal region of the Hopedale block, Labrador, showing gabbroic dykes of the Kikkertavak and Harp dyke swarms. (Adapted from Ermanovics, 1979, 1981b and 1984)*

width. Dykes of the Kikkertavak swarm have no consistent orientation except for the larger gabbro bodies (>20 m width), which trend north to northeast. The Harp dykes have a strong northeast-southwest orientation (parallel to the Fiordian trend) irrespective of dyke width. Dykes of both swarms are only locally concordant with the gneissic foliation where planar fabrics are especially well developed (Cadman, *this volume*).

Neither the Kikkertavak nor Harp dykes show any evidence of post-intrusion reorientation by crustal folding or tilting, but shearing and low-grade alteration does affect dykes of the Kikkertavak swarm toward the Kanairiktok shear zone, which forms the boundary between the Hopedale block and the Proterozoic Makkovik Province. The Kikkertavak dykes are dated at ca. 2200 Ma (Rb–Sr whole-rock data, B.J. Fryer, in Grant *et al.*, 1983) and the Harp dykes at ca. 1200 Ma, (Rb–Sr whole-rock data, F.R. Voner, in Ermanovics *et al.*, 1982; Grant *et al.*, 1983).

Two other periods of mafic dyke injection are present in the Hopedale block. The late Archean Hopedale dykes were deformed by the Fiordian event and now consist of amphibolite boudins and discontinuous bands. Dioritic and lamprophyric dykes, intruded ca. 1640 Ma and termed the Kokkovik intrusions, are found rarely throughout the Hopedale block, with small sills present in the west of the area. Both dyke groups are volumetrically minor compared to the Kikkertavak and Harp swarms and are not discussed here.

CLASSIFICATION OF THE DYKE SWARMS

Geochemically, the Proterozoic dyke swarms of the Hopedale block can be divided into three types: tholeiitic basalts, high-magnesian–low-iron dykes, and high-magnesian–high-iron dykes. Tholeiitic magmas form the vast majority of intrusions in both the Kikkertavak and Harp dyke swarms.

The largely unaltered post-Fiordian rectiplanar intrusions, which make up the bulk of the dykes in the area, were first mapped solely as 'Kikkertavak' dykes and then reclassified on the basis of petrography as being either altered diabasic or gabbroic dykes with a simple gabbroic mineralogy (Kikkertavak) or fresh olivine-bearing diabases–gabbros having affinities to the Harp dykes (Ermanovics and Raudsepp, 1979; Ermanovics *et al.*, 1982) described from around the Harp Lake intrusive complex (Meyers and Emslie, 1977).

THE KIKKERTAVAK DYKES

Petrographically, the Kikkertavak dykes are classified as containing clinopyroxene, plagioclase (labradorite), magnetite, ilmenite and secondary hornblende, rare biotite, quartz and myrmekitic alkali feldspar (Ermanovics, *in press*). The labradorite forms an ophitic to subophitic texture with clinopyroxene, is commonly zoned and locally consists of partially resorbed cores surrounded by euhedral-zoned overgrowths. Alteration of feldspar to sericite, especially in crystal cores, is ubiquitous in the Kikkertavak dykes. Opaque minerals also show common crystal zoning from titanium-rich cores to magnetitic rims, whereas others show unzoned magnetite compositions.

Kikkertavak dykes are often plagioclase phyric and heavily zoned in terms of the volumetric abundance of phenocrysts across the width of the dyke: phenocrysts are commonly around 1 cm in length, zoned, euhedral and locally have glomeroporphyritic textures. In places, in highly differentiated dykes, plagioclase megacrysts up to 15 cm long are present in thin (< 3 m) phenocryst-rich margin-parallel zones. Microphenocrysts of clinopyroxene and plagioclase are also commonly present in thin sections of chilled margins. Other observed textural features included gabbroic cognate xenoliths. Xenoliths of country rock are rare within the dykes and where present consist of host-rock screens separated from the wall rock during the initial stages of dyke dilation.

THE HARP DYKES

The primary mineralogy of the Harp dykes consists of olivine, Ti-rich clinopyroxene, plagioclase (labradorite–andesine), magnetite, ilmenite and apatite (Ermanovics, *in press*). Dykes are rarely phyric and where present, plagioclase phenocrysts are sparse. Microphenocrysts of clinopyroxene, olivine and (most commonly) plagioclase are also common in thin sections of samples taken at chilled margins. The larger gabbroic Harp intrusions often contain patches of dioritic pegmatite (Ermanovics *et al.*, 1982) along with euhedral megacrysts of plagioclase, clinopyroxene and hornblende up to 10 cm in length.

DISCRIMINATION OF KIKKERTAVAK AND HARP SWARMS

Kikkertavak and Harp dykes have traditionally been discriminated on the basis of petrology and alteration textures (e.g., Ermanovics and Raudsepp, 1979). However, in practice, neither is a wholly satisfactory guide to swarm classification. Dykes of the Kikkertavak swarm frequently have brecciated, sheared or altered margins (Kranck, 1953; Ermanovics and Raudsepp, 1979) for distances of up to 20 km north of Kanairiktok Bay, probably as a consequence of Proterozoic tectonism along the Kanairiktok shear zone. The Late Proterozoic Harp dykes do not show this feature and thus, sheared margins are a confirmation of a Kikkertavak age. Associated alteration reaches amphibolite facies within 2 km of the Kanairiktok shear zone where feldspar is replaced by sericite, and clinopyroxene by hornblende, actinolite and uralitic amphiboles. At greater distances, clinopyroxene is unaltered except for the rare presence of secondary hornblendic rims on some crystals, whereas feldspar remains seriticized to variable degrees throughout the field area. Sericitic alteration is also common to a lesser extent in dykes classified as 'Harp' intrusions, and hence, cannot be used as a feature exclusive to Kikkertavak dykes.

Away from the Kanairiktok shear zone, a previous criteria for the classification of non-phyric dykes as belonging to the Harp swarm, namely the presence of olivine, is not always conclusive. In one major north-northeast-trending gabbroic dyke stretching from the mouth of Little Bay to the mouth of Kanairiktok Bay, accessory olivine is replaced by magnetite. Within 5 km of Kanairiktok Bay, alteration of plagioclase and clinopyroxene increases and olivine disappears as the shear zone is approached. To the north of this dyke, intrusions of similar size and orientation have the megacrystic texture characteristic of some Kikkertavak dykes. Hence, this olivine-bearing dyke is almost certainly of Kikkertavak age. The absence of olivine in southern portions of this dyke is probably due to the complete alteration of the mineral to serpentine. Similarly, in fresher intrusions classified as 'Harp dykes', olivine maybe completely pseudomorphed by serpentine whereas other minerals are left unaltered. In more highly altered dykes, such pseudomorphs become much more diffuse and as a consequence the parent mineral is dificult to identify. Therefore, the presence of olivine and degree of alteration maybe to some extent mutually dependent criteria unassociated with the primary petrological characteristics of the dyke magma.

The larger intrusions can be classified on the basis of their field trend: Kikkertavak gabbroic dykes and some thick (width > 10 m) diabases have a north to north-northeast trend, whereas the majority of gabbroic dykes (10 to 100 m in width) have consistent strikes of 050 to 060° that are characteristic of Harp dykes (Ermanovics and Raudsepp, 1979). Some smaller diabase dykes can also be classified as Harp on the basis of maintaining a consistent northeast trend. However, the wide variety of other orientations causes problems in classification unless they possess some of the other diagnostic features described above.

High-Magnesian–Low-Iron Dykes

Four picrite dykes were identified in the field area. One 20-m-wide dyke, 5 km northwest of the Kanairiktok shear zone has well-developed actinolitic rims on clinopyroxenes and a sheared margin characteristic of some Kikkertavak dykes. The primary mineralogy consists of olivine, clinopyroxene, plagioclase and opaques. These dykes also show a high degree of alteration: olivine is commonly 60 to 100 percent replaced and pseudomorphed by serpentine; clinopyroxene is replaced by hornblende, actinolite and uralite; and plagioclase is replaced by sericite.

Another picrite dyke, 10 km northwest of the Kanairiktok shear zone on Kikkertavak Island, displays well-developed crenulated fabrics, complete alteration of the original mineralogy, and contains few remaining pseudomorphs. Two other picrites 20 km northwest of the shear zone show similar alteration states. These latter three picrites are laterally impersistent, narrow (< 5 m) and have a deep green colouration. This degree of alteration well away from the Kanairiktok shear zone is probably a consequence of the susceptibility of serpentine to deformation, rather than to a higher metamorphic grade having been attained by these dykes in comparison to altered tholeiitic intrusions.

High-Iron–High-Magnesian Dykes

Two dykes in the field area have this unique geochemistry and are very distinct from the dykes discussed above. They appear black and fresh both in the field and in thin section, and therefore, are classed as members of the Harp swarm. One such dyke, striking 044°, contains 20 to 30 percent euhedral olivine phenocrysts largely altered to serpentine pseudomorphs. The groundmass consists of opaque phases, clinopyroxene and plagioclase, and the proportion of opaques is highest at the northwest margin (50 percent). Reaction rims are well developed against both the tonalitic country rock, and around partially resorbed olivine crystals that lie at the margin. Both reaction rims and resorption of the olivines decrease toward the centre of the dykes. The southeastern margin has a much coarser mineralogy, containing olivine (45 percent), plagioclase (45 percent) and opaques (10 percent) and lacking groundmass or evidence of reaction haloes in the crystals or against country rocks.

GEOCHEMISTRY

The geochemistry of the two dyke swarms is based on samples positively identified by the features discussed above as belonging to either the Kikkertavak or Harp swarm. The majority of the samples are at present unclassified and have therefore, not been used in the interpretation of the geochemistry.

The geochemistry of the Kikkertavak and Harp dyke swarms is summarized in a number of variation diagrams. Figures 3 to 8 are trace-element spidergrams and REE plots for the Kikkertavak dykes. Figures 9 to 12 show similar plots for the Harp dyke swarm. Figures 13 to 21 illustrate major-element versus trace-element variation diagrams for the Kikkertavak and Harp swarms. All samples are tholeiitic basalts unless otherwise stated.

CRYSTALLIZATION PROCESSES

Despite the petrographic differences between the tholeiitic dykes in the Kikkertavak and Harp swarms, their geochemistry shows many similarities. Both suites show good correlation between CaO percent and MgO percent (Figure 13), suggesting clinopyroxene–plagioclase fractionation. This trend is common to many flood basalt provinces: for example, Deccan Plateau basalts (e.g., Cox and Hawksworth, 1985), Karoo volcanics series (e.g., Cox, 1980, 1983) and Columbia River basalts (Basaltic Volcanism Study Project, 1981). The absence of olivine (except rarely in accessory amounts) in the Kikkertavak tholeiite dykes suggests that this phase is not likely to be involved in fractionation of the tholeiitic basalts.

The high-iron (Fe_20_3) concentrations (total iron = 9.21 percent) reached by both Kikkertavak and Harp magmas point to plagioclase being the major crystallizing phase in the Labrador swarms. This is supported by the plagioclase megaphyric textures of some Kikkertavak dykes (Cadman, 1989) and the absence of any other phenocrystal phases. However, the Harp dykes show the development of an equally strong iron-enrichment pattern without the development of porphyritic textures.

The negative Sr anomaly seen in spidergrams for all dyke types discussed (Figures 3, 4, 9 and 10) could be due to derivation from a Sr depleted source, a consequence of plagioclase fractionation, or a mixture of both. Selected spidergrams for the Kikkertavak tholeiites (Figure 5) show a deepening of the Sr anomaly with increasing incompatible element concentration. The most primitive samples in the spidergram have no Sr anomaly. This pattern suggests that the Sr anomaly is entirely developed by plagioclase fractionation.

Figure 16 shows Fe_2O_3 percent against the measured Sr anomaly (Sr*) for the Kikkertavak and Harp dykes. In both swarms, the Sr anomaly is clearly highly sensitive to increases in Fe_2O_3 content. Apart from a few dyke-centre samples that plot with positive Sr anomalies, which are probably due to the accumulation of feldspar crystals, samples plotted with anomalies approaching zero ranged between 10 to 16 percent Fe_2O_3. The onset of plagioclase fractionation quickly drives the Sr anomaly to be deeply negative as Fe_2O_3 content increases.

Spidergrams for the Kikkertavak and Harp tholeiites (Figures 3 and 9) showed that most samples have a pronounced negative Nb anomaly. Similarly, Figure 17 shows that the most iron-poor tholeiites in both swarms are strongly depleted in Nb, with normalized Nb/La = 0.2. More iron-rich magmas showed higher normalized Nb/La ratios with $Nb/La > 1$ in samples from both swarms where Fe_2O_3 is > 18 percent.

The two Kikkertavak dyke samples with primordial mantle-normalized $Nb/La>1$ correspond to two data points that have much higher Nb/Zr ratios than the rest of the Kikkertavak tholeiitic sequence on Figure 21. High V (Figure 15) and TiO_2 (Figure 20) contents are also present in these samples, and therefore, these samples may represent cumulates containing large amounts of ilmenitic or titanomagnetitic material.

Similarly, the high-magnesian dykes classified as belonging to the Kikkertavak swarm show a large variation in CaO:MgO ratios (Figure 13) and may contain cumulate material, though their spidergrams show similar negative Sr and Nb anomalies to the Kikkertavak tholeiites (Figure 4).

The Harp dykes show a similar trend to the Kikkertavak tholeiitic dykes in Fe_2O_3 vs. V (Figure 15), Fe_2O_3 vs. normalized Nb/La (Figure 17) and Fe_2O_3 vs. TiO_2 (Figure 20), suggesting that the two dyke swarms were formed by comparable geochemical processes. The high-magnesian–high-iron dykes classified as belonging to the Harp swarm are those more enriched in TiO_2, V and Nb and also have distinctly higher Nb/Zr ratios than other Harp tholeiites (Figure 21). The described petrography of these rocks suggests that they contain cumulates of olivine and/or titaniferous

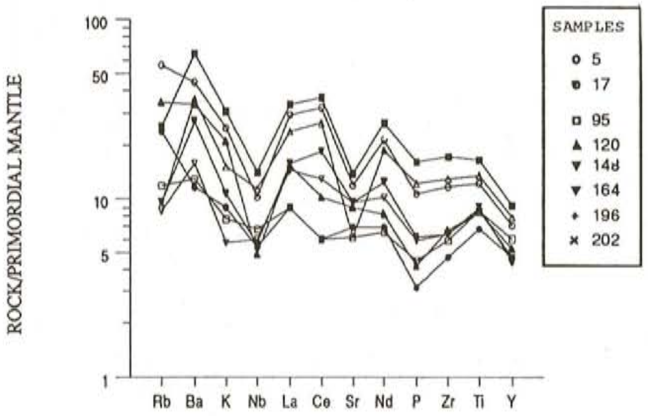

Figure 3. *Spidergram for Kikkertavak tholeiitic dykes. Note the Nb and Sr negative anomalies and the variable Rb/Ba ratio.*

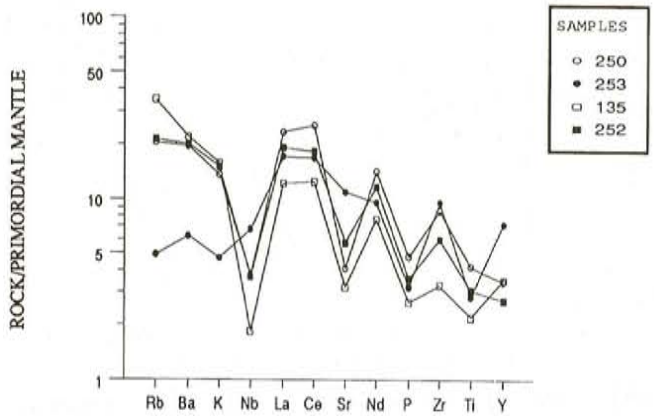

Figure 4. *Spidergram for high-magnesian dykes of suspected Kikkertavak age.*

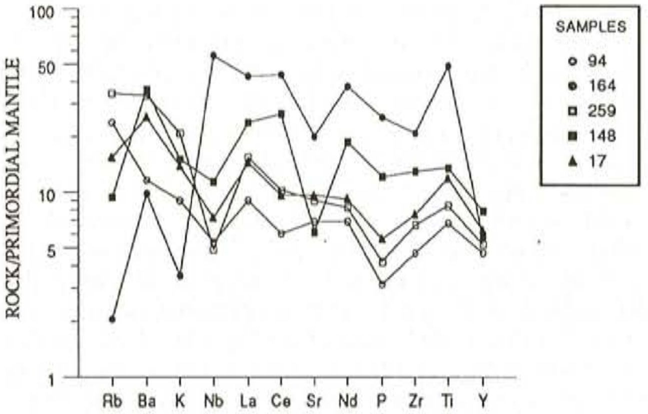

Figure 5. *Spidergram for selected Kikkertavak tholeiites, showing the development of the Sr anomaly in dykes with higher incompatible element abundances.*

phases, as the reaction rims on the olivine phenocrysts suggest non-equilibrium with the predominantly metal oxide groundmass.

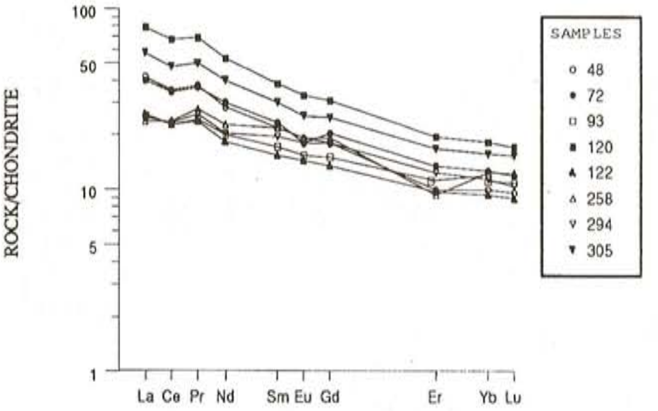

Figure 6. *Plot of rare earths for Kikkertavak tholeiites, showing slight HREE depletion.*

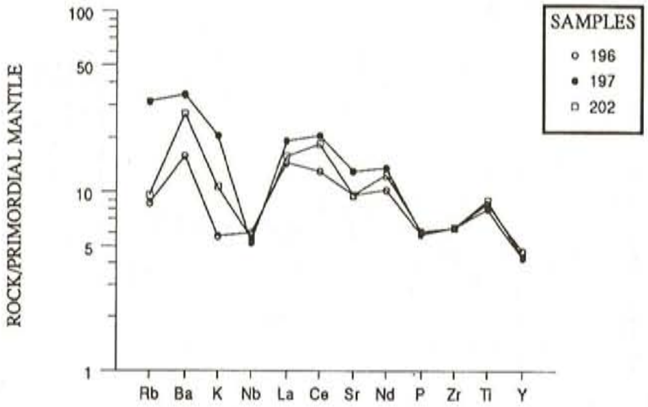

Figure 7. *Plot of three samples representing the margins (hollow symbols) and centre of a single Kikkertavak dyke. The depletion of Rb at the margins suggests that the wall rock has not contributed incompatible elements to the dyke margins.*

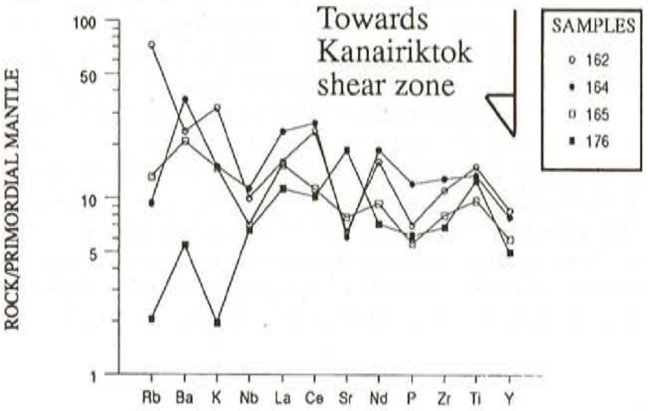

Figure 8. *Plot of samples in a single dyke in descending order toward the Kanairiktok shear zone, showing the progressive depletion in large-ion lithophile elements.*

Rare-earth patterns for the Kikkertavak tholeiitic suite show a consistent heavy rare-earth depletion, which probably signifies the presence of garnet in the source residue (Figure

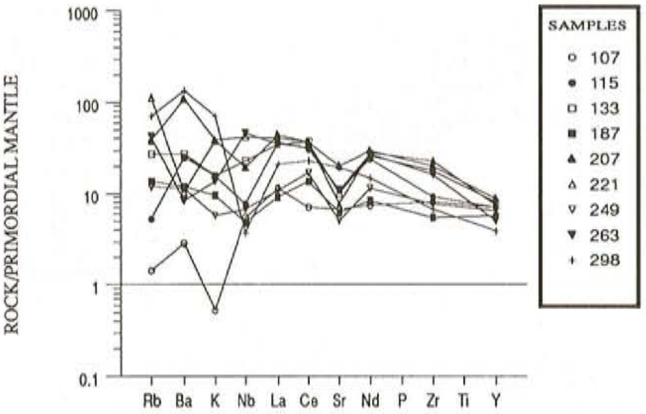

Figure 9. *Spidergram for Harp tholeiitic dykes. Note the similarity to Kikkertavak dykes in terms of negative Sr and Nb anomalies and highly variable LILE ratios and concentrations.*

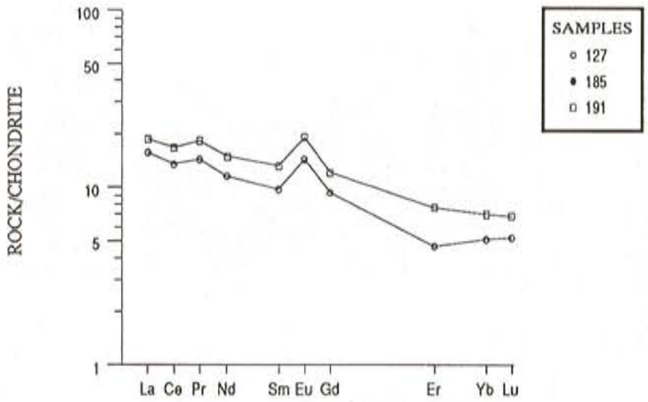

Figure 11. *Plot of rare earths for Harp dykes with positive Eu anomalies.*

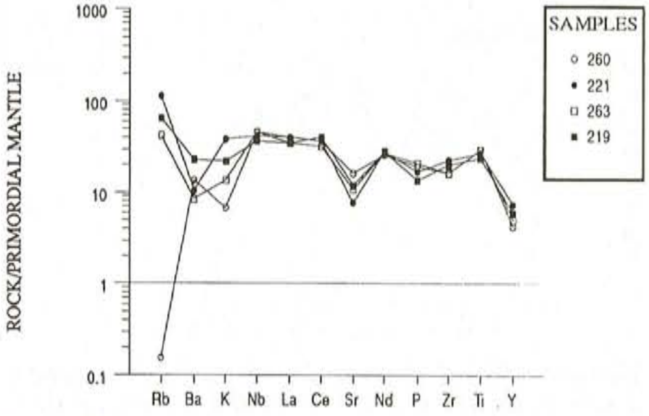

Figure 10. *Spidergram for high-iron–high-magnesium dykes of suspected Harp age.*

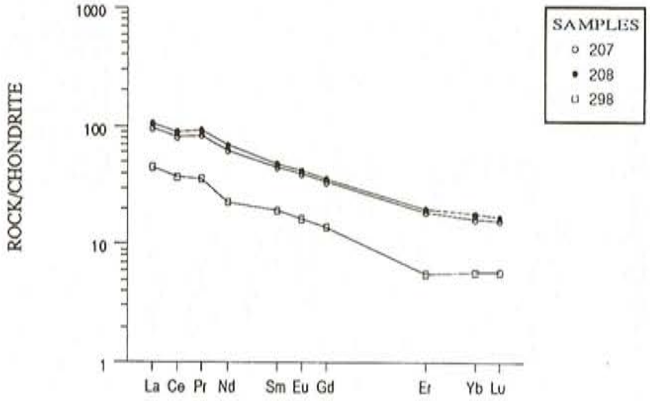

Figure 12. *Plot of rare earths for the Harp swarm showing higher La/Lu ratios compared to the first rare-earth group and no Eu anomaly.*

6), but no negative Eu anomaly (which would be consistent with plagioclase fractionation) suggesting that Eu was oxidized to its +3 valency state. In comparison, the Harp dykes show two distinct rare-earth patterns (Figures 11 and 12): one with a small positive Eu anomaly and a small degree of heavy rare-earth depletion, the second with no Eu anomaly but with much higher total abundances of rare earths and more pronounced heavy rare-earth depletion. Therefore, it appears that at least two different mantle sources supplied magma for the Harp swarm. The greater scatter in Harp data compared to Kikkertavak dykes in other Harker oxide variation diagrams (e.g., Figure 13) is in agreement with this conclusion.

Contamination and Alteration

The relationship between Rb and Ba in the spidergrams of the Kikkertavak and Harp dykes show great degrees of variation, which may reflect magma processes, wall-rock contamination or secondary alteration (Figure 18).

Crustal contamination is often invoked to explain the high concentrations of large-ion lithophile elements in continental flood basalts (e.g., Thompson, 1974, 1975). Assimilation and enrichment of large-ion lithophiles from the wall rocks may be expected to occur if magma was flowing turbulently; a condition thought to occur in basic dykes over 3 m in width (Huppert and Sparks, 1985), and therefore, in most Kikkertavak and Harp intrusions. Alternatively, dyke margins may become enriched in incompatible elements once dyke flow has stopped if the magma at the wall rock–dyke interface is still liquid ('Residence' contamination, Fratta and Shaw, 1974). However, there is no field evidence of wall-rock partial melting during emplacement of tholeiites of either the Kikkertavak or Harp dyke swarms: wall-rock irregularities can be matched on both sides of the dykes and dyke margins are always chilled. Dykes are always rectiplanar in outcrop and are associated with the process of emplacement by the dilation and linkage of *en echelon* crack arrays (Nicholson and Pollard, 1985). Therefore, processes of brittle failure dominated dyke intrusion and the exposed depth of intrusion is likely to have been upper crustal. Figure 7 shows a spidergram for margin-centre pairs of analyses for a Kikkertavak dyke. As Rb is more depleted at the dyke margins compared to the centre, this also suggests that contamination of the dyke by the wall rock at the exposed crustal level did

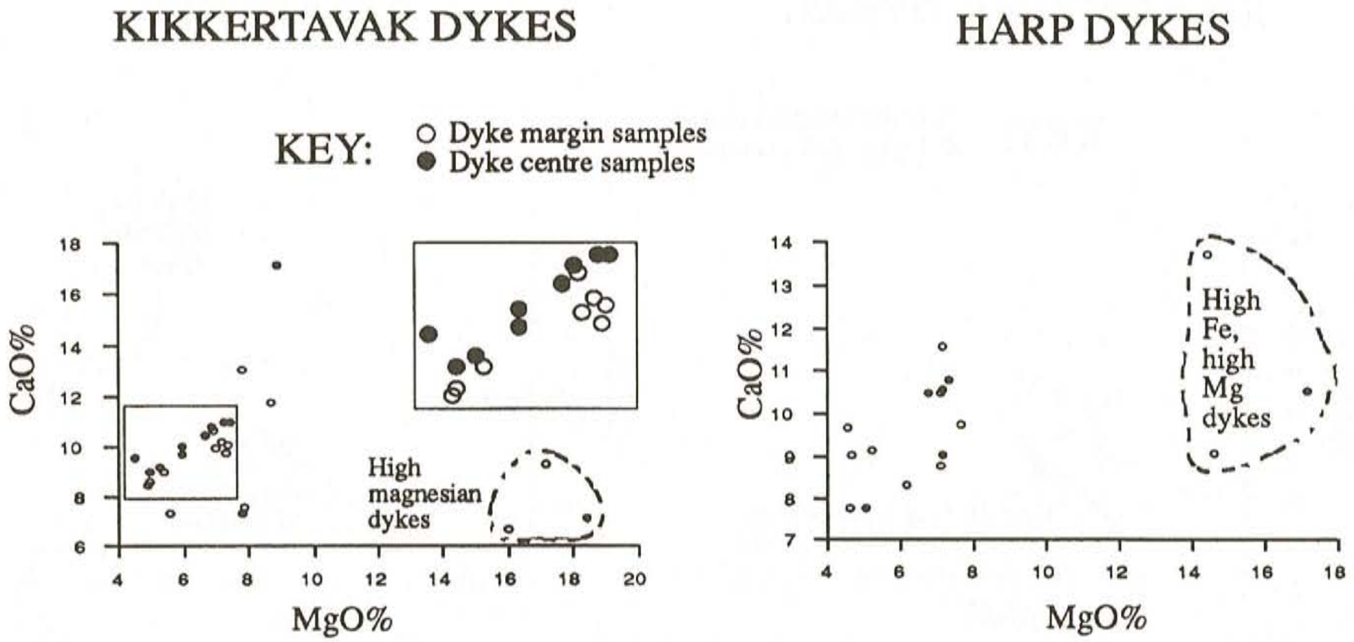

Figure 13. *Plots of CaO% versus MgO% for Kikkertavak and Harp dykes. Note the slightly more calcic nature of the dyke centres in the Kikkertavak swarm due to accumulation of plagioclase phenocrysts.*

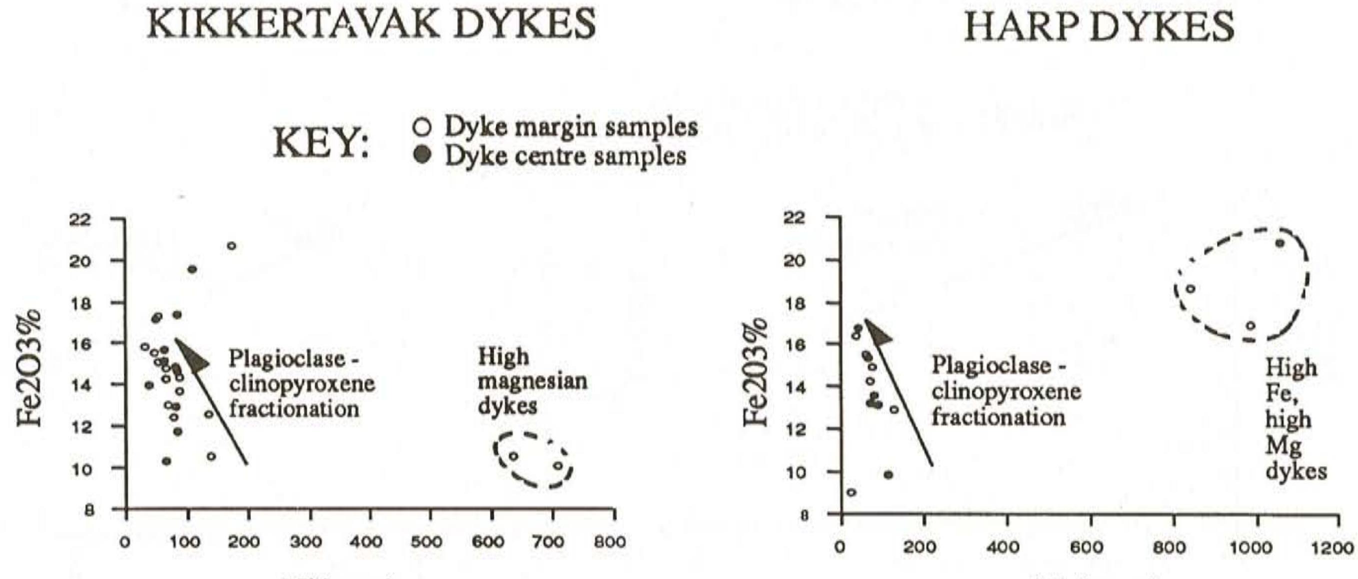

Figure 14. *Plot of Fe_2O_3% versus Ni (ppm).*

not occur, as the host Fiordian tonalite contains much greater abundances of Rb than the dyke.

There is no evidence of significant tilting in the Hopedale block after the injection of either swarm, and hence, progressively deeper crustal environments of intrusion where contamination is perhaps more likely, cannot be studied here. However, Archean terranes such as the Lewisian in northwest Scotland, intruded by the Scourie dyke suite, are exposed at mid-crustal levels. The Sourie dykes in this area still retain chilled margins and similarly do not show active assimilation of the more acidic wall rocks (Weaver and Tarney, 1981, 1983; Cadman *et al.*, 1990).

Another potential source of alteration is the Lower Proterozoic tectonism associated with the Kanairiktok shear zone: Kikkertavak dykes commonly show high degrees of metasomatic alteration within 10 km of the Makkovik Province–Hopedale block boundary, suggesting they may have been used as channelways by syn-tectonic migrating

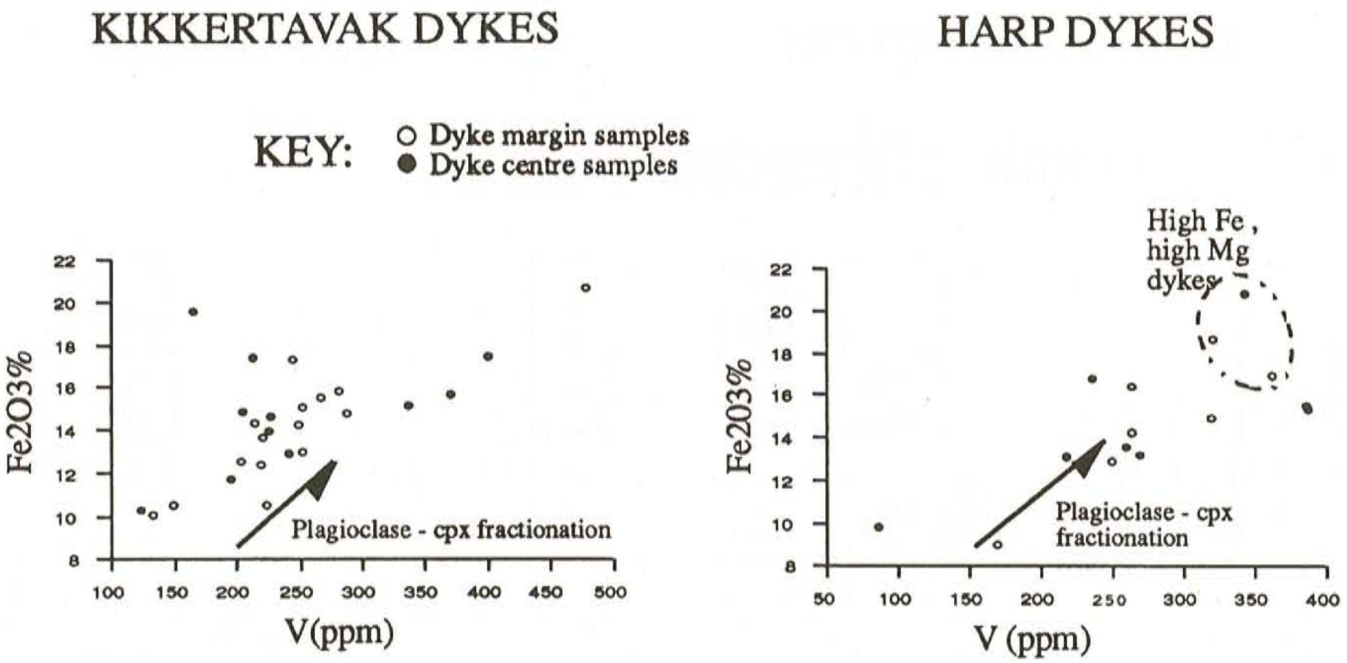

Figure 15. *Plot of Fe_2O_3% versus V (ppm).*

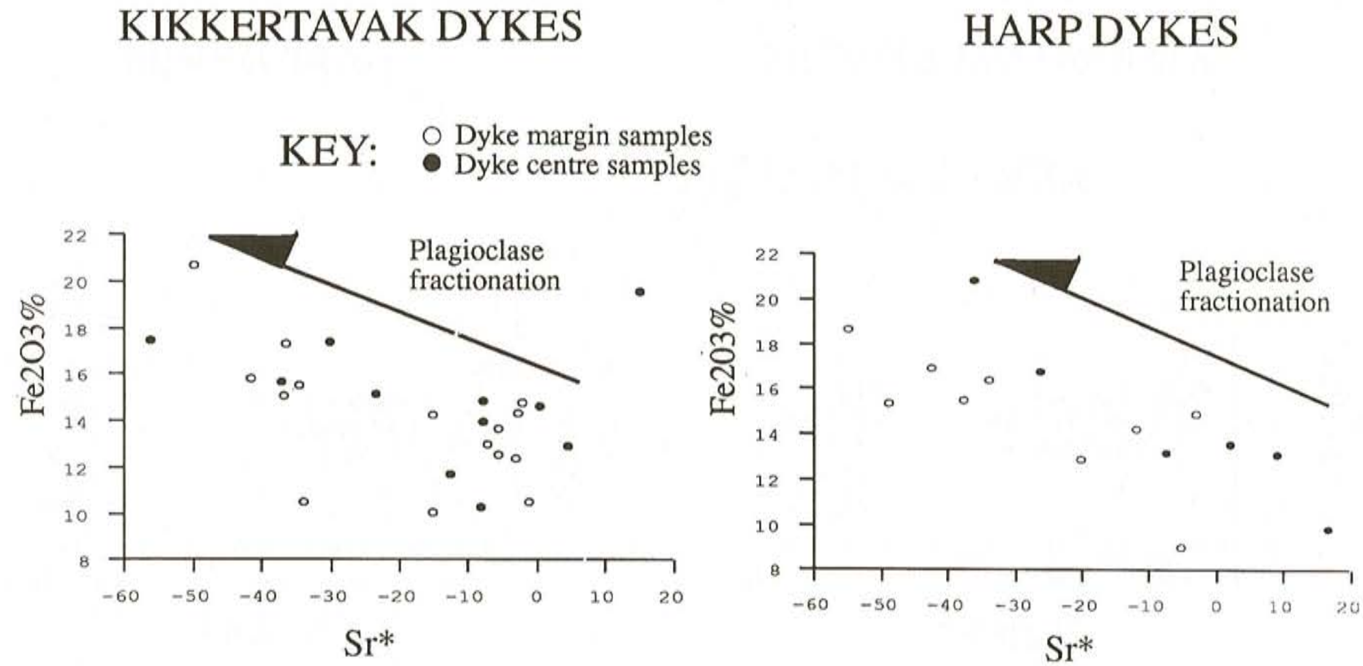

Figure 16. *Plots showing the development of Sr anomaly (Sr*) with increase in Fe_2O_3 content.*

fluids. The sheared dyke margins were often at high angles to the northeast-southwest orientation of the Kanairiktok shear zone and the presence of such fluids is more likely to be the dominant factor in initializing marginal shears rather than the prevailing orientation of shear stresses in the southern Hopedale block.

Figure 8 shows spidergrams for samples taken within 5 km of the Kanairiktok Bay shear zone. Samples taken closer to the shear zone show a progressive depletion in Rb and to a lesser extent, Ba.

This depletion in Rb in the Kikkertavak dykes relative to other large-ion lithophile elements approaching the shear zone can be seen clearly in Figure 18. The Rb anomaly (Rb*) is calculated relative to Ba and K. As the shear zone is approached, an initially positive Rb* begins to fall and becomes negative. Dyke-margin samples show higher levels

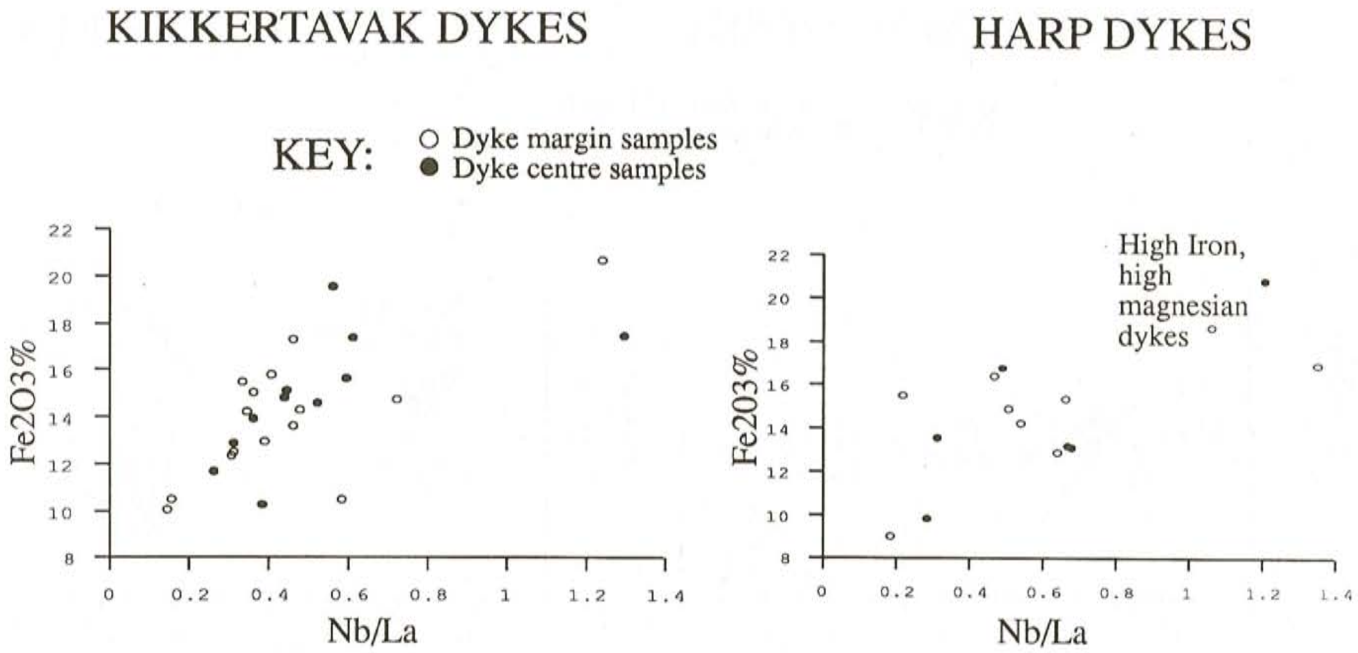

Figure 17. *Plots showing increase in Nb/La ratio (after normalization of both elements against primordial mantle abundances) with increasing* Fe_2O_3 *content.*

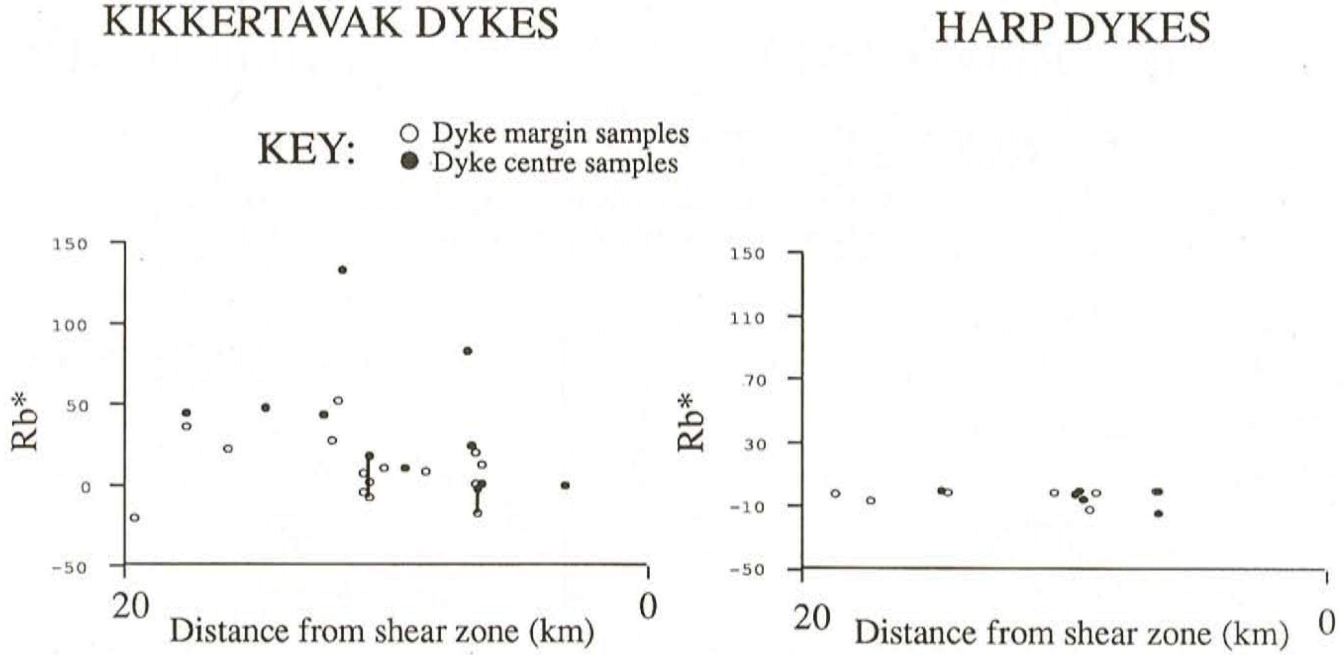

Figure 18. *Plots showing the differing behaviour of the Rb anomaly (Rb*) for Kikkertavak and Harp dykes approaching the Kanairiktok shear zone. Tie lines denote dyke-margin-centre sample pairs taken at same locality.*

of depletion than associated centres, which is in agreement with the observed tendency toward greater alteration.

Rb* becomes strongly positive at greater distances from the shear zone but remains highly variable. This confirms that the Kikkertavak dykes were affected by another alteration event unrelated to the Kanairiktok shear zone, as suggested by the pervasive low-grade alteration seen in the Kikkertavak dykes throughout the Hopedale block (Cadman, *this volume;* Ermanovics, 1979). Ermanovics (*in press*) states that this low-grade alteration is also seen in the Fiordian gneisses and is partially due to deuteric alteration in the dykes and might also be partially due to metamorphism and consequent dewatering of the Moran Lake Group, which may once have overlain much of the Hopedale block.

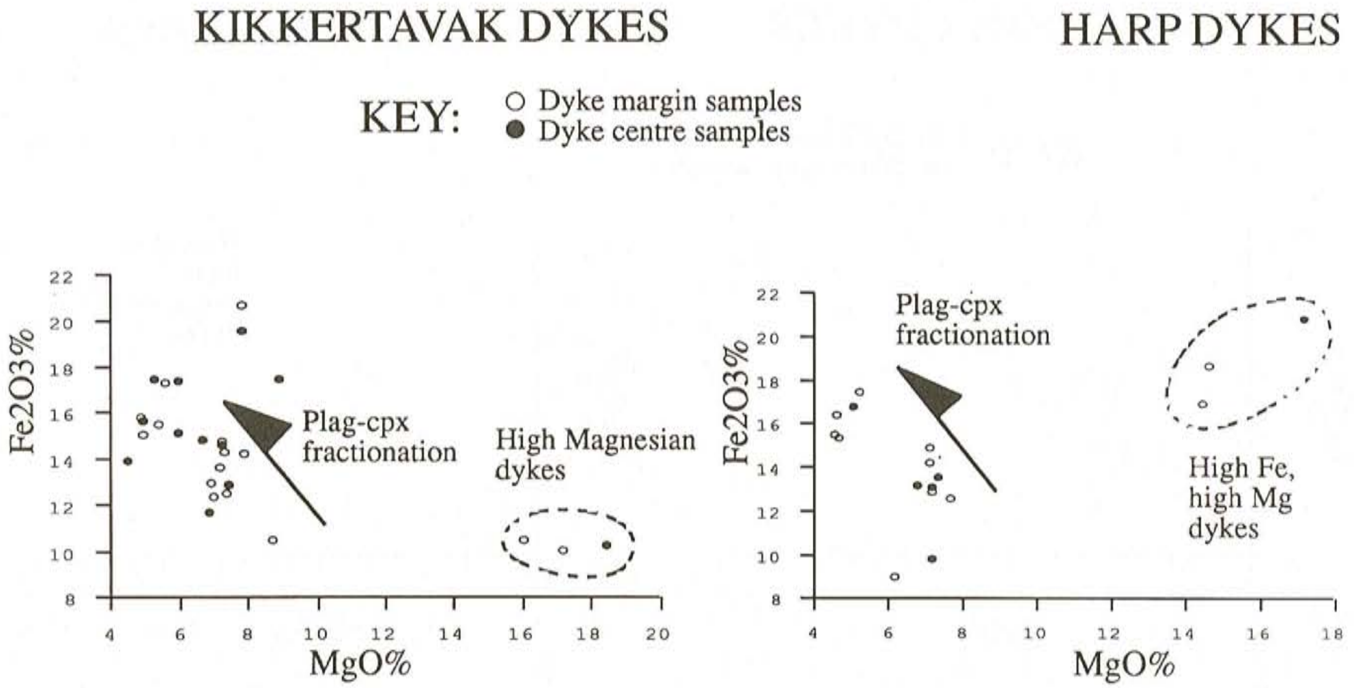

Figure 19. *The plot of* Fe_2O_3*% versus MgO% shows the general increase in* Fe_2O_3 *content with decreasing MgO as plagioclase and clinpyroxene are crystallized.*

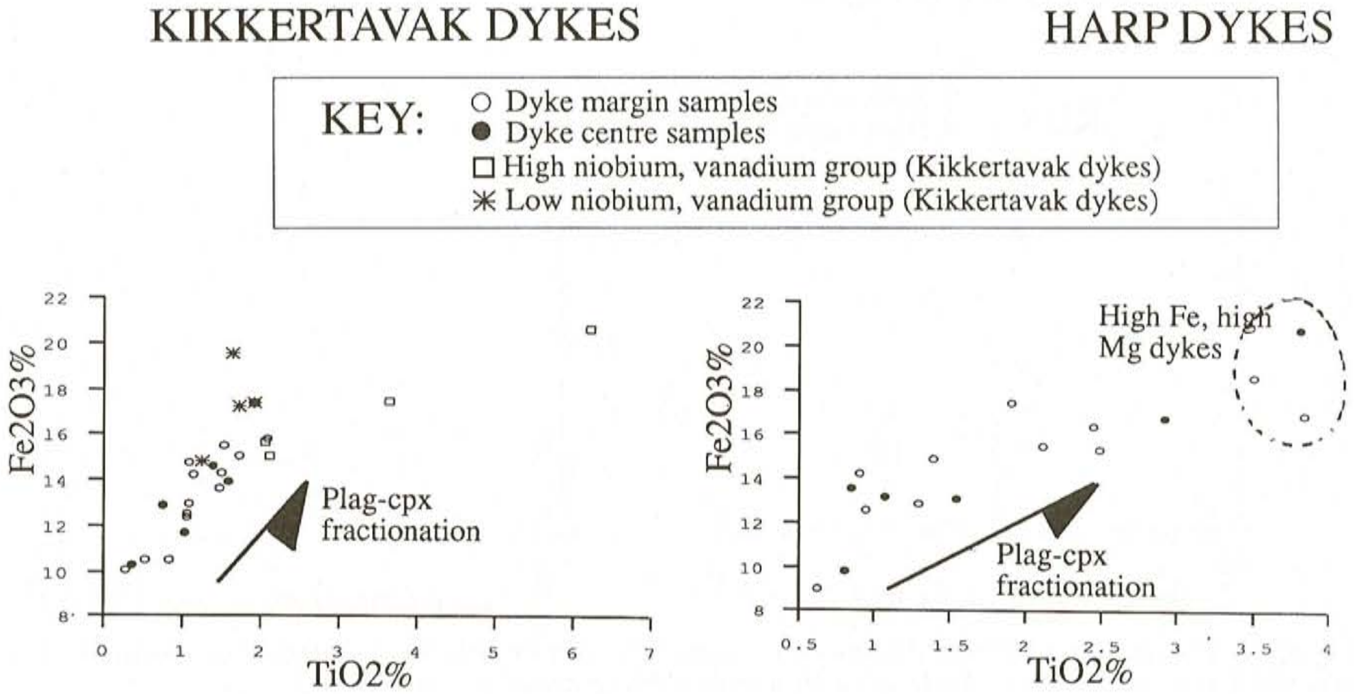

Figure 20. *Plots showing correlation in* Fe_2O_3 *and* TiO_2 *contents. In both swarms, the samples with high* TiO_2 *(Ti>3%) may not represent primary liquids.*

In comparison, the Harp dykes show a flat Rb* trend approaching the shear zone; the Rb anomaly is weakly negative and shows little variation, which is in concordance with the low alteration state of the Harp dykes.

THE KIKKERTAVAK AND HARP SWARMS: A COMPARISON OF MAGMATISM

The complex magma evolution patterns outlined above for both swarms, especially the Kikkertavak dykes, may be

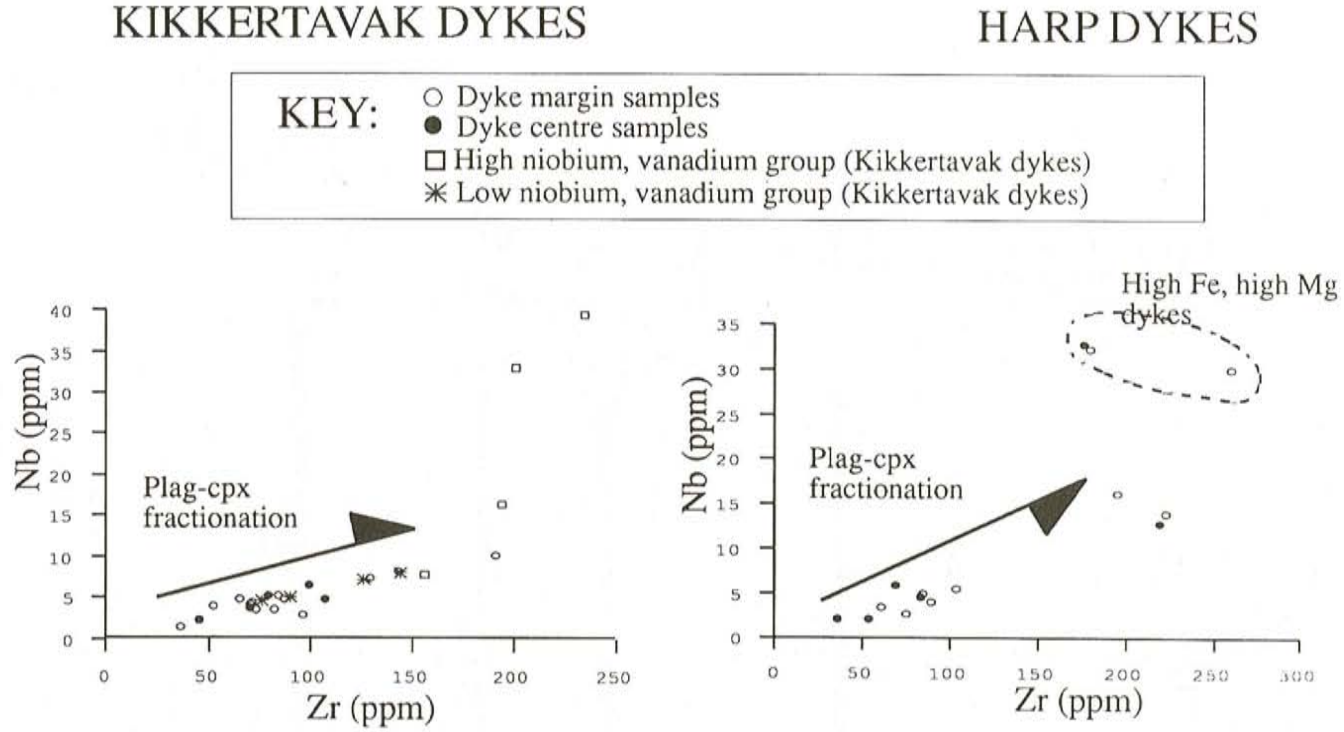

Figure 21. *These diagrams show most clearly of all that high Nb- and V-bearing samples currently attributed to both swarms do not lie on the tholeiitic fractionation trend and may represent cumulates or magmas derived from very different sources.*

due to initial mantle source heterogeneties, magma-chamber processes or a combination of the two.

Magma chambers are often invoked to explain significant degrees of fractionation and mixing by allowing comparitively long magma-storage times before dyke injection (e.g., Huppert and Sparks, 1985; Defant and Nielsen, 1989). Cox (1980) argues that the typically low Ni content of tholeiitic continental flood basalts and the good correlation between CaO and MgO suggest low pressure fractionation of clinopyroxene and plagioclase. However, Thomson (1974) showed that plagioclase–clinopyroxene crystallization was possible at Moho depths, and shallow-level or mid-crustal magma chambers are very rare considering the vast regions of flood basalts, or their root dyke swarms, that are exposed. Those that are, for example, the Muskox intrusion, often show a range of compositions that are not mirrored in the slightly later dykes (e.g., Mackenzie swarm; LeCheminant and Heaman, 1989) that crosscut them. The linear pattern of Proterozoic dyke injection is also very different from the radial or concentric patterns associated with the stress systems of magmatic centres, such as the radial swarm seen at Spanish Peaks, Colorado (Ode, 1957). The Harp dykes, for example, do not radiate outward from the Harp Lake gabbro–anorthosite complex, which they crosscut (Meyers and Emslie, 1977).

If magma chambers situated within the upper crust are not thought to exist in relation to either dyke swarm, then shallow-level processes must take place wholly within the evolving dyke system. The presence of gabbroic cumulate layers developed parallel to the dyke margins in some Kikkertavak intrusions supports a degree of shallow-level fractionation within individual dykes, though generally, in aphyric intrusions of either the Kikkertavak or Harp swarm, dyke centres are not significantly compositionally different from dyke margins. This suggests that active fractionation within the dyke conduit is small compared to the total amount of fractionation that has occurred in the system over time.

The presence of coarse, layered plagioclase–clinopyroxene cognate xenoliths and large gabbroic xenoliths (> 1 m) within Kikkertavak diabases (Cadman, *this volume*) suggests that magma-cooling rates decreased with depth and magma flow stagnated for long enough periods to allow gravity settling of material to take place. Magmatism during the intrusion of the Kikkertavak dykes seems to have consisted of cycles of high magma-flow rates punctuated by more quiescent periods. The partially resorbed cores, surrounded by euhedral overgrowths, seen in the plagioclase feldspars in many Kikkertavak dykes suggest that input of new magma pulses has driven evolving magmas back up the fractionation path. The incorporation of large cognate xenoliths, cumulate material and the scouring textures observed in one Kikkertavak dyke (Cadman, 1989, *this volume*) suggest that dyke paths were rejuvenated by the injection of high-energy magma flows that were capable of entraining solidified and fractionating material. Hence, processes that allow the cyclic build up and release of pressure, such as the emptying and refilling of a small magma chamber, have operated during dyke injection.

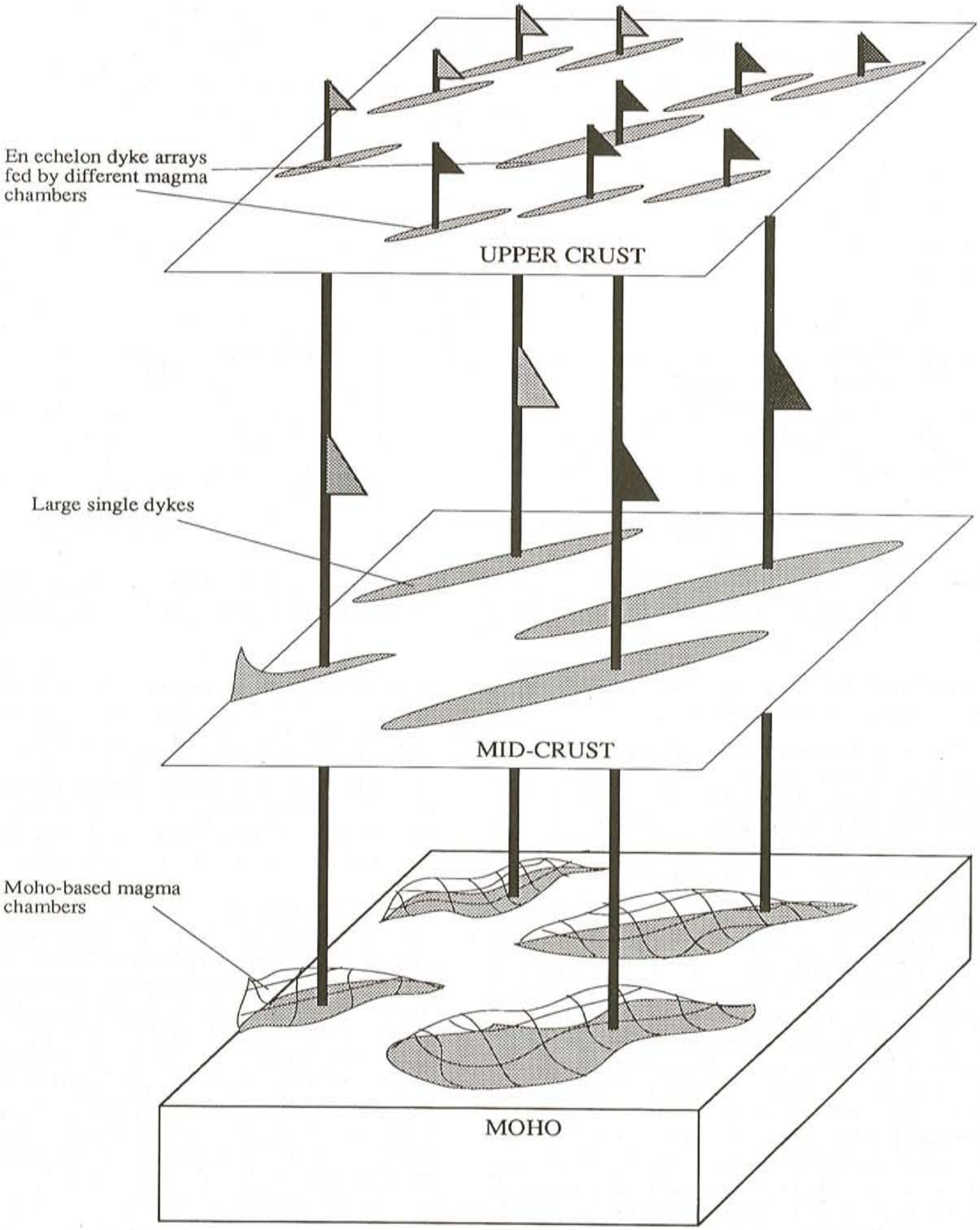

Figure 22. *Diagram showing the relationship between dyking and discrete magma chambers.*

Bruce and Huppert (1989) show that the hotter initial temperatures of wall rock at mid- or lower-crustal depth would allow cooling rates in dykes to be many orders of magnitude slower than at upper-crustal conditions. An increase of dyke width at depth would allow even slower cooling rates. Consequently, rather than Moho-based magma chambers being single 'blisters' supplying magma for a whole dyke swarm, magma chambers could in fact be dyke-like bodies of linear or ellipsoid form. Each such magma chamber might feed one, or a small number of intrusions, which it directly underlies, in a linear array (Figure 22). Hence, each linear array of dykes would show little along-length variation but considerable variation between arrays of dykes across the width of the swarm would be possible.

The petrological differences seen between adjacent parallel basaltic and komatiitic intrusions in the Forte Frances swarm, Canada (Halls, 1986) support this argument. Similarly, the megacrystic texture observed in the Kikkertavak dykes is found sporadically within a narrow linear array of intrusions parallel to the strike of the swarm and only at one locality outside of this array.

In contrast, the Harp dyke swarm shows much less textural variation and may represent more stable magmatic injection into the crust, with dykes consisting of single-phase intrusions with no evidence of magma flow-rate fluctuations during emplacement. (The olivine crystals are, for example, out of equilibrium with the oxide-dominated groundmass judging from the alteration of their rims.) The more regular northeasterly trend of the Harp dykes for both diabases and gabbros suggests that the regional stress in the crust during this time had a significant northwest-southeast tensional component that allowed easy access of the magma into the crust. However, during injection of the Kikkertavak dykes sigma 3 crustal stresses were perhaps less consistent, resulting in a greater spread of dyke orientation for all but the widest dykes.

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