Origin of anorthosites, gabbros and potassic ultramafic rocks from the Gardar Province, South Greenland: Sr isotopic ratio studies

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Precise initial $^{87}Sr/^{86}Sr$ ratio data ($2\sigma \sim 0.00006$) for five xenolithic anorthosites and five host gabbros from the late phase (~ 1170 m. y.) of activity in the Narssaq area of the Gardar Province, South Greenland, show that the two rock-types had an identical mean initial $^{87}Sr/^{86}Sr$ ratio of 0.70297 at 1170 m.y. The samples define a line of 1150 ± 142 m. y. which is in agreement wtih their known age. The concordance of initial $^{87}Sr/^{86}Sr$ ratios strongly suggests a related origin and favours models for differentiation of Gardar magmas which involve plagioclase fractionation. Initial $^{87}Sr/^{86}Sr$ ratio data for rocks and minerals from small potassic ultramafic bodies belonging to the same magmatic cycle and intruding the gabbros are also uniformly low (~ 0.703). These values are similar to the low initial $^{87}Sr/^{86}Sr$ ratios obtained for other, uncontaminated Gardar intrusions and make any significant crustal contamination of the ultramafic magmas improbable.

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The Gardar Province of south Greenland comprises a region extending some 200 km (E–W) by 80 km (N–S) which experienced extensive alkaline magmatism 1350–1150 m.y. before present. An Early Gardar sequence of interbedded continental sandstones and basaltic to trachytic lavas is succeeded by a widespread and repetitive association of central complexes of alkaline felsic rocks and dykes and dyke complexes composed dominantly of dolerites and gabbros.

Xenoliths of anorthosite and megacrysts of plagioclase occur in intrusions throughout the province, most abundantly in rocks of hawaiitic or mugearitic composition, and more rarely in rocks of either less or more differentiated compositions than these. Bridgwater & Harry (1968) inferred the presence at depth of a widespread body of anorthosite and sympathetic variation between the compositions of xenolith or megacryst plagioclase and host rock suggested a close relationship between anorthosite genesis and the differentiation of Gardar magmas.

A quantitatively minor but recurring association in the Gardar comprises silica- and alumina-poor lamprophyres, mica pyroxenites, mica peridotites and carbonatites. These rocks are significant because their relationships to one another and to the prevalent basaltic to phonolitic or rhyolitic associations of the province cannot be explained in terms of relatively low-pressure fractionation processes (Upton & Thomas 1973).

This paper presents initial $^{87}Sr/^{86}Sr$ ratio determinations on samples from mafic and ultramafic intrusions in the vicinity of Narssaq (fig. 1), occurring in close proximity to each other and having well-defined chronological relationships. Samples analysed comprise:

1. Alkali-olivine gabbros of a large dyke complex.
2. Anorthosite xenoliths contained in these gabbroic rocks.
3. Mica-pyroxenites and mica-peridotites intruding the gabbros.

It has been suggested (Upton 1971; Upton & Thomas 1973) that all these rocks are related

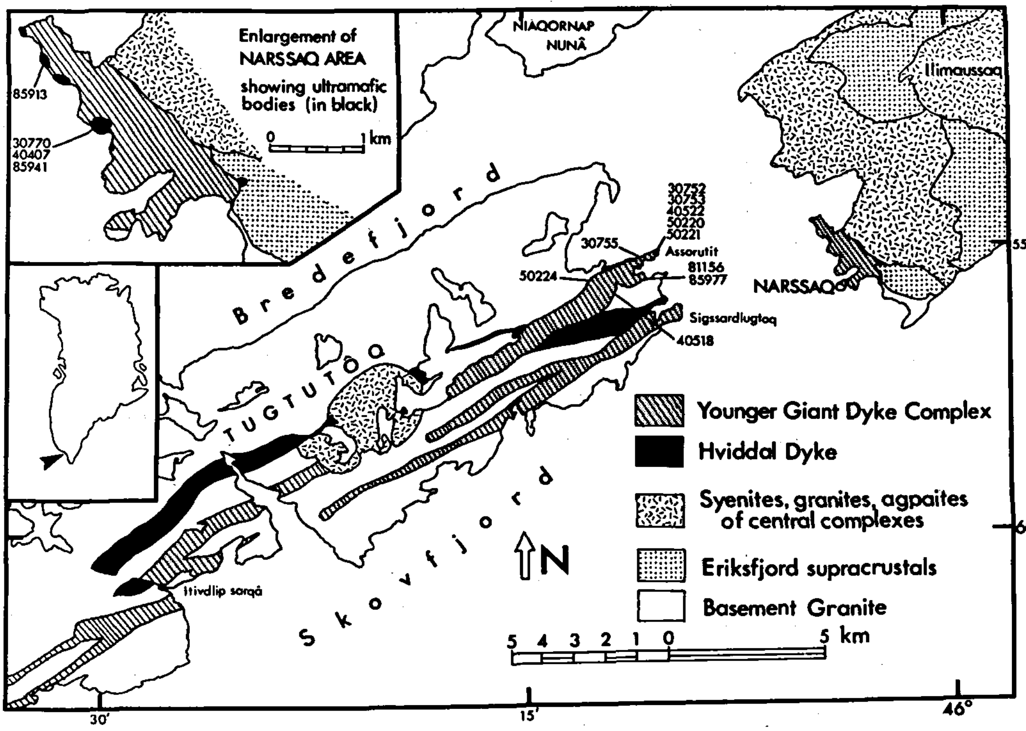

Fig. 1. Simplified geological map of the Tugtutôq-Narssaq area showing sample locations of anorthosites, gabbros and ultramafic rocks.

by the operation of polybaric crystal fractionation processes on similar parental magmas.

Geological Setting

The rocks studied occur at the north-east end of Tugtutôq island and on the adjacent mainland around Narssaq (fig. 1). They intrude the pre-Gardar Julianehåb granite complex dated at 1780 ± 20 m.y. (van Breemen, Aftalion & Allaart 1974), with cooling ages of ~ 1600 m.y. and belong to the Late Gardar magmatic cycle in this area at ~ 1170 m.y. (Blaxland, van Breemen, Emeleus & Anderson in press).

The earliest event in the magmatic cycle was intrusion of the gabbroic to foyaitic Hviddal giant dyke of Tugtutôq, dated at 1175 ± 9 m.y. (van Breemen & Upton 1972: age adjusted to a new calibration based on NBS stoichiometric standard salts). The activity continued with emplacement of further large dykes on Tugtutôq composed of gabbro, syenogabbro and subordinate quartz syenite and it is in the gabbroic rocks of these giant dykes that anorthositic material first appears in the area. Plagioclase megacrysts up to 15 cm occur sparsely through large parts of the dyke complex and become more common in the northern dyke at the eastern end of Tugtutôq (fig. 1); at Assorutit anorthosite xenoliths up to 100 m across are abundant. They are laminated with plagioclase crystals up to 15 cm and show a crude layering. These rocks, interpreted as labradorite cumulates (Upton 1964), consist of plagioclase, olivine, ilmenite, magnetite, apatite, augite and biotite. Whereas there is some evidence of slight alteration of the gabbros and anorthosites (growth of minor chlorite and epidote), there is none to suggest that the anorthosites have been penetrated or remelted by the gabbro or that either have been affected by fluids emanating from later intrusions. This is not the case for the contiguous gabbro on the mainland where both host rocks and anorthositic material have been strongly affected by alkaline metasomatism associated with later cross-cutting alkaline complexes; for this reason, samples from the mainland were not included.

Small hypabyssal intrusions (plugs and sills) of fine-grained mica-pyroxenite and mica peridotite were emplaced either within or alongside the gabbro intrusions and form a coherent group in terms of composition and field relationships (Upton & Thomas 1973). These ultramafic rocks are fresh and appear wholly free of the metasomatism which affected some of the gabbroic rocks in the Narssaq area.

The gabbroic and ultramafic intrusions are cut by a swarm of hawaiite to mugearite dykes carrying abundant plagioclase megacrysts and anorthositic material (the "Big-Feldspar dykes"). After further intrusion of trachyte, phonolite and comendite dykes, activity in the Narssaq area terminated with emplacement of the Tugtutôq Central Complex, dated at 1168 ± 37 m.y. (van Breemen & Upton 1972) and the Ilímaussaq complex, dated at 1168 ± 21 m.y. (Blaxland, van Breemen & Steenfelt 1976).

The rocks studied are thus bracketed by the ages 1175 ± 9 m.y. and 1168 ± 21 m.y. and an age of 1170 m.y. is used for initial ratio calculation.

Analytical Procedures and Results

Crushed whole-rock samples and washed, uncrushed mineral samples underwent an HF–$HClO_4$ dissolution in pre-spiked PTFE beakers and ion exchange was performed in a glass column using Bio-Rad 50W-X8 200–400 mesh resin. Mass analysis was carried out on an AEI-GEC MS-12 solid source mass spectrometer with a 12 inch radius and 90° sector, using a Faraday cup and Cary 401 vibrating-reed electrometer with 10^{11} ohm resistor. Measured peaks were corrected for signal decay and ^{85}Rb was continuously monitored during Sr runs.

Overall blanks measured during the period of analysis gave 5 ng Rb and 4 ng Sr. The systematic error in the initial ratio due to this Rb blank is always less than 2 % of the quoted error for the anorthosite and gabbro samples (table 1), and considerably less than 1 % of the quoted error for the ultramafic samples (table 2); therefore no blank correction is made. A mean value for the Eimer and Amend $SrCO_3$ standard of 0.70804 ± 0.00012 (2σ) was obtained, based on sixteen analyses made over the general period of study.

Results are listed in tables 1 and 2. All errors used for calculation or quoted in the tables are at the 2σ level. An estimated 2σ uncertainty of 1.4 % on $^{87}Rb/^{86}Sr$ is used for all samples and for the anorthosites and gabbros the error on the initial $^{87}Sr/^{86}Sr$ ratio is calculated by adding this $^{87}Rb/^{86}Sr$ component to the in-run 2σ standard error on $^{87}Sr/^{86}Sr$. For the ultramafic samples an estimated 2σ uncertainty of 0.1 % on $^{87}Sr/^{86}Sr$ is used (estimated uncertainties are based on previous replicate analyses). The decay constant for ^{87}Rb of 1.39×10^{-11} yr^{-1} is used for all calculations.

The five anorthosites and the five gabbros have identical mean initial $^{87}Sr/^{86}Sr$ ratios of 0.70297. These ten analyses were regressed by the method of York (1969) using 1σ errors of 0.7 % on $^{87}Rb/^{86}Sr$ and 0.0035 % on $^{87}Sr/^{86}Sr$; the latter figure represents the mean of the ten individual in-run 1σ standard errors. The age obtained is 1150 ± 142 m.y., with an initial $^{87}Sr/^{86}Sr$ ratio of 0.70297 ± 0.00005 (errors at 2σ) and a value of 4.12 for MSWD, showing that the samples are quite close to defining an isochron relationship (Brooks, Hart & Wendt 1972). The regression age agrees with the true age of ~ 1170 m.y. Initial ratios of ultramafic samples are also low (~0.703) and, within analytical uncertainty, are identical for the two bodies studied.

Discussion

The anorthosites occur as xenoliths in the gabbro and have been carried in the magma; it is therefore possible that the $^{87}Sr/^{86}Sr$ of the anorthosite was readjusted to that of the gabbro during dyke emplacement. This is consid-

TABLE 1. Rb-Sr data for anorthosites and gabbros.

Sample	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$**	
Anorthosite						
30752	2.15	1807.1	0.003447	0.703053	0.70300	± 0.00005
30753	31.12	1800.8	0.049981	0.703776	0.70296	± 0.00006
40522	3.27	1603.1	0.005588	0.702969	0.70288	± 0.00006
50220	1.78	1840.1	0.002796	0.703077	0.70303	± 0.00007
50221	9.96	1849.2	0.015578	0.703232	0.70298	± 0.00005
Mean anorthosite value					0.70297	± 0.00011
Gabbro						
30755	6.42	1328.7	0.013965	0.703210	0.70298	± 0.00006
40518	16.69	1095.4	0.044073	0.703747	0.70303	± 0.00006
50224	14.81	1141.8	0.037514	0.703531	0.70292	± 0.00006
81156	10.00	1187.6	0.024361	0.703386	0.70299	± 0.00005
85977*	11.43	1127.5	0.029314	0.703369	0.70289	± 0.00006
85977*	11.17	1124.9	0.028708	0.703432	0.70296	± 0.00006
Mean Gabbro value					0.70297	± 0.00008

Sample numbers refer to GGU sample files.
* Duplicated analysis: mean initial ratio 0.70293 ± 0.00006.
** Errors quoted at the 2σ level.

TABLE 2. Rb-Sr data for ultramafic rocks

Sample	Rb ppm	Sr ppm	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$	$(^{87}Sr/^{86}Sr)_0$**	
85913 (wr)	108.46	600.4	0.52286	0.71152	0.70294	± 0.00082
85913 (pyroxene)	0.79	695.5	0.00330	0.70289	0.70284	± 0.00070
30770 (wr)	136.78	376.9	1.05115	0.71942	0.70218	± 0.00094
30770 (pyroxene)	1.92	450.2	0.01233	0.70271	0.70251	± 0.00070
40407 (wr)	12.79	460.7	0.08031	0.70479	0.70347	± 0.00072
40407 (pyroxene)	0.50	327.2	0.00438	0.70317	0.70310	± 0.00070
40407 (apatite)*	0.08	1568.7	0.00014	0.70319	0.70318	± 0.00070
85941 (pyroxene)	1.39	424.0	0.00945	0.70345	0.70330	± 0.00070
85941 (apatite)*	1.69	1771.9	0.00276	0.70323	0.70319	± 0.00070

Sample numbers refer to GGU sample files.
* Contains olivine impurity.
** Errors quoted at the 2σ level.

ered unlikely because the anorthosites have undisturbed cumulate textures and show no signs of significant alteration. Accidental derivation of the xenoliths from Archaean anorthosite, the nearest occurrence of which is ~ 100 km to the WNW, can be ruled out because these occur as deformed enclaves in gneisses, whereas the anorthosites of this study are cumulate rocks unaffected by any deformation. Texturally, the rocks have more in common with the Proterozoic anorthosites of Labrador and south Norway; however, apart from having higher initial $^{87}Sr/^{86}Sr$ ratios (0.7031 to 0.7059 according to Heath & Fairbairn 1968), these Proterozoic anorthosites are generally orthopyroxene-bearing (e.g. Anderson 1968), whereas the anorthosites of this study contain olivine, augite, apatite and biotite suggesting an alkaline affinity.

The marked concordance of the anorthosite and gabbro initial ratio data strongly suggests that the two rock-types are closely related, though not necessarily crystallised from the same magma. This conclusion is supported by rare-earth element patterns in anorthosite, gabbro and syenogabbro of the giant dyke complex (Blaxland & Upton in preparation).

Experimental studies on two uncontaminated chills of the gabbro giant dykes (Upton 1971 and unpublished data) indicate olivine as the liquidus phase from 1–10 kb, replaced by clinopyroxene at higher pressures; plagioclase crystallisation began 10–50°C below the liquidus temperature. Consequently, cumulates having plagioclase as the first crystallising phase, such as the anorthosites, cannot have formed from the magma represented by the gabbro dyke chills. However, Upton (1971) suggested that extended clinopyroxene fractionation at pressures >10 kb from magmas similar to those of the gabbro dyke chills could have yielded a highly aluminous liquid which at lower pressures would have plagioclase on the liquidus.

In this way magmas generated early in the Late Gardar magmatic phase (from ~ 1200 m.y. onwards), rising slowly into the lower crust and fractionating clinopyroxene could have been responsible for the genesis of magmas from which large volumes of anorthosite crystallised at shallower levels. These anorthosites were disrupted and carried upwards by subsequent batches of magma to appear both in the gabbro giant dykes and various younger intrusions. This and similar hypotheses hold that plagioclase fractionation at depth was an important means of differentiation of Gardar magmas (Upton 1964; Bridgwater 1967; Bridwater & Harry 1968; Upton 1971; 1974). The initial $^{87}Sr/^{86}Sr$ data suggest a closely related origin for xenoliths of cumulate anorthosite and their host gabbros and thus lend support to this argument. The common failure of more felsic magmas to carry anorthosite can be attributed either to their insufficient density or to their generation by low-pressure fractionation above the level of anorthosite accumulation.

The potassic ultramafic rocks cannot be related to the gabbroic magmas by low-pressure fractionation; the combination of relatively high Mg, Ni and Cr with high Ba, Zr, Ti and K is incompatible with fractionation schemes involving plagioclase and pyroxene (with or without olivine). Possible origins consistent with the geochemistry (Upton & Thomas 1973) include (1) small-scale partial melting of an upper mantle source region containing phlogopite, (2) a form of "zone refining" process whereby the ascending ultramafic magma scavenges incompatible elements from the surrounding mantle material and (3) fractional crystallisation of garnet and clinopyroxene from a picritic mantle partial melt.

The uniformly low initial $^{87}Sr/^{86}Sr$ ratios obtained for the potassic ultramafic rocks (all values agree at 2σ with 0.703) cannot be used to determine precisely the *mechanism* of origin, but can yield useful information on the provenance of the magmas. The results obtained compare (allowing for age difference) with the lowest values reported by Barrett & Berg (1975) for mantle-derived South African kimberlites, and fall in the lower half of the range of mantle source region values for 1170 m.y. (e.g. Faure & Powell 1972). The initial $^{87}Sr/^{86}Sr$ ratios for the ultramafic rocks are also comparable to the anorthosite and gabbro values presented here, and fall low in the range of Gardar initial $^{87}Sr/^{86}Sr$ ratios reported by Blaxland et al. (in press). On these grounds it seems unlikely that any significant amount of crustal strontium can have been incorporated into the potassic ultramafic magma before or during emplacement.

Conclusions

1. The initial $^{87}Sr/^{86}Sr$ ratios of gabbros and anorthosite xenoliths from a giant dyke on Tugtutôq in the Gardar Province of south Greenland are identical at 0.70297. This suggests a cognate relationship, as proposed by several authors for Gardar anorthosites in general, and supports hypotheses involving plagioclase fractionation as an important means of differentiation for Gardar magmas.
2. Initial $^{87}Sr/^{86}Sr$ ratios from penecontemporaneous potassic ultramafic rocks also have uniform low (~ 0.703) values similar to those reported for other, uncontaminated, Gardar intrusions, and give no grounds for supposing significant crustal contamination of the ultramafic magmas.

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Dansk sammendrag

For fem anorthosit indeslutninger og fem prøver af den gabbro hvori disse indeslutninger forekommer er det primære $^{87}Sr/^{86}Sr$ forhold (initial ratio) bestemt med stor precision (± 0.00006). Gabbro'erne hører til den sene fase af magmatisk aktivitet (~ 1170 millioner år) i Narssaq området i Gardar provinsen, Syd Grønland. De to bjergartstyper har i gennemsnit det samme primærforhold, 0.70297 ved 1170 mill. år. De undersøgte prøver giver en isochron alder af 1150 ± 142 mill. år, hvilket er i overensstemmelse med den kendte alder. Overensstemmelsen i $^{87}Sr/^{86}Sr$ primærforhold tyder stærkt på en beslægtet oprindelse og støtter et differentiationsforløb for Gardar magmaerne hvorunder plagioklas krystalliserede ud i et tidligt stadium.

Det primære $^{87}Sr/^{86}Sr$ forhold for bjergarter og mineraler fra små kalium-rige ultramafiske legemer som tilhører samme magmatiske periode og intruderer gabbro'en er ligeledes lave (~ 0.703). Disse værdier ligner de lave primærforhold fundet for andre ukontaminerede Gardar intrusioner og gør det usandsynligt at de ultramafiske magmaer under opstigningen i nævneværdig grad blev opblandet med skorpemateriale.

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