Nd and Sr isotope compositions from the Gardiner Complex, East Greenland Tertiary igneous province

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The Gardiner Complex formed during the early Tertiary opening of the North Atlantic. The complex is strongly alkaline and referred to a zone of alkaline flank magmatism 100 km west of the melting anomaly in the initial rift of the North Atlantic. Earlier investigations have documented that most rocks of the complex can be referred to three suites which are all suggested to have been formed from a single parental melanephelinitic liquid. The Nd and Sr isotope compositions presented here support this conclusion. Minor deviations are believed to be due to interaction with Archaean basement. The isotopic characteristics suggest that the alkaline magmatism originated in a source similar to that of the contemporaneous picritic and basaltic tholeiites. The isotopic composition of the source is less depleted than pervalent mantle (PREMA) and sets an upper enrichment limit to the composition of the Icelandic plume component 50 Ma ago.

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Introduction

The strongly alkaline, 50 Ma old, carbonatite-bearing Gardiner Complex (Frisch and Keusen, 1977; Nielsen, 1980, 1981 and 1990) formed during the early Tertiary opening of the North Atlantic. The complex is located at the centre of a regional dyke swarm parallel to the "failed arm" of the Kangerdlugssuaq triple junction (see fig. 1 and Brooks, 1973) and is contemporaneous with syenitic and basaltic magmatism at the continental margin (Gleadow and Brooks, 1979). The Gardiner Complex belongs to a zone of alkaline flank magmatism 100 km West of the melting anomaly in the initial oceanic rift in this part of the North Atlantic (Nielsen, 1987) and is also emplaced over the supposed focus of the Icelandic mantle plume in early Tertiary times (Brooks, 1973; White and McKenzie, 1989).

The complex is composed of a wide variety of alkaline rock types including ultramafic cumulates, fine-grained alkaline mafic dykes, melilite-rich plutonic rocks (melilitolites), strongly evolved phonolites and carbonatites related to the melilitolites. The ultramafic cumulates (fig. 2) formed from series of pulses of mafic alkaline liquids emplaced into an open shallow level magma chamber beneath a nephelinitic volcano (Nielsen, 1981). Later radial and ring dykes are formed from new pulses of magma emplaced into earlier formed cumulates of the complex and into the feeder system of the complex. The late dyke swarms record the waning phases of magmatism in the subvolcanic complex of the volcano.

Geochemical investigations show (see below and fig. 3) that dyke compositions define three distinct lines of liquid descent which evolved from many pulses of a "common" melanephelinitic parent (Nielsen, 1990). Nielsen and Buchardt (1985) concluded on the basis of limited variations in initial Sr-isotope compositions ($Sr_i = (^{87}Sr/^{86}Sr)_{t=50\ Ma}$) that all rocks of the Gardiner complex (apart from few contaminated contact rocks) evolved from the common source, which was also responsible for some of the contemporaneous tholeiitic activity in the spreading zone to the East.

The aim of the present investigation is to test these suggestions with high precision methods and more specifically to:

1) determine the isotopic characteristics of geochem-

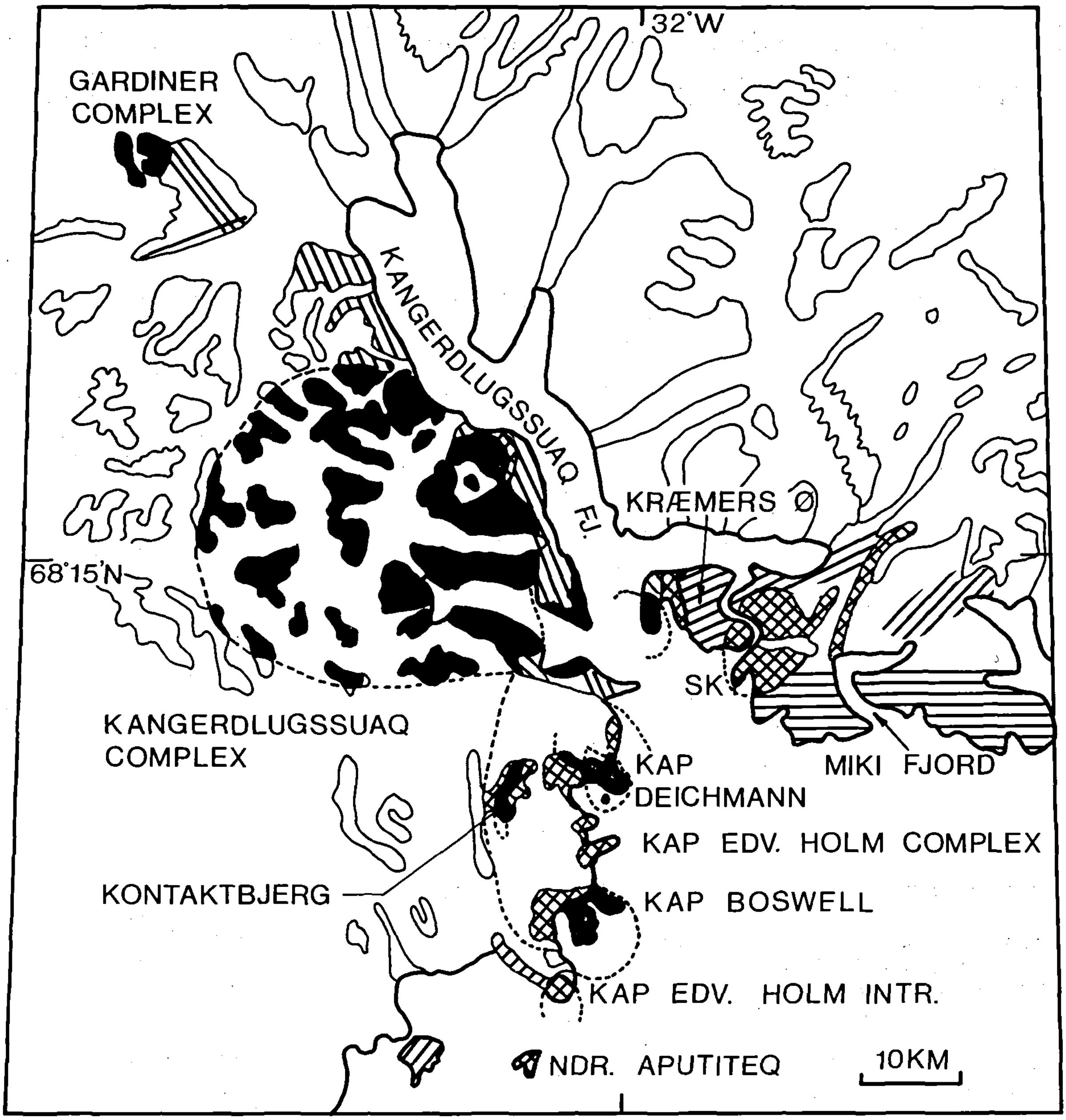

Fig. 1. Outline of the Kangerdlugssuaq area. Regional dyke swarms are shown schematically (after Nielsen 1987). Alkaline plutons: black; , tholeiitic gabbro plutons: cross hatched.

ically identified groups of rocks related to individual lines of liquid descent.

2) relate isotopic characteristics, emplacement mechanisms and petrogenesis of individual lines of liquid descent.
3) attempt to relate the alkaline magmatism in the Gardiner Complex to previously identified sources for the Tertiary tholeiitic magmatism in the North Atlantic.

Liquids of the Gardiner complex

The 35 km^2 Gardiner ring complex is dominated by ultramafic rocks (dunites, peridotite and alkaline pyroxenites) that host swarms of radial and ring dykes and related inclined sheets (Frisch and Keusen, 1977; Niel-

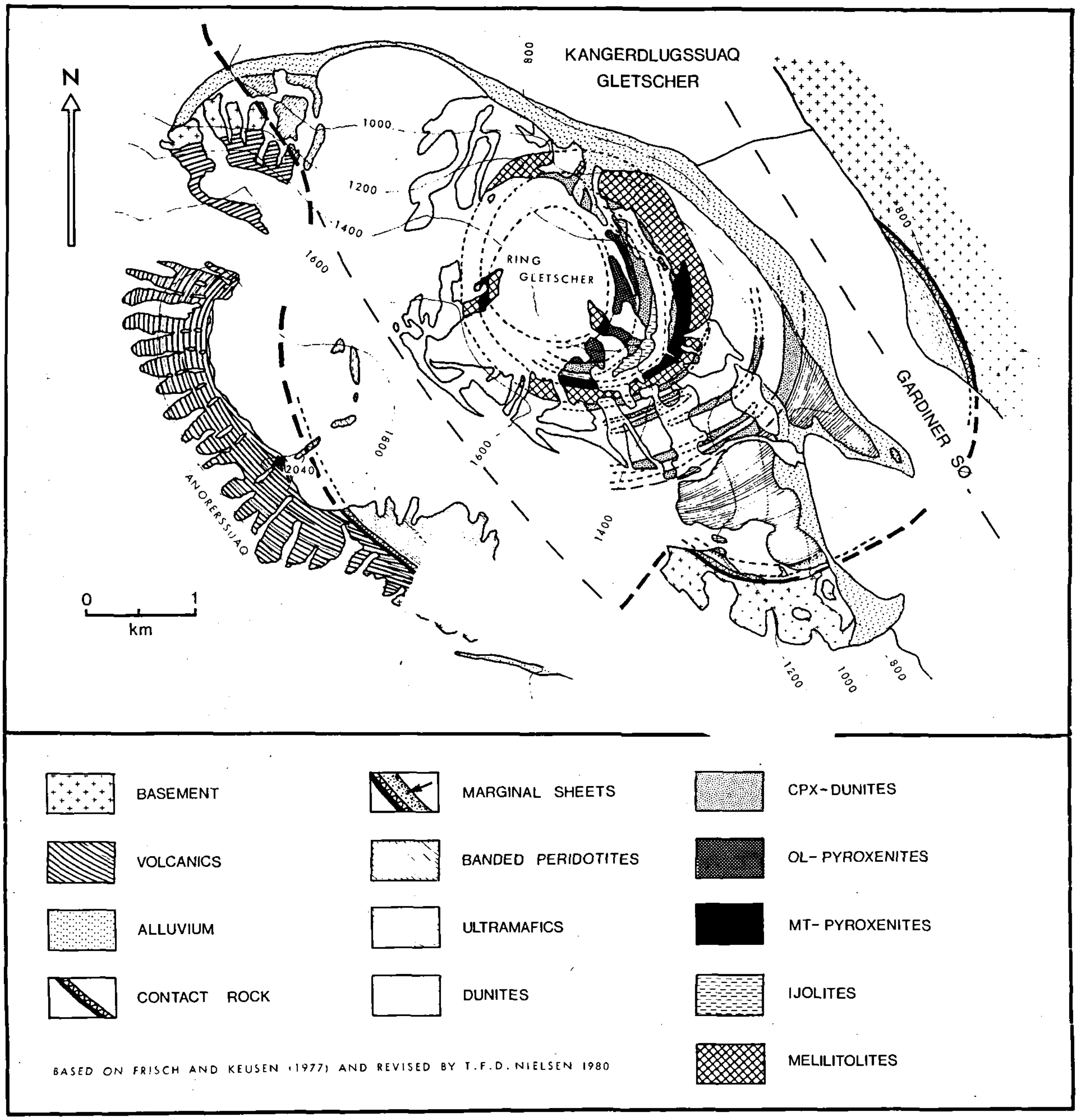

Fig. 2. General geology of the Gardiner Complex (after Nielsen, 1981). Legend in figure.

sen, 1981). The complex is emplaced into the centre of a regional dyke swam, which is well defined in terms of geochemistry and mineralogy and includes melanephelinites, nephelinites and nepheline trachytes (fig. 3; Nielsen, 1990 and in press). Based on the compositions of olivine and clinopyroxene phenocrysts in the dykes and olivine and clinopyroxene primocrysts in the ultramafic cumulates Nielsen (1981) argued that the ultramafic cumulates of the Gardiner complex formed from pulses of melanephelinitic and nephelinitic liquids similar to those found in the preceding regional dyke swarm, who's line of liquid descent is shown as Trend R in fig. 3.

On a structural basis the later radial dykes and ring dykes are interpreted to originate from shallow magma chambers below the present level of exposure, i.e. in magma chambers within or at the base of the complex (Nielsen, 1990 and in press). On the basis of mineralogy, chemistry and chronology these dykes are divided

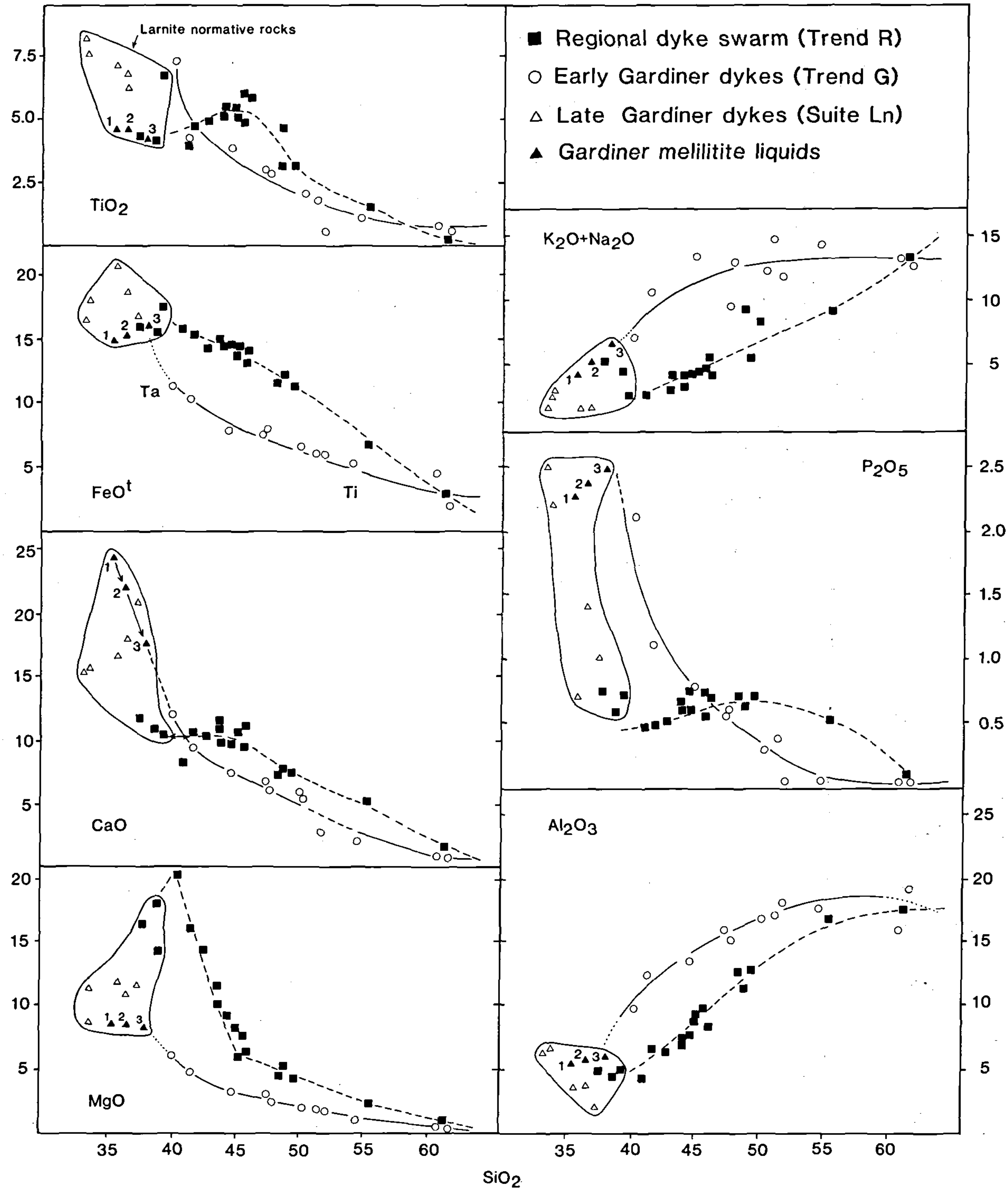

Fig. 3. Major element variations in the regional dyke swarm (Trend R) parallel with the failed arm of the Kangerdlugssuaq triple junction (see fig. 1), the early generation of nephelinitic to phonolitic radial and ring dykes (Trend G) and the late suite of larnite-normative melanephelinites, ultramafic lamprophyres and melilitites (Suite Ln). Filled triangles represent calculated liquids of melilitolite ring dyke system (unpublished; Nielsen, 1990). Ta: tawite dyke (Frisch and Keusen, 1977) and Ti: tinguaite (Brooks and Rucklidge, 1974). The composition of melanephelinite parental pulses in the Gardiner Complex corresponds to compositions at the low silica end of Trend R adjacent to the field of Suite Ln.

Table 1. Neodymium and Strontium isotope compositions from the Gardiner complex and related dyke swarm, Kangerdlugssuaq, Southern East Greenland.

Sample	Rock type	$^{143}Nd/^{144}Nd$	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_{t=50Ma}$
Suite ln							
MM 29970/1	dyke margin, melaneph.	0.512861± 2	1.5	891	0.00487	0.703710	0.703707
MM 29965	dyke, melaneph.	0.512889±17	1.3	1212	0.00310	0.703727	0.703725
Trend G							
MM 29927/2	sheet, syenite	0.512800± 6	18	2244	0.02321	0.704452	0.704436
MM 29910B	sheet, syenite	0.512833±10	54	1252	0.12478	0.704160	0.704071
MM 29953/A	sheet, syenite	0.512799±12	6.5	3017	0.00623	0.704061	0.704057
MM 29956	sheet contact, syenite	0.512817±23	18	4112	0.01266	0.704121	0.704112
MM 29912	dyke, phonolite	0.512846± 9	75	3030	0.07161	0.703740	0.703689
Trend R							
MM 29928/1	dyke margin, melaneph.	0.51273x±4x	34	352	0.27949	0.706010	0.705811
GM 55201D	dyke, melaneph.	0.512841± 4	34	361	0.27250	0.705185	0.704991
GM 55201E	dyke, melaneph.	0.512883±14	55	640	0.24861	0.703979	0.703802

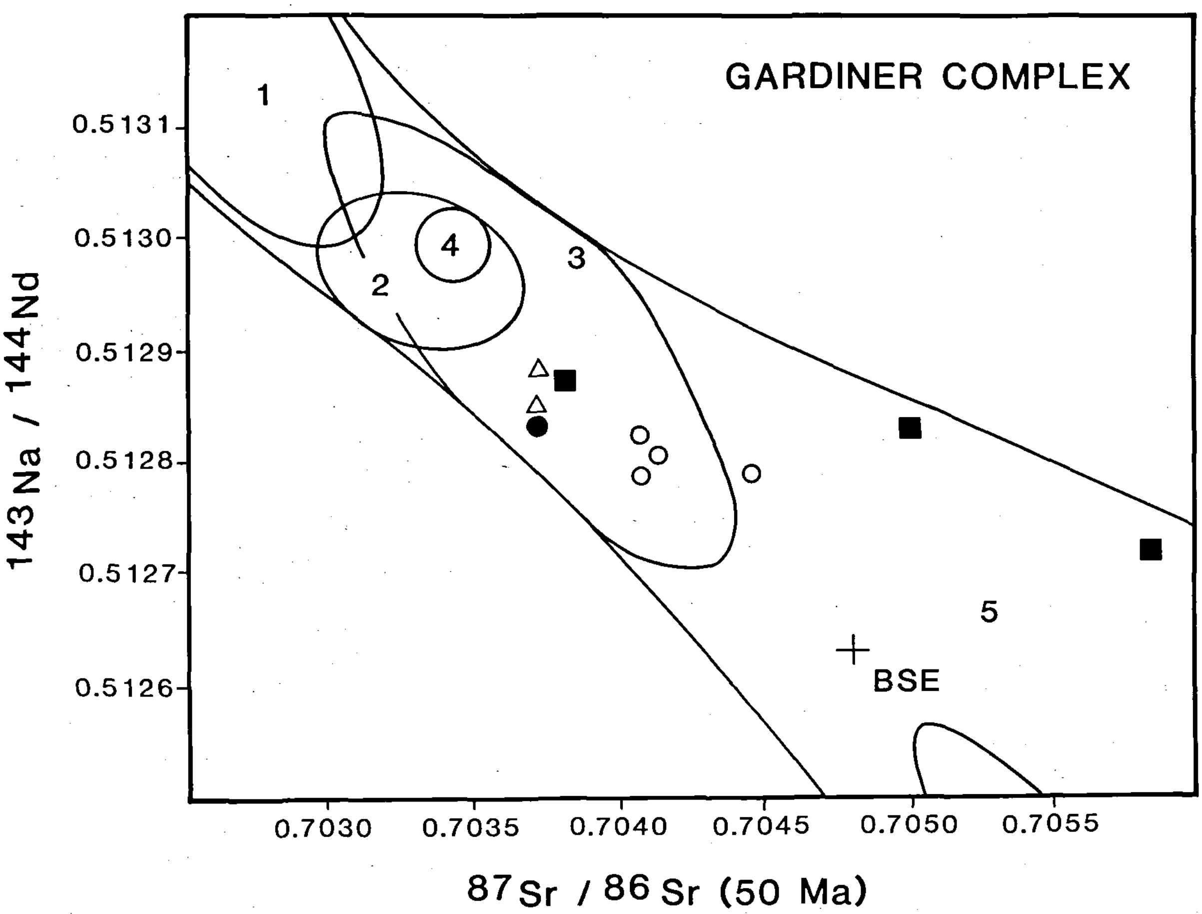

Fig. 4. Sr and Nd isotope compositions of samples from the Gardiner Complex. Sr isotope composition at 50 Ma. Filled sqares: melanephelinites of Trend R; filled circles: Trend G phonolite dyke and open circles: syenites of Trend G. Triangles: larnite-normative melanephelinites of Suite ln. Field 1: compositions of MORB's; field 2: Icelandic compositions; field 3: compositions of Mikis Fjord Formation lavas from the Kangerdlugssuaq area, Tertiary of East Greenland (Holm, 1988); field 4: composition of prevailing mantle (PREMA, Zindler and Hart, 1985) and field 5: oceanic basalts (Zindler and Hart, 1985). BSE denotes Bulk Silicate Earth.

into an early nephelinite to phonolite Gardiner trend (Trend G, fig. 3) and a younger suite of larnite-normative rocks (Suite Ln, fig. 3). Suite Ln includes the last major intrusive event in the complex comprising a major ring dyke of melilite-rich plutonic rocks (melilitolites) and related immiscible carbonatite dykes.

The early regional Trend R (which also represents the liquids that formed the ultramafic cumulate series of the Gardiner Complex) evolved under vapor-poor conditions to nepheline trachytes in response to fractionation of olivine and clinopyroxene in a vented system, whereas the late "Suite Ln" evolved to melilititic and carbonatitic compositions in response to fractionation of kaersutite and/or phlogopite under closed and hydrous conditions (Nielsen 1990 and in press).

The Gardiner trend (Trend G) formed after Trend R and the ultramafic cumulate series but prior to Suite Ln and Trend G evolved partly under hydrous and partly under vapour-poor conditions. The most mafic Trend G dykes have compositions which in many respects resemble those of ultramafic lamprophyres of Suite Ln (fig. 3) but the trend evolves to phonolitic compositions in response to loss of vapour phase and replacement of hydrous liquidus phases (phlogopite and amphibole) by clinopyroxene. The evolved Trend G melts were subsequently emplaced as dykes in radial and ring fratures from shallow level magma chambers within or at the base of the complex.

The chronology of the intrusive events thus record the closure of the feeder system under a "hydrous melanephelinitic" volcano and fractionation under increasingly closed and hydrous conditions.

Isotopic investigation

The samples selected for the isotopic investigation include three melanephelinites from Trend R, two melanephelinites from Suite Ln and from Trend G one phonolite dyke and four syenites from related intrusive sheets. The results are given in table 1 and fig. 4. One melanephelinite of Trend R and the two melanephelinites of Suite Ln have very similar Sr_i and Nd isotopic ratios of 0.7037–0.7039 and 0.51289–0.51286, respectively. Two Trend R melanephelinites have more radiogenic Sr_i (0.7052–0.7060) and at least one has has less radiogenic Nd with a $^{143}Nd/^{144}Nd$ ratio of 0.51273.

The isotopic ratios obtained from samples of Trend G show significant variations. The phonolite dyke plots with the melanephelinites of Suite Ln. Three syenites form a tight group with only slightly more radiogenic Sr (0.7041–0.7045) and slightly less radiogenic Nd (0.51280–0.51283) than the phonolite dyke. The last syenite has a similar Nd-isotope ratio but a more radiogenic Sr_i than the group of three syenites.

Discussion

Seven of the samples selected to represent the magmatism in the Gardiner Complex show restricted variation in isotopic composition of Sr and Nd. All seven samples have high Sr abundances (640–4112 ppm). The two melanephelinites with relatively high Sr_i have lower Sr abundances (c. 350 ppm). The syenite with slightly high Sr_i has a relatively high Sr (2244 ppm).

One melanephelinite of Trend R and and the melanephelinites of Suite Ln lie on the line that connects the isotopic composition of Bulk Silicate Earth (BSE) and the field of isotopic compositions of Icelandic lavas and MORB's. They are strongly undersaturated and have high Sr and Nd contents and no interaction with the continental crust can be assumed nor can any change in the primary isotopic ratios be assumed. The isotopic characteristics of these dykes are accordingly taken to represent the composition of common parental melanephelinite of the complex and the source.

The two melanephelinites of Trend R emplaced into Archaean basement have distinctly higher Sr_i ratios than the chemically equivalent melanephelinite of Trend R. The restricted change in Nd isotope ratio in at least one of these dykes suggests a process of isotopic exchange with crustal Sr. Although all melanephelinites of the regional dyke swarm (Trend R) are chemically very similar, the two dykes with high Sr_i are less evolved (normative cpx + ol = 66–67% compared to 58%), have higher Rb/Sr (0.274 to 0.279 compared to 0.248) and have much lower total Sr (352 and 361 compared to 640 ppm, table 1) than the third Trend R melanephelinite. The less evolved character of the two melanephelinites with higher Sr_i accounts for the lower total Sr. The higher Sr_i and the higher Rb/Sr is taken to indicate addition of crustal Rb (and ^{87}Sr) as a result of interaction with the Archaean basement host during their final emplacement and solidification.

The scatter in both Sr and Nd isotope ratios in Trend G is believed to be of petrogenetic significance. The isotope-ratios of the phonolite dyke which plots together with the melanephelinites is assumed to represent the isotopic composition of the parental melanephelinite of Trend G. The syenites all have more radiogenic Sr and less radiogenic Nd. Trend G is assumed to have developed in magma chambers in the base of the Gardiner Complex (Nielsen, 1990 and in press) and a likely explanation for the variability in Sr and Nd isotope ratios in Trend G is that Trend G is composed of suites of liquids evolved from several pulses of parental melanephelinite that have interacted to variable extends with the Archaean basement during their fractionation at the base of the complex. Still the chemical interaction must have been limited or else the evolutionary trend (Trend G) would have been less well defined. Alternatively the source of the individual pulses of "common" melanephelinite may have been marginally inhomogeneous in isotopic composition.

The isotopic compositions of the defined suites thus conform with the conclusions reached on the basis of chemistry and chronology of the three identified trends and suites (Nielsen, 1990 and in press). They may all have evolved from a series of pulses of very similar melanephelinitic magma. The early regional dykes may or may not show interaction with the Archaean basement host during their accent and development, as was also argued by Nielsen and Buchardt (1985) for the ultramafic cumulate series formed during the early open stage of the subvolcanic Gardiner Complex. The subsequent suite of dykes refered to Trend G and Suite Ln not only record the closing of the subvolcanic system but also the progressive shielding of the fractionating magmas from interaction with the basement.

The relationship to the dominant tholeiitic and syenitic magmatism in the East Greenland Tertiary igneous province is not entirely clear. Nielsen and Buchardt (1985) suggested on the basis of Sr isotope relations that melanephelinites of the Gardiner Complex and some of the picrites in the initial rift along the East coast of Greenland could have originated from the same source. On the assumption that the isotopic compositions of the melanephelinites of Suite Ln and the one melanephelinite of Trend R represent the source for the pulses the melanephelinite parent of the Gardiner Complex, the source of the complex would be slightly enriched compared to the present-day Icelandic tholeiitic lavas formed over the centre of the Icelandic mantle plume. The Gardiner composition, however, falls within the field of the penecontemporaneous Lower Tertiary tholeiitic lavas (Miki Fm) of East Greenland (fig. 4).

Investigations of the Sr_i and Nd isotope ratios in lavas in East Greenland led Holm (1988) to suggest the occurence of 4 different mantle sources. He concluded that the mantle plume component of the magmas generated under the Kangerdlugssuaq triple junction had $^{143}Nd/^{144}Nd > 0.5128$, a Zr/Nb ratio <10 and $^{87}Sr/^{86}Sr$ <0.7043 (fig. 4 and unpublished). The melanephelinites from within the complex which in isotopic composition represent the gardiner Complex source satisfy these criteria. A crustal component can not be detected but the possible amount of lithospheric component in the isotopic composition is unknown. The Gardiner complex composition may thus represent the pure plume component or at least the "upper" enriched compositional limite for the plume component. The composition ($Sr_i = 0.7037$ ($E_{Sr} = -10.5$) and $^{143}Nd/^{144}Nd = 0.5129$ ($E_{Nd} = +5.1$) is more enriched than the "plume component" suggested on the basis of the West Greenland Tertiary picrite magmatism (Sr_i = c. 0.7032 ($E_{Sr} = -15$–-18) and $^{143}Nd/^{144}Nd$ = c. 0.5130 ($E_{Nd} = +7.5$–$+ 8.5$) (Holm et al. 1993). The latter may, however, contain a proportion of depleted astenosphere and can only be regarded as a – maybe very close – estimate of the Icelandic plume component 50 Ma ago. The conclusion must then be that the plume source had an Sri of 0.7032 – 0.7037 and a 143Nd/144Nd of 0.5129–0.5131, representing a depleted source, but less depleted than the astenosphere as represented by MOR-basalts in fig. 4).

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Dansk sammendrag

Gardiner komplekset er et subvulkansk komplex i Kangerdlugssuaq området (68°N) i den tertiære Østgrønlandske magma provins. Det dannedes i forbindelse med åbningen af Nordatlanten. Komplekset er 50 millioner år gammelt og er beliggende ca. 100 km inden for Østgrønlands kontinentalrand. Komplekset er dannet i midten af en regional gangsværm af melanephelinitiske til nephelintrachytiske gange parallel med »failed arm« af Kangerdlugssuaq »triple junction« (fig. 1). Gardiner komplekset består hovedsaglig af ultramafiske kumulatbjergarter (Ultramafic Cumulates Series, fig. 2), der senere er intruderet af radierende gange og ringgange i de afsluttende faser af kompleksets udvikling. Mineralkemiske undersøgelser har vist, at de ultramafiske kumulatbjergarter kunne være dannet fra flere pulser af smelter svarende til smelterne representeret i den regionale gangsværm. Gangsværmen er geokemisk set veldefineret (Trend R, fig. 3) og udviklet under fraktionel krystalisation af olivin og klinopyroksen. De senere gange kan opdeles i en tidlig generation af nephelinitiske til phonolitiske gange og relaterede syenitlegmer (Trend G; Gardiner trend) og en senere »Suite Ln«. »Suite Ln« består af larnit-normative (larnit = Ca_2SiO_4) kaersutit, phlogopit- og perovskitbærende gange omfattende en sen op til 300 m bred ringgang med en diameter på ca. 2 km af melilit-rige plutoniske bjergarter med relaterede karbonatitgange.

Geokemiske og kronologiske undersøgelser viser at alle tre grupper (Trend R, Trend G og Suite ln) antageligvis udvikledes fra en og samme type af melanephelinitisk smelte. Forskellene i udvikling af de tre grupper relateres til forskelle i P_{H20} og fraktionerende faser. Trend R udvikledes under lavt P_{H20} ved fraktionering af olivin og klinopyroksen. Suite Ln udvikledes under højt P_{H20} ved fraktionering af kaersutit og phlogopit. Trend G, der tidsmæssigt ligger mellem Trend R og Suite Ln udvikledes først som Suite Ln i lukkede magmakamre indplaceret i de ultramafiske kumulater eller i fødekanalerne under komplekset og siden – efter tab af gasfase

– under lavt P_{H2O} ved frationeret krystalisation domineret af klinopyroxen.

Strontium og neodymium isotopforholdene er i overenstemmelse med ovennævnte petrogenetiske model (tab. 1; fig. 4). Alle undersøgte prøver, med undtagelse af to melanephelinitgange fra grundfjeldet uden om komplekset falder på en linie mellem isotopsammensætningerne for islandske lavaer og sammensætningen for »Bulk Silicate Earth, BSE« i $^{143}Nd/^{144}Nd$ versus $^{87}Sr/^{86}Sr$ diagrammet. De to prøver, der har særligt høje $^{87}Sr/^{86}Sr$ forhold, antages at være forurenede med Sr fra grundfjeldet. De fleste prøver viser en meget begrænset spredning og melanepheliniter fra Suite Ln og en melanephelinit fra Trend R med relativt højt $^{143}Nd/^{144}Nd$ (0.512861–0.512889) og relativt lavt $^{87}Sr/^{86}Sr$ (0.7037) antages at representere den isotopmæssige sammensætning af kilden til den melanephelinit smelte type, der er fælles for alle tre grupper defineret oven for. Mindre variationer i sammensætning af Sr og Nd isotoper inden for Trend G er henført til varierende grad af vekselvirkning med omgivende grundfjeld i magma kamre nederst i eller i fødesystemet til Gardiner komplekset.

Den antagne isotopsammensætning for den fælles type af ophavsmelte i Gardiner komplekset svarer til sammensætningen af samtidige tholeiitiske smelter i den unge spredningszone langs Grønlands østkyst. Disse forhold fører til konklusionen, at ophavssmelterne til Gardiner komplekset representerer en lavtgradig opsmeltning fra »mantle plume« kilden. I Nordatlantisk sammenhæng er denne kilde bedst sammenlignet med den mest berigede del af islandske basalter og må antages at representere en øvre (beriget) grænse for den isotopmæssige sammensætning af »plume« komponenten i den islandske »mantle plume«.

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