GRØNLANDS GEOLOGISKE UNDERSØGELSE
RAPPORT Nr. 71

The Geological Survey of Greenland
Report No. 71

Mineralogy and geochemistry of two Amîtsoq gneisses from the Godthåb region, West Greenland

by

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KØBENHAVN 1975

Grønlands Geologiske Undersøgelse

(The Geological Survey of Greenland)
Øster Voldgade 10, DK-1350 Copenhagen K

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Abstract

Amîtsoq gneisses are of granodioritic composition, consisting largely of quartz, oligoclase, microcline, and biotite, with accessory amounts of hornblende, epidote, sphene, apatite, zircon, and allanite. Two of these rocks and their constituent minerals have been analysed for Rb, Sr, Y, Zr, Nb, Cs, Ba, the lanthanides, Hf, Pb, Th, and U by spark source mass spectrometry. The trace element abundances and the lanthanide distribution patterns for these rocks are not significantly different from those in relatively young rocks of similar bulk composition.

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INTRODUCTION

The Amîtsoq gneisses of the Godthåb district, West Greenland, have yielded ages of about 3700 m.y. by Rb-Sr whole rock isochron, Pb-Pb whole rock isochron and zircon concordia-discordia methods (Black *et al.,* 1971; Moorbath *et al.,* 1972; Baadsgaard, 1973), and are the oldest granitic rocks yet dated.

Amîtsoq gneisses have been recognized within an area some 200 km long, extending from the margin of the Inland Ice at Isua (65°15′N), 40 km north of the head of Godthåbsfjord, south almost as far as the fjord Sermilik (63°35′N). The geology of the central part of this area, in the vicinity of the town of Godthåb, has been described by McGregor (1973). The Amîtsoq gneisses are recognized in the field because they contain very abundant broken-up fragments of amphibolite derived from a swarm of basic dykes, the Ameralik dykes. After the intrusion of the Ameralik dykes the Amîtsoq gneisses had a complex history of intense reworking under plutonic conditions (McGregor, 1973; Bridgwater *et al.,* 1974).

Amîtsoq gneisses derived from homogeneous, originally coarse-grained granites and granodiorites, many of which contained abundant megacrysts of potash feldspar, are found south of Godthåb in an area extending from the mouth of Ameralik to the islands south of Qilángârssuit (Baadsgaard, 1973, fig. 1). McGregor (1973, figs 7,8) has figured one of the least modified of these granites. The parent rock was a big-feldspar granite that appears in the field to have been very similar to many younger granites of late tectonic type. Four of the gneisses considered in this study (GGU 155817, 155818, 155819, 110869) are derived from this big-feldspar granite. One (GGU 155820) is from a raft of much darker, even-grained gneiss some tens of metres across enclosed in the granite. It could be an earlier, more basic phase of the same intrusive suite. The last specimen (GGU 110999) is a gneiss derived from an even-grained, homogeneous tonalite.

All of these rocks are quartz-feldspathic gneisses of fairly uniform mineralogy and composition. The dominant minerals, making up 70-85 % of the rocks, are plagioclase (about An_{25}), quartz, and microcline. Biotite is the most abundant ferromagnesian mineral, and is accompanied by minor amounts of hornblende and epidote; in some of the rocks the epidote has cores of allanite. Accessory minerals are sphene, apatite, and zircon. Opaque minerals (ilmenite, magnetite, pyrite) are rare or absent.

Major element chemistry

Because of the overall similarity of the rocks, two, 155818 and 155819, were selected for detailed investigation; 155818 was notably more feldspathic than 155819,

Table 1. Analyses, norms and modes of Amîtsoq gneisses

	Analyses			Norms			Modes	
	155818	155819		155818	155819		155818	155819
SiO_2	67.5%	67.5%	Q	19.2%	23.3%	Quartz	24%	27%
TiO_2	0.64	0.81	Or	33.5	18.5	Microcline	26	10
Al_2O_3	15.0	14.5	Ab	25.6	29.6	Plagioclase	32	40
FeO	4.24	5.08	An	10.4	14.5	Biotite	14	15
MnO	0.09	0.08	Di	0.7	1.5	Hornblende	1	4
MgO	0.64	0.80	Hy	8.0	9.2	Epidote	2	2
CaO	2.48	3.52	Il	1.2	1.5	Allanite	-	0.2
Na_2O	3.03	3.51	Ap	0.4	0.4	Sphene	0.9	1.2
K_2O	5.68	3.14				Apatite	0.4	0.4
P_2O_5	0.16	0.19				Zircon	<0.1	<0.1

All Fe reported as FeO

and had prominent augen of pale orange microcline. Samples were fused with lithium tetraborate flux and the resulting glasses analysed with the microprobe; the results are given in Table 1, along with the norms calculated therefrom and the observed modes. The probe analyses do not differentiate ferrous and ferric iron, and all the iron is reported as FeO; since iron is relatively low, this does not greatly affect the norm calculation.

As can be seen, the differences in bulk composition between the two rocks are not great. The composition is that of a granodiorite or adamellite, and corresponds closely with Nockolds' average of 41 analysed hornblende-biotite adamellites (Nockolds, 1954). The Fe/Mg ratio is notably high, and is reflected in the iron-rich nature of the biotite and hornblende. Differences between the norms and the modes are due to peculiarities in the mineral composition (Table 2). Modal quartz is higher than normative quartz because of the low SiO_2 content of the biotite and hornblende. Modal microcline is lower than normative orthoclase, since much of the potassium is combined as biotite. Modal plagioclase is a little lower than normative plagioclase

Table 2. Microprobe analyses of some of the minerals in two samples of Amîtsoq gneisses

	Plagioclase		Microcline		Biotite		Hornblende	Epidote	Allanite	Sphene
	155818	155819	155818	155819	155818	155819	155819	155819	155819	155819
SiO_2	61.9	61.5	64.7	64.7	34.5	34.6	39.0	37.8	33.2	30.8
TiO_2	-	-	-	-	2.63	2.59	1.14	0.09	0.41	36.3
Al_2O_3	24.1	24.5	18.4	18.4	16.2	15.6	12.4	24.9	17.9	1.63
FeO	<0.08	<0.08	<0.08	<0.08	26.9	26.9	25.4	12.9	14.2	0.71
MnO	-	-	-	-	0.27	0.26	0.43	0.16	0.26	0.15
MgO	-	-	-	-	4.51	5.42	3.82	<0.06	0.34	0.06
CaO	5.06	5.51	0.10	0.17	<0.08	0.14	11.1	23.9	15.6	28.8
Na_2O	9.27	8.50	0.37	0.21	<0.10	<0.10	1.33	-	-	0.09
K_2O	0.25	0.25	16.4	16.5	9.53	9.46	1.72	-	-	0.07
RE_2O_3	-	-	-	-	-	-	-	0.3	13.3	0.3

All Fe reported as FeO, except for epidote (Fe_2O_3)

because some calcium is combined in hornblende and epidote. The rocks contain no ilmenite, all the titanium being combined in biotite, hornblende, and sphene.

In thin section the minerals of these rocks are seen to be remarkably fresh. Neither the biotite nor the hornblende shows any trace of chloritization. The feldspars also are completely unaltered, except for some of the larger plagioclase grains in 155818, which show a small degree of clouding. The rock was evidently equilibrated in the amphibolite facies and has suffered no subsequent retrograde metamorphism. The distribution of the elements between the different minerals should thus reflect this equilibrium situation. Noteworthy features of the major element distribution between the minerals are the low K_20 in the plagioclase and the very low Na_20 in the microcline; the greater concentration of TiO_2 and lower concentration of MnO in biotite compared to hornblende; and the remarkable segregation of the light lanthanides (La–Nd) in the allanite. In 155819 the allanite is overgrown by epidote, but the boundaries between the two minerals are sharp. The allanite is not metamict, which may seem remarkable in such an old rock, but is probably related to a low content of Th and U.

Minor and trace elements

Minor and trace elements were determined in the rocks and the mineral separates by spark source mass spectrography, using the technique described by Taylor (1971). This technique utilizes lutetium as an internal standard, and is very satisfactory for most rocks and minerals. However, difficulties arise when lutetium is present in appreciable amounts in the sample, and when a high concentration of hafnium is present (due to interference of ^{176}Hf with ^{176}Lu). As a result, zircon could not be satisfactorily analysed, and the results for sphene (which contains 10–20 ppm Lu) are less reliable than for the other minerals. A pure sample of allanite could not be separated from 155819 for analysis; a mixture of epidote and allanite in the proportion of 9:1 was analysed, and the figures for allanite obtained by correcting for the epidote using the figures for the pure epidote in 155818.

The data are set out in Tables 3 and 4, tabulated according to the procedure recommended by Taylor & White (1966). The procedure groups together those elements whose geochemical behavior is similar, and within each group lists them in sequence of decreasing ionic radius.

The first group comprises the large cations which occur in 8–12 fold coordination with oxygen in silicates, and form essentially ionic bonds. Potassium is the dominant major cation. The largest cation, Cs, resides almost entirely in biotite; this preference for biotite is evidently due to the presence of the large 12-coordinated K site in this mineral. Barium and rubidium, with ionic radii close to that of potassium, are concentrated in biotite and microcline, although appreciable amounts are present in plagioclase; Ba shows a preference for microcline, whereas Rb is present in approximately equal concentration in both microcline and biotite. Lead was measured in all minerals, except biotite and sphene in 155818; it is concentrated in the feld-

Table 3. Minor and trace elements in Amîtsoq gneiss 155818, and constituent minerals, in ppm

	Rock	Plagioclase	Microcline	Biotite	Epidote	Sphene	Apatite
Cs	0.83	<0.1	0.50	8.8	<0.1	<0.1	<0.1
Rb	41	25	>150	>150	8.6	<0.3	<0.3
Ba	510	240	1700	660	12	<2	4.0
Pb	12	19	30	<1	70	<1	5.5
Sr	98	210	130	12	920	14	130
Th	0.62	<0.5	<0.5	<0.5	11	<0.5	<0.5
U	0.28	<0.2	<0.2	<0.2	<0.3	6.2	7.3
Zr	160	100	47	190	59	140	160
Hf	5.1	4.7	2.9	8.2	<2	10	10
Nb	7.3	<0.2	<0.2	11	31	390	1.3
La	16	1.6	4.9	6.7	720	120	140
Ce	42	3.4	6.8	14	1700	430	470
Pr	5.0	0.36	0.66	1.7	170	150	67
Nd	22	1.2	2.0	5.7	530	760	290
Sm	4.2	0.23	0.45	1.1	54	230	65
Eu	1.9	0.19	0.83	0.41	15	110	23
Gd	4.4	0.35	1.3	1.2	68	220	97
Tb	0.57	<0.1	<0.1	0.26	4.3	34	int
Dy	3.5	<0.4	0.95	0.82	20	220	62
Ho	0.66	<0.1	<0.1	<0.1	4.4	54	14
Er	1.9	<0.4	<0.4	<0.4	8.7	130	40
Tm	<0.3	<0.3	<0.3	<0.3	1.0	19	5.3
Yb	2.1	<0.4	<0.4	<0.4	6.8	120	35
Y	15	<0.4	<0.4	2.6	160	>500	460

int = not determined because of interference

spars, and in epidote and allanite. Strontium shows an interesting pattern, being relatively concentrated in the feldspars, epidote, allanite, and apatite, and relatively depleted in biotite, hornblende, and sphene. It shows geochemical coherence with calcium, but evidences a preference for larger, 8–9 coordinate sites (as in the feldspars, epidote, allanite, and apatite)rather than the 6–7 coordinate sites in hornblende and sphene.

Turning now to the second group of elements in Tables 3 and 4, the data on Th and U are of special interest. The rocks are notably low in these elements (crustal averages 9.6 ppm Th and 2.7 ppm U). This is consistent with the observation by Black *et al.* (1971), that the Pb from these rocks is extremely unradiogenic. The whole-rock Th/U ratio is low, 2.2–2.6, compared to the crustal Th/U ratio, 3.6. These elements are concentrated in the accessory minerals, but are remarkably fractionated between them. Epidote and allanite concentrate Th and have Th/U ratios of 9 or greater; apatite and sphene concentrate U and have Th/U ratios of less than unity. The data of Baadsgaard (1973) show that zircon from these rocks also concentrates U relative to Th, with Th/U ratios less than unity. The reason for this remarkable fractionation of these two elements between different minerals can hardly be directly due to differences in ionic size, since Th^4 (1.02Å) is not significantly larger than U^4 (0.97Å); more subtle influences must be operative. The low Th/U ra-

Table 4. Minor and trace elements in Amîtsoq gneiss 155819, and constituent minerals, in ppm

	Rock	Plagioclase	Microcline	Biotite	Hornblende	Sphene	Apatite	Allanite
Cs	1.0	0.20	0.39	13	<0.1	<0.1	<0.1	<0.1
Rb	46	30	150	120	7.7	<0.3	<0.3	4.9
Ba	480	250	3700	1400	28	2.0	3.2	250
Pb	15	16	20	3.3	7.3	4.1	4.9	57
Sr	180	280	250	4.0	13	4.8	120	440
Th	1.1	<0.5	<0.5	<0.5	<0.5	1.6	0.86	1000
U	0.42	<0.2	<0.2	<0.2	<0.2	4.2	2.1	110
Zr	320	87	170	21	76	88	120	1000
Hf	8.2	1.3	3.5	<2	2.8	9.2	9.5	45
Nb	12	<0.2	<0.2	5.6	11	80	1.0	75
La	48	0.95	0.51	1.1	15	58	44	2.10%
Ce	120	2.2	0.77	1.3	42	420	180	5.05%
Pr	16	0.24	0.10	0.24	6.6	89	31	0.54%
Nd	58	1.2	<0.5	1.1	31	510	170	2.35%
Sm	11	0.47	<0.2	<0.2	9.7	230	70	4900
Eu	1.8	0.27	<0.2	<0.2	1.6	41	12	630
Gd	12	0.82	<0.2	<0.2	12	270	87	4600
Tb	1.4	<0.1	<0.1	<0.1	1.7	46	int	370
Dy	7.7	<0.4	<0.4	<0.4	9.5	260	62	1300
Ho	1.7	<0.1	<0.1	<0.1	2.4	66	16	280
Er	4.5	<0.4	<0.4	<0.4	6.0	170	45	540
Tm	0.55	<0.3	<0.4	<0.4	0.71	24	6.2	60
Yb	3.5	<0.4	<0.4	<0.4	4.4	140	41	330
Y	42	0.48	0.43	0.36	50	>500	250	>500

int = not determined because of interference

tios in apatite, sphene, and zircon may be due to the early crystallization of allanite removing practically all the Th from the system, but the particular affinity of allanite for this element remains to be explained.

Most of the Zr and Hf in these rocks is contained in accessory zircon. The Zr/Hf ratios for the rocks, 31 and 39, are matched fairly closely by the individual minerals, except for sphene and apatite, which have low value (10–16) for this ratio. If these minerals were a late crystallization, this implies a progressive increase in the concentration of Hf relative to Zr during crystallization.

Niobium is concentrated in sphene and allanite. The ability of sphene to concentrate Nb has been noted previously, e.g. Mason (1972), and is evidently due to coupled substitution of the type NaNb = CaTi.

The data for the lanthanides are plotted in Figs 1 and 2, normalized to average chondritic abundances. The data for biotite, plagioclase, and microcline are not plotted since they are incomplete, the abundances of the heavier lanthanides being below the detectability level. The data for hornblende in 155819 are not plotted, because the pattern for Sm through Yb practically coincides with that for the bulk rock. For comparison purposes, the lanthanide abundances in the Bonsall tonalite of Cretaceous age, from Towell *et al.* (1965), are plotted in Fig. 1, and those for a composite of North American shales, from Haskin & Haskin (1968), are plotted in Fig. 2.

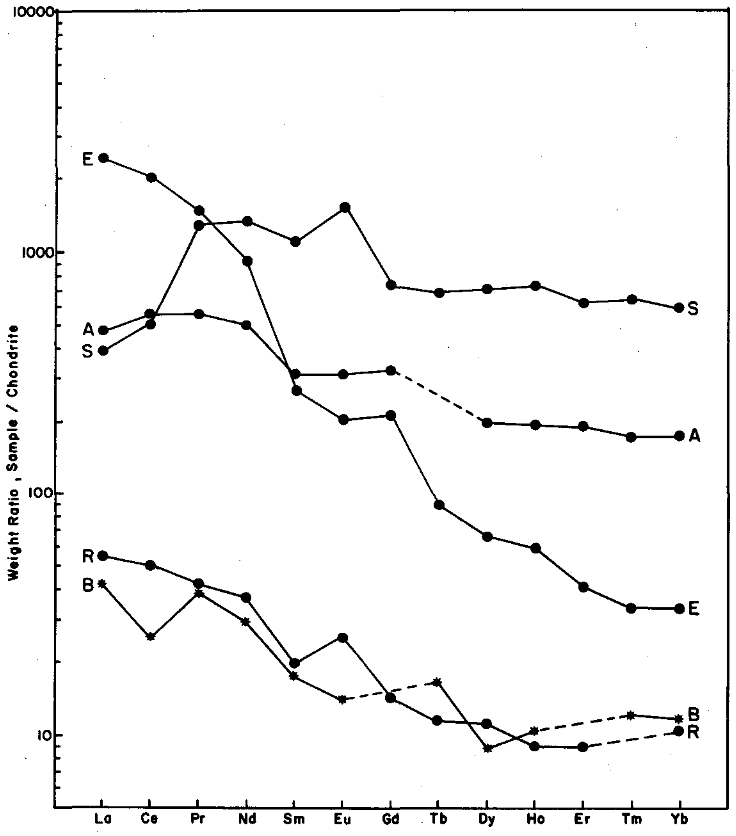

Fig. 1. Abundances of the lanthanides in GGU 155818, normalized to the average chondritic abundances; E = epidote, A = apatite, S = sphene, R = bulk rock, B = Bonsall tonalite.

Considering first the data for the rocks themselves, we see that the plotted distribution patterns are smooth curves of decreasing relative abundances towards the heavier lanthanides, on which are superposed a small positive Eu anomaly in 155818 and a small negative anomaly in 155819. Rock 155819 contains approximately twice the concentration of each lanthanide as 155818, except for Eu. The positive Eu anomaly in 155818 is linked with the presence of a considerable amount of microcline with a relatively high Eu concentration. The plots for the Bonsall tonalite and the shale composite were superimposed on Figs 1 and 2 to demonstrate that the lanthanide distribution pattern in these ancient Greenland gneisses is not significantly different from that of much younger crustal rocks; in particular, the composite of North American shales is probably a good average for crustal material.

O'Nions & Pankhurst (1974) have analysed eight specimens of Amîtsoq gneisses for Ce, Nd, Sm, Eu, Gd, Dy, Er, and Yb. Data for these elements in my two samples fall within the range of values reported by these authors; 155818 is closely com-

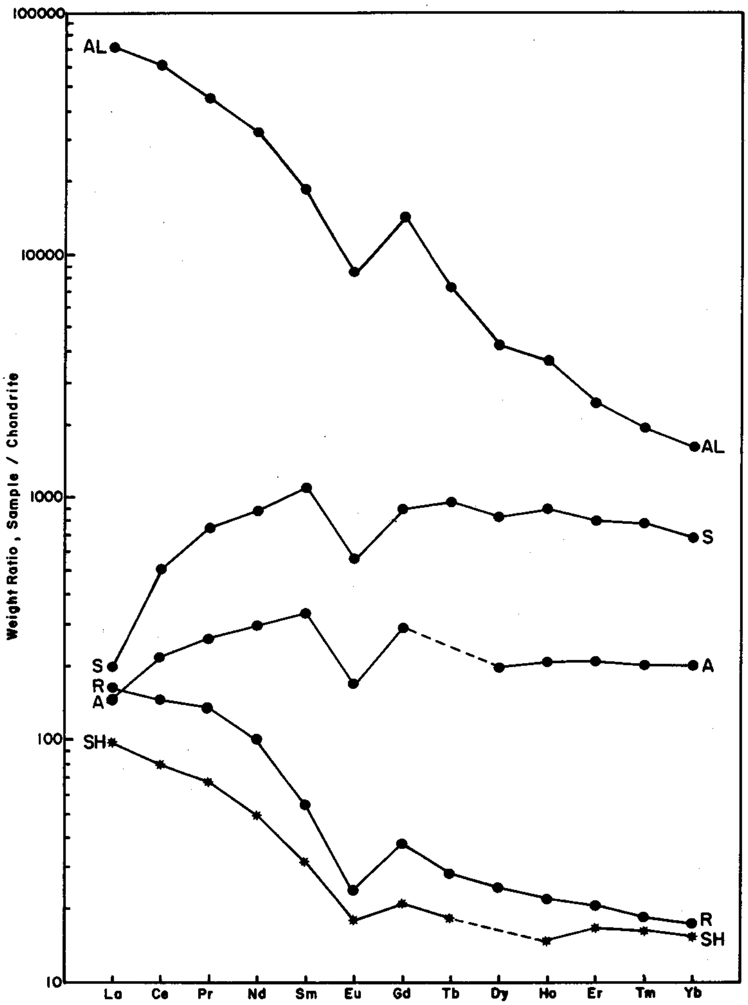

Fig. 2. Abundances of the lanthanides in GGU 155819, normalized to the average chondritic abundances: AL = allanite, S = sphene, R = bulk rock, A = apatite, SH = North American shale composite.

parable with their 125519, 155819 to 155702. Some of their specimens show very strong depletion in the heavy lanthanides; Ce/Yb ratios for their specimens range up to 112, whereas this ratio is 20 for 155818 and 34 for 155819.

Turning now to the individual minerals, we see that practically all the lanthanides in these rocks are contained in the accessory minerals apatite, sphene, epidote, together with allanite in 155819. The contribution of zircon could not be quantitatively evaluated, due to spectral interferences; however, the spectra showed clearly that zircon concentrates the heavier lanthanides relative to the lighter ones, and because of its low abundance ($< 0.1\%$) it would not contribute appreciably to the total lanthanide concentrations in the rocks.

Reference to Fig. 2 shows that the lanthanide distribution in 155819 is almost completely controlled by the allanite. The allanite pattern closely parallels that for the bulk rock, even to the negative Eu anomaly. Beyond Gd the abundances of the heavier lanthanides fall off more rapidly in allanite than in the bulk rock; this is compensated by the relatively flat distribution pattern for the heavier lanthanides in sphene and apatite. The pattern of relatively increasing abundances from La to Sm shown by both apatite and sphene reflects the rapidly declining abundances in these elements for allanite. A reasonable explanation is that allanite crystallized first among the accessory minerals and removed practically all the La and Ce and diminishing amounts of the heavier lanthanides from the system, and the apatite and sphene crystallizing later took up these elements proportionally to the concentrations remaining. Textural relations suggest that the allanite in 155819 may be an original igneous crystallization, largely unaffected by subsequent metamorphism that produced the gneissose structure. The allanite occurs as small grains, overgrown by epidote which probably formed during the metamorphism. It is significant that, in spite of the identity of structure of allanite and epidote, the relationship is one of overgrowth rather than the formation of a single homogeneous phase.

The relationships in 155818 are similar, except that this rock contains epidote and no allanite. Epidote has a similar lanthanide distribution pattern to allanite, but with much lower concentrations; it characteristically concentrates La and Ce and progressively diminishing amounts of the heavier elements. Sphene shows a complementary impoverishment in La and Ce.

Acknowledgements

This research was supported by a grant from the Smithsonian Research Foundation. I am indebted to the Geological Survey of Greenland and Mr. V.R. McGregor, Dr. D. Bridgwater, and Dr. H. Baadsgaard for the opportunity to work on these rocks; Dr. Baadsgaard provided mineral separates prepared in his laboratory. Mr. J. Nelen provided the major element analyses of the bulk rocks. The trace element determinations were made while I was Honorary Fellow in the Research School of Earth Sciences of the Australian National University, and I wish to thank Mrs. P. Muir and Mr. W. Nance for assistance in this work.

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