

Petrogenesis and geochemistry of metabasaltic and metasedimentary enclaves in the Amîtsoq gneisses, West Greenland

V. R. MCGREGOR

Geological Survey of Greenland, Copenhagen, Denmark

AND BRIAN MASON

Smithsonian Institution, Washington, D.C. 20560¹

Abstract

The oldest rocks recognized in the Greenland Archean are metamorphosed basic, ultrabasic, and sedimentary rocks enclosed in the *ca.* 3700 m.y. old Amîtsoq gneisses of the Godthåb region, West Greenland. Specimens from enclaves from the area south and south-east of the town of Godthåb have been analyzed for major elements and for a range of minor and trace elements (U, Th, Pb, Hf, REE, Ba, Cs, Zr, Nb, Y, Sr, Rb, Cr, Ni, Co, Cu). These rocks, for which the term *Akilia association* is introduced, include basic and ultrabasic rocks, some with komatiitic and others with Fe-rich tholeiitic affinities; banded ironstones; and gneisses of detrital sedimentary origin. The range of lithologies suggests that the rocks of the Akilia association are fragments of a greenstone-belt type of sequence that was intruded and disrupted by the granitic parents of the Amîtsoq gneisses.

Introduction

The oldest terrestrial rocks recognized to date give isotopic ages in the range 3600–3800 m.y. Ages in this range have been obtained from the Godthåb district of West Greenland (see below); northern Labrador (Hurst *et al.*, 1975; Barton, 1975); the Minnesota River Valley (Goldich *et al.*, 1970; Goldich and Hedge, 1974); Rhodesia (Hawthorn *et al.*, 1975), and East Antarctica (Sobotovich *et al.*, 1976). With the exception of the 3700–3800 m.y. Isua supracrustals of West Greenland (see below), the very old rocks that have been dated are all quartzo-feldspathic gneisses which, where well exposed and relatively little affected by later reworking, can be seen to be derived from intrusive granitic parents (Goldich *et al.*, 1970; McGregor, 1973; Bridgwater and Collerson, 1976). Correspondingly old ages have not yet been reported from the volcanic-sedimentary sequences of greenstone belts in any area except for West Greenland, where the Isua supracrustals may be a fragment of a greenstone belt.

The 3600–3800 m.y. gneisses commonly contain inclusions of basic, ultrabasic, and metasedimentary

rocks (*e.g.* Goldich *et al.*, 1970; McGregor, 1973; Wilson, 1973). These inclusions are of special interest since they are remnants of even older sequences that were intruded by the granitic (*sensu lato*) parents of the gneisses. In most cases, however, it is difficult to ascertain the primary nature of these sequences because of the intense modification of the inclusions, both during their intrusion by the granitic parents of the gneisses and during later reworking of the old rocks.

This paper reports the results of a reconnaissance study of such inclusions in the *ca.* 3700 m.y. Amîtsoq gneisses of the Godthåb region, West Greenland. The Amîtsoq gneisses are the older of two lithostratigraphic complexes of quartzo-feldspathic gneisses in the Godthåb region (McGregor, 1973; Bridgwater *et al.*, 1974; 1976). They are cut by or contain broken-up fragments of an extensive and abundant swarm of basic dykes, the Ameralik dykes (Gill and Bridgwater, 1976). Amîtsoq gneisses collected from an area 180 km long have yielded Rb–Sr and Pb–Pb whole-rock isochron ages of 3700–3800 m.y. (Moorbath *et al.*, 1972; 1975), and U–Th–Pb dates on zircons of 3600–3700 m.y. (Baadsgaard, 1973). All of the Amîtsoq gneisses appear to have been reworked to varying degrees during a period of plutonic activity

¹ Address for reprint request

between about 3000 and 2500 m.y. ago. Over much of the Godthåb district they were tectonically interleaved with supracrustal rocks, dominantly amphibolites (the Malene supracrustals), and with anorthositic rocks and were intruded by very large amounts of syntectonic tonalite and granodiorite (deformed and recrystallized to gneisses—the Nûk gneisses). All of these rocks were affected by several phases of folding and by metamorphism that reached amphibolite facies and, in some parts of the area, granulite facies grade about 2800 m.y. ago (Black *et al.*, 1973).

Wherever the Amîtsoq gneisses preserve recognizable primary features, it can be seen that they are derived from intrusive granitic parents. Most of the Amîtsoq gneisses appear to be derived from syntectonic tonalites and granodiorites. K- and Fe-rich augen and dioritic gneisses derived from a suite of big-feldspar granites and associated Fe-rich gabbros make up a small proportion of the Amîtsoq complex in the area south of the mouth of Ameralik (Fig. 1).

In many areas the Amîtsoq gneisses contain rafts and inclusions of older meta-igneous and metasedimentary rocks (McGregor and Bridgwater, 1973). These vary greatly in size, from quite small inclusions up to extensive units hundreds of metres long and tens of metres thick. The largest body of older rocks in the Amîtsoq gneisses is an arcuate belt of supracrustal rocks some 32 km long and between 0.8 and 3 km wide enclosed by Amîtsoq gneisses at Isua, 35 km

north of the head of Godthåbsfjord (Fig. 1) (Bridgwater and McGregor, 1974; Bridgwater *et al.*, 1976; Allaart, 1976). Relations between the gneisses and the supracrustals are partly obscured by later deformation, but in several places the supracrustal rocks are clearly intruded by the gneisses. No evidence has been found of granitic rocks older than the supracrustal rocks. The Isua supracrustal rocks are by far the best-preserved pre-Amîtsoq rocks known, and although they have been metamorphosed up to amphibolite-facies grade and affected by at least two phases of strong deformation, they still preserve recognizable primary features in places. The most important lithologies in the Isua supracrustal belt are as follows:

(1) Amphibolites with the composition of Fe-rich tholeiites are the most abundant lithology. They are thought to be derived from basaltic volcanic parents, although no primary volcanic features have been recognized.

(2) Finely laminated quartzites, thought to be derived from cherts, and banded quartz-magnetite ironstones. These rocks form a thick unit where the supracrustal belt disappears under the Ice Cap. Thin layers of ironstone are commonly interbedded with other lithologies elsewhere in the belt.

(3) Ultramafic rocks, many now talc-tremolite schists, but including many large bodies of partly serpentinized dunite.

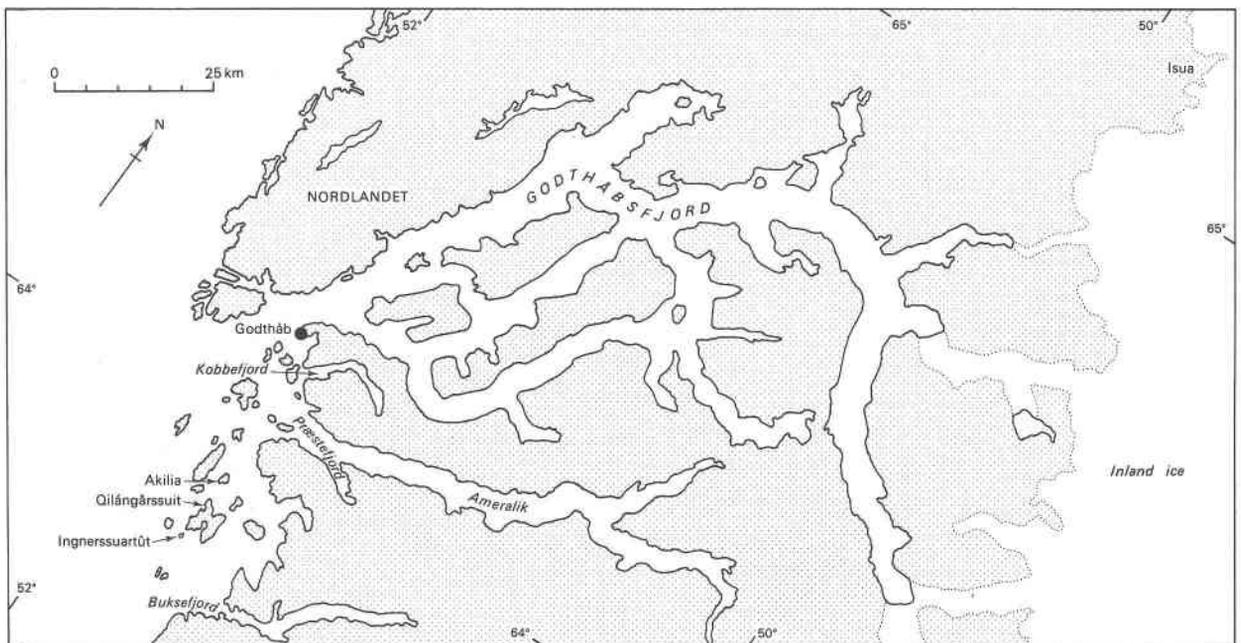


Fig. 1. Locality map.

(4) Carbonate-bearing rocks which at one locality are associated with thin quartz-pebble conglomerates.

(5) A thick conglomeratic unit in which the clasts are derived from rhyolitic to dacitic lavas. This may be a lahar deposit. Fine-grained massive granitic rocks, possibly lavas, are probably present along strike. Clasts from the conglomeratic unit which were previously reported to be coarse-grained granitic rocks (Bridgwater and McGregor, 1974) have proved on closer examination to be derived from acid volcanics.

(6) Massive greenschists apparently derived from basic sills.

The ironstones in the Isua supracrustal belt have yielded a Pb–Pb whole-rock isochron age of 3760 ± 70 m.y. (Moorbath *et al.*, 1973), and the volcanic conglomerate has yielded a Rb–Sr whole-rock isochron age of 3710 ± 90 m.y. (Moorbath *et al.*, 1975).

Elsewhere in the Godthåb region the bodies of older rocks in the Amîtsoq gneisses are much smaller, more strongly metamorphosed, and no longer preserve primary textural features, except in a few occurrences of finely laminated quartz-magnetite ironstones.

This account is concerned with the inclusions in the Amîtsoq gneisses in the area south and southeast of the town of Godthåb (Fig. 1). Inclusions of older rocks have been noted almost everywhere that Amîtsoq gneisses have been recognized, but are especially abundant both north and south of the head of Kobbefjord, in the vicinity of Praestefjord and the adjacent parts of Ameralik, and on the islands between the mouths of Ameralik and Buksefjord, especially on Akilia, the southern part of Qilângârssuit, Ingerssuartût, and the small islands to the south.

One of the largest and best exposed occurrences of older rocks in the Amîtsoq gneisses south of Godthåb is on the southwestern tip of the island of Akilia. This is designated the type locality for the *Akilia association*, an informal term introduced here for all the enclaves of older rocks in the Amîtsoq gneisses in the Godthåb region with the exception of those in the Isua supracrustal belt.

On Ingerssuartût, rocks of the Akilia association are intruded by Ca-rich leucogabbros which in turn are intruded by augen gneisses belonging to the Amîtsoq gneisses.

Methods and techniques

In an attempt to elucidate the origin of these rocks, 115 samples have been examined microscopically, 30 have been analyzed by XRF at Leeds University for

major and a number of minor elements (Rb, Ba, Pb, Sr, Y, Zr, Nb, Cr, Ni, Co, Cu, Mn) and a further 68 for minor elements only. A complete list of analyses can be obtained from the Librarian, Geological Survey of Greenland, Østervoldgade 10, DK 1350 Copenhagen K, Denmark. Of the analyzed rocks, twelve, covering the full range of chemical and mineralogical compositions, were selected for more extensive minor and trace element analysis, including rare-earth elements (REE).

Trace elements were determined by spark source mass spectrography, using the technique described by Taylor (1965, 1971). Quantitative abundance data were obtained for U, Th, Pb, Hf, REE, Ba, Cs, Nb, Zr, Y, Sr, and Rb. The technique uses the rare-earth element Lu as an internal standard, so its abundance cannot be directly determined. The rare earth Tm suffers a serious interference from a multiple carbon molecule, so its abundance is also not determined. The abundance of both Tm and Lu can be estimated from the rare-earth pattern. Accuracy and precision of the method are dependent on the total number of exposures used to calculate the abundance of each element, as well as other factors. For this study two photoplates were exposed for each sample, each with about 15 exposures, and determinations for many elements were based on more than one isotope. This resulted in the measured abundance of each element being based on 8–20 determinations. The precision obtained for all elements was about ± 5 percent. Results obtained by this technique on lunar samples agree well with results obtained on the same samples by other methods (Taylor *et al.*, 1973). This and other comparisons indicate that the accuracy of the method is about ± 10 percent.

All the rocks of the Akilia association have been intruded by granitic (*s.l.*) magmas and have been metamorphosed up to amphibolite- or granulite-facies grade. Many of the analyzed specimens were collected from relatively small bodies of Akilia rocks enclosed in gneisses derived from intrusive quartz monzonites, granodiorites, and tonalites. Although these specimens were collected as far as possible from gneisses, pegmatites, veins, *etc.*, abnormally high contents of, for example, K, Rb, and Ba in a number of the samples indicate that some of these rocks have undergone metasomatic alteration. Clearly these elements cannot be used when comparing Akilia lithologies with little or unmetamorphosed rocks elsewhere. We have concentrated our attention on elements that are less likely to have been mobile (*e.g.* Fe, Mg, Ti, REE, Cr, Ni), and have looked for fea-

tures characteristic of groups of lithologically and chemically similar rocks. We feel that it would be dangerous to regard any of the analyses as necessarily representing the compositions of the parent rocks before they were intruded by the Amîtsoq gneisses.

Metamorphic grade

Most rocks in the area south and southeast of the town of Godthâb have amphibolite-facies mineral assemblages, but in the southwest, especially on the small islands south of Qilângârssuit, granulite-facies mineral assemblages are preserved as relict cores within some of the larger bodies of basic and ultrabasic lithologies of the Akilia association. Relict high-grade cores occur in some thick Ameralik dykes in the same area. Resinous brown-weathering Amîtsoq gneisses of presumed granulite-facies grade have been noted on one small island south of Ingerssuartût. Textures in Amîtsoq gneisses at several other localities south of the mouth of Ameralik suggest that these gneisses have been retrogressed from granulite facies. No evidence of granulite facies metamorphism has been noted in the very extensive outcrops of amphibolites belonging to the Malene supracrustals within the same area. On the coast south of the central part of Ameralik, Amîtsoq gneisses and Ameralik dykes preserve evidence of a granulite-facies metamorphism earlier than the intrusion of thin, syntectonic dykes of Nûk gneiss type.

This evidence appears to indicate that the rocks of

the Akilia association, Amîtsoq gneisses, and Ameralik dykes in some areas in the southern part of the Godthâb region were metamorphosed up to granulite-facies grade before they were intercalated with the Malene supracrustals and before the intrusion of the Nûk gneisses, but that most of them were subsequently retrogressed to amphibolite facies. Some of the thin gneiss and pegmatite veins that cut the Akilia rocks and Ameralik dykes have granulite-facies mineralogy within the high-grade cores. Deformational fabrics and minor folds cross the gradational contacts between the high-grade cores and the enclosing amphibolite-facies rocks. The granulite-facies metamorphism was thus later than at least some of the migmatization and deformation that affected the Akilia association and the Ameralik dykes.

In Figure 2, the compositions (determined by microprobe analysis) of individual minerals in some basic and ultrabasic rocks are plotted on a Ca-Fe-Mg diagram. Most of these specimens are from the relict high-grade cores mentioned above. The mineral compositions indicate equilibration or near-equilibration at the highest grade of metamorphism. This is supported by the uniformity of composition and lack of chemical zoning in the individual minerals, and the overall parallelism of the mineral tie-lines. Almandine garnet is present in rocks with relatively high Fe/(Fe + Mg) ratios and is absent from more magnesian ones, whereas orthopyroxene shows the reverse relationship. One rock, 119213, with an

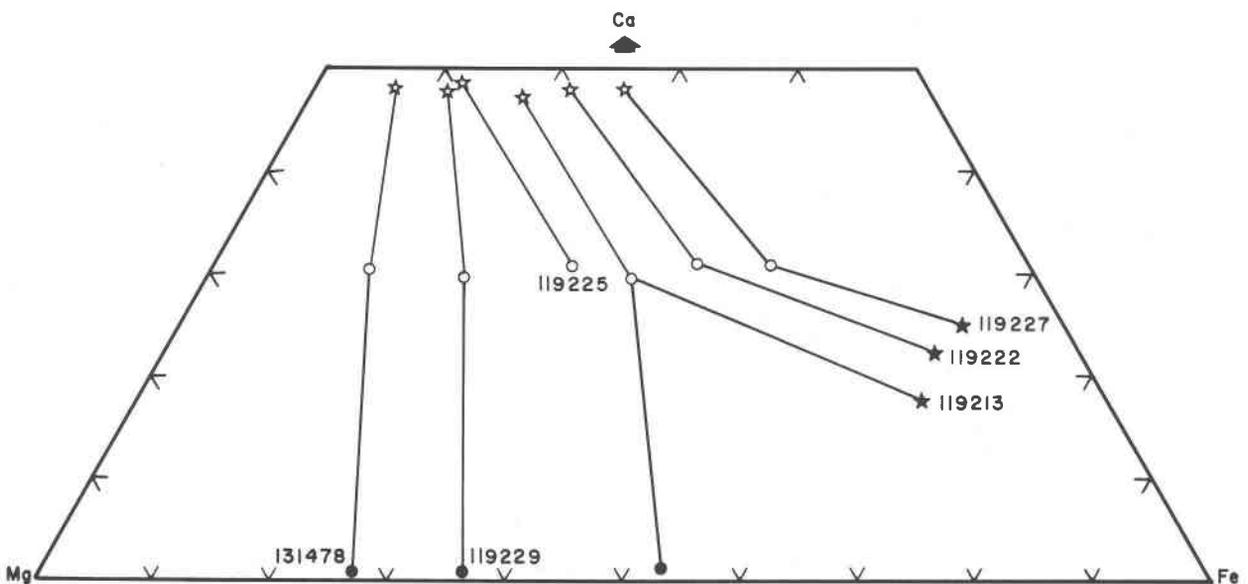


Fig. 2. Atomic percentages of Ca, Fe, and Mg in coexisting minerals in metabasaltic enclaves: open stars = clinopyroxene, open circles = hornblende, solid circles = orthopyroxene, solid stars = almandine.

Fe/(Fe + Mg) ratio of 0.48, contains both orthopyroxene and garnet. The compositions of these rocks and minerals are closely comparable with those of granulite-facies metamorphic rocks described by Himmelberg and Phinney (1967).

Akilia lithologies

The widely scattered enclaves that make up the Akilia association include a considerable variety of lithologies. Much of the work in this study has consisted of grouping the specimens on the basis of common petrographic and chemical characteristics. Almost all the specimens can be included in one of the following groups:

(1) Ultrabasic rocks (7 specimens)

Ultrabasic rocks occur associated with basic lithologies or as separate enclaves. Most are olive-green, rather homogeneous rocks, similar in appearance to the ultramafic rocks associated with the Malene supracrustals (McGregor, 1973). Some contain relict olivine together with tremolite, actinolite, or hornblende. The specimens analyzed for minor elements are characterized by very high contents of Cr (5000–6000 ppm), high contents of Ni (1500–2000 ppm) and Zn (60–200 ppm), and very low contents of all other minor elements. Only one specimen, 131477, has been analyzed for major elements. It is very similar in composition to peridotitic komatiites from the Onverwacht Group (Viljoen and Viljoen, 1969b) and, except for Al₂O₃ and CaO, to Arndt *et al.*'s (1977) average peridotitic komatiite from Munro Township, Ontario (Table 1).

(2) Basic rocks (46 specimens)

Basic rocks (amphibolites, pyriboleites, clinopyroxenites, and hornblendites) are the dominant lithologies in the Akilia association. Of these, layered amphibolites are the most abundant. They are similar in the field to many layered amphibolites in the Malene supracrustals, but lack diagnostic features (relict pillow-lava structures, calc-silicate lenses, relict conglomerate structures) which might show that they were derived from volcanic parents. Some of the basic rocks appear to be derived from coarse-grained gabbroic parents.

The basic rocks are subdivided into 3 groups on the basis of their chemistry.

High-chromium basic rocks (29 specimens). This group comprises most of the basic rocks with Cr contents greater than 600 ppm. There is a break in the range of Cr contents of the basic rocks between 320

and 600 ppm (Fig. 3). The rocks with more than 600 and less than 320 ppm respectively have other features in common that suggest that they are related.

The high-Cr basic rocks include pyroxene-bearing amphibolites composed of hornblende, plagioclase, clinopyroxene, and minor quartz. Plagioclase is usually andesine, but a few rocks contain labradorite or bytownite. There is a complete transition with decrease in the content of plagioclase and hornblende from amphibolites into pale green clinopyroxenites. In the Akilia association as a whole, clinopyroxenites are much less common than amphibolites, but they are one of the most characteristic and widespread lithologies of the association. Clinopyroxenites are rare in other stratigraphic units in the Godthåb region, including the Malene supracrustals. In most clinopyroxenites the pyroxene is spongy and partly replaced by hornblende. There is a complete gradation between unaltered clinopyroxenites and hornblendites.

Relict granulite-facies cores in the amphibolites contain garnet and/or orthopyroxene, and hornblende is green-brown instead of blue-green in the amphibolites.

Epidote is common in some rocks, with an earlier generation that is bright lemon-yellow, and later generations of colorless epidote or clinozoisite that replace plagioclase. Biotite is present in rocks with more than 0.5 percent K₂O, but may be in part at least the product of metasomatic introduction of potash.

Chemically the high-Cr basic rocks are characterized by high contents of MgO, Cr, and Ni, and low contents of Al₂O₃, TiO₂, and Na₂O (Table 1). The rocks form a series with MgO decreasing from 22 to 7 percent. Cr and Ni decrease regularly with decreasing MgO, Cr from 3000 to 600 ppm (Fig. 3) and Ni from 1200 to 170 ppm. Both Al₂O₃ and TiO₂ are very low for basaltic rocks, and increase with decreasing MgO, Al₂O₃ from 3.5 to 11.5 percent and TiO₂ from 0.3 to 0.9 percent. Most rocks have less than 1.5 percent Na₂O. Yttrium (average 15 ppm) is also low for basaltic rocks.

Most of the high-Cr basic rocks have CaO contents of 10–14 percent, but four of the analyzed specimens have between 16 and 22 percent CaO (Table 1). Two of the rocks have contents of Cr and Ni that are considerably higher than other high-Cr rocks with comparable MgO contents (Fig. 3). For example, sample 119230 has 21.7 percent CaO, 2600 ppm Cr, and 1160 ppm Ni, but only 7.1 percent MgO. One plausible explanation is that these two rocks are de-

rived from clinopyroxene cumulates. In the other two rocks with high CaO contents, Ca may have been introduced metasomatically. It is possible that it entered the rocks as CaCO₃ and that CO₂ was lost during high-grade metamorphism.

Chondrite-normalized REE patterns for 4 high-Cr basic rocks are shown in Figure 4. All have very low levels of REE with the light REE (La-Sm) slightly enriched relative to the heavy REE. Samples 131478, 119229, and 119222 are normal high-Cr rocks and show a progressive increase in REE with decreasing MgO. All have distinct negative europium anomalies. Sample 119225, a rock with 20 percent CaO, 2610 ppm Cr, and 852 ppm Ni, has significantly lower REE contents and no Eu anomaly. This is in agreement with the suggestion that it is a cumulate rock

which could be expected to be impoverished in REE relative to the normal high-Cr rocks.

North of the head of Kobbefjord there is a thick unit of layered metagabbro belonging to the Akilia association. It is now coarse-grained amphibolite that contains pods of green pyroxenite and brown magnesian ultramafics. No major-element analyses of specimens from this body are available, but two specimens from it contain *ca.* 1400 ppm Cr and 450–500 ppm Ni.

Low-chromium basic rocks (11 specimens). These are basic rocks with MgO generally less than 6.5 percent and Cr less than 350 ppm (Table 1). All the rocks are amphibolites. In places they have relict higher-grade cores with garnet, clinopyroxene and, in some rocks, orthopyroxene and green-brown horn-

Key to Tables 1a and 1b

Rocks from the Akilia association.

(a) normal high-Cr ultrabasic and basic rocks (komatiites) in order of decreasing MgO.

- 1: 131477, olivine-hornblende-clinopyroxene (-serpentine-ore), Ingerssuartût, 63°50.0'N, 51°41.1'W.
- 2: 131478, clinopyroxene-orthopyroxene-biotite-hornblende (-ore), same locality as 131477.
- 3: 119229, hornblende-clinopyroxene-orthopyroxene (-ore), unnamed island, 63°47.3'N, 51°45.5'W.
- 4: 119221, hornblende-clinopyroxene-actinolite-plagioclase (-epidote-carbonate-apatite-biotite), same locality as 119229.
- 5: 119222, clinopyroxene-hornblende-plagioclase-garnet (-ore-epidote-biotite-carbonate-apatite), same locality as 119229.

(b) high-Cr basic rocks of probable cumulate origin.

- 6: 119225, clinopyroxene-hornblende-plagioclase-biotite (-ore-carbonate), same locality as 119229.
- 7: 119230, clinopyroxene-epidote-hornblende (-quartz-plagioclase-magnetite-pyrrhotite-carbonate), same locality as 119229.

(c) low-Cr basic rocks (high-Fe tholeiites)

- 8: 119213, hornblende-clinopyroxene-plagioclase-orthopyroxene-garnet (-biotite-ore-apatite), Ingerssuartût, 63°50.3'N, 51°41.1'W.
- 9: 119227, clinopyroxene-plagioclase-hornblende-garnet (-quartz-magnetite-apatite-carbonate), same locality as 119229.
- 10: 131442, hornblende-plagioclase-quartz (-biotite-sphene-apatite-epidote-allanite), north of head of Kobbefjord, 64°9.6'N, 51°22.4'W.

(d) alkali-rich ?metagabbro

- 11: 117906, hornblende-biotite-plagioclase-quartz (-allanite), island off south coast of Quilángârssuit, 63°51.0'N, 51°28.3'W.

Rocks from other Archean areas

- 12: peridotitic komatiite (88J), Onverwacht Group, South Africa (Viljoen and Viljoen, 1969b); cf. 131477, column 1.
 - 13: average non-cumulate peridotitic komatiite, Munro Township, Canada (Arndt et al. 1977); cf. 131477, column 1.
 - 14: average pyroxenitic komatiite, Munro Township (Arndt et al., 1977).
 - 15: average basaltic komatiite, Munro Township (Arndt et al., 1977).
 - 16: average tholeiitic basalt, Munro Township (Arndt et al., 1977), cf. columns 9 and 10.
 - 17: average Fe-rich tholeiite, Yakabindie, Western Australia (Naldrett and Turner, 1977), cf. columns 9 and 10.
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blende. Many of the low-Cr rocks contain biotite, some as much as 15 percent. Graphite was noted in one low-Cr amphibolite, suggesting perhaps that it might be derived from a water-laid basaltic tuff.

Compared with the high-Cr basic rocks, the rocks of this group have higher Al_2O_3 (mainly 14–16%), higher TiO_2 (1.0–1.8%, average 1.4%), and higher, although variable, Na_2O . Nine out of eleven rocks have more than 2.0 percent Na_2O . Among the minor elements, Y is consistently higher in the low-Cr rocks (average 30 ppm), Cr (average 230 ppm) and Ni (average 104 ppm) are consistently lower, and Zn is

mainly higher (average of 81 ppm in the low-Cr rocks compared with an average of 40 ppm in the high-Cr rocks).

The low-Cr basic rocks have unusually high iron contents for basaltic rocks, with total iron as FeO between 13.6 and 15.0 in 5 rocks analyzed for major elements and 17.4 in a sixth rock. The latter, however, has unusually high contents of K_2O (2.7%) and Rb (102 ppm), suggesting that it has suffered metasomatic alteration.

Chondrite-normalized REE patterns for two low-Cr rocks, 119227 and 119213, are shown in Figure 4.

Table 1a. Representative analyses of ultrabasic and basic rocks, Akilia association, Godthåb region, and of similar rocks from other Archean areas. All Fe is reported as FeO; Cr and Ni in ppm, other components in weight percent; columns 1 and 3–11 Leeds XRF analyses, column 2 glass-bead microprobe analysis, except Cr and Ni (Leeds XRF); H_2O determined on 6 (0.99%), 11 (0.86%), and 12 (6.10%).

	1	2	3	4	5	6	7	8	9
SiO_2	45.00	51.1	48.80	48.04	49.51	46.95	49.27	47.00	46.85
TiO_2	0.32	0.44	0.44	0.65	0.79	0.36	0.28	1.07	1.59
Al_2O_3	3.08	3.54	6.03	8.15	10.76	6.85	9.52	11.22	14.90
FeO	11.03	11.15	11.15	13.90	12.41	9.25	10.18	15.04	14.93
MnO	0.25	0.18	0.22	0.25	0.30	0.29	0.49	0.24	0.33
MgO	26.82	21.70	16.70	12.34	8.17	12.57	7.14	9.50	5.17
CaO	9.31	10.31	12.63	12.63	13.90	19.97	21.78	11.69	12.43
Na_2O	0.31	0.30	0.2	0.9	1.8	0.4	1.0	2.1	2.3
K_2O	0.22	0.97	0.25	0.80	0.42	0.71	0.01	0.69	0.25
P_2O_5	0.04	0.03	0.09	0.08	0.19	0.07	0.07	0.08	0.17
Cr	5540	3090	1740	1050	600	2610	2600	290	280
Ni	1580	1230	850	260	180	852	1160	133	97

	10	11	12	13	14	15	16	17
SiO_2	51.69	50.90	44.85	46.0	50.2	51.6	51.1	51.64
TiO_2	1.24	0.54	0.51	0.32	0.61	0.65	1.70	1.61
Al_2O_3	14.22	13.50	2.66	7.4	11.6	13.3	13.3	13.70
FeO	14.70	10.40	11.12	11.51	11.11	11.7	15.0	14.90
MnO	0.25	0.21	0.20	0.22	0.19	0.19	0.28	0.30
MgO	4.12	10.50	24.96	26.5	14.3	10.0	5.92	4.09
CaO	9.54	6.63	7.01	7.4	9.6	10.4	8.6	8.96
Na_2O	2.13	2.2	0.41	0.45	2.34	2.16	3.9	2.37
K_2O	1.11	3.12	0.05	0.10	0.05	0.11	0.25	0.28
P_2O_5	0.14	0.17	-	-	-	-	-	-
Cr	95	670	-	-	-	-	193	94
Ni	59	400	-	-	-	-	76	76

Table 1b. Minor and trace elements in analyzed Akilia rocks, in ppm; nd = not detected.

	1	2	3	5	6	7	8	9
Cs	0.80	2.0	nd	0.12	0.16	nd	nd	0.14
Rb	4.8	34	1.8	1.4	7.8	0.33	3.5	1.5
Ba	2.7	7.0	6.9	21	48	5.0	33	16
Pb	2.1	1.8	2.4	5.1	3.5	26	13	4.0
Sr	24	7.2	20	110	30	310	150	56
La	1.3	1.9	2.6	1.7	1.0	2.7	3.6	2.5
Ce	3.9	5.0	7.0	5.2	2.5	6.2	8.7	9.0
Pr	0.51	0.77	1.2	0.78	0.38	0.88	1.4	1.8
Nd	2.5	4.2	5.6	4.1	1.9	4.2	7.3	10
Sm	0.65	1.3	1.6	1.4	0.66	1.1	2.3	3.4
Eu	0.37	0.30	0.40	0.46	0.23	0.44	0.76	1.0
Gd	0.74	1.6	1.8	2.1	0.81	1.8	2.9	4.5
Tb	0.13	0.26	0.43	0.37	0.15	0.31	0.55	0.75
Dy	0.65	1.5	2.1	2.2	0.85	1.8	4.0	4.7
Ho	0.15	0.32	0.45	0.46	0.18	0.42	0.76	1.1
Er	0.43	0.90	1.2	1.2	0.50	1.2	2.3	3.3
Yb	0.42	0.78	1.1	1.1	0.43	1.2	2.0	3.2
Y	3.8	9.7	12	15	4.4	11	25	28
Th	nd	nd	nd	nd	0.43	2.2	nd	nd
U	nd	nd	nd	nd	0.19	1.8	nd	nd
Zr	14	11	38	31	14	16	42	56
Hf	nd	nd	0.64	0.96	0.40	0.57	1.1	1.4
Nb	0.68	0.79	1.2	0.82	0.73	1.7	1.9	2.3

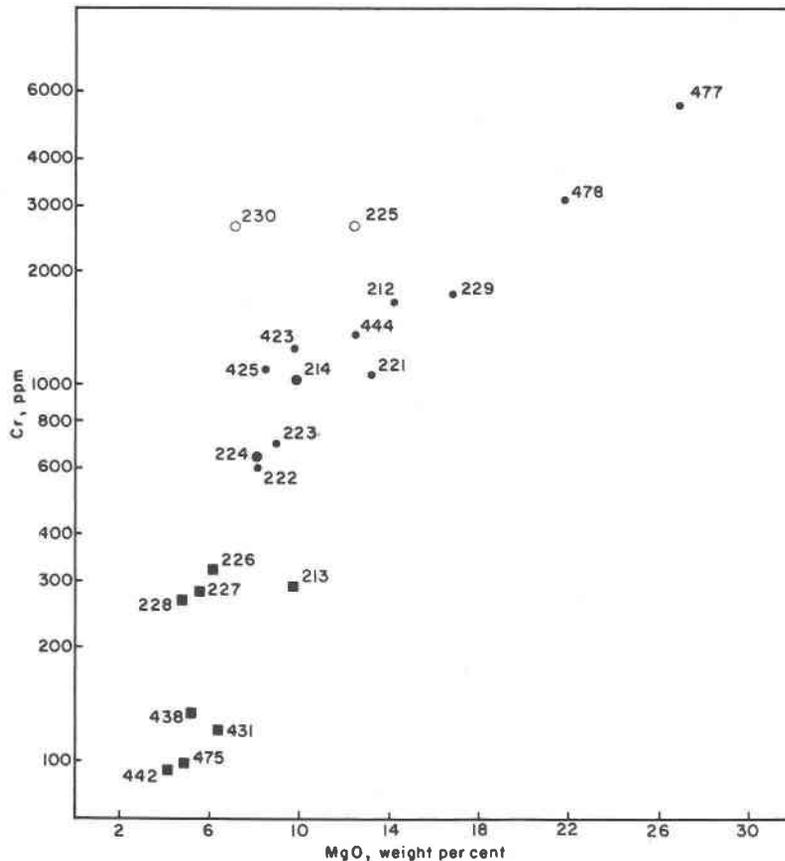


Fig. 3. MgO-Cr relationship in metabasaltic enclaves, the high-Cr rocks indicated as solid circles, the low-Cr rocks as squares, open circles are rocks of probable cumulate origin. Sample numbers are 1314xx and 1192xx.

Both have distinctly higher levels of REE than the high-Cr rocks analyzed, only weak negative Eu anomalies and one, 119227, has marked depletion of La.

Alkali-rich basic rocks (6 specimens). Massive, homogeneous, biotite-rich basic rocks have been noted from several localities. Most are very coarse-grained and contain sub-equal amounts of hornblende, plagioclase, and biotite, together with smaller amounts of quartz in some rocks. Their appearance in the field suggests that they are derived from massive gabbroic parents.

Only two rocks from this group have been analyzed for major elements. Chemically they are very similar. Both have high contents of alkalis with 3.1 and 3.4 percent K_2O , 2.2 percent Na_2O , and 268 and 403 ppm Rb. In addition both have low TiO_2 (0.4 and 0.5%) and moderately high MgO (10.5%), Cr, and Ni. One possible explanation for the high alkali contents is that these rocks are metasomatically altered high-Cr basic rocks, but this is difficult to reconcile with their massive homogeneous nature in the field.

(3) Banded iron formation (35 specimens)

Rocks with a high proportion of iron-rich minerals (magnetite, grunerite, almandine, etc.) are a minor, but very widespread component of the Akilia association. Similar rocks have not been found in other stratigraphic units in the Godthåb region except in the Isua supracrustals. In favorable localities the

Akilia ironstones can be seen to form thin layers within sequences of layered basic rocks. The largest occurrence is ca. 20 m thick and most are much thinner. In a few outcrops primary lamination is clearly preserved, with layers of magnetite and other Fe-rich minerals a few mm thick alternating with somewhat thicker layers of quartz. Sulphide minerals are relatively common, and many of the rocks are conspicuous because of the rusty weathering of their outcrops.

Compositional data on four of these rocks, selected to cover as wide a range in composition as possible, are given in Table 2; one of them, 131463, consists almost entirely of subequal amounts of grunerite and almandine, whereas the other specimens are quartz-magnetite-silicate rocks. The concentrations of minor and trace elements are generally low in comparison to the ultrabasic and basic group, and are roughly proportional to the concentrations of "extraneous" major components, i.e. those other than SiO_2 and FeO. This, of course, is consistent with extremely low content of minor and trace elements in quartz and magnetite. Of particular note are the low alkalis and chromium throughout, and low titanium in all except 131463.

The REE distribution patterns (Figure 5) are approximately flat and parallel throughout, except for a positive Eu anomaly in 119232, in contrast to a negative anomaly in the other samples. The concentration relative to chondrites ranges from about 3 for 119233

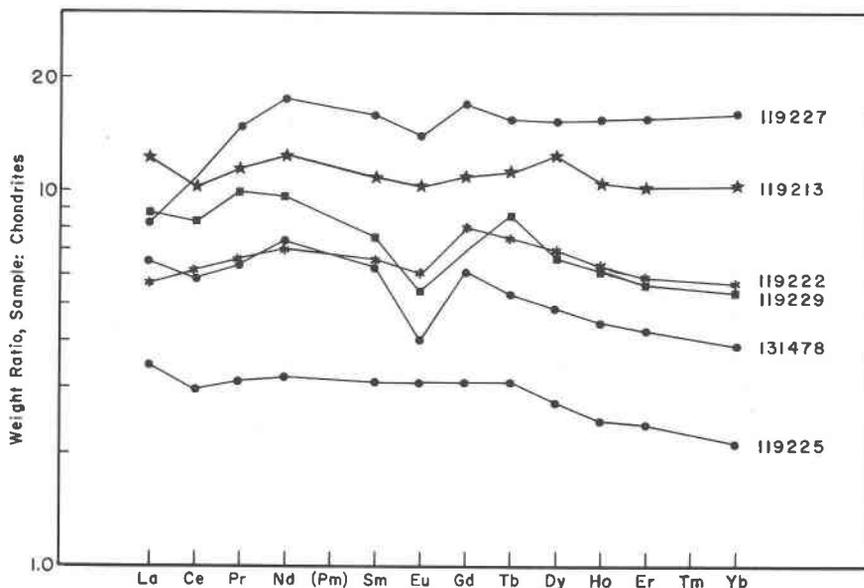


Fig. 4. REE abundances in metabasaltic enclaves, normalized to the average chondritic abundances; MgO percentages: 119225, 12.57; 131478, 21.70; 119229, 16.70; 119222, 8.17; 119213, 9.50; 119227, 5.17.

Table 2. Analyses of banded iron formation (119233, 119232, 119217, 131463) and metasedimentary enclaves (119215, 131429); oxides in weight percent, elements in parts per million. All Fe is reported as FeO; nd = not detected.

	119233	119232	119217	131463	119215	131429
SiO ₂	50.90	43.67	57.39	41.76	60.27	70.53
TiO ₂	0.08	0.05	0.08	1.05	0.75	0.84
Al ₂ O ₃	0.33	0.90	5.00	11.39	16.71	12.99
FeO	41.4	46.8	30.1	32.0	6.06	5.25
MnO	0.13	0.15	0.15	0.49	0.14	0.06
MgO	2.97	2.40	2.70	6.38	3.40	2.25
CaO	1.38	2.58	1.95	3.55	6.34	1.98
Na ₂ O	0.13	0.12	0.09	0.28	1.09	3.00
K ₂ O	0.26	0.05	0.03	0.28	3.16	1.72
F ₂ O ₅	0.08	0.21	0.11	0.35	0.23	0.06
Cr ₂ O ₃	0.00	0.01	0.01	0.03	0.03	0.04
Cs	nd	nd	nd	0.50	3.9	8.1
Rb	nd	0.42	0.23	5.6	110	24
Ba	0.86	2.1	0.85	16	69	390
Pb	1.6	16	2.0	1.8	12	7.5
Sr	nd	3.4	1.9	8.1	46	95
La	0.77	1.9	8.2	9.6	12	14
Ce	2.0	3.4	17	26	22	27
Pr	0.26	0.49	2.2	3.3	4.4	4.1
Nd	1.3	2.5	11	16	18	15
Sm	0.44	0.69	2.8	3.5	3.3	3.0
Eu	0.13	0.59	0.50	0.90	0.99	1.1
Gd	0.55	0.96	2.1	4.5	2.7	3.5
Tb	0.10	0.17	0.36	0.92	0.37	0.67
Dy	0.65	1.4	2.3	6.0	1.9	3.7
Ho	0.16	0.37	0.53	1.4	0.41	0.76
Er	0.51	1.1	1.6	4.2	1.1	2.4
Yb	0.49	1.0	1.5	4.0	1.0	2.3
Y	4.7	13	15	45	14	17
Th	nd	nd	1.2	1.1	0.34	3.0
U	nd	nd	nd	0.32	0.15	0.63
Zr	1.7	1.9	5.9	59	44	63
Hf	nd	nd	nd	4.6	3.5	3.6
Nb	0.90	0.53	3.2	3.1	6.3	7.7

Location and mineralogy of analyzed rocks (major mineral given first in order of decreasing abundance; accessory minerals less than 10%, in brackets):

119233:	quartz-grunerite-magnetite-actinolite(-apatite), Ugpik, 64°5.2'N, 51°34.9'W.
119232:	magnetite-quartz-actinolite(-clinopyroxene-apatite), Praestefjord, 64°1.7'N, 51°19.6'W.
119217:	quartz-garnet-grunerite-magnetite-actinolite (-apatite), Ingnerssuartût, 63°50.3'N, 51°41.1'W.
131463:	garnet-actinolite-hornblende(-ore-biotite-apatite-allanite-carbonate), Ugpik, 64°5.8'N, 51°33.3'W.
119215:	plagioclase-biotite-quartz(-hornblende-ore-garnet-apatite-scapolite), Ingnerssuartût, 63°49.9'N, 51°41.5'W.
131429:	quartz-plagioclase-biotite(-ore-garnet-zircon-graphite), south coast of Ameralik east of Praestefjord, 64°3.5'N, 51°21.4'W.

to about 20 for 131463. These patterns are quite unlike those of detrital sediments, which consistently show strongly fractionated REE distributions relative to chondrites, with marked depletion in the heavy REE (e.g., Wildeman and Haskin, 1973).

The nature of these patterns provides some clues as to the origin of these rocks. Neither quartz nor magnetite accepts REE in its structure, so these elements

are contained in the silicate minerals and the small amounts of accessory apatite. The following possibilities may be envisaged: (1) the REE were chemically precipitated along with the silica and iron oxides; (2) the REE were introduced into the original sediments as a detrital component; (3) the REE were introduced by metasomatism. On first consideration the second explanation might be favored, since the abundances of the REE increase in parallel with the abundances of the "extraneous" major components, and their distribution pattern is quite similar to that of the ultrabasic and basic group. This suggests the possibility that the REE and the "extraneous" components might represent a contribution of basaltic tuff to the silica-iron oxide material. However, comparison of the proportions of the "extraneous components" with that in the ultrabasic and basic group shows that they cannot be matched compositionally.

The compositional data provide little support for the third possibility. The field collection of these rocks was specifically designed to avoid material affected by metasomatism, and the analytical data, specifically the very low alkali concentrations, bear this out.

The evidence therefore supports the first explanation. The increase in concentration of REE from one sample to another is paralleled by an increase in concentration of P₂O₅, suggesting precipitation in a phosphate phase. Another possibility is original precipitation in a carbonate phase, but this is less likely in view of the generally low CaO content, which shows little correlation with the REE concentrations.

At many localities rocks of the Akilia association with unusually high contents of quartz have been noted. Superficially they resemble banded ironstones, but the minerals associated with the quartz as well as the contents of minor elements (e.g. high contents of Cr and Ni in some cases) suggest that they are rocks of varied parentage (clinopyroxenites, other basic rocks, volcanic-detrital sediments, banded iron formation) which have suffered intense silica metasomatism, often with quartz introduced along the layering of the parent rocks.

(4) Detrital metasedimentary gneisses (8 specimens)

Recognition of gneisses derived from detrital sediments is more difficult than for the other lithologies, since their overall composition is not grossly different from the host rocks, the AmÏtsoq gneisses (McGregor, 1975; McGregor and Bridgwater, in preparation). However, compared with the AmÏtsoq grey

gneisses, which are derived from tonalitic and granodioritic intrusive rocks, the Akilia detrital metasedimentary gneisses have much higher contents of Y, Cu, Zn, Cr, Co, and Ni, somewhat higher contents of Rb and lower contents of Sr (Table 2). In the field they can usually be distinguished from AmÏtsoq gneisses by their higher contents of biotite and the presence in most of them of pink garnet, which is virtually absent from the AmÏtsoq gneisses. They commonly weather rusty-brown. Graphite has been noted in a number of specimens.

Detrital metasedimentary gneisses are rather abundant between Ameralik and the head of Kobbefjord, but have been noted at only a few localities outside of this area. They commonly form units several tens of metres thick.

Comparatively few rocks of this type have been collected, and of these, two were selected for detailed investigation. They are quartz-plagioclase-biotite rocks, but differ notably in plagioclase composition—in 119215 it is An_{80} , in 131429 it is An_{26} . Accessory minerals in 119215 are hornblende, almandine, scapolite, apatite, and zircon, in 131429 ilmenite and apatite. They differ considerably in quartz content, 119215 having about 10 percent whereas 131429 has almost 50 percent. However, their major-element compositions can be matched up with graywackes. The analytical data are given in Table 2.

Table 3. Average minor element contents (ppm) of AmÏtsoq grey gneisses (20 specimens) and Akilia detrital metasediments (7 specimens); analyses by Dr. G. Hornung, University of Leeds.

	AmÏtsoq grey gneisses	Akilia detrital metasediments
Rb	83	119
Cu	<20	139
Sr	299	99
Ba	408	523
Zn	30	102
Y	4	26
Zr	125	159
Pb	20	16
Nb	6	9
Cr	39	285
Co	18	32
Ni	10	110

The REE distribution patterns (shale-normalized) are plotted in Figure 6, along with that for the Fig Tree Shales in the South African Archean (Wildeman and Condie, 1973). The patterns for the two Greenland samples are closely similar for the light REE (La-Sm) but deviate somewhat for the heavier REE, in which 119215 is somewhat depleted relative to 131429. The match between 131429 and the Fig Tree Shale is remarkably close throughout.

A notable feature of these Greenland rocks is the marked positive Eu anomaly relative to the North American shale composite (composed of Paleozoic and younger rocks). This feature seems to be a

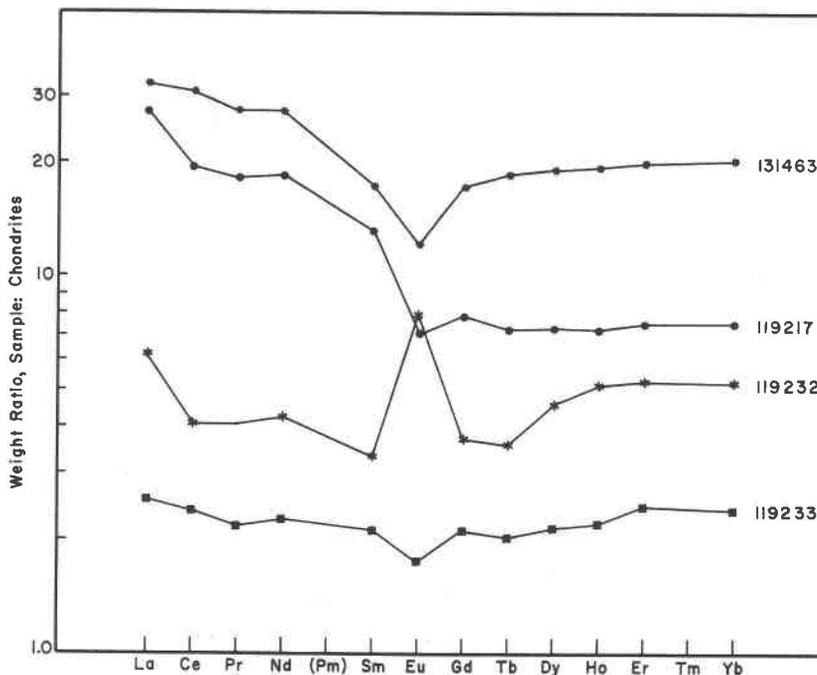


Fig. 5. REE abundances in banded iron-formation enclaves, normalized to the average chondritic abundances.

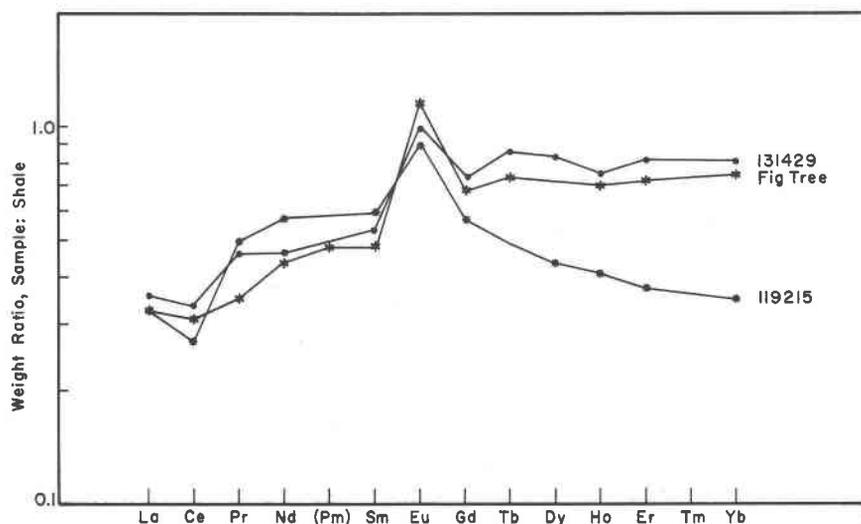


Fig. 6. REE abundances in metasedimentary enclaves, normalized to the average shale abundances.

unique characteristic of Precambrian sedimentary rocks, and has been commented on and discussed by Wildeman and Haskin (1973), Wildeman and Condie (1973), and Jakes and Taylor (1974). Jakes and Taylor propose that this Eu excess in Precambrian sedimentary rocks relative to those of younger age is derived from volcanic rocks of ancient island arcs as source materials for the sediments. It is clearly inappropriate to draw wide-ranging conclusions from the two analyzed samples of highly metamorphosed Greenland metasediments, but their geochemical consistency with relatively unmetamorphosed Archean sediments is significant and serves to further extend the sedimentary record back into the oldest known rocks.

One gneiss examined (131454), composed mainly of quartz, plagioclase, and hornblende with small amounts of biotite, grunerite and garnet, and accessory graphite, contains 915 ppm Cr and 333 ppm Ni. It seems best explained as derived from material from a high-Cr basic source (? ash) mixed with pelitic sediment.

Finely-foliated quartzofeldspathic gneisses that are intruded by typical AmÏtsoq gneisses have recently been recognized on Ingnerssuartût, but have not been investigated chemically by us. It is possible that they are derived from acidic to intermediate volcanics.

Element distribution between coexisting minerals

Little work has been reported in the literature on the distribution of minor and trace elements between coexisting minerals in metamorphic rocks. In view of this, and because these rocks show good evidence of

complete recrystallization at high metamorphic grade and little or no subsequent alteration, we decided to separate coexisting minerals and analyze them by the same techniques used for the rocks. For this purpose we selected 119213, a rock with the largest number of coexisting minerals. Major phases are hornblende, clinopyroxene, plagioclase, orthopyroxene, and almandine; accessory phases are apatite and ilmenite. These minerals (except ilmenite) were separated from the rock at 99 percent or better purity by a combination of heavy liquid and magnetic techniques. The analytical results are reported in Table 4.

The distribution of the REE is illustrated in Figure 7. The bulk rock has an essentially unfractionated distribution pattern averaging 11 times chondritic abundances, whereas some of the minerals, specifically almandine, apatite, and plagioclase show strongly fractionated patterns. Hornblende and clinopyroxene show bow-like patterns, with broad maxima between Nd and Dy modified by slight negative Eu anomalies; absolute abundances of the individual elements in clinopyroxene are uniformly about 4–5 times lower than in hornblende. Concentrations of the REE in orthopyroxene are considerably lower than in clinopyroxene, and the distribution pattern is somewhat different, showing a gradual increase in chondrite-normalized abundances towards the heavier REE. The plagioclase pattern is characterized by a rapid drop in abundances from La towards Sm, followed by a large positive Eu anomaly, typical of many analyzed plagioclases from terrestrial and lunar rocks; the pattern could not be followed beyond Gd because the abundances of the heavier REE were below the detection limits.

Table 4. Analyses of minerals in basic enclave 119213; oxides in weight percent, elements in parts per million. All Fe is reported as FeO; nd = not detected.

	Apatite	Almandine	Hornblende	Clinopyroxene	Orthopyroxene	Plagioclase
Weight %	0.3	5	50	20	10	15
SiO ₂	-	37.9	42.5	53.0	51.5	59.8
TiO ₂	-	0.08	1.99	nd	0.64	-
Al ₂ O ₃	-	21.0	11.1	1.47	nd	25.4
FeO	-	29.0	18.3	13.9	31.5	-
MgO	-	4.28	9.65	12.0	15.4	-
CaO	55.2	6.88	11.7	22.1	0.52	7.22
Na ₂ O	-	-	1.59	0.36	nd	7.62
K ₂ O	-	-	1.14	nd	nd	0.21
P ₂ O ₅	41.3	-	-	-	-	-
Rb	0.15	0.26	4.3	0.23	0.45	0.45
Ba	290	1.9	54	2.6	4.4	64
Pb	2600	7.4	3.0	1.6	6.8	8.1
Sr	900	4.7	33	9.8	4.9	780
La	70	0.12	3.6	0.75	0.34	1.1
Ce	130	0.55	13	2.5	1.1	1.3
Pr	14	0.10	2.0	0.42	0.15	0.07
Nd	56	0.72	11	2.3	0.77	0.22
Sm	10	0.76	3.6	0.78	0.27	nd
Eu	3.7	0.56	1.2	0.24	0.09	0.32
Gd	12	5.1	4.5	1.0	0.39	nd
Tb	1.5	1.8	0.79	0.19	0.08	nd
Dy	8.0	19	4.5	1.1	0.54	nd
Ho	1.2	6.1	0.90	0.23	0.13	nd
Er	2.1	25	2.1	0.58	0.39	nd
Yb	0.90	32	1.3	0.44	0.39	nd
Y	52	190	23	5.0	3.4	0.57
Zr	27	14	39	19	6.2	1.0
Hf	nd	nd	1.5	0.92	nd	nd
Hb	0.85	0.24	2.3	0.29	0.24	0.27

Apatite and almandine show strongly fractionated patterns, almandine being highly enriched in the heavy REE, apatite in the light REE. The almandine pattern is characteristic for garnet, which is known to be the only abundant rock-forming mineral to concentrate the heavy REE in rocks of basaltic composition. This almandine, with Ce = 0.55 ppm, Yb = 32 ppm, Yb/Ce = 58, may be compared with a pyrope from Kakanui, New Zealand, with Ce = 0.47 ppm, Yb = 9.1 ppm, Yb/Ce = 19 (Mason and Allen, 1973). The high degree of fractionation in the almandine is demonstrated by a comparison with the Yb/Ce ratio in the rock, which is 0.24. In garnet the REE must occupy the eight-coordinated lattice site which evidently discriminates against the larger lighter elements of the group. The fractionation in the apatite is in the opposite direction, presumably because the larger nine-coordinated cation site in this mineral preferentially accommodates the lighter REE.

In spite of the great enrichment of some of these elements in apatite and garnet, of the total REE in the rock (36 ppm), much (24 ppm) is contained in the

hornblende (50% of the rock, total REE 48 ppm). This can be contrasted with the situation in some igneous rocks, where most of these elements are present in accessory minerals; in the Muzzle River gabbro (Mason, 1972) apatite and sphene contain a dominant proportion of the REE in the rock.

Of the other trace elements determined, Rb is highly concentrated in hornblende, the only mineral with an appreciable K content; Ba is concentrated in apatite, with considerable amounts in hornblende and plagioclase; Sr is strongly concentrated in plagioclase and in apatite; Y follows the REE, usually plotting close to Ho on the chondrite-normalized diagram, as would be expected from the correspondence in their ionic radii; Zr is present in the hornblende at approximately the same concentration as in the bulk rock, with detectable amounts in all the other minerals; Nb shows a similar pattern to Zr. Neither U nor Th were detected in any mineral nor in the bulk rock (detectability limit is approximately 0.1 ppm for each element); this impoverishment in radioactive elements appears to be a characteristic of high-

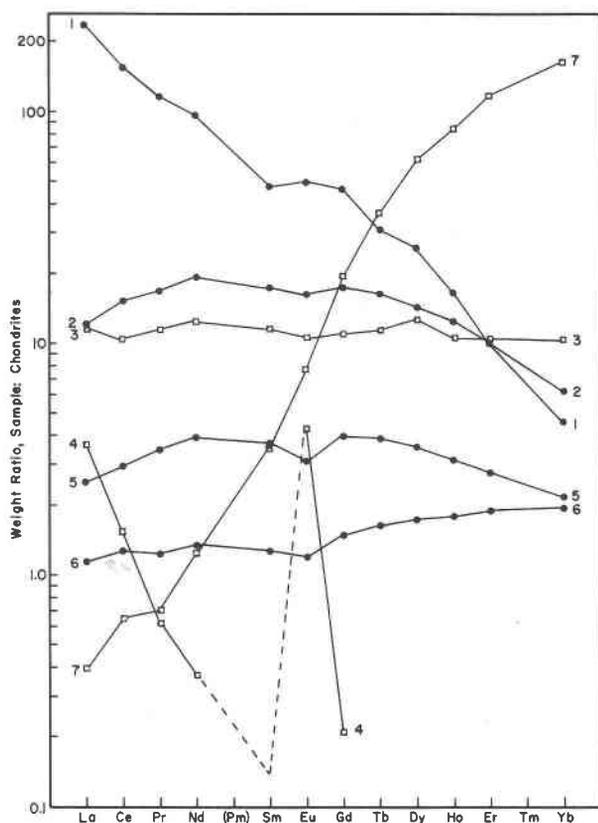


Fig. 7. REE abundances in 119213 and its constituent minerals, normalized to the average chondritic abundances; 1 = apatite, 2 = hornblende, 3 = bulk, 4 = plagioclase, 5 = clinopyroxene, 6 = orthopyroxene, 7 = almandine.

grade metamorphic rocks (Heier and Thoresen, 1971).

Chemical affinities of Akilia basic rocks

(1) Komatiite affinities

The term komatiite has been applied to a series of igneous rock that range in composition from peridotitic to basaltic and even andesitic (Viljoen and Viljoen, 1969b; Brooks and Hart, 1974; Arndt *et al.*, 1977). Komatiites are characterized by high contents of Mg, Ni, and Cr, very low alkali contents, and low Ti. Many have high Ca/Al ratios. In less altered occurrences, characteristic quench textures (*e.g.* spinifex texture) are common in many varieties, and show that these rocks crystallized from magmas that were completely liquid.

Viljoen and Viljoen (1969b) first recognized this series in the lower formations of the Onverwacht Group in the Barberton Mountain Land greenstone belt of South Africa and Swaziland. Komatiitic asso-

ciations have since been recognized in many Archean greenstone belts (see below). In studies where large numbers of analyses have been available, it has been found that the series encompasses a continuous range of compositions with, for example, MgO ranging from 39 to 7 percent (Arndt *et al.*, 1977).

Many of the type Onverwacht komatiites have CaO/Al₂O₃ ratios greater than 1, and in this respect they differ from most other little-metamorphosed komatiites described in the literature. Arndt *et al.* (1977) and Naldrett and Turner (1977) have used a plot of FeO^{tot}/(FeO^{tot} + MgO) against Al₂O₃ to distinguish komatiites from associated tholeiites in the Munro Township area, Canada, and in the Eastern Goldfields, Western Australia. On such a plot many of the Onverwacht komatiites fall in the tholeiitic field because of their low contents of Al₂O₃ (Fig. 8). Nesbitt and Sun (1976) consider the high CaO/Al₂O₃ ratios of many of the Onverwacht komatiites to be the result of non-isochemical metamorphism, with either loss of Al or introduction of Ca, perhaps in carbonate. Carbonation is very widespread in the Onverwacht mafic volcanics, but was considered by Viljoen and Viljoen (1969a) to result in a decrease in CaO. Several workers (*e.g.* Williams, 1972; Nesbitt and Sun, 1976) have been unwilling to apply the term komatiite to lavas from other areas that clearly belong to the same series as the type komatiites, but that have CaO/Al₂O₃ ≤ 1. Arndt *et al.* (1977) have proposed a redefinition of the term komatiite so that it includes all the rocks now recognized as belonging to this magma series.

Komatiites from Munro Township have very low levels of rare earth elements and strong depletion of the lighter REE (J. G. Arth, personal communication).

The Akilia high-Cr basic rocks no longer preserve original structures that could demonstrate that they were derived from lavas, but chemically their komatiitic affinities are clear. Two of the analyzed specimens with CaO > 16 percent seem best interpreted as komatiitic cumulate rocks, while the remainder are chemically very comparable with komatiitic lavas (*cf.* columns 1–5 with columns 12–15 in Table 1). The following similarities between established komatiite associations and the Akilia high-Cr basic rocks may be noted: (a) a range in MgO contents (from 26 to 8% in the Akilia rocks) with Al₂O₃ and TiO₂ increasing and Cr and Ni decreasing with decreasing MgO, except in the possible cumulate rocks; (b) consistently low TiO₂ contents; (c) very high contents of Cr and Ni, with Cr contents more than twice as great as Ni;

(d) very low contents of rare-earth elements. In this respect they resemble the more primitive abyssal tholeiites (Frey *et al.*, 1974; Bence and Taylor, 1977) as well as one group of the Ameralik dykes (Isua type) which cut the Amitsoq gneisses and Akilia association (Gill and Bridgwater, 1976). The major-element chemistry of the Akilia high-Cr basic rocks is quite different from these, however.

The Akilia high-Cr basic rocks resemble the type Onverwacht komatiites and differ from most other described komatiites in that they almost all have $\text{CaO}/\text{Al}_2\text{O}_3$ ratios greater than 1 and they fall in the same field on an $\text{FeO}^{\text{tot}}/(\text{FeO}^{\text{tot}} + \text{MgO})$ vs. Al_2O_3 diagram (Fig. 8).

It is possible that some of the Akilia high-Cr basic rocks are derived from cumulates in which clinopyroxene was an important primary cumulate phase. Brooks and Hart (1974) have pointed out that peridotitic komatiites are chemically equivalent to many other ultramafic rocks with significant contents of clinopyroxene or calcic amphibole, and that pyroxene cumulate rocks with the compositions of basaltic komatiites are known. Cumulate komatiite flows and sills have been recognized in some areas (Pyke *et al.*, 1973; Arndt *et al.*, 1977). Metamorphic recrystallization and deformation have destroyed any textural evidence that could indicate whether the Akilia rocks were cumulate or derived from liquids of the same compositions. In places they are interlayered with thin units of banded ironstones and gneisses of detrital sedimentary origin, but this does not exclude the possibility that they are derived from layered cumulate sills intruded into a sedimentary-volcanic succession.

(2) *Tholeiitic affinities*

Most Archean komatiite suites are associated with tholeiitic lavas that differ from other Archean and younger tholeiites in their high contents of iron and titanium (Arndt *et al.*, 1977; Naldrett and Turner, 1977; Jolly, 1975). In the Munro Township area tholeiitic rocks can be distinguished chemically from komatiites by their higher $\text{FeO}^{\text{tot}}/(\text{FeO}^{\text{tot}} + \text{MgO})$ ratios at given Al_2O_3 contents, higher TiO_2 contents at given SiO_2 or MgO contents, and lower contents of MgO , Cr and Ni. Rare-earth contents are higher than in komatiites.

(2) Tholeiitic affinities

The Akilia low-Cr basic rocks are closely similar in chemistry to the Munro Township and other Archean high-Fe tholeiites (compare columns 8–10 with

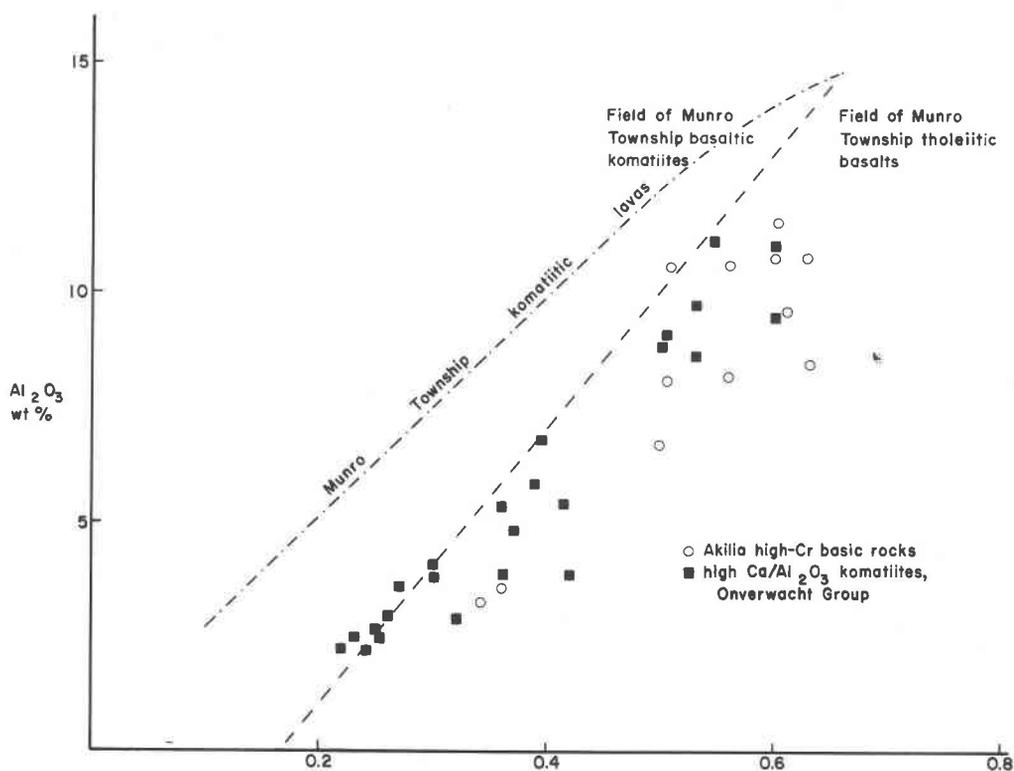


Fig. 8. Plot of $\text{FeO}^{\text{tot}}/(\text{FeO}^{\text{tot}} + \text{MgO})$ vs. Al_2O_3 for komatiites and tholeiites; Munro Township data from Arndt *et al.*, 1977).

columns 16 and 17 in Table 1). Other early Archean tholeiitic rocks in the Godthåb region (Isua supracrustal amphibolites and one group, Godthåb type, of Ameralik dykes) are similar to the Akilia low-Cr basic rocks in, for example, their high iron contents (Allaart, 1976; Gill and Bridgwater, 1976).

Geological significance of the Akilia association

Komatiite suites have been described from many Archean shield areas: the Superior Province of Canada, Western Australia, India, and the Kapvaal and Rhodesian cratons of southern Africa (see Arndt *et al.*, 1977, for references). Post-Archean komatiitic rocks have been reported, but are not common (Brooks and Hart, 1974). The Archean komatiites occur within sequences of pillowed basalts and cherty sediments in greenstone belts. They are commonly, if not universally, associated with high-Fe tholeiites. At Munro Township, for example, tholeiitic lavas occur in successions 500–1500 m thick which alternate with slightly thinner successions of komatiitic lavas. The komatiites and high-Fe tholeiites generally occur at the base of volcanic/sedimentary cycles, although not necessarily at the base of the greenstone-belt sequences as a whole.

The range of lithologies in the Akilia association south of Godthåb—basic rocks with the compositions of komatiites and Fe-rich tholeiites, together with minor banded ironstones and gneisses of detrital sedimentary origin—strongly suggests that these enclaves are derived from a typical Archean greenstone-belt type of sequence that was intruded and broken up by the granitic parents of the AmÏtsoq gneisses.

The rocks in the Isua supracrustal belt, which are chronologically equivalent to the Akilia rocks discussed here, are also of general greenstone-belt type, but there are differences between the two suites. No komatiitic rocks have been recognized within the Isua belt. Dunites are an important component of the Isua suite, but have not been recognized in the Akilia association south of Godthåb. The main ironstone unit at Isua is very much thicker than the ironstones in the Akilia enclaves, and is underlain by a thick unit of quartzites derived from cherts. No pure quartzites have been noted in the Akilia association. Carbonate-rich lithologies are important components of the Isua succession, but have not been noted in the Akilia association.

The Uivak gneisses of northern Labrador (Bridgwater and Collerson, 1976) are very similar to the AmÏtsoq gneisses, both chemically and in their field characters. They have yielded a Rb/Sr isochron

age of 3622 ± 72 m.y. (Hurst *et al.*, 1975). It seems likely that the Uivak and AmÏtsoq gneisses formed part of a single complex within the pre-drift North Atlantic craton. Grey Uivak I gneisses contain inclusions of earlier supracrustal and other mafic and ultramafic rocks that include amphibolites, quartz-banded ironstones, rare biotite schists (some with graphite), calc-silicate units, clinopyroxenites, hornblende-clinopyroxenites, and layered leucogabbros. The range of lithologies in the Uivak inclusions does not match that of the Akilia association exactly, but there is considerable overlap between the two (Dr. D. Bridgwater, personal communication).

The oldest rocks in the North Atlantic craton (the Isua supracrustals, the Akilia association, and probably also the inclusions in the Uivak gneisses) are thus made up of greenstone belt-type lithologies. The *ca.* 3700 m.y. gneisses that intrude them are mainly derived from syntectonic, calc-alkaline tonalites and granodiorites. The AmÏtsoq grey gneisses are chemically very similar to the younger Nûk gneisses of the Godthåb region. The chemistry of the AmÏtsoq grey gneisses, like that of the Nûk gneisses, seems best explained in terms of partial melting of basaltic rocks, perhaps equivalent to the Akilia and Isua basaltic rocks, in some kind of subduction environment (McGregor, 1975; McGregor and Bridgwater, in preparation). There is no evidence of granitic rocks older than the dominantly basaltic rocks of the Akilia association and the Isua supracrustals.

The oldest rocks in the Godthåb region record the following sequence of events, which appears to have taken place within a period of less than 200 m.y. about 3700 m.y. ago: (1) Extrusion of basic volcanics (komatiites, tholeiites) and smaller amounts of acid volcanics, and deposition of chemical and clastic sediments—the parents of the Isua supracrustals and Akilia association. Intrusion of some anorthositic (leucogabbroic) rocks into the Akilia association. Emplacement of dunites into the Isua supracrustals, perhaps associated with mantle-tapping thrust faults. (2) Intrusions of syntectonic, calc-alkaline, granitic rocks in amounts greatly exceeding those of the supracrustal rocks preserved at the present level of exposure. (3) Strong deformation. (4) Intrusion of abundant basic dykes. (5) Metamorphism culminating in granulite-facies conditions in part of the area.

The orogenic activity that occurred around 3700 m.y. was thus similar in many respects to the orogenic activity that affected the Godthåb rocks around 2800 m.y. ago (Bridgwater *et al.*, 1974; Moorbath and Pankhurst, 1976). The early phases of the *ca.* 2800

m.y. activity were dominated by sub-horizontal movement which Bridgwater *et al.* (1974) suggested was caused by some form of subduction, although not necessarily analogous to the subduction associated with present-day plate tectonics. In both orogenic periods slightly older supracrustal sequences made up mainly of basaltic rocks were intruded by great volumes of syntectonic calc-alkaline magmas that make up over 80 percent of the rocks now exposed.

There is no evidence of orogenic activity in the Greenland Archean during the *ca.* 700 m.y. that separated these two orogenic periods.

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