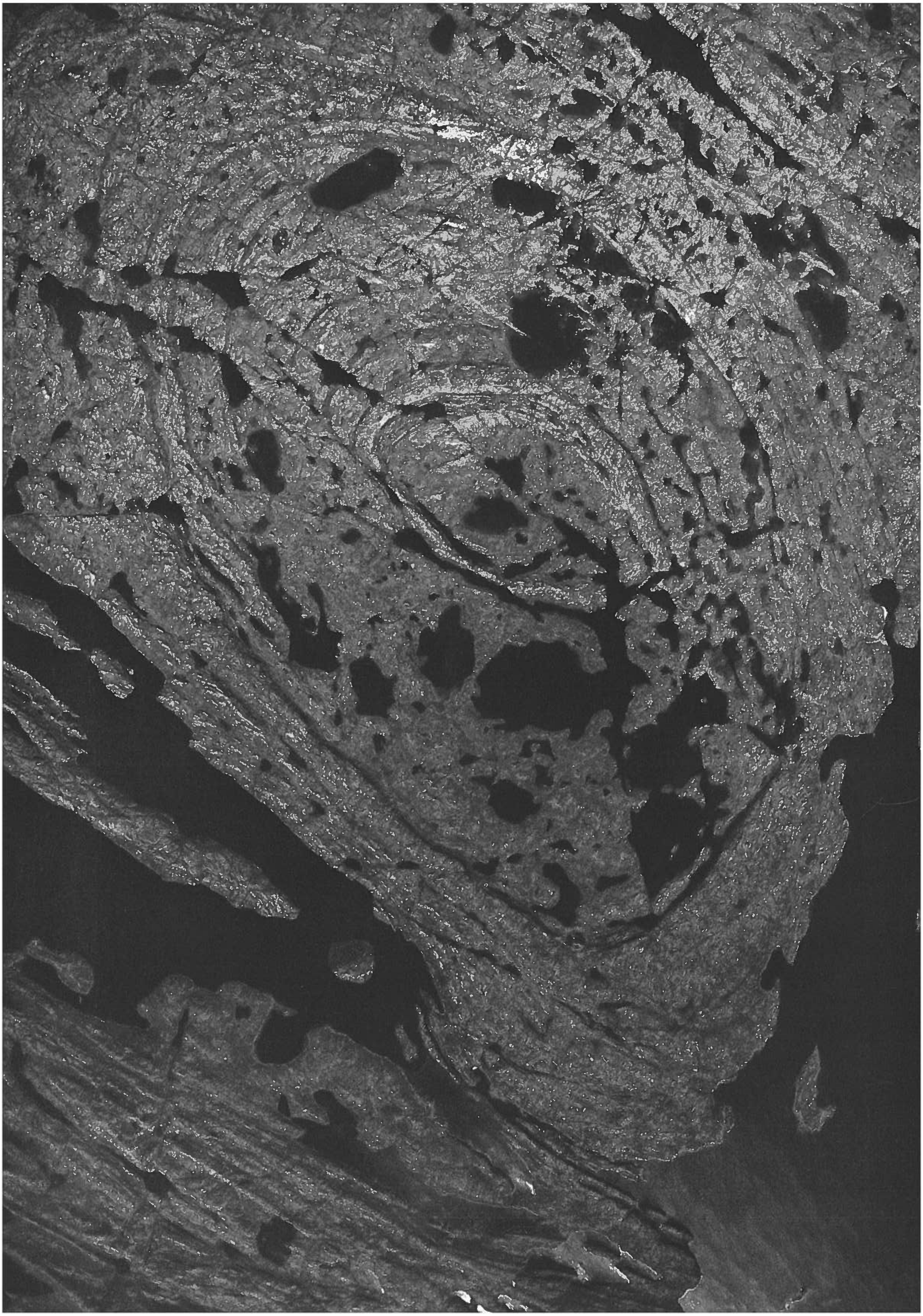

Archaean gneiss complex of Greenland

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L. Keto
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Fig. 3. The Ipernat dome of gneiss and amphibolite north of Godthåbsfjord, located on fig. 60. Copyright Geodetic Institute, Denmark. The dome is elongated N–S with NE to the top of the photograph. Scale: 2.7 cm = 1 km.

Introduction

The gneiss complex which extends from Itivdleq to Ivigtut on the west coast and from Gyldenløves Fjord to Mogens Heinesen Fjord on the east coast (fig. 4) has remained unaffected by major metamorphic, tectonic or magmatic events for the last 2600 m.y. Similar rocks occur in north-west Scotland (Peach *et al.*, 1907 pp. 191–252) and Labrador (Bridgwater *et al.*, 1973c; Bridgwater *et al.*, 1975) and the area described here is the largest and best exposed fragment of the Archaean North Atlantic craton which was broken up by Phanerozoic continental drift. Isolated remnants of similar Archaean rocks occur within the younger mobile belts to the north and south suggesting that the Archaean craton was once much larger and that a large part of it was reworked to varying degrees by younger tectonic and metamorphic events.

The mapping of the Archaean gneiss complex is far from complete and this account is only a summary of data and interpretations current in early 1975. Rather than attempt to cover the whole area equally, emphasis is given to parts which have yielded the most significant results either in terms of stratigraphy or the understanding of the origin of the various rocks of which the complex is composed. Responsibility for the regional interpretation and compilation of the maps lies with two of us (D. B. and J. S. M.); L. Keto is responsible for data obtained during the work of Kryolitselskabet Øresund A/S north of Godthåbsfjord and for some of the information from the Isua belt of supracrustal rocks; V. R. McGregor is responsible for the field work in the Godthåbsfjord region, the chronology of which is used as a framework to discuss the development of the Archaean complex as a whole. Published and unpublished maps of the Geological Survey of Greenland and Kryolitselskabet Øresund A/S have been used in making the regional compilation. The Oxford University Isotope Geology Laboratory is largely responsible for the studies which have allowed us to build up the geochronological framework of the area.

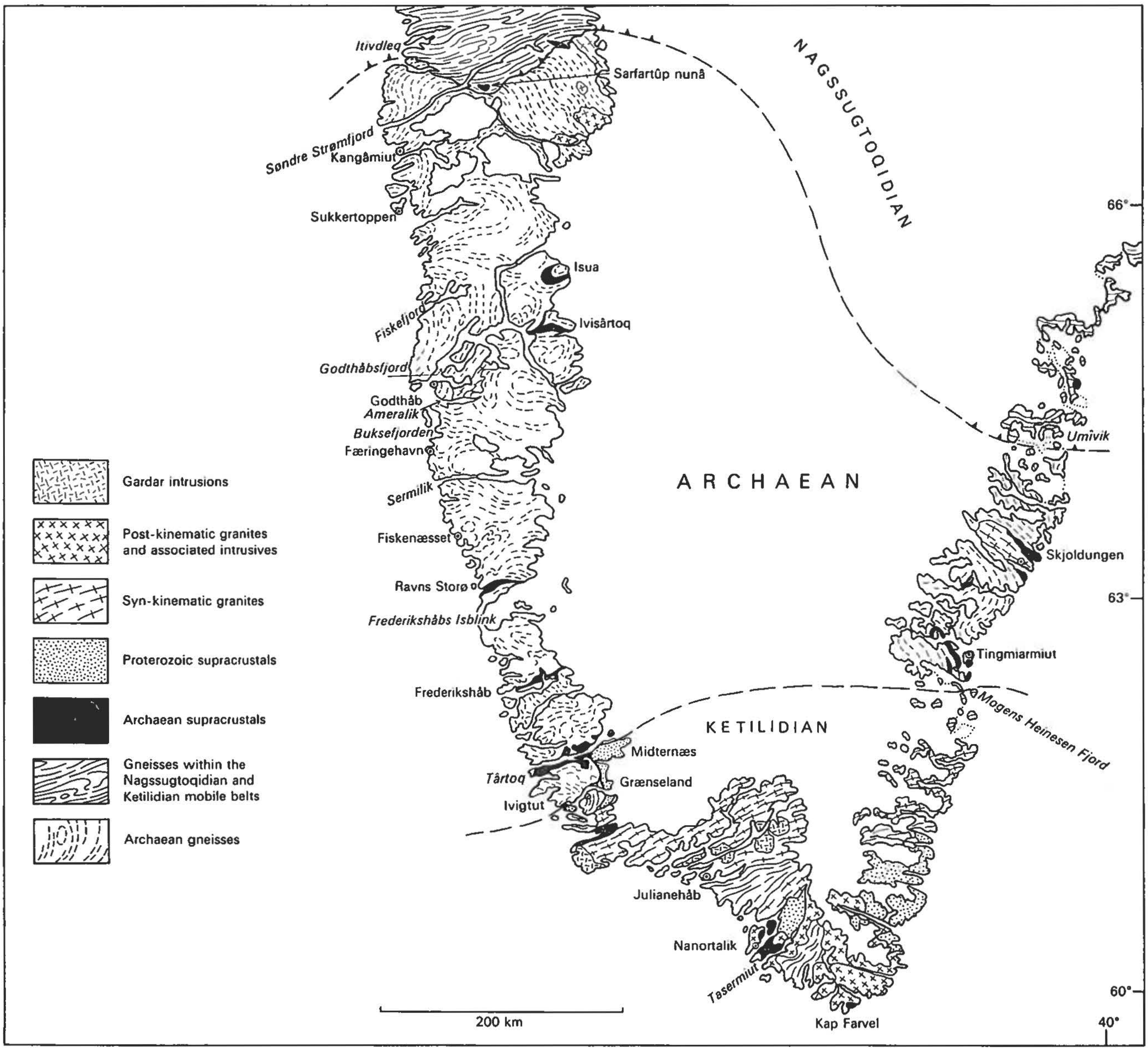
Geological summary

Between 80 and 90 per cent of the Archaean complex consists of granitoid quartzo-feldspathic gneisses, of which major parts appear to have been derived from acid or intermediate igneous rocks. They are intercalated with units of amphibolite (fig. 5) which appear to be mainly derived from metavolcanics, a minor amount of metasedimentary gneisses, and concordant units of meta-anorthosite and associated metabasic igneous rocks characterised by very calcic plagioclase. These units range from a few centimetres to a few kilometres in thickness.

The layered nature is thought in part to be due to the extensive injection of igneous sheets and in part due to intense deformation during which it is thought that rocks of different type and possibly of widely different provenance were interleaved and folded together.

The Archaean rocks are characterised by high

Fig. 4. Simplified map of the Archaean complex of Greenland.



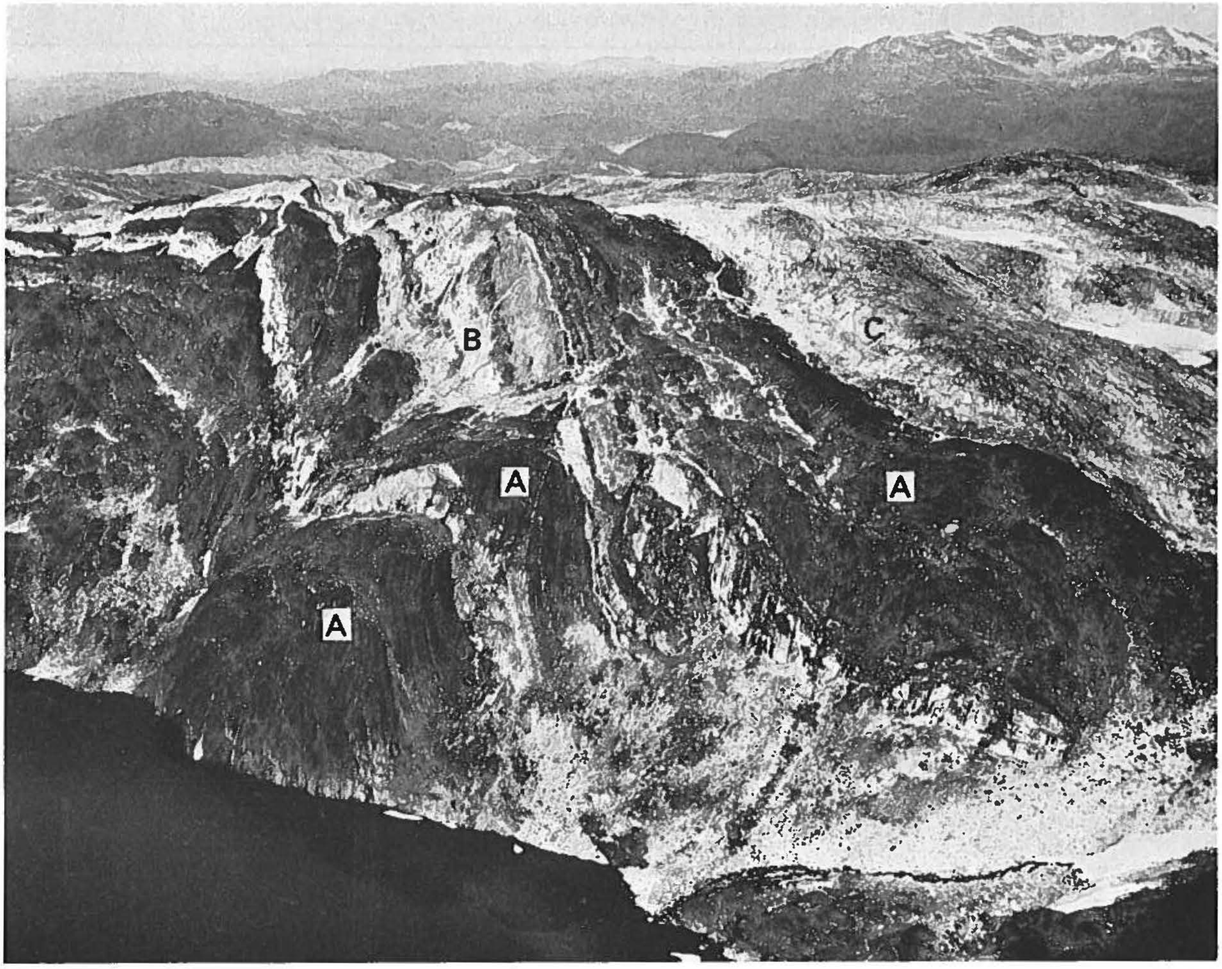


Fig. 5. Units of amphibolite derived from metavolcanics (A), layered leucogabbro-anorthosite (B), and quartzo-feldspathic, pegmatite-banded gneiss (C). View north-westwards from Qagsse, east of Fiskenæsset. Height of hill above the lake is 200 m.

grade polymetamorphic mineral assemblages, chiefly in high amphibolite and hornblende granulite facies. Over large areas the main mineral assemblages appear to have formed late in the history of the gneiss complex, after the main tectonic events which produced the layering and complex folds of the gneisses. Most rocks possess high temperature, medium pressure mineral assemblages; high pressure assemblages have rarely been seen. Most changes in metamorphic grade are gradual (Kalsbeek, in press) and suggest that gentle thermal gradients were attained during the final stages of metamorphism of the complex.

A variety of igneous rocks ranging from norites to granites and small carbonatite diatremes were intruded during late Archaean time and were cut by several swarms of basic dykes between 2700 and 2000 m.y. ago.

Geochronological framework

Geological studies in the Godthåbsfjord–Isua region (McGregor, 1973; Bridgwater & McGregor, 1974a,b) in conjunction with detailed isotopic investigations by the Oxford Isotope Geology Laboratory and the University of Alberta (Black *et al.*, 1971, 1973; Moorbath *et al.*, 1972, 1973; Pankhurst *et al.*, 1973 a, b; Baadsgaard, 1973) have established that the Archaean gneiss complex in this region is made up of six major lithostratigraphic and chronostratigraphic units ranging in age from 3750 m.y. or older to 2600 m.y. old (Table 1). The sequence of events established in Godthåbsfjord is used as a framework for the descriptions given in this account although it must be emphasised that the divisions established by McGregor only apply within a small area in which the individual units can be mapped out. No strict correlation between the rock units in Godthåbsfjord

Table 1. Simplified table of events from the Archaean of Greenland

(1) Early crust providing source rocks for the Isua sediments.	Early crust
(2) Deposition of the Isua supracrustals. Basic and ultrabasic lavas and intrusions, basic tuffs, quartzites, siltstones, pelites, ironstones and calcareous rocks. Acid volcanic fragments in a conglomerate.	Isua supracrustals $\geqslant$ 3750 m. y. (a, b)
(3) Intrusion of syntectonic and late tectonic granites (parents of the Amîtsoq gneisses), possibly contemporaneous with upper acid volcanic part of the Isua supracrustals.	Amîtsoq gneisses *c.* 3750 m.y. (a)
(4) Deformation and metamorphism of the Amîtsoq gneisses and Isua supracrustals.	
(5) Intrusion of abundant swarms of basic dykes (Ameralik dykes) during regional stress.	Ameralik dykes
(6) Extrusion of basic and intermediate volcanics (locally pillow lavas); intrusion of ultrabasic bodies and layered basic igneous bodies; deposition of sediments including pelites, aluminous quartzites, minor calcareous units (Malene supracrustals).	Malene supracrustals > 3040 m. y. (possibly 3750 m. y. or earlier)
(7) Emplacement of major stratiform anorthosites and gabbro anorthosites.	Anorthosite complexes > 3040 m. y.
(8) Major thrusting intercalating the Amîtsoq gneisses, Malene supracrustals and anorthosites.	
(9) Emplacement of ultrabasic bodies, mostly between Malene supracrustal rocks and Amîtsoq gneiss units.	
(10) Intrusion of major suites of syntectonic and late tectonic calc-alkaline rocks as subconcordant sheets (Nûk gneisses).	Nûk gneisses 3040 m. y. (c)
(11) Intense deformation with the formation of major nappes, followed by less intense deformation which produced upright folds and widespread dome and basin interference patterns. These were partly modified in sub-linear belts of very intense deformation.	Major folding 3040–2800 m.y.
(12) Emplacement of syn- and late tectonic granites, partly formed by the remobilisation of earlier gneisses during increasing regional metamorphism. Emplacement of norites, andesine anorthosites and quartz monzonites.	Late granites 3000–2800 m.y. (d)
(13) High grade metamorphism outlasting (11) and (12) and culminating in the widespread crystallisation of granulite facies minerals under late to post-tectonic conditions.	Granulite facies metamorphism 3000–2700 m.y. (e, f)
(14) Deposition (or tectonic mis-en-plas) of Tartoq Group and Sarfartûp nunâ supracrustals.	Tartoq Group supracrustals
(15) Tectonic activity mostly concentrated in distinct shear belts (particularly in northern part of craton). Widespread homogenisation of granitic gneisses under amphibolite facies conditions. Local injection of granitic sheets and late tectonic granite-diorite complexes.	*c.* 2700 m. y.
(16) Emplacement of potash granites associated with NE–SW flexures in the Godthåbsfjord area (Qôrqut granite). Widespread post-tectonic pegmatite swarms.	Qôrqut granite *c.* 2600 m. y. (g)
(17) Emplacement of at least three regional swarms of basic dykes; transcurrent movement on NE and SE faults. Plutonic activity in areas to north and south of craton.	Dykes 2600–1750 m. y.
(18) Slight metamorphism throughout Archaean block (or uplift above level at which Rb–Sr mineral ages become stable).	Rb–Sr systems closed *c.* 1600 m. y. (g)
(19) Intrusions of several sets of basic dykes between 1600–1000 m.y. particularly in the south of the craton (Gardar dykes). Sporadic kimberlites 600–200 m.y. on west coast. Mesozoic alkali basalt dyke swarm in south-west Greenland. Local intrusion of Tertiary basic dykes near Godthåb and Tingmiarmiut.	Minor intrusions 1600–50 m. y.

Isotope age work quoted

(a) Moorbath *et al.*, 1972
(b) Moorbath *et al.*, 1973
(c) Pankhurst *et al.*, 1973a
(d) Pidgeon *et al.*, in press
(e) Black *et al.*, 1973
(f) Gulson & Krogh, 1972
(g) Pankhurst *et al.*, 1973b

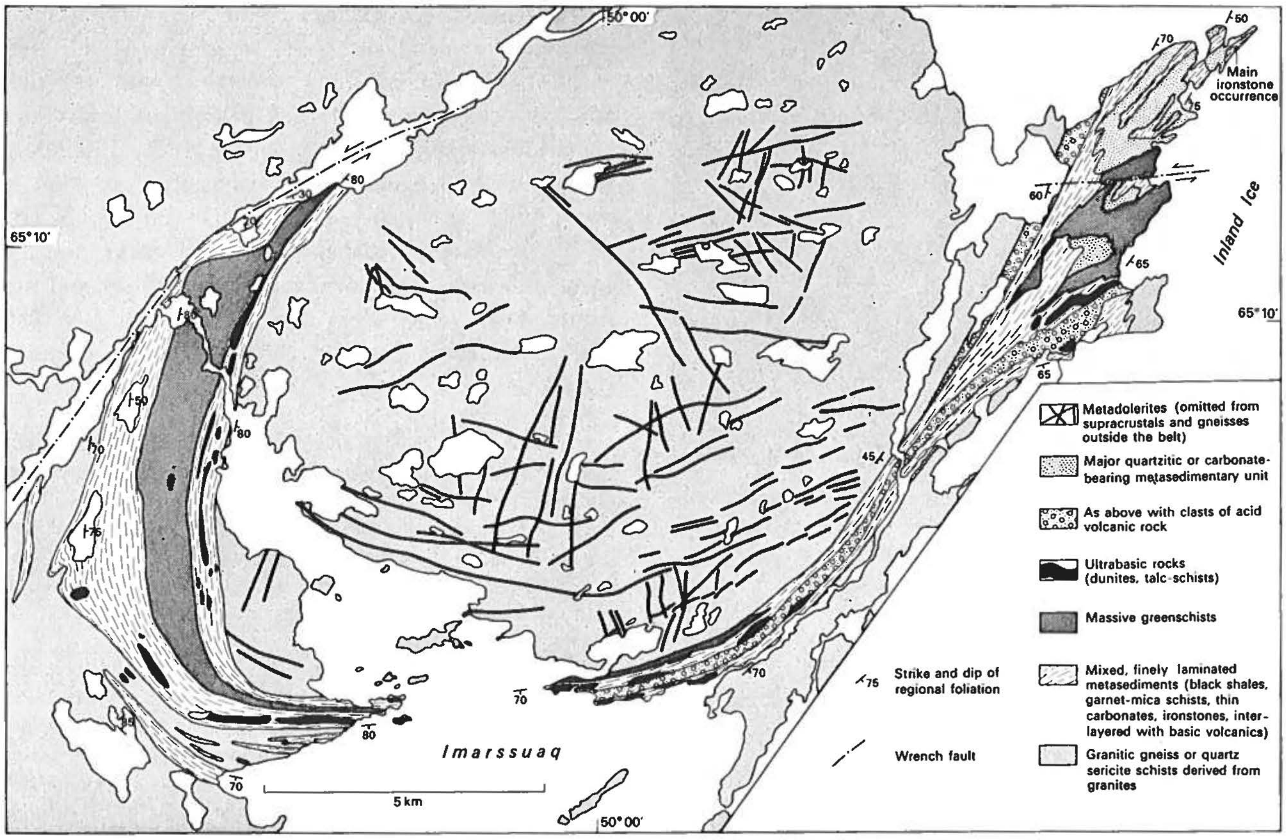


Fig. 6. Map of the Isua supracrustal belt, simplified after mapping by Kryolitselskabet Øresund A/S and later modified by GGU.

and those in other parts of the Greenland Archaean has yet been established either by field work or isotopic studies.

Isua supracrustals

The oldest rocks so far identified in Greenland are a variety of basic and ultrabasic greenschists, metasediments and quartzo-feldspathic rocks. They occur in a semicircular arc 10–20 km in diameter around a dome of gneiss (fig. 6), near the margin of the Inland Ice at Isua, 150 km north-east of Godthåb. The supracrustal belt has a maximum width of about 2 km at the margin of the Inland Ice, but is less than 1 km wide at the lake called Imarssuaq. Contacts with the enclosing gneisses are sharp and near vertical. Intrusive relationships are preserved at a few points along the contact and the quartzo-feldspathic gneisses surrounding the belt are interpreted (D. B. and V. R. M.) as derived from younger granites.

Planar structures and contacts between the different lithological units within the belt dip steeply and follow the trend of the belt itself. The supracrustal rocks have a strongly marked, steeply plunging, linear fabric defined by pencil-like rods and elongated conglomerate pebbles. This fabric is considered (D. B. and V. R. M.) to be an extension fabric sub-parallel to the main direction of tectonic transport.

Gneisses collected mainly along the contact of the belt have given a Rb-Sr whole rock isochron date of 3700 ± 140 m.y., which is identical, within analytical error, with Rb-Sr whole rock isochron dates from the type Amîtsoq gneisses near Godthåb (Moorbath *et al.*, 1972). Ironstones from the supracrustals have given a Pb-Pb whole rock isochron age of 3760 ± 70 m.y. This could represent a metamorphic event that was accompanied by severe uranium depletion (Moorbath *et al.*, 1973) or deuteric equilibration of uranium close to the time of deposition of the ironstones. No other major unit of supracrustal rocks comparable in age or lithology to the Isua succession has yet been discovered in Greenland.

Two sets of metadolerite dykes cut the supracrustal rocks and the gneisses both within and outside the dome. Within the dome they are little deformed, but 3 km south of the supracrustal belt they are recrystallised and boudinaged. They resemble Ameralik dykes of the Godthåb area (described later).

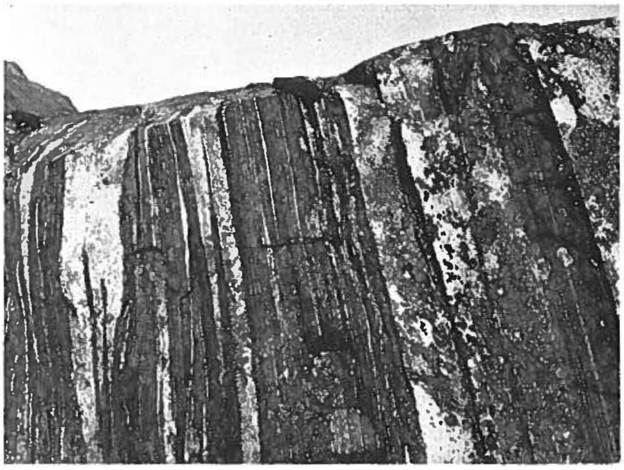


Fig. 7. Intercalation of strongly deformed basic (supracrustal) and acid (intrusive granite) gneisses of the south-east margin of the Isua supracrustal belt.

The supracrustal belt is cut off to the north-west by a major fault that marks the edge of a belt with a strong NNE-trending fabric. This is thought to be the boundary of a tectonic enclave that escaped the widespread and intense post-Ameralik dyke deformation and plutonic activity (Table 1). Most of the Isua supracrustals contain amphibolite facies mineral assemblages which have been partly retrogressed to greenschist facies assemblages.

Stratigraphy and petrology

The Isua supracrustal suite is regarded as a fragment of a once more extensive sequence and has similarities with younger greenstone belts. The rocks are highly deformed and the original stratigraphy has been disturbed by thrusting.

To the east of Imarssuaq the supracrustal rocks show a general bilateral symmetry, with an outer unit of mixed metasediments, basic metavolcanics and ultrabasic rocks, enclosing a central unit of metasedimentary rocks (fig. 6). To the west of Imarssuaq the succession is dominated by a massive greenschist unit which occurs near the transition between the outer unit of mixed metasediments and the inner metasediments. Part of this greenschist unit, together with others which occur near the Inland Ice, are considered to represent basic sills. Interleaved units of garnet biotite schist are interpreted as derived from basic tuffaceous sedimentary rocks.

Inclusions of amphibolite and magnesian ultramafic rocks in the gneisses surrounding the belt are presumed to be derived from earlier units rafted off during the emplacement of the surrounding granitic gneisses. The *outer units of the belt* are dominated by a laminated sequence of colour banded amphibolite, massive metabasic rocks interlayered with thin garnet-biotite schist bands, quartzites with iron-rich minerals, dark amphibole-rich calcareous layers and concordant units of talc-actinolite rock. Individual layers in the sequence are generally less than a metre thick and many are less than 20 cm. A few layers of quartzo-feldspathic material occur (fig. 7), some of which show local intrusive features and are regarded as veins from the surrounding gneisses, others may represent original acid volcanic parts of the sequence.

In thin section the massive *basic rocks* in the outer units of the belt are seen to be amphibolites with quartz, andesine-labradorite, hornblende, sphene and opaque minerals. They range in composition from low potassium to normal tholeiites and appear to be derived from sills or lavas. These amphibolite-facies basic rocks are commonly retrogressed with the formation of clinozoisite and scapolite mainly at the expense of plagioclase.

The *metasediments* in the outer units of the belt are characteristically layered on a fine scale and variable in composition. They are commonly dark in colour and dominated by iron and calcium-bearing minerals suggesting that they represent iron-rich marls. Thin carbonate-rich layers are common. Biotite-hornblende rocks with variable amounts of garnet, plagioclase, magnetite and quartz are common. Clinozoisite, scapolite, and chlorite were formed at the expense of the higher grade assemblages. Quartz layers are frequently streaked-out and were locally remobilised and penetrate the surrounding rocks. Some iron-rich rocks with streaked-out pods of garnet and epidote minerals occur with clinopyroxene apparently as a stable assemblage. Staurolite occurs locally rimming garnet in pockets of schist within the massive greenstones. Magnetite quartzite layers a few tens of centimetres thick form extremely persistent units within the mixed marginal succession. Laminated graphite-

Fig. 8. Folded calcareous metasediments near the central part of the Isua supracrustal belt. The rock consists of alternating layers of carbonate, diopside and actinolite.

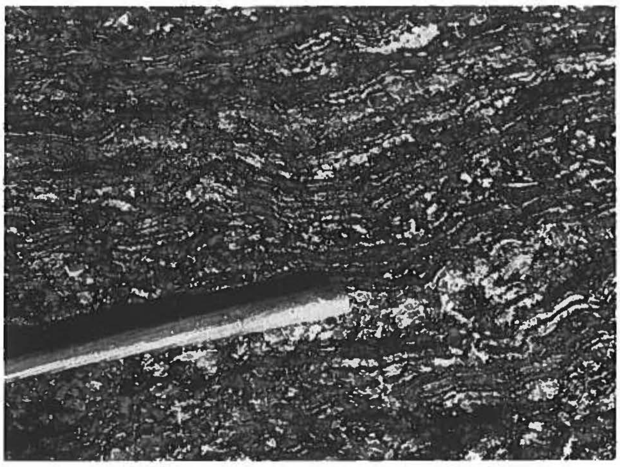


Fig. 9. The Isua ironstone showing magnetite and quartz-rich layers.

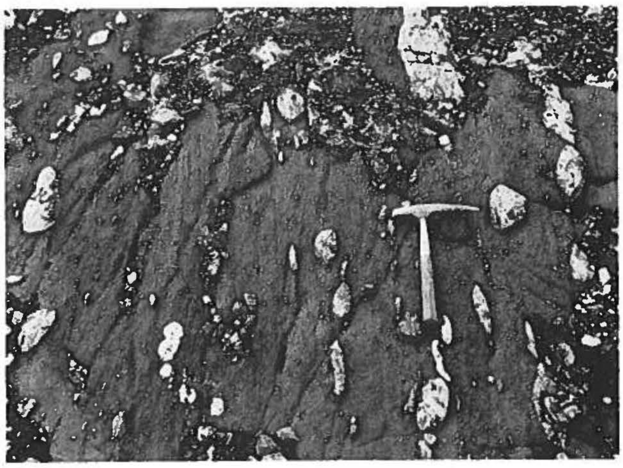


Fig. 10. Acid volcanic cobbles in a carbonate-rich, quartz-feldspar-biotite sedimentary matrix, Isua supracrustal belt.

bearing impure quartzites or siltstones with quartz, sericite, albite and some garnet have been noted as thin septa enclosed in massive greenstones to the north-west of the lake Imarssuaq (fig. 6).

The *massive greenschist unit* which forms the major rock type to the west of Imarssuaq consists largely of basic rocks commonly with a garbenschiefer texture. Well-developed hornblende needles occur in a silver coloured matrix consisting largely of sericite and chlorite. No primary characters were observed in the field. Chemical analyses from rocks of this unit show a marked range in potash content (from less than 0.1 % to 3.4 % K_2O) suggesting that this unit is not entirely composed of metabasalt lavas; it may contain layers of basic tuff with a potash-bearing, non-volcanic component, such as forms the thin layers of garnet pelite between the massive basic units.

The main concentration of *ultrabasic rocks* occurs in the transition zone between the mixed border group and the dominantly sedimentary rocks forming the central part of the belt (fig. 6). Some ultrabasic pods are a kilometre long and 50–100 m thick. The majority consist of talc-actinolite-chlorite schist with well-developed layering. Some pods, particularly those occurring nearer to the inner contact of the belt, consist largely of forsterite (Fo_{90}) partly altered to serpentine. Thin magnetite-quartz horizons occur adjacent to the ultrabasic masses. The ultrabasic rocks are locally associated with layered, dark green, pure amphibole rock apparently of metasedimentary origin. Thin concordant layers of actinolite-chlorite schist also occur within the succession.

The *metasedimentary rocks* found near to the centre of the supracrustal belt contain a high proportion of carbonate or calcium-bearing minerals. Well-layered quartzo-feldspathic rocks with a high carbonate content in the matrix are found adjacent to brown weathering almost pure carbonate rocks interlayered with strings, lenses and layers of diopside and actinolitic amphibole (fig. 8).

The easternmost outcrops of the belt contain a major banded *ironstone unit* estimated to contain at least two thousand million tons of ore (Keto, 1969; see also Nielsen, this volume). The solid outcrops of this body consist of alternating layers of magnetite and quartz (fig. 9) with some iron-rich amphiboles and chlorites. The ironstones pass gradationally into thick quartzites with patches and schlieren of cummingtonite and some carbonate with progessively fewer magnetite layers. These siliceous rocks are interpreted as chemical sediments. They are interlayered with chlorite-rich basic rocks interpreted as basic sills.

Close to the shore of Imarssuaq, the central sedimentary units contain a well defined *meta-conglomerate unit* with cobbles and boulders of acid volcanics ranging from a few centimetres to two metres in diameter, set in a finer grained, locally laminated, matrix (fig. 10). This distinctive unit can be traced for at least 28 km along the strike and reaches a maximum width of over 100 m. Over a major part of the outcrop the fragments are so deformed and sheared out that they are pale elongate discs within a slightly darker, buff-coloured matrix.

A relatively little deformed outcrop of this unit occurs on the eastern shore of Imarssuaq. At this locality the boulders consist of pale, fine-grained, muscovite-rich, quartzo-feldspathic rocks some of which have a gneissose texture. The least deformed boulders contain aggregates of quartz and muscovite representing original quartz and potash feldspar megacrysts set in a finer grained matrix with a rhyolitic texture. Available analyses show that the boulders are highly potassic granites with up to 9 % K_2O. Carbonate metasomatism has occurred along the borders of many of the boulders with carbonate apparently derived from the surrounding matrix. In some outcrops the boulders form distinct beds, in others they are scattered throughout the matrix. Many of the boulders are lithologically and chemically similar to massive muscovite-rich units of pale quartzo-feld-

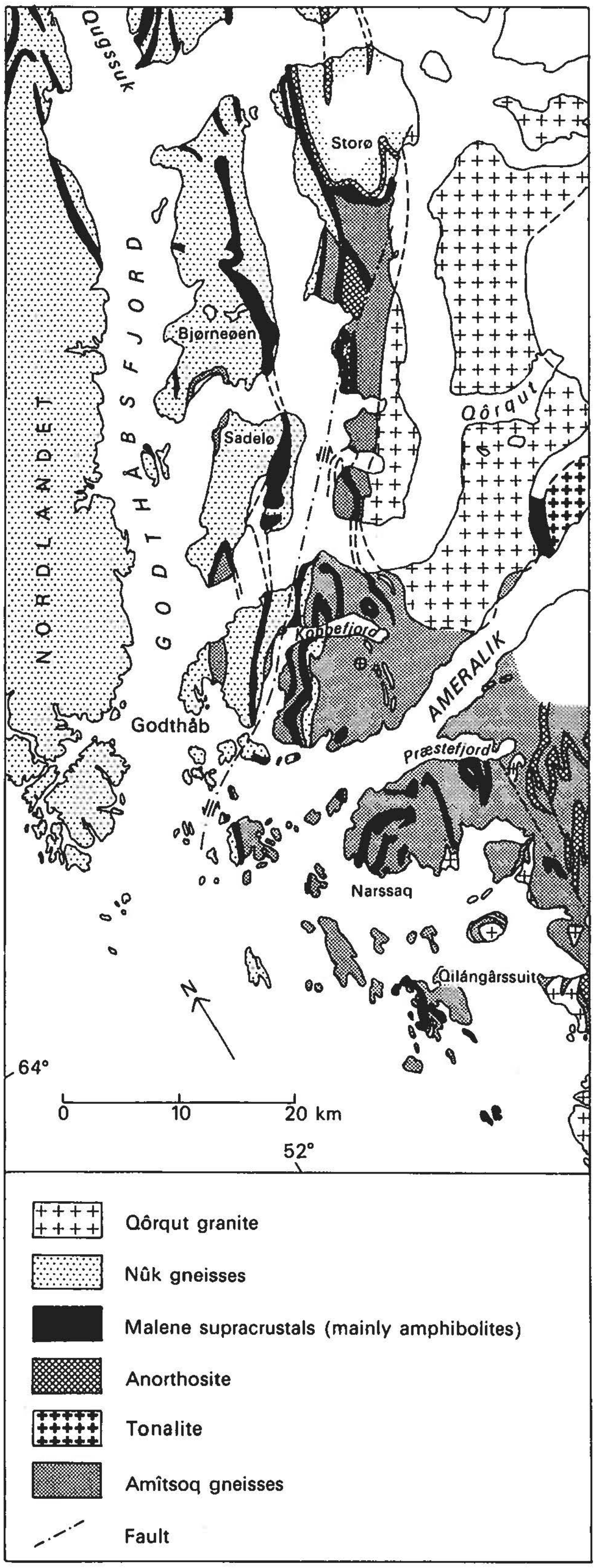


Fig. 11. Map showing the main stratigraphical divisions of the Godthåbsfjord – Ameralik region.

spathic rock which occur as sheets within the supracrustal succession to the west of Imarssuaq. Some of these sheets are demonstrably intrusive into the supracrustal succession though others probably represent acid volcanic layers in the sequence.

The matrix of the conglomeratic unit appears to be homogeneous and consists of quartz, biotite, carbonate, some potash feldspar (or muscovite), and plagioclase with variable anorthite content. Locally the meta-conglomerate contains thin layers of biotite-hornblende-magnetite rock with abundant euhedral crystals of tourmaline. The meta-conglomerate is interlayered with carbonate-actinolite-diopside rock (fig. 8) and with thin quartz-magnetite units. It is not known whether the meta-conglomerate originated as a purely clastic sediment with fragments derived from an older acid volcanic part of the succession or whether volcanism and sedimentation were essentially contemporaneous.

Inclusions in the Amîtsoq gneisses

Isolated inclusions and rafts of supracrustal rocks of up to several hundred metres in length occur within the quartzo-feldspathic Amîtsoq gneisses near Godthåb (fig. 11). They are most abundant at the head of Kobbefjord and on the skerries south and east of Qilángârssuit (McGregor, 1973; McGregor & Bridgwater, 1973). Lithologies similar to those of the Isua succession include layered amphibolites of metabasaltic composition, pods of magnesian ultramafic rocks, garnet-mica-graphite quartzo-feldspathic gneisses, and finely laminated quartz-magnetite-iron silicate rocks. Many of these inclusions have textures suggesting that they were deformed and penetrated by silica before or during their inclusion in the Amîtsoq gneisses, a feature seen locally at Isua. Other inclusions in the Amîtsoq gneisses cannot be matched with rocks from Isua or their higher grade equivalents.

Outside the Godthåbsfjord region, for example on the south-east coast of Greenland (Andrews *et al.*, 1973), many of the Archaean quartzo-feldspathic rocks contain inclusions of material with marked similarities to the inclusions in the Amîtsoq gneisses south of Godthåb. It may prove possible to recognise gneisses equivalent to the Amîtsoq gneisses in areas where Ameralik dykes are absent on the basis of the inclusions they contain.

The inclusions in the Amîtsoq gneisses can be subdivided petrographically into groups according to their mineralogy, trace element chemistry and possible origin.

(a) *Layered amphibolites* are the most common lithology. They are lithologically similar to some of the layered amphibolites in the Malene supracrustals, and are composed mainly of hornblende and plagioclase with varying minor amounts of clinopyroxene, quartz and/or biotite. The limited chemical data available are compatible with a basaltic origin. Two main types can be distinguished on the basis of minor elements. One type contains 1000–1500 ppm Cr and 300–400 ppm Ni. Biotite is absent from these rocks and they are petrographically very similar to adjacent Ameralik dyke amphibolites. The other type contains less than 350 ppm Cr and less than 150 ppm Ni and with respect to these and other minor element concentrations, is similar to the metadiorites of group (e) below. Amphibolites of this type commonly contain significant amounts of biotite. The two types of amphibolite occur together, though the second type is more common in the samples so far collected.

(b) *Layered rocks* composed of salite, hornblende, garnet and *c.* 20 % plagioclase (An_{35-45}). Orthopyroxene may also be present. Rocks of this type are especially common on the small islands north-west of the mouth of Buksefjorden. Some appear to be very similar chemically to the layered amphibolites of group (a) and the difference in mineralogy is attributed to a higher grade of metamorphism. Others occur as individual layers in normal layered amphibolites from which they differ chemically, having for example a higher titanium content.

(c) *Pale green rocks* composed mainly of salite form a very characteristic, though minor lithology in the suite. In most rocks the clinopyroxene is partly replaced by hornblende and there are all gradations between pure clinopyroxene rocks and hornblendites. The pyroxenites are layered and intimately associated in the field with rocks containing plagioclase in addition to clinopyroxene and hornblende. There is a complete transition between these rocks and the pyroxenites and the rocks of type (b). The minor element chemistry of the pyroxenites suggests that they are derived from igneous, basaltic parents rather than from metasediments.

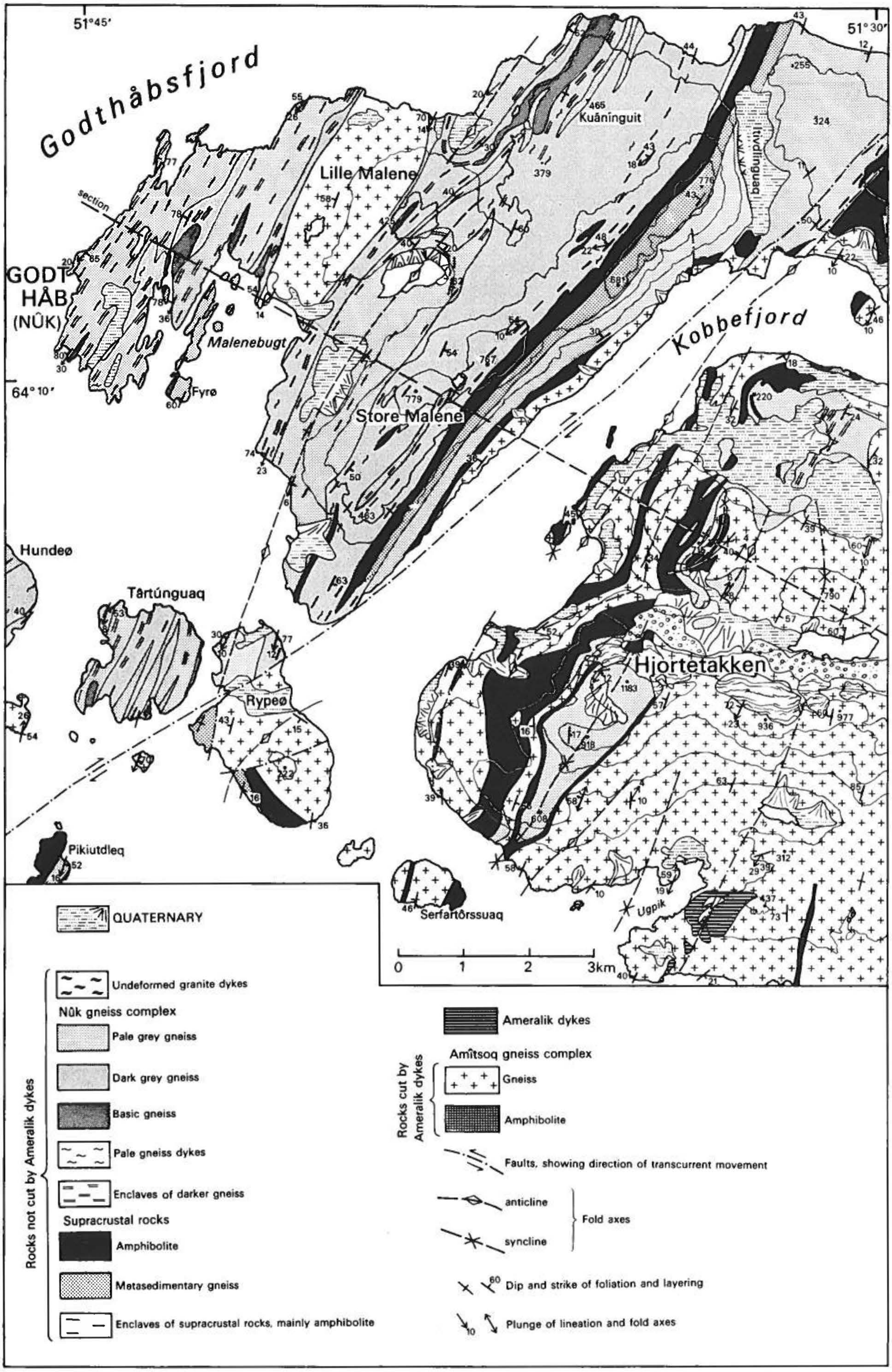
(d) *Coarse-grained, layered basic and ultrabasic rocks* that appear to be derived from a layered gabbro have been found north of the head of Kobbefjord.

(e) *Massive homogeneous rocks* composed of hornblende, plagioclase, biotite and quartz appear to be derived from dioritic parents. Their minor element chemistry is rather different from most of the rocks of types (a) to (d), although it is similar to one of the two main types of layered amphibolite.

(f) *Magnesian ultramafic rocks,* some containing relict olivine have been noted in places, but are not common. Many of them are well layered. They have very high contents of Cr, Co and Ni.

(g) *Quartz-ironstones* are another minor, but very characteristic lithological type. Quartz is dominant and usually associated with magnetite and grunerite. Actinolite, garnet, iron-rich orthopyroxene, clinopyroxene and pyrrhotite are also common. Most of the quartz-ironstones have a fine lamination suggesting that they are of sedimentary origin. They are commonly associated with layered amphibolites,

Fig. 12. Pegmatite-banded Amîtsoq gneisses cut by a folded Ameralik dyke, near the mouth of Ameralik on the north side of the fjord.


51°45'
51°30'
64°10'
Godthåbsfjord
Kobbefjord
GODTHÅB
(NÛK)
Malenebugt
Fyrø
Lille Malene
Store Malene
Kuâninguit
Itivdlinguaq
Hundeø
Târtûnguaq
Rypeø
Pikiutdleq
Hjortetakken
Serfartôrssuaq
Ugpik
section
0 1 2 3km
QUATERNARY
Undeformed granite dykes
Nûk gneiss complex
Pale grey gneiss
Dark grey gneiss
Basic gneiss
Pale gneiss dykes
Enclaves of darker gneiss
Supracrustal rocks
Amphibolite
Metasedimentary gneiss
Enclaves of supracrustal rocks, mainly amphibolite
Rocks not cut by Ameralik dykes
Ameralik dykes
Amîtsoq gneiss complex
Gneiss
Amphibolite
Rocks cut by Ameralik dykes
Faults, showing direction of transcurrent movement
anticline
syncline
Fold axes
Dip and strike of foliation and layering
Plunge of lineation and fold axes

and in some places form isolated layers in the amphibolites. Association with pyroxenites has also been noted.

(h) *Quartz-plagioclase-biotite (-garnet) gneisses* locally containing graphite are thought to be derived from pelitic and semipelitic sediments. Transitional rock types to quartz-ironstones contain in addition grunerite and actinolite. Some of these also contain graphite.

Amîtsoq gneisses

Definition

The Amîtsoq gneisses are the older of two major groups of quartzo-feldspathic gneisses which occur in the Godthåb region (figs 11, 13) (Black *et al.*, 1971; McGregor, 1973). They were distinguished in the field because they contain abundant bodies of amphibolite derived from basic dykes, called the Ameralik dykes (McGregor, 1968, 1969) (fig. 12). Intensive isotopic studies of Amîtsoq gneisses collected over a large area have yielded very consistent ages: Rb-Sr whole rock isochron dates of 3700–3750 m.y. (Moorbath *et al.*, 1972) and zircon concordia and Pb-Pb whole rock isochron dates of *c.* 3650 m.y. (Baadsgaard, 1973; Black *et al.*, 1971). The isotopic studies confirmed the unity of the Amîtsoq gneisses and showed that the gneisses surrounding the supracrustal rocks at Isua also belong to this group.

Amîtsoq gneisses have now been recognised within an area that extends from Sermilik in the south to the edge of the Inland Ice at Isua (fig. 4). They form about 20 to 40 per cent of this area. To the south and to the north-west they become lost in a flood of younger gneisses. Outside the Isua–Godthåb–Sermilik area there is no isotopic evidence of the presence of rocks equivalent to the Amîtsoq gneisses. It is possible that a major part of the Archaean complex consists of very old quartzo-feldspathic rocks reworked and perhaps remelted to varying degrees during later tectonic and metamorphic events, although one of us (V.R.M.) considers this unlikely.

Field characters and petrography

The Amîtsoq gneisses have generally been so heavily reworked that all primary structures have been erased or modified beyond recognition. The reworked Amîtsoq gneisses are very inhomogeneous rocks with well developed, thin pegmatite layering. In most places they contain numerous tabular bodies of basic rocks, mostly derived from Ameralik dykes, and many sheets of younger pegmatite and paler gneisses (fig. 14).

The Amîtsoq gneisses preserve primary igneous features in an area of about 120 km² at Isua. There the Amîtsoq gneisses were strongly deformed along with the supracrustal rocks they enclose, but escaped the reworking that affected the remainder of the Amîtsoq gneisses after the intrusion of the Ameralik dykes. In the Isua area the Amîtsoq gneisses are rather monotonous grey granodioritic gneisses with biotite as the main mafic mineral. In parts of the area the gneisses are polyphase with two or more phases which differ in mafic content and feldspar type. The paler phases invariably intrude the darker phases. Elsewhere in the area there are more homogeneous grey gneisses with fine pegmatite layering.

The samples so far examined show remarkably little variation in mineral content. All are biotite-oligoclase gneisses with variable, but generally low contents of microcline. The main differences observed are in the amount of biotite present (5–20 %) and in the degree of deformation. Epidote is present in all thin sections examined and partly replaces the mica; biotite is slightly altered to chlorite, plagioclase to sericite and calcite; apatite, titanite and iron ore minerals are common accessories. Plagioclase crystals tend to be resistant to shearing and are often preserved

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Fig. 13. Detailed map and section of the area around Godthåb, after McGregor (1973).

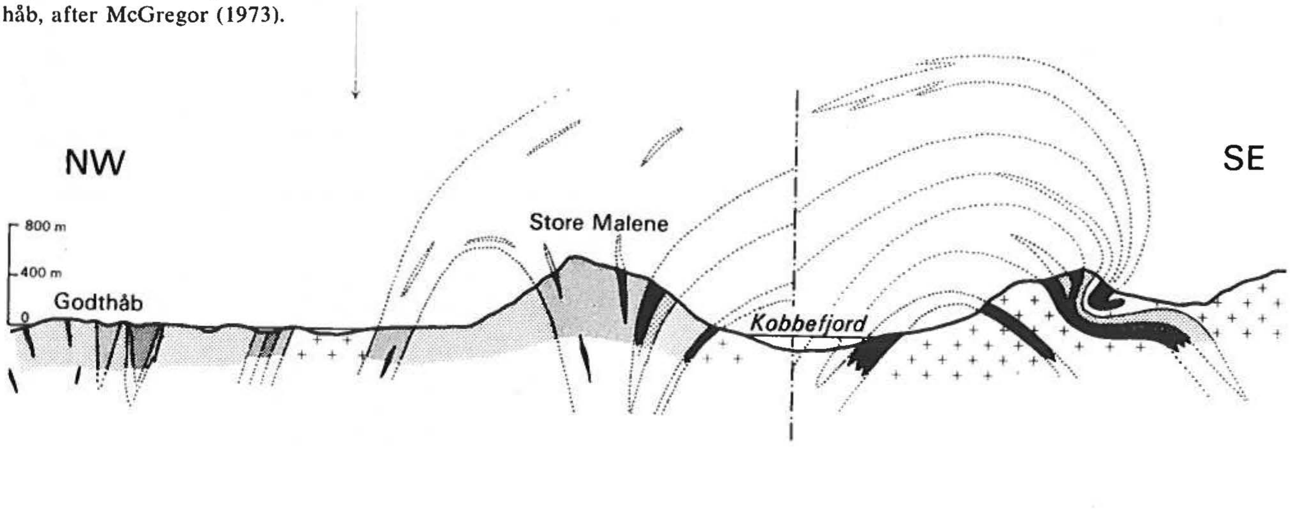


Fig. 14. Strongly deformed Amîtsoq gneiss and Ameralik dyke, east of Serfarssuit on the south coast of Godthåbsfjord.

as single crystals, or aggregates up to 0.5 cm across in a finer grained matrix.

The Isua gneisses are very similar both in field characters and in composition to many of the Nûk gneisses and like the Nûk gneisses they are interpreted as a syntectonic, calc-alkaline intrusive suite. Both the polyphase structure and the pegmatite layering are considered to be primary features reflecting movement during crystallisation.

Outside the Isua area pre-Ameralik dyke features in the Amîtsoq gneisses are preserved only locally, mainly around the outer part of Ameralik and on the islands to the south-west.

A very distinctive lithology crops out intermittently between the mouth of Ameralik and the islands south of Qilángârssuit (fig. 11). It is a dark, homogeneous, granitic to granodioritic augen gneiss containing abundant partly or wholly recrystallised megacrysts of potash feldspar (fig. 15). According to Chadwick *et al.* (1974a) this augen gneiss was emplaced into gneisses which had already been through at least two episodes of strong deformation. However at all localities seen by one of the writers (V. R. M.) it appears that the augen gneiss is the earliest phase of the Amîtsoq suite and was intruded by pegmatite-layered grey gneisses similar to those in the Isua area. Small bodies of homogeneous dioritic gneiss are closely associated with augen gneiss on the coast just south of the mouth of Ameralik and on the south-east corner of Qilángârssuit (Berthelsen, 1955). In places the augen gneiss is cut by sheets of very leucocratic gneisses derived from pegmatitic or aplitic parents.

The augen gneiss is moderately coarse grained and has aggregates of feldspar recrystallised from earlier megacrysts (mainly potash feldspar) up to 2–3 cm in diameter (fig. 15). The groundmass consists of quartz, biotite, microcline plagioclase (An_{15} and An_{30} co-existing: J. Krupicka, personal communication, 1974), traces of hornblende, epidote, sphene and apatite. The total potash feldspar exceeds 50 per cent of the combined feldspar content.

Grey Amîtsoq gneisses derived from homogeneous tonalites have been noted in several places, for example in Præstefjord, a small branch of Ameralik (fig. 11), where they contain many small, sharply-bounded inclusions of basic and ultrabasic rocks.

In most places in Godthåbsfjord where Ameralik dykes are clearly discordant to Amîtsoq gneisses it can be seen that the gneisses had a strongly developed pegmatite layering at the time the dykes were intruded. McGregor (1973) found that pegmatite layering of this type could be developed in originally homogeneous gneisses and suggested that it was produced by strong deformation under conditions approaching or just within the field of anatexis (fig. 16).

Chemistry

Major element and rare earth chemistry both suggest that the Amîtsoq gneisses are polygenetic. At least two and perhaps three main groups can be distinguished (fig. 17a).

(a) Grey, layered to homogeneous gneisses of calc-

Fig. 15. Amîtsoq augen gneiss derived from porphyritic granite, south of the mouth of Ameralik.

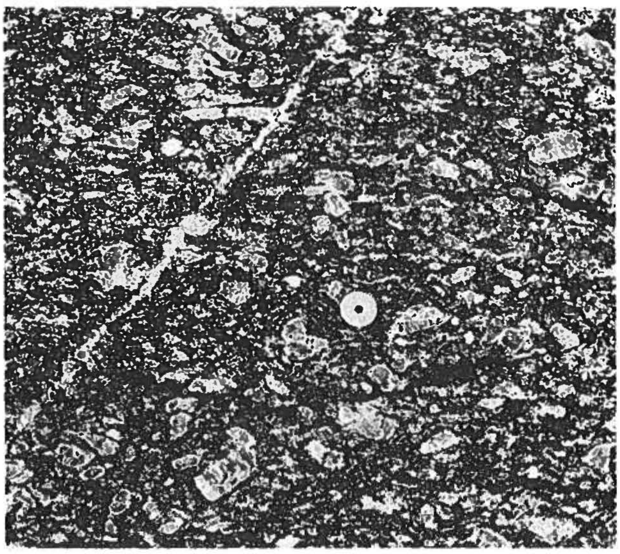
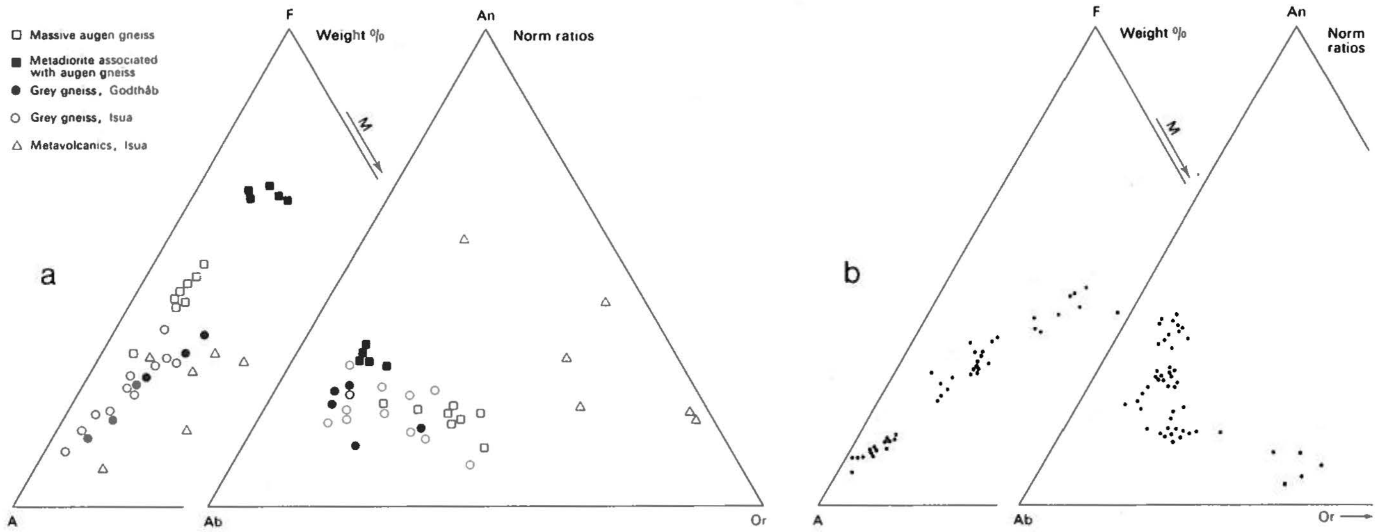


Fig. 16. Pegmatite-banded Amîtsoq gneiss derived by deformation and metamorphic segregation from the same parent as the augen gneiss of fig. 15. South of the mouth of Ameralik.

alkaline type. This group includes all the Isua gneisses, the homogeneous tonalitic gneisses from south of Godthåb, and the few more strongly reworked gneisses which have been analysed. These rocks are mainly granodioritic, tonalitic or trondhjemitic in composition. They are broadly similar in chemistry to the younger Nûk gneisses and to tonalitic gneisses of other ancient shield areas (for example southern Africa: Hunter, 1970), although they have a greater range of potash/soda ratios.

(b) The augen gneisses and dioritic gneisses associated with them have unusually high potassium contents and high iron/magnesium ratios. They appear to be chemically unique among early Archaean

Fig. 17. *a*. AFM and Ab–An–Or diagrams of Amîtsoq gneisses. *b*. AFM and Ab–An–Or diagrams of Nûk gneisses from Godthåbsfjord.



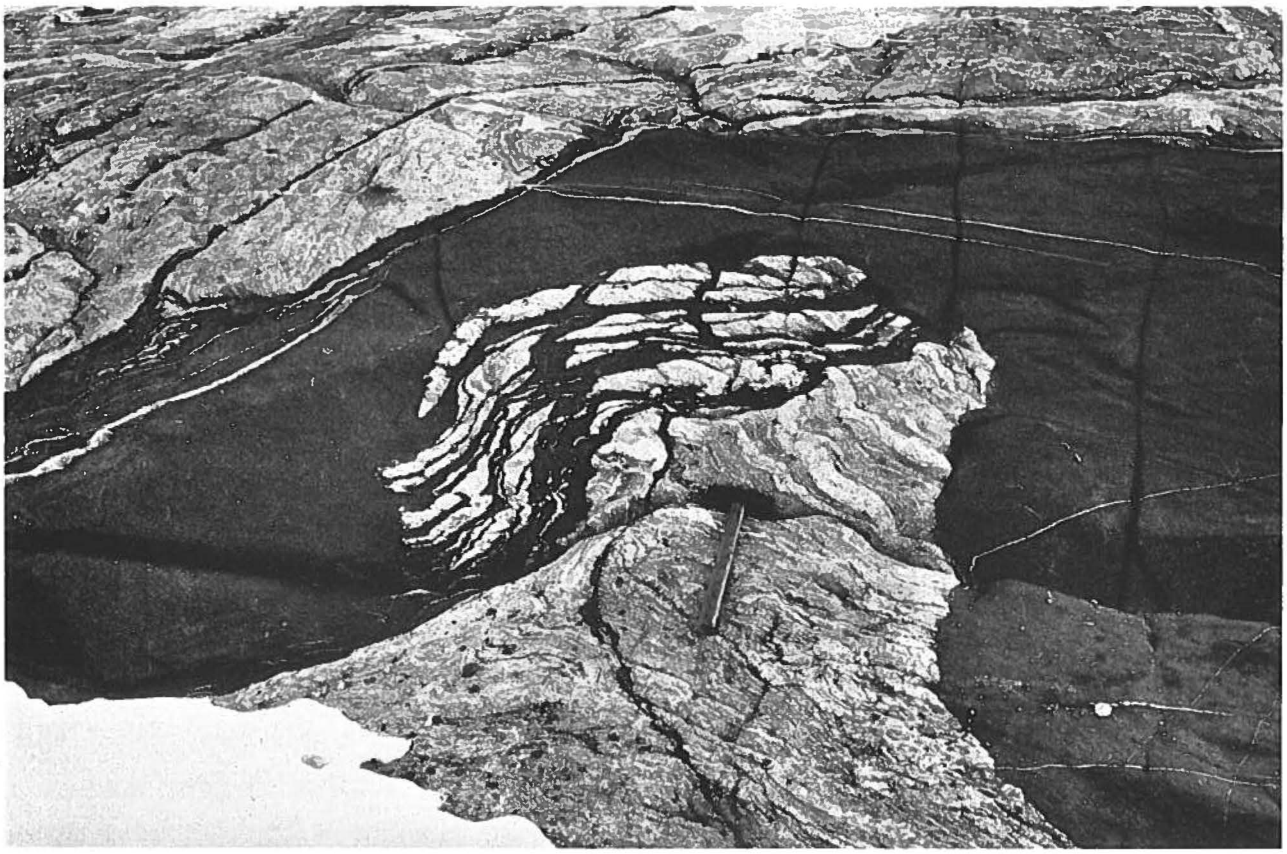


Fig. 18. Discordant Ameralik dyke with numerous small apophyses, between Kobbefjord and the mouth of Ameralik (fig. 11).

granitic rocks. One of us (D. B.) interprets them as crystallised under low oxygen fugacities, possibly in conditions resembling those of more recent rapakivi granite suites. Another of us (V. R. M.) suggests that they may be a relic of protocrust, formed as late differentiates during the crystallisation of the outer part of the mantle.

(c) Leucocratic sheets cutting the augen gneisses. One sample shows an extremely fractionated rare earth pattern with very low individual abundances especially for the heavy rare earth elements (Ce_N/Yb_N exceeding 320 compared with between 2.5 and 25 for other Amîtsoq gneisses). O'Nions and Pankhurst (1974) concluded that because of the great variation in the degree of rare earth fractionation, the Amîtsoq gneisses could not have been derived from a single cogenetic suite of igneous rocks.

The Pb-Pb whole rock determinations show that many of the Amîtsoq gneisses were depleted in uranium at an early stage in their history and Th/U ratios are always higher than the crustal average of 4 (Taylor, 1964). This is apparently a secondary feature since there is no correlation between Th/U and K/U ratios and major element chemistry.

K/Rb ratios from the Amîtsoq gneisses vary considerably. The gneisses from Isua and the majority of banded gneisses from Godthåbsfjord have K/Rb ratios of 250 or less, that is approximately the same as or lower than average ratios from the continental crust (Taylor, 1964). There is no evidence either that these rocks were depleted in rubidium early in their history or that they were derived from Rb poor sources. The augen gneisses, diorites, and later phases of pale banded gneisses from the Narssaq–Qilángârssuit area have markedly higher K/Rb ratios (between 250 and 1300, average 600) suggesting either that the rocks in this area are derived from different source material or that they were partly depleted in Rb 3700 m.y. ago, the age at which the Rb-Sr whole rock system closed.

Ameralik dykes

The Ameralik dykes are a suite of metadolerites, and amphibolites which occur as dykes or concordant layers and lenses in Amîtsoq gneisses (fig. 18). They have only been recognised in the area between Isua and Sermilik, south of Godthåb (fig. 4), and although insignificant in volume, they provide the main field evidence for subdivision of the gneisses in this region. They were first described by Berthelsen (1955) who used them to divide the plutonic history of the area into two phases separated by a hiatus during which the dykes were emplaced as dolerites. One was also figured by Ramberg (1956, plate 4, fig. 4).

McGregor (1968, 1969) called them Ameralik dykes and recognised that they were present only in one group of the quartzo-feldspathic gneisses in the Godthåb region and he used this to establish the chronology in this area. More recently Ameralik dykes were found to cut the Isua supracrustals.

Metamorphosed basic dykes, many of which are identical in lithology to Ameralik dykes, occur over a wide area of south-east and south-west Greenland. In general they are less abundant than the Ameralik dykes at Ameralik. They are strongly deformed amphibolites but they locally survive in an undeformed state and show relict doleritic textures. In the Fiskenæsset region they cut a variety of gneisses, metavolcanic amphibolite units, metasediments and the anorthosite complex, but it is not known if they are the same age as the Ameralik dyke swarm.

In some parts of the Godthåbsfjord region metamorphosed basic dykes, some of them lithologically identical to Ameralik dykes, have been noted in the widespread amphibolite and metasedimentary suite called the Malene supracrustals and in rocks of the anorthosite complex. Similar metamorphosed basic dykes with large relict plagioclase phenocrysts are also abundant in many metavolcanic amphibolite outcrops in the Fiskenæsset region, such as the Ravns Storø belt, where they also form thick sills. Similar dark amphibolite dykes, but which lack plagioclase phenocrysts, are abundant within the Fiskenæsset anorthosite complex where they cut deformed igneous layering.

Field characters

In the Isua area the Ameralik dykes are preserved as undeformed and slightly deformed metadolerites with original intrusion forms, apophyses and igneous textures and strike either N–S or E–W (figs 6, 19).

The dykes vary from under a metre to 20–30 m across, and individual dykes can be traced for 7 km or more (fig. 6). Most of the dykes are medium to fine-grained metadolerites. A small proportion contain scattered sericitised megacrysts and recrystallised aggregates of plagioclase commonly concentrated close to one margin of the dyke, a feature which has been noted from the type Ameralik dykes in the Godthåbsfjord region to the south (McGregor, 1973; Chadwick *et al.*, 1974 a).

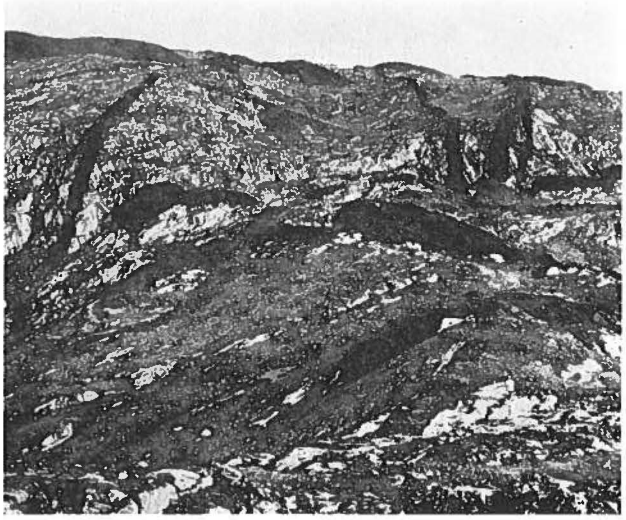


Fig. 19. Well preserved Ameralik dykes cutting Amîtsoq gneisses at Isua. Note the two dominant directions and the pod-like form of the east-west dykes (left to right).

The dykes cutting the gneisses within the Isua dome are generally rectilinear bodies. The E–W swarm which is locally parallel to the strike of the gneisses is arched around the domal structure and some dykes are boudinaged. The elongated pod-like form of many dykes is considered to indicate that the

Fig. 20. Strongly deformed Ameralik dyke fragments in banded Amîtsoq gneiss derived from the same parent as the augen gneiss of fig. 15. South of the mouth of Ameralik.

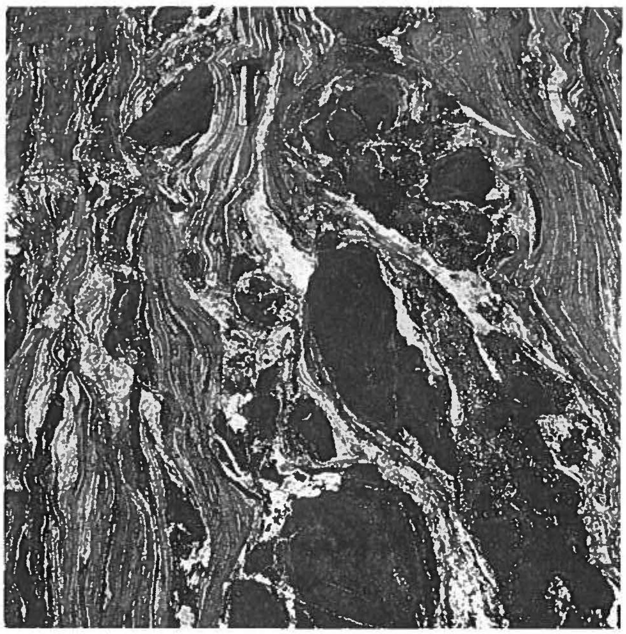


Fig. 21. Strongly deformed Ameralik dyke with aggregates of plagioclase replacing plagioclase phenocrysts concentrated along one side of the dyke. South coast of Storø (fig. 11).

dykes were emplaced into plastic country rocks during deformation. Dykes that trend at a high angle to the regional structure are more regular in form. A number of dykes extend from the gneisses in the centre of the Isua dome, into the belt of supracrustal rocks where they become schistose and display small folded apophyses. South of the supracrustal belt the dykes become progressively more deformed and recrystallised, and about three kilometres south of the supracrustal rocks they are completely recrystallised to amphibolites, slightly boudinaged and cut by thick pegmatites. At this stage they are indistinguishable from the least deformed Ameralik dykes seen in the Amîtsoq gneisses in the area south-east of Godthåb.

Fig. 22. Initially homogeneous Ameralik dyke with feldspathic segregations formed during metamorphism and deformation. Præstefjord, south-east of Godthåb.

South and east of Godthåb, where the Ameralik dykes were first recognised and described, most dykes are now concordant with the surrounding gneisses and their interpretation as dykes rather than inclusions of basic supracrustal material or of metagabbro is often a matter of faith (fig. 20). Most of these amphibolites are interpreted as dykes because in the field every gradation can be followed from metadolerites with clear discordant contacts (figs 12, 18) to trains of fragments of amphibolite (figs 14, 21). It is considered that almost all of the dykes or dyke fragments have been rotated into parallelism with the regional fabric of the surrounding gneiss. In general the dyke fragments are more massive, black and homogeneous than most of the supracrustal amphibolite inclusions which are generally finely laminated (fig. 22).

Most of the least deformed Ameralik dykes in the Godthåbsfjord–Sermilik area are between 20 cm and several metres thick but they vary in thickness from massive sheets 100 m or more across to apophyses a centimetre or two across. In many areas the prevalence of thin closely spaced dykes is mainly a result of later tectonic thinning. However, evidence from less deformed areas suggests that in many parts of the Godthåb area the original swarm may have been characterised by a large number of thin dykes with many apophyses. The larger bodies tend to preserve original textures and igneous features better than the thinner dykes and apophyses.

Petrology and chemistry

Most of the Ameralik dykes appear to have crystallised from tholeiitic magmas as normal medium-grained pyroxene-bearing basic rocks with doleritic textures. In the dykes from Isua there are transitions from rocks with clearly preserved original pyroxenes and plagioclases to highly deformed amphibolites composed of hornblende, plagioclase, quartz and biotite. The majority of Ameralik dykes, however, show little evidence of their original igneous texture and mineralogy. Three petrological varieties have been distinguished: (1) dykes with pyribolite or retrogressed pyribolite centres, (2) diopside-bearing amphibolites, and (3) normal amphibolites.

The bulk composition of the various petrological varieties appears similar, apart from some variation in potash content which may be the result of slight metasomatism. Some dykes are chemically separable from other Ameralik dykes by their high silica and magnesium and low alumina contents. These are thought to represent dykes which originally contained cumulate olivine and pyroxene in a moderately well differentiated matrix, comparable to the post-metamorphic dykes described by Berthelsen & Bridgwater (1960) from the Sukkertoppen district.

Small patches of pyribolite (metamorphic rocks with andesine-labradorite, hornblende and both ortho- and clinopyroxene, Berthelsen, 1960) are found in thick Ameralik dykes on the coast south of Narssaq (Ghb) (fig. 11). These patches are regarded as relicts of earlier high-grade mineral assemblages within dykes which have almost completely recrystallised to amphibolite. The least retrogressed pyribolites contain the assemblage hornblende-diopside-hypersthene-biotite-plagioclase-quartz-garnet. Retrogressed pyribolites contain polysynthetically twinned cummingtonite replacing the hypersthene, while diopside is replaced by hornblende. It is uncertain whether the two-pyroxene-garnet pyribolite assemblage indicates that the area had passed through an early granulite facies event, or reflects the effect of regional amphibolite facies metamorphism on comparatively water-poor rocks, or is the result of primary crystallisation under regional metamorphic conditions.

Ameralik dykes with diopside-amphibole-oligoclase-andesine or andesine-diopside-garnet-amphibole assemblages have been seen south of Godthåb, at the head of Præstefjord, and south and west of Qilángârssuit (fig. 11). Like the pyribolites these rocks occur as relicts within normal amphibolites. Several dykes contain small relicts of diopside, or textures suggesting replacement of earlier diopside and garnet by hornblende-plagioclase intergrowths.

The majority of the unmigmatised Ameralik dykes outside the Isua area contain hornblende-oligoclase-quartz-biotite-sphene assemblages dominated by hornblende and plagioclase. Apatite is an ubiquitous accessory and a few samples contain opaque grains. Mafic minerals make up about half the rocks. Epidote is found as a late alteration product of plagioclase in many dykes.

Plagioclase aggregates and anorthosite inclusions

Scattered inclusions of plagioclase megacrysts, anorthosite xenoliths up to 20 cm long or feldspathic aggregates formed from the recrystallisation of megacrysts and xenoliths, are found as a minor constituent of a small proportion of the Ameralik dykes (figs 21, 23). Several of the inclusions have a core of calcic plagioclase (up to An_{85}) which is commonly replaced by an epidote mineral and colourless mica. The cores are enclosed by a mosaic of fresh, less calcic plagioclase.

These plagioclase phenocrysts and anorthosite xenoliths can usually still be recognised as white lenses, often highly deformed, even in strongly broken up and migmatised dykes. They are a valuable aid in recognising fragments of Ameralik dykes in areas where other primary dyke features have been lost.

Fig. 23. Anorthosite fragments in an Ameralik dyke. South of Godthåb.

Malene supracrustals and similar rocks

Ten to twenty per cent of the Archaean gneiss complex consists of conformable units of amphibolitic rock (fig. 24) associated with smaller amounts of pelite, semipelite and quartz-cordierite (±sillimanite) schists of supracrustal origin. These supracrustal units are commonly associated with ultrabasic layers and pods, some of which appear to be in place and to have formed part of the original successions (Bridgwater *et al.*, 1973c). Others may represent ultrabasic material emplaced along contacts between the supracrustal units and Amîtsoq gneisses during later movements (McGregor, 1973). Adjacent units may differ markedly in composition, one unit consisting dominantly of metavolcanic amphibolite, the next consisting dominantly of metasediment. No regional differences have been recognised between groups of supracrustal units from widely separated parts of the Archaean complex and for descriptive purposes they are treated as a single suite of rocks.

In some earlier accounts, the best preserved supracrustal units were described as low grade belts of mainly greenschist rocks downfolded into an older basement of high grade gneisses (Windley, 1966, 1968, 1969a; Windley & Bridgwater, 1971). Careful work in Godthåbsfjord (McGregor, 1968, 1969) (fig. 13) and the Ravns Storø area (Andersen & Friend, 1973) (fig. 25), together with regional studies in South-East Greenland (Andrews *et al.*,

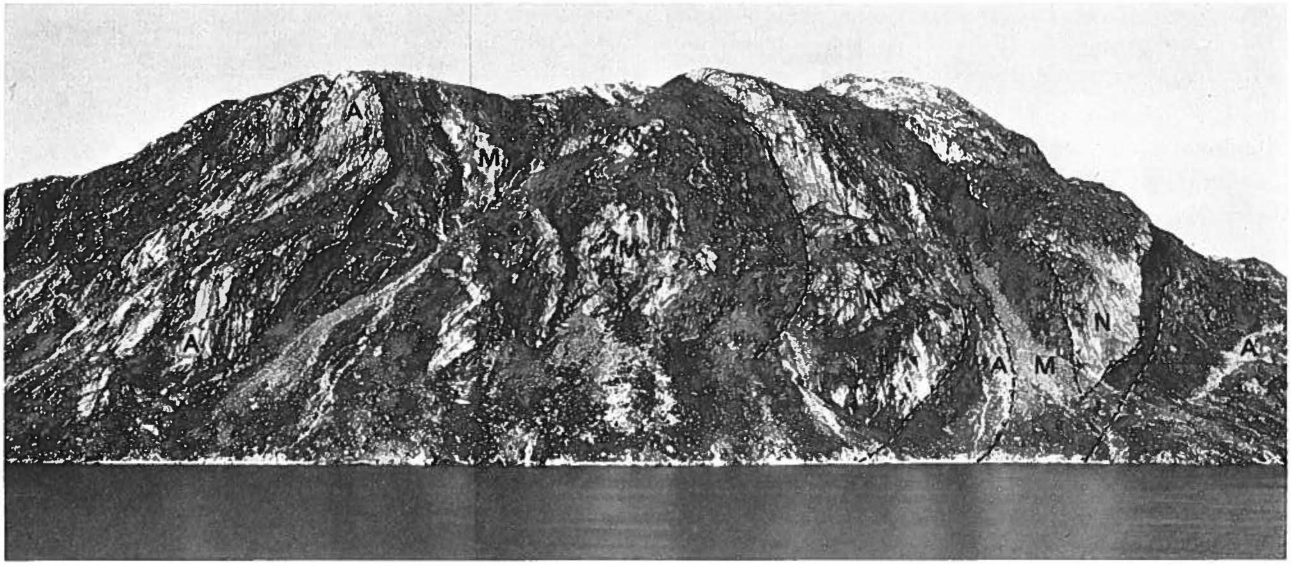


Fig. 24. Cliff face showing the intercalation of three major units; Amîtsoq gneiss (A), Malene supracrustal amphibolite (M), and Nûk gneiss (N). View eastwards at the mouth of Kobbefjord, south-east of Godthåb (fig. 11).

1973) has shown: (1) that greenschist facies rocks are restricted to isolated localities, (2) that the supracrustal rocks are cut by sheets of granitoid rocks similar to much of the gneisses around them, and (3) that both the supracrustal units and the gneisses which intruded them can be traced into areas where they were affected by granulite facies metamorphism 2800 m.y. ago. Only two groups of Archaean supracrustal rocks are now regarded as possibly younger than the major metamorphic event which affected the complex about 2800 m.y. ago, and these are described later (Tartoq and Sarfartûp nunâ supracrustals).

The name Malene supracrustals was given to a group of amphibolites and metasediments in the Godthåbsfjord region which were derived from a variety of basic and ultrabasic volcanics, intrusives and metasediments (McGregor, 1969, 1973) (figs 11, 13). They appear to be typical of similar units which occur throughout the craton, although they may not all be of the same age.

The Malene supracrustals were intruded by and are therefore older than the Nûk gneisses, one suite of which has yielded a Rb-Sr whole rock isochron age of 3040 m.y. (Pankhurst *et al.*, 1973a). They do not appear to have been intruded by the major swarm of Ameralik dykes found in adjacent units of Amîtsoq gneiss and are therefore assumed to be younger than 3700 m.y. However, many contacts between Malene supracrustals and Amîtsoq gneisses are tectonic and no certain primary contact relationships have been seen.

Attempts to obtain either the age of deposition of the Malene supracrustals or the possible age of source rocks of the sediments using Rb-Sr whole rock and U-Pb zircon determinations have so far proved unsuccessful. A U-Pb diffusion age of 2800 m.y. on zircons from an intermediate volcanic unit from a supracrustal belt at Tingmiarmiut in South-East Greenland (Gulson & Krogh, 1972; Andrews *et al.*, 1973) has been interpreted as the age of high grade regional metamorphism. More recent U-Pb zircon work by Baadsgaard (personal communication, 1974) and Rb-Sr whole rock determinations by the Oxford Isotope Geology Laboratory (Moorbath personal communication, 1974) have given ages of about 2800 m.y. from units of Malene supracrustal rocks which are clearly older than the 3040 m.y. old Nûk gneisses in the same area.

Field relations

Individual supracrustal units can be traced along strike as folded layers for many tens of kilometres (figs 13, 25). Some thin from 5 km across to a few metres thick and then continue as a series of pods and inclusions in quartzo-feldspathic gneiss. No primary sedimentary contacts between the supracrustal rocks and older gneisses have been seen, and contacts are generally tectonic or show intrusion of younger gneiss into the supracrustals (fig. 24). In the Godthåbsfjord area (fig. 13) the contacts between Malene supracrustals and the Amîtsoq gneisses, although concordant, transgress across parts of

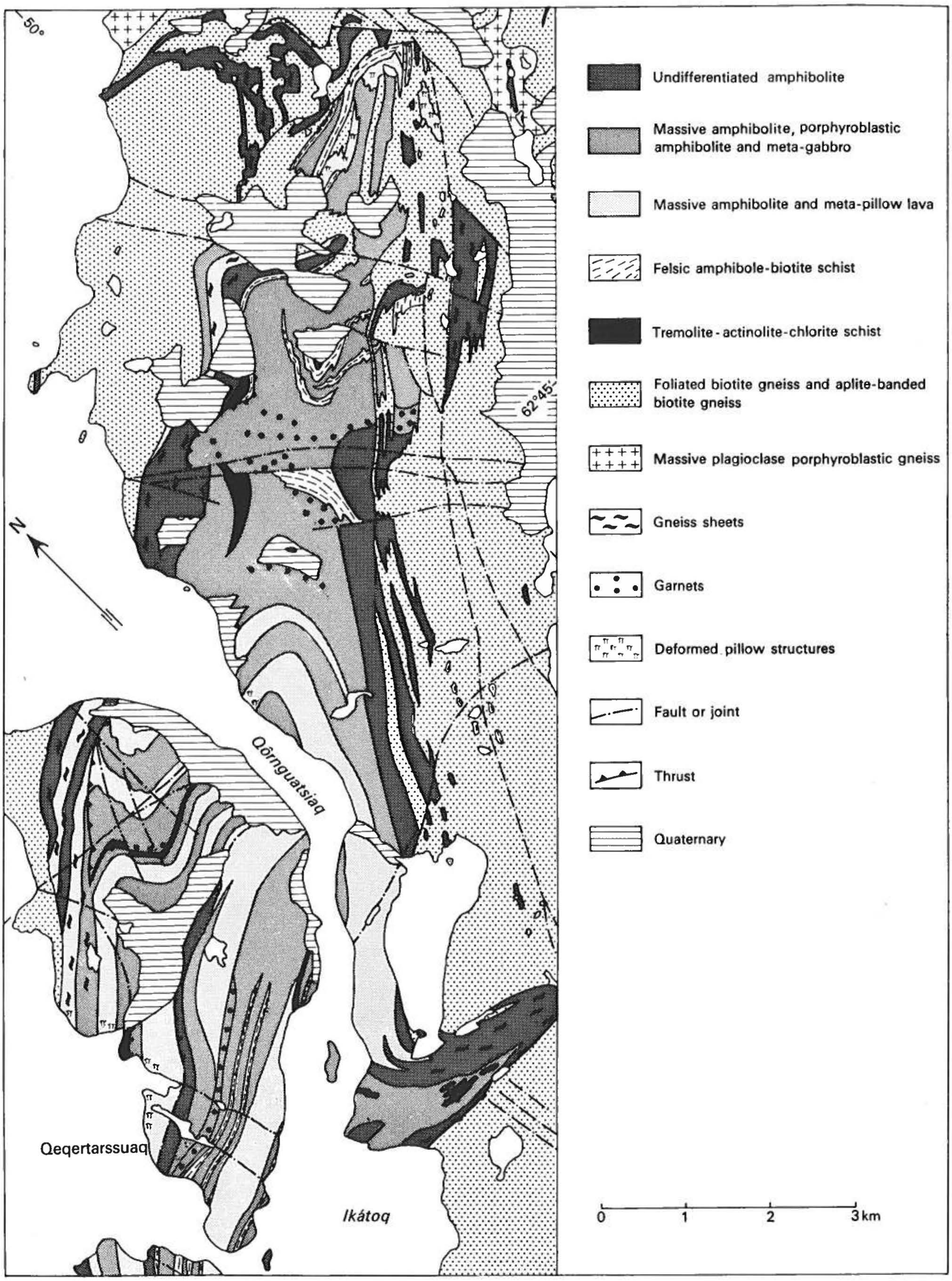


Fig. 25. Map of the north-eastern part of the Ravns Storø amphibolite belt in the Fiskenæsset region (fig. 33). Simplified from mapping by Andersen (1974).

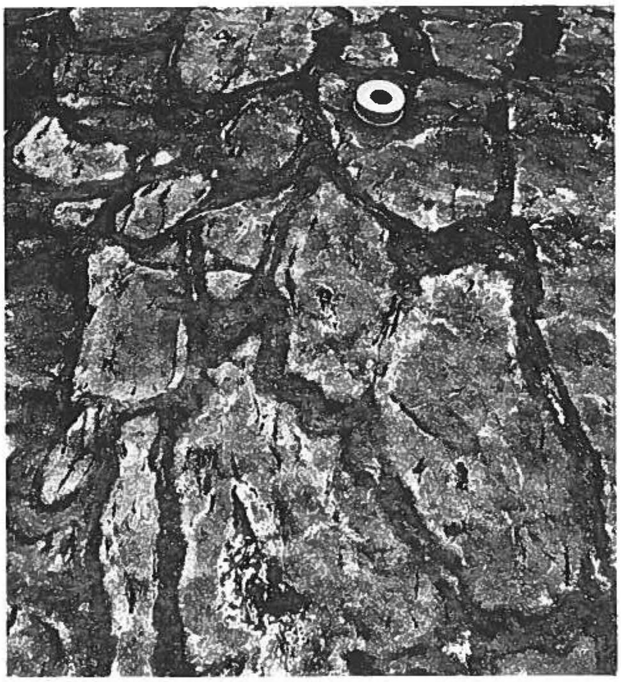


Fig. 26. Deformed pillow lava, south coast of Bjørneøen, Godthåbsfjord (fig. 11).

the supracrustal sequence, suggesting that units of Amîtsoq gneiss were emplaced into the supracrustal pile as thrust slices. Therefore individual supracrustal units may have been parts of a thicker, continuous sequence which was split by thrust wedges of Amîtsoq gneisses and later by the injection of subconcordant sheets of Nûk gneisses. Similar evidence of thrusting between Archaean supracrustal units and adjacent quartzo-feldspathic gneisses has been found in the Angmagssalik district (Andrews *et al.*, 1973; Wright *et al.*, 1973) while several authors have suggested that Alpine type tectonics played an important role at an early stage in the evolution of the Archaean complex (Berthelsen, 1960, 1972; Rivalenti & Rossi, 1972).

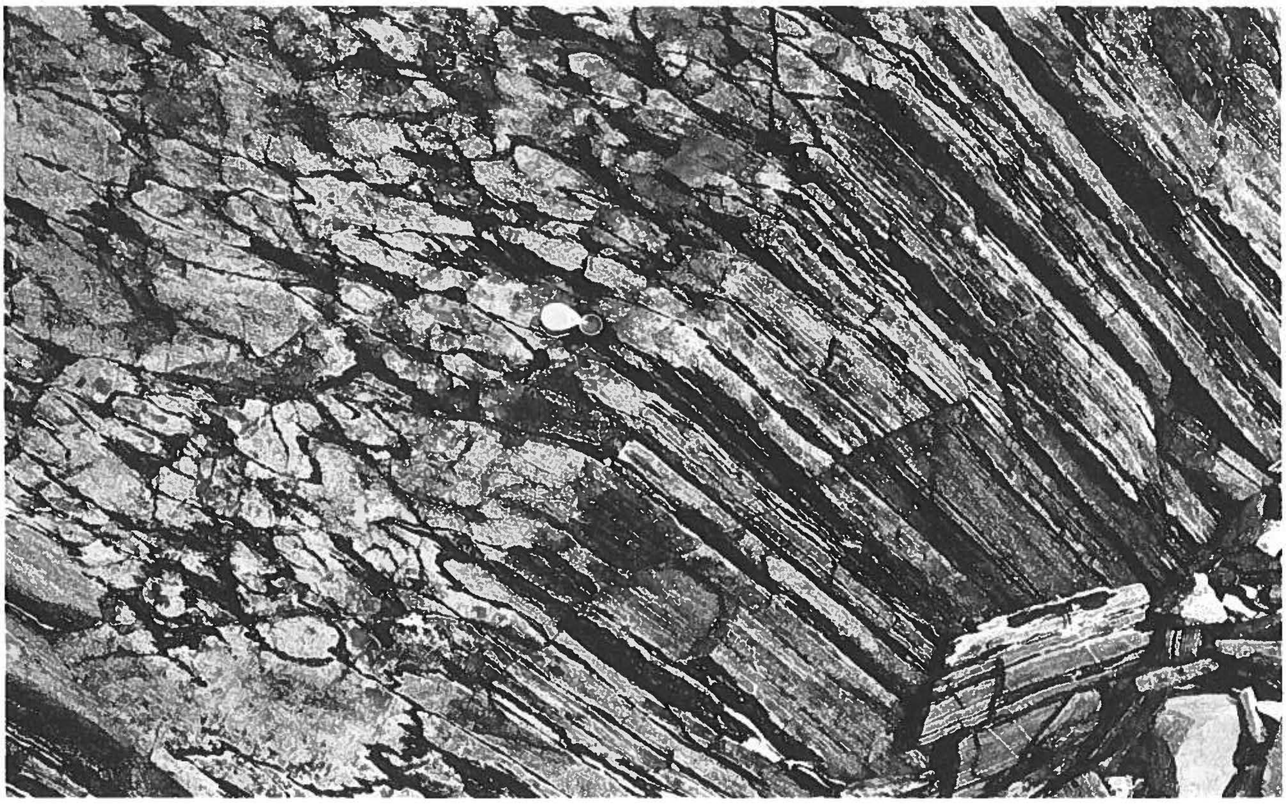
As a working hypothesis, it is supposed that the supracrustal sequences throughout the Archaean complex represent thrust slices of previously thicker successions which were disrupted by early subhorizontal movements on a regional scale (Bridgwater *et al.*, 1974).

Lithologies

Amphibolite and pyribolite

Amphibolite and its higher grade equivalent, pyribolite (Berthelsen, 1960), are the most abundant

Fig. 27. Strongly deformed pillow lava, Dalagers Nunatakker, south-east Fiskenæsset region.



lithologies. In general the amphibolites lack any primary features or record of their origin but can be divided into a number of types according to metamorphic texture and composition. In some places primary structures and textures are preserved which show a supracrustal origin. The main types of amphibolite, based on either primary characters or metamorphic textures, are described below.

Basic metavolcanics

Well preserved pillow lava structures have been seen in a number of amphibolite outcrops, in the Fiskenæsset region on Dalagers Nunatakker (Dawes, 1970), the Ravns Storø area (Andersen & Friend, 1973) (fig. 25), a nunatak east of Sermilik (J. C. Escher & Myers, 1975), and in the Godthåbsfjord region on Bjørneøen (fig. 26) and at Ivisârtok. In some cases the asymmetrical shapes indicate the original way up of the pillow lavas. Many pillows have thin dark rims which are probably relict chilled margins and some contain relict vesicles. Most of the relict pillow lavas are strongly deformed and individual pillows are rod shaped (fig. 27). Most pillow lavas analysed are tholeiitic.

In parts of the Fiskenæsset region (Escher & Myers, 1975) the best preserved pillow lavas are associated with very large numbers of thin leucocratic amphibolite dykes and sills (locally called the Sarqarigsup nunâ dykes by Friend, in press). The dykes are irregular in shape, in many cases they interfinger with individual pillows (fig. 28), and Escher considers that they were closely associated in time with the eruption of the pillow lavas. On Sarqarigsup nunâ in the Fiskenæsset region there are primary variations in the packing density of pillows from almost solid layers of pillows to pillows scattered in a fine-grained, probably tuffaceous matrix.

Many of the least deformed pillows have leucocratic amphibolite cores and melanocratic rims. In some places this zonation was accentuated by segregation during metamorphism which formed epidote-rich cores with garnet, scapolite and diopside. This mineral zonation generally persisted during deformation of the pillows. Generally as the pillows were deformed their dark margins became indistinguishable from the dark matrix between the pillows and only the cores remained distinct. Such remnants of strongly deformed and recrystallised pillow lava structures are widespread in amphibolites throughout West Greenland (Walton, 1966). With increasing deformation the lenses became streaked out to form a banded amphibolite with thin discontinuous leucocratic and melanocratic layers (fig. 29).

Fig. 28. Little deformed pillow lava and leucocratic amphibolite dyke, nunatak east of Sermilik.

The bulk composition of the zoned epidote-garnet-scapolite-diopside lenses shows a lower alkali content than tholeiitic rocks. This alteration of the tholeiitic pillow lavas is considered (D.B.) to represent deep-sea weathering of the lavas, although in the Fiskenæsset region (J.S.M.) the development of this mineral zonation is seen to be associated with increasing regional metamorphism in upper greenschist and amphibolite facies, perhaps by accentuation of

Fig. 29. Composition-banded amphibolite derived from strongly deformed pillow lava. The lighter layers are relics of the cores of pillows and the darker layers are relics of the margins and matrix of the pillows. 25 km north-east of Fiskenæsset.

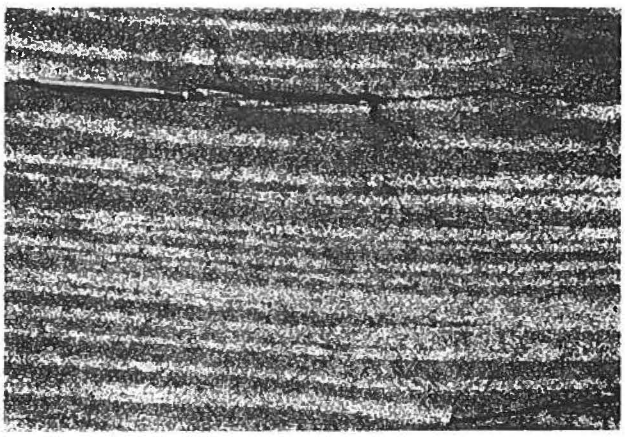


Fig. 30. Composition-banded amphibolite in Malene supracrustals, thought to be derived from intermediate tuff. Qugssuk, Godthåbsfjord.

chemical differences which were initiated during zeolite facies metamorphism.

Agglomerate or pillow lava breccia structures are preserved in the Ravns Storø area and other parts of the Fiskenæsset region, and on Bjørneøen in Godthåbsfjord. They occur interbedded with pillow lavas and are only seen where pillow lava structures are well preserved. They consist of angular fragments of leucocratic amphibolite with a variety of shapes and sizes, which are irregularly distributed in a matrix of more melanocratic amphibolite.

Layered basic sills

Layered amphibolites with relict igneous textures and layering have been seen in a few places where pillow lava structures are well preserved, on Dalagers Nunatakker (Dawes, 1970) and in the Ravns Storø area (Andersen & Friend, 1973). The most abundant type of igneous layering is centimetre-scale composition graded layers with hornblende rich bases and plagioclase rich tops. Leucogabbro and anorthosite layers also occur in the Ravns Storø amphibolite belt and are cut by amphibolite dykes and sills with large relict plagioclase crystals concentrated near one side.

Intermediate metavolcanics

Finely layered, medium-grained, light coloured units of intermediate composition are a minor constituent of many supracrustal belts and may represent intermediate bedded tuffs (fig. 30). They are associated with layers of similar rock which contain small angular fragments with various shapes and compositions and may represent intermediate pyroclastics (fig. 31). These rocks are known from Bjørneøen and other localities in the Malene supracrustals, in the Ravns Storø area (Andersen & Friend, 1973) and other places in the Fiskenæsset region, and at Tingmiarmiut (Andrews *et al.*, 1973).

Metasediments

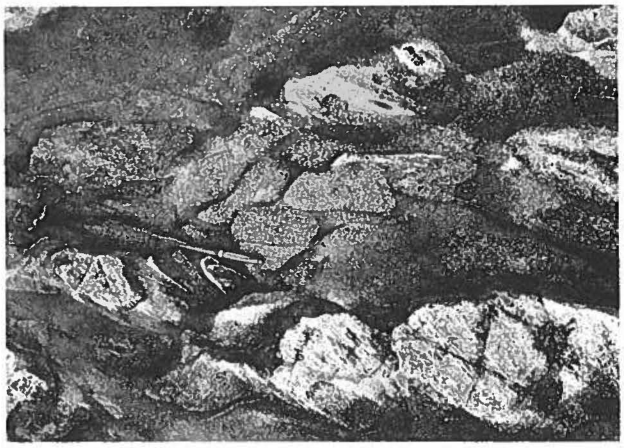
Brown schists and semipelitic and pelitic gneisses

The most abundant metasedimentary rocks are rusty brown weathering quartz-plagioclase rocks (with abundant biotite and variable amounts of potash feldspar, garnet, cordierite, sillimanite and pale coloured amphibole), quartz-cordierite gneisses and magnesium-rich amphibolites. They occur as thin layers throughout the Archaean complex in the regions of Alángua (Berthelsen, 1962), Angmagssalik and Skjoldungen (Andrews *et al.*, 1973), Frederikshåb (Masson, 1970), Ivigtut (Fladland and Ika schists: Berthelsen & Henriksen, 1975) and Fiskenæsset (Myers, 1973a; Andersen, 1974). In the Godthåbsfjord region they are an integral part of the Malene supracrustal amphibolite succession and are more abundant than basic rocks in the southern part of this region.

Brown schists in the Godthåbsfjord region comprise quartz, plagioclase and biotite, with lesser amounts of muscovite, sillimanite, garnet and potash feldspar. In some cases they also contain small amounts of spinel, staurolite, tourmaline graphite and apatite.

The Isorssua brown schists of the Frederikshåb area consist essentially of quartz, feldspar (mainly plagioclase), garnet sillimanite and cordierite (Masson, 1970). Accessories

Fig. 31. Fragments of coarse-grained igneous rocks (mainly diorite or gabbro) in a fine-grained banded intermediate matrix. Note the composite nature of some of the fragments. Bjørneøen, Godthåbsfjord.



include rounded zircons, tourmaline, apatite, graphite, staurolite and pyrite. Kyanite is reported from one locality (Rivalenti & Rossi, 1972). Sillimanite nodules 1–2 cm across with a little biotite and garnet, and sheathed by cordierite, occur locally. Tourmaline is ubiquitous, and is ascribed by Masson to boron concentrations due to sedimentary clay minerals. A comparable concentration of boron in metasedimentary units in the Fiskenæsset region produced the mineral kornerupine in the contact metamorphic aureole of the anorthosite complex (Herd, 1973).

Quartz-cordierite (± sillimanite) gneisses

Major horizons of white or brown, quartz-cordierite gneisses occur in several of the Malene supracrustal units. They are most abundant between Godthåb and Narssaq (Ghb), and on Qilángârssuit, Simiútat and nearby islands between Godthåb and Færingehavn (Chadwick *et al.,* 1974a) (fig. 11). Aluminium and magnesium-rich quartzites of similar composition outcrop in the Fiskenæsset district (Andersen & Friend, 1973; Herd, 1973; Hopgood, 1973; Myers, 1973a), and make up part of the brown schist units in the Frederikshåb and Ivigtut areas (Preston, 1969; Masson, 1970; J. C. Escher, 1971; Rivalenti & Rossi, 1972; Berthelsen & Henriksen, 1975). The kyanite-rich schists in the supracrustal rocks to the west of Angmagssalik (Andrews *et al.,* 1973; Wright *et al.,* 1973) probably represent a similar unit affected by higher pressure metamorphism during the formation of the Nagssugtoqidian mobile belt.

Leucocratic quartz-cordierite gneisses are most common in the Godthåbsfjord area and may locally contain augen of cordierite up to 8 cm long. In thin section they comprise quartz, cordierite, pale orthorhombic amphibole, pale brown mica, colourless chlorite and sillimanite. In darker gneiss varieties, a darker brown biotite is present together with garnet and staurolite. Zircon is abundant, and tourmaline and rutile are common accessories.

Magnesium-rich amphibolites

Brown rocks consisting largely of magnesium amphibole form a distinctive layer of the Malene supracrustals south and east of Godthåb. The amphibole is cummingtonite or anthophyllite-gedrite, and other minerals include plagioclase, garnet, accessory quartz and staurolite. The magnesium-rich amphibolite layers are associated with normal amphibolites and ultrabasic rocks and in places they are finely banded rocks.

Similar layers are abundant in the Ravns Storø amphibolite belt in the Fiskenæsset region where they are interlayered with basic metavolcanics and sills (Andersen, 1974).

The magnesium-rich amphibolites are often associated with the quartz-cordierite gneisses. Both rock types have high alumina and low alkali contents, and widely variable Mg/Fe ratios. Both are associated with basic and intermediate volcanic rocks, and transitions into pelitic and semipelitic rock types have been described. The origin of both the magnesium amphibolites and quartz-cordierite gneisses is uncertain.

Fig. 32. Deformed calc-silicate layers in Archaean supracrustal rocks near Isertoq, Angmagssalik.

Calc-silicate rocks

Thin layers of calc-silicate rocks and marble considered to be derived from impure limestones or marly sediments have been seen in several units of amphibolite and metasediment in the Fiskenæsset region (Kalsbeek & Myers, 1973; Hopgood, 1973) and in South-East Greenland (Andrews *et al.,* 1973).

A spectacular suite of calc-silicate rocks occurs in an Archaean supracrustal succession within the margin of the Nagssugtoqidian mobile belt in South-East Greenland (Andrews *et al.,* 1973; Wright *et al.,* 1973) (fig. 32).

Quartzites with green mica

Quartzite units less than 1 m thick characterised by a bright green mica containing less than 0.5 % Cr_2O_3 occur at many localities in the Malene supracrustals between Qilángârssuit and the head of Godthåbsfjord (Bridgwater & McGregor, 1974a; Chadwick *et al.,* 1974 a, b). They are generally associated with pelitic and semipelitic units.

Supposed conglomerate

Conglomeratic layers rich in sulphide minerals occur within some amphibolite horizons in the Fiskenæsset area and are considered to be metamorphosed conglomerates (Appel, 1971). The largest unit can be followed for up to 30 km along strike and averages 1.5 m thick. It consists of rounded fragments, chiefly of ultramafic rocks and a few gneisses, between a few millimetres and 30 cm in diameter, in a matrix of chiefly pyrite and pyrrhotite. Similar layers which are locally discordant to amphibolite units were found (J.S.M.) to be intrusion breccias formed during the intrusion of now gneissose granodiorite into and alongside ultramafic layers.

Ultramafic rocks

Ultramafic rocks are a minor but widespread associate of the supracrustal rocks and are generally considered to be part of the supracrustal successions. They occur as concordant ultramafic schist layers and elongate lenses within and along the contacts of the supracrustal units, and in gneisses as lenses and pods from a few centimetres to more than a kilometre in diameter. No primary igneous textures have been identified with certainty but locally some of the larger bodies show a poorly developed layering which may represent original cumulate structures.

Ultramafic rocks have been studied in most detail in the Frederikshåb and Ivigtut areas (Dawes, 1970; Andrews, 1970; Mísař, 1973; Rivalenti & Rossi, 1972; Walton, 1966). They vary in mineralogy and appearance but two main types are commonly recognised: hornblendite, and peridotite or harzburgite. Individual bodies show a variety of mineral assemblages commonly in metamorphic disequilibrium with each other, suggesting that the ultramafic rocks lagged behind the enclosing gneisses in their response to changes in metamorphic conditions. Many bodies are zoned due either to disequilibrium between the outer and inner parts during deformation and metamorphism, or to local segregation of material within the bodies and the exchange of some constituents with the surrounding gneisses.

Major bodies of ultramafic rock occur between Godthåb and Sukkertoppen in the Fiskefjord complex where geologists of Kryolitselskabet found primary chromitite layers in a large ultrabasic mass consisting largely of dunite. A second major dunitic body occurs at Siorarssuit (Sørensen, 1954).

The earliest recognisable mineral assemblages within the ultramafic rocks include nearly pure olivine rocks, olivine-orthopyroxene rocks (Fo_{70-98} + En_{70-100}) and olivine-clinopyroxene rocks. Textures generally suggest that these assemblages are metamorphic, although some of the dunites and olivine-clinopyroxene rocks may contain original igneous minerals. These early assemblages recrystallised first to olivine–bronzite–hornblende±spinel, olivine–bronzite–hornblende, olivine–hornblende±clinopyroxene, or hornblende–clinopyroxene–sphene–magnetite rocks, and later to tremolite–cummingtonite–hornblende or anthophyllite–talc–serpentine bearing assemblages. Some bodies show the late formation of chlorite, talc and calcite.

Zoned balls show a variety of features probably depending both on the amount of metasomatism and short-distance segregation which took place and the mineralogical composition of the bodies at the time that zoning developed. Zoned balls typically contain a centre of serpentinised dunite surrounded by actinolite-tremolite and then anthophyllite-rich layers. Generally the inner shell is finer grained than the outer shell. Biotite or phlogopite rims locally rich in apatite occur around some of the ultrabasic inclusions in quartzo-feldspathic gneisses.

Depositional environment

The most striking regional feature of the supracrustal rocks is their uniformity throughout the whole Archaean complex. The same rock types occur in areas as far apart as the margin of the Archaean block at Itivdleq in West Greenland to Tingmiarmiut in South-East Greenland, and these in turn resemble the supracrustal suites recorded from the Labrador coast (Bridgwater *et al.*, 1973c) and north-west Scotland (Coward *et al.*, 1969).

Metavolcanic rocks vary from basic pillow lavas and pillow lava breccias to rocks probably derived from andesitic or dacitic pyroclastics. Layered basic and ultramafic intrusive rocks are abundant within the successions. Metasediments are characterised by a high proportion of either chemical or clay-rich sediments with small amounts of clastic material. No major units of clastic sediments have been recognised in the unmodified parts of the Greenland Archaean. Magnesium-rich and magnesium-iron-rich sediments with unusually low alkali contents form distinct units.

All these rocks appear to be submarine, and volcanics appear to be more abundant than non-volcanic sediments, but their precise depositional environment is controversial.

The association of basic and ultrabasic rocks within the supracrustal pile has been compared by several writers to more recent ophiolite suites (Wager, 1934; Berthelsen, 1960; Rivalenti & Rossi, 1972), whereas Andersen (1974) considers that the composition of similar rocks in part of the Ravns Storø belt indicates an island arc environment. The intermediate and acid rocks, such as those from the Malene supracrustals on Bjørneøen, also suggest formation under conditions similar to present day island arcs, whereas a large number of analyses of amphibolites in the Frederikshåb region (Kalsbeek & Leake, 1970) and of pillow lavas from the Ravns Storø belt (C. R. L. Friend, personal communication, 1974) correspond to oceanic tholeiites.

Metamorphosed tholeiitic pillow lavas with compositions similar to modern ocean floor basalts occur interleaved with intermediate and ultrabasic rocks. Bridgwater & Fyfe (1974) suggested that such supracrustal piles may represent relatively small ocean basins overlying a thin extensive sial which had insufficient strength to form major continental masses from which clastic sediments could be derived.

Anorthosite and associated gabbroic rocks

Metamorphosed calcic anorthosites and associated leucogabbroic and gabbroic rocks form one of the most distinctive rock units in the Archaean gneiss complex. They occur as concordant layers and trains of inclusions throughout the complex in both West and South-East Greenland. They provide one of the best marker horizons for tracing out structures on a regional scale, for making lithostratigraphic correlations from one part of the complex to another, and locally they provide way-up criteria. They are of special interest, not only because of their unusual composition with extremely calcic plagioclase, but because more than any other rock group in the Archaean, they extensively preserve their primary textures and in some places primary igneous minerals. They provide some of the oldest layered igneous rocks on earth available for study.

They were first recognised in Greenland during regional mapping in the decade following 1946 (Ellitsgaard-Rasmussen & Mouritzen, 1954; Noe-Nygaard & Ramberg, 1961) and were thought to be derived from calcareous sediments (Sørensen, 1955; Berthelsen, 1957) or volcanic ash bands (Berthelsen, 1960). In 1964–65 chromite layering was discovered by Windley near Fiskenæsset and was mapped in detail by Ghisler (1966). This discovery led Windley (1966) to conclude that the anorthosites were metamorphosed gravity stratified igneous rocks similar to the Sittampundi complex of India (Subramaniam, 1956).

The types of relic igneous texture and bulk lithology of inclusions and layers of anorthosite throughout the Archaean complex are remarkably similar, and they are now all regarded as derived from stratified basic igneous complexes although chromite has not been recognised outside the Fiskenæsset area. Large units of anorthosite are most abundant between Fiskefjord and Frederikshåbs Isblink where they may form 3 to 5 per cent of the total outcrop. Individual layers can be traced in continuous outcrop for up to 25 km and are typically less than 500 m wide. Outside this area most of the anorthosites occur as trains of inclusions within quartzo-feldspathic gneisses, some of which can be followed as mappable horizons for many tens of kilometres (Berthelsen & Henriksen, 1975). In general they are thoroughly recrystallised although primary igneous textures are preserved even in small inclusions less than 20 cm in diameter.

Primary igneous features are best preserved in the Fiskenæsset region where both anorthositic and gabbroic rocks occur together as part of a single or small number of layered stratiform intrusions, collectively called the Fiskenæsset complex (fig. 33) (Windley, 1969 a). Well-developed gravity-stratified layering indicates that the anorthosites were emplaced as sub-horizontal sheets. Original contacts between the anorthosites and older country rocks are seldom preserved but show that the anorthosite complex was intruded into metavolcanics probably equivalent to the Malene supracrustals (J. C. Escher & Myers, 1975). Similar anorthosites in the Godthåbsfjord area were intruded by the Nûk gneisses (*c.* 3040 m.y. old), but are not seen to be intruded by Amîtsoq gneisses. They are locally cut by thin basic dykes similar to those which cut the Malene supracrustal rocks and Amîtsoq gneisses.

The isotopic age of intrusion of the anorthosite bodies has not yet been determined. Rb-Sr whole rock isochron ages (Eversen, in Windley, 1973b), U-Pb zircon ages (Nunes *et al.*, 1974) and Pb-Pb ages (Black *et al.*, 1973) from widely different localities have all yielded ages between 2700–2900 m.y. These ages are the same as the age of granulite facies metamorphism which was the last of a long sequence of intrusive, tectonic and metamorphic events which post-date the intrusion of the anorthosite complex.

Fiskenæsset complex

The Fiskenæsset complex consists of metamorphosed anorthosite ($<$ 10 % mafics), leucogabbro (10–35 % mafics) and gabbro (35–65 % mafics) with minor amounts of ultramafic rocks and chromitite. The average composition of the whole complex appears to be leucogabbro with 20 % mafics.

The igneous stratification of the Fiskenæsset complex was first mapped in 1966 by Gormsen (1971) who distinguished units of amphibolite, meta-anorthosite, metagabbro, ultrabasic and chromitite layers. In 1970 the complex was further subdivided by Windley (1971) who recognised a sequence of 10 units which were repeated as a mirror image about the centre of a 400 m wide layer on Qeqertarssuatsiaq in the western part of the Fiskenæsset

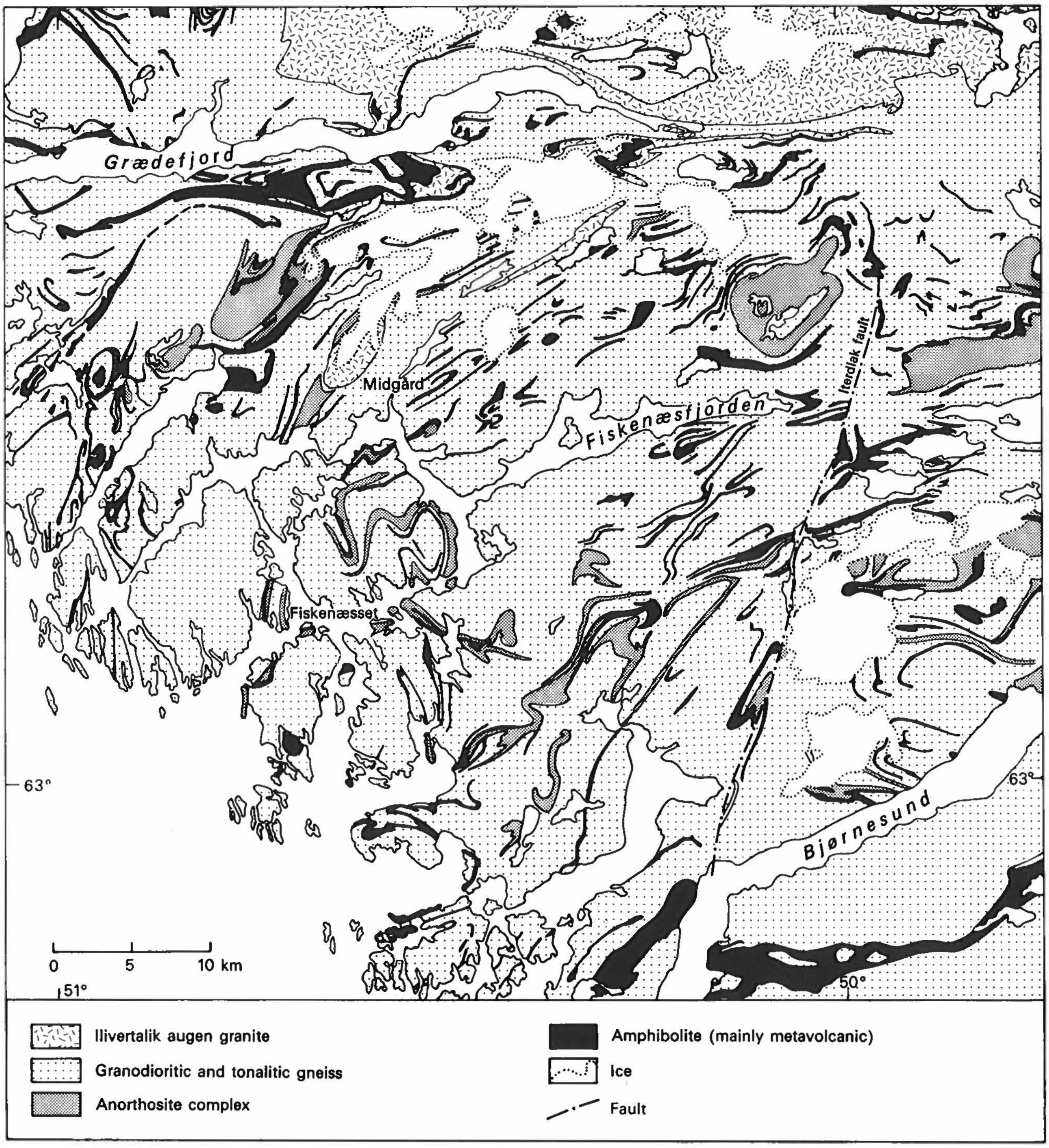


Fig. 33. Simplified map of the Fiskenæsset region (after compilation by J. S. Myers).

area (Table 2 & fig. 34). At the same time Bowden (1970) independently discovered that the chemical differentiation trend shown by whole rock analyses of a suite of samples collected across the same layer showed a similar repeated pattern. In addition the differentiation trend shown by the geochemical results indicated the primary way-up of the layered intrusion; that the outer, more mafic parts of the layer originally formed the lower part of the intrusion, whereas the inner more leucocratic parts formed the top of the intrusion, and that the whole 400 m wide layer thus represents an isoclinal syncline.

Bowden (1970) also discovered that the amphibolites (zones 1 and 10 of Windley, 1971) were much richer in iron than other parts of the complex and lay off the differentiation trend, and therefore that they did not appear to be part of the same layered complex as the anorthosites and gabbroic rocks.

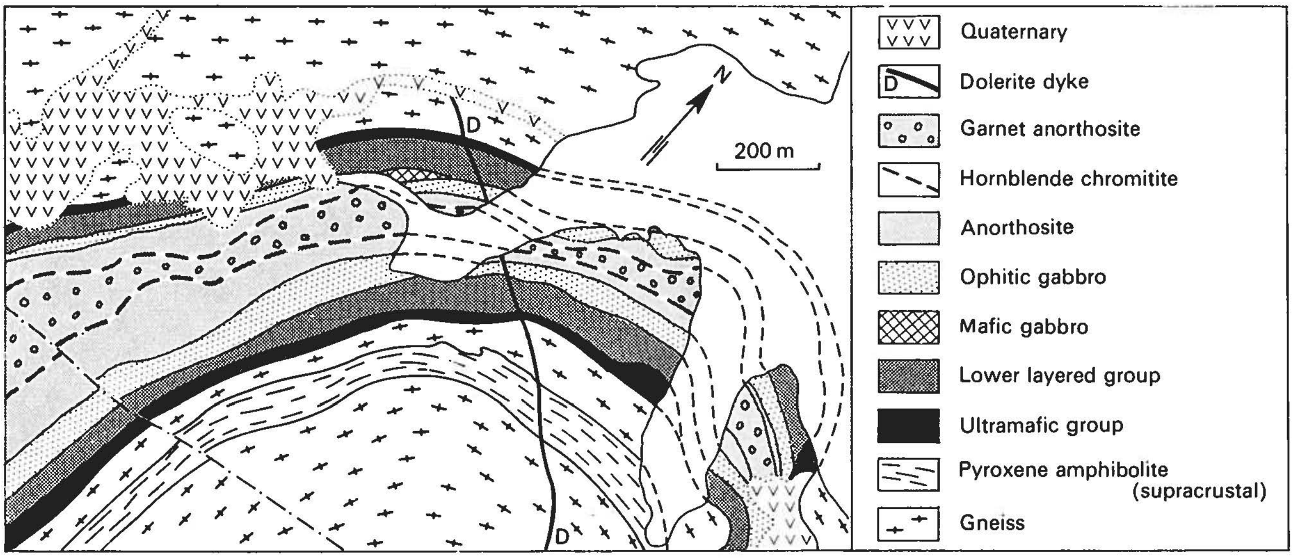


Fig. 34. Map of the stratigraphy of part of the Fiskenæsset complex on Qeqertarssuatsiaq, after Windley (1971).

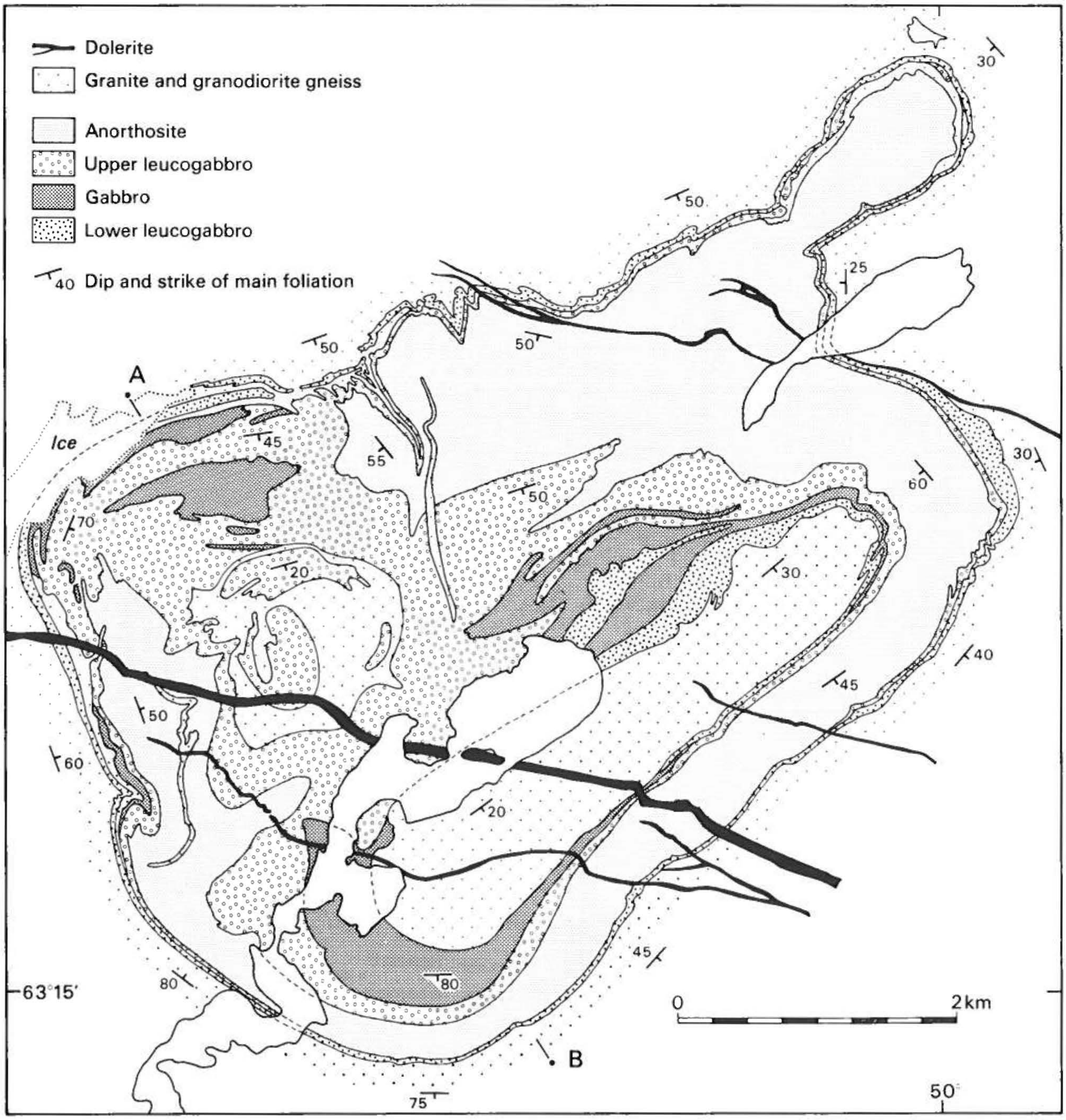
This opinion was substantiated as the regional mapping progressed (see Kalsbeek, 1971, 1972) when layers of mica schist and calc-silicates of probable supracrustal origin were found in the amphibolites which bordered the complex. Detailed work by Herd (1972, 1973) showed the presence of distinctive aluminous metasedimentary rocks within the amphibolitic zone of the complex which can be matched lithologically with the quartz-cordierite gneisses and related rocks of the Malene supracrustal suite. The name *Fiskenæsset complex* in this account is therefore restricted to the plutonic, layered intrusive anorthosites and the associated gabbroic and ultramafic rocks following Myers (in press a). Contrary to the usage of Windley (1971, 1973a) and Windley, Herd & Bowden (1973) it is not used to include the metavolcanic amphibolite layers as well, as these are part of the supracrustal group described in an earlier section. The basal ultramafic unit described by Windley *et al.* is retained as part of the complex although there is some doubt whether this belongs to the anorthositic suite or to the supracrustal succession.

There appear to have been primary regional variations in the igneous stratigraphy of the Fiskenæsset complex, and its primary thickness appears to have been greater in the east than in the area described by Windley *et al.* (1973) in the west of the region. In the extreme east, the gabbroic and leucogabbroic rocks are less abundant and the complex is dominated by anorthosite *sensu stricto,* but it is extensively disrupted by granitic intrusions, now represented by gneiss. The igneous stratigraphy and primary structures, textures and minerals appear to be best pre-

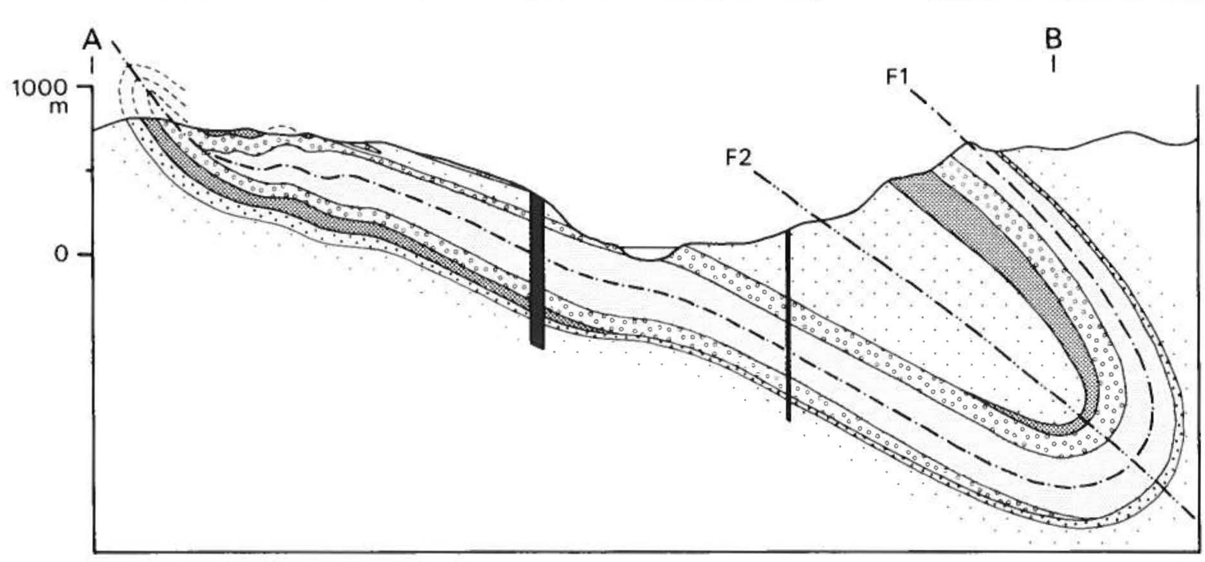
Table 2. Simplified stratigraphy of major units of the Fiskenæsset complex

On Qeqertarssuatsiaq (from Windley, 1971; Windley *et al.*, 1973)				Majorqap qâva outcrop (from Myers, in press a)	
zones			Maximum thickness in metres	units	Average thickness in metres
(10)	9	pyroxene amphibolite (supracrustal)	50		
(9)		(ultramafic group – only in Windley, 1971)			
	8	garnet anorthosite	75		
	7	hornblende chromitite	20		
	6	anorthosite	130	4 anorthosite	200
	5	homogeneous leucogabbro (ophitic gabbro, 1971)	250	3 upper leucogabbro	60
	4	dark gabbro (mafic gabbro, 1971)	60	2 gabbro	40
	3	lower layered leucogabbro group	100	1 lower leucogabbro	50
	2	ultramafic group	100		
	1	pyroxene amphibolite (supracrustal)	200		

Thicknesses on Qeqertarssuatsiaq are from Windley, 1973a.



Dolerite
Granite and granodiorite gneiss
Anorthosite
Upper leucogabbro
Gabbro
Lower leucogabbro
40 Dip and strike of main foliation
A
B
Ice
63°15'
50°
0
2km
30
50
25
50
50
45
55
50
30
60
70
20
30
40
45
50
60
20
45
80
80
75



A
B
1000
m
0
F1
F2

served in the central part of the region where unequivocal igneous way-up structures and primary minerals were first recognised in the field in 1971 by Myers (1973b) and Walton (1973). According to Walton (1973), the southernmost of these outcrops has a similar igneous stratigraphy to that described by Windley *et al.* (1973), whereas the stratigraphy of the northern outcrops of Majorqap qâva (mapped by J. S. Myers) and Sinarssuk (mapped by G. A. G. Nunn) differ in their stratigraphy within the upper anorthosite *sensu stricto* part, as well as lacking the major unit of ultramafic rocks at the base of the succession.

Details of the stratigraphy of the Qeqertarssuatsiaq outcrop of the Fiskenæsset complex taken from Windley *et al.* (1973) are shown in Table 2 where they are compared with the succession mapped from Majorqap qâva (figs 35, 36) (Myers, 1973b & in press a).

Igneous stratigraphy

The major lithological units are described in upward succession, based on the Majorqap qâva outcrop (Myers, in press a) unless otherwise stated.

(a) Lower ultramafic unit (zone 2 of Windley *et al.*, 1973). It is composed of dunite, pyroxenite, hornblende peridotite, hornblende pyroxenite and hornblendite. Minerals include olivine, hypersthene, hornblende, spinel, magnetite and ilmenite. The rocks have equigranular metamorphic textures with grain sizes up to 8 mm.

(b) Lower leucogabbro. The lowermost unit of the Majorqap qâva outcrop consists chiefly of relict, equant, cumulus plagioclase 1–5 mm in diameter and recrystallised intercumulus hornblende (fig. 37). With variation in the proportion of mafic minerals, it grades into layers of gabbro and anorthosite with similar texture. Layers of ultramafic rocks up to 2 m thick occur which show composition grading upwards from olivine-pyroxene-magnetite, to pyroxene-hornblende-magnetite cumulates to hornblendite, which grades upwards into gabbro and leucogabbro.

(c) Gabbro unit. The overlying gabbro unit is chiefly made up of metamorphic plagioclase-hornblende rocks with relict sub-ophitic texture. It contains thin gravity stratified layers each a few centimetres thick (fig. 38); they have a sporadic distribution but many are concentrated into narrow vertical columns. Two layers of olivine-pyroxene-magnetite-spinel cumulate each capped by anorthosite and 1–2 m thick occur in the middle of the gabbro unit.

←

Fig. 35. Map and section of the Majorqap qâva outcrop of the Fiskenæsset complex (after Myers, in press a).

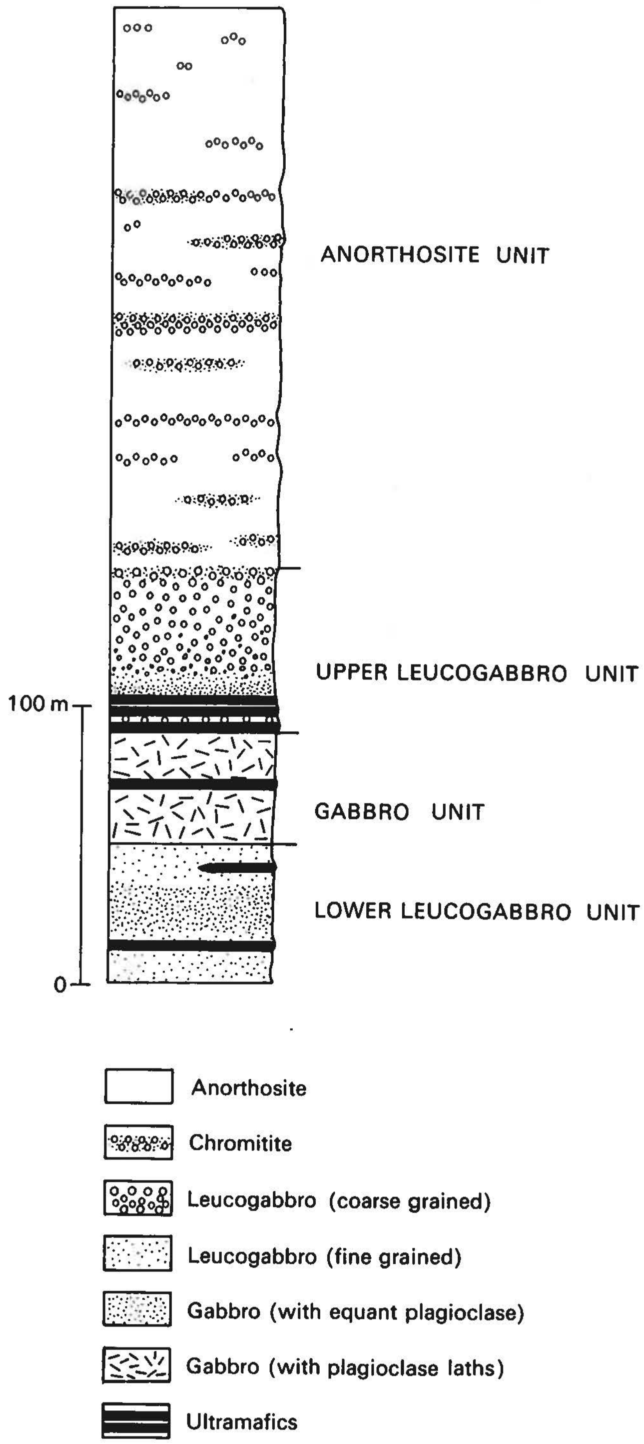


Fig. 36. Simplified stratigraphic succession of the Majorqap qâva outcrop of the Fiskenæsset complex (after Myers, in press a).

(d) Upper leucogabbro unit. The base of the upper leucogabbro unit is marked by aggregates 20 cm in diameter of equant cumulus plagioclase crystals 1–5 cm in diameter. Locally they are interlayered with gabbro at the top of the gabbro unit (fig. 39). They form a layer generally 10 m thick and represent the first formed crystals which aggregated and

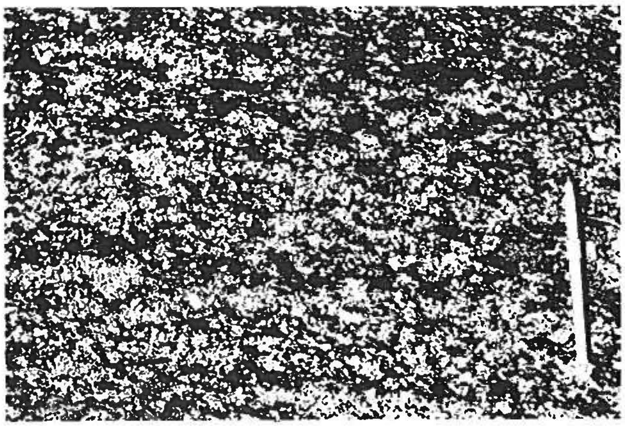


Fig. 37. Typical relict igneous texture in the lower leucogabbro unit of the Majorqap qâva outcrop, made up of plagioclase and hornblende.

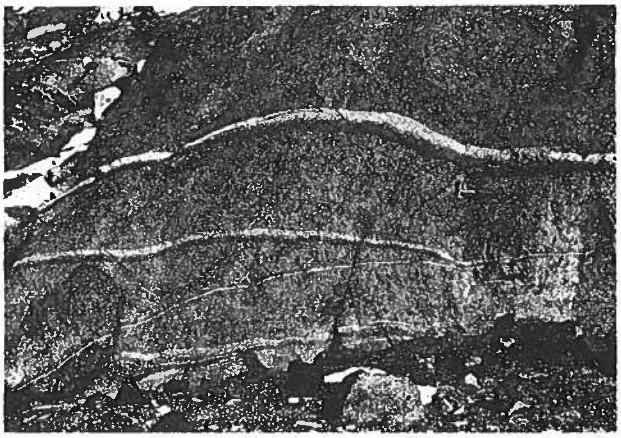
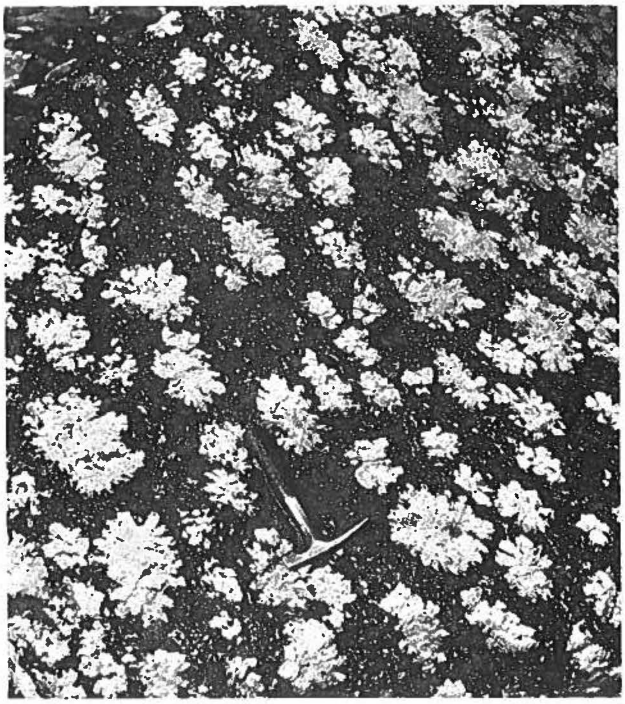


Fig. 38. Gravity-stratified layering between uniform metagabbro composed of plagioclase and hornblende. The gabbro unit of the Majorqap qâva outcrop.



sank within the upper part of the intrusion. Generally between one and three ultramafic layers 1–3 m thick occur near the base of the upper leucogabbro unit. In some places an ultramafic layer occurs below the layer of plagioclase aggregates and others occur just above it interlayered with plagioclase-hornblende and plagioclase-chromite cumulates. The ultramafic layers show mineral grading upwards from hypersthene-hornblende-magnetite to olivine-magnetite, and to hypersthene-hornblende-magnetite cumulates.

There is a steady upward increase in the size of cumulus plagioclase within the upper leucogabbro unit, from 1–5 cm in diameter near the bottom to 5–10 cm near the top (fig. 40). Generally the grain size is relatively uniform in any one place. Plagioclase crystals are equant and are enclosed in a matrix of hornblende with local pockets rich in chromite. Chromite also forms a major cumulus mineral at the top of the upper leucogabbro unit with equant cumulus plagioclase, 10 cm in diameter, and interstitial biotite and hornblende.

(e) Anorthosite unit. The overlying anorthosite unit is generally more strongly deformed than the lower three units and is more thoroughly recrystallised. It generally consists of a mosaic of plagioclase 1 mm in diameter with minor amounts of hornblende and mica. In some places primary plagioclase crystals occur up to 10 cm in diameter suggesting that the anorthosite was originally coarser grained. Where the anorthosite is little deformed it contains irregular shaped patches of leucogabbro (fig. 41) and a smaller number of plagioclase-grossularite lenses, as well as discontinuous strips of leucogabbro with hornblende, chromite and mica. Generally these patches and lenses are strongly deformed and form thin schlieren (fig. 42).

Whole rock and mineral chemistry

The Fiskenæsset anorthosite complex appears to have crystallised from a high-alumina, basaltic magma under conditions of high vapour pressure (Herd, 1972, 1973; Windley *et al.*, 1973). Whole rock analyses of 18 samples from a section across the stratigraphy on Qeqertarssuatsiaq (Windley *et al.*, 1973) indicate an upward increase in the Fe/Mg ratio, Co/Ni ratio, and total alkalis, aluminium and calcium, with decrease in total iron, magnesium, manganese and cobalt (fig. 43 *b*). These general trends are substantiated by 70 whole rock analyses from the Majorqap qâva outcrop (Myers, 1975) but the upward

←

Fig. 39. Plagioclase aggregates in metagabbro at the top of the gabbro unit of the Majorqap qâva outcrop.

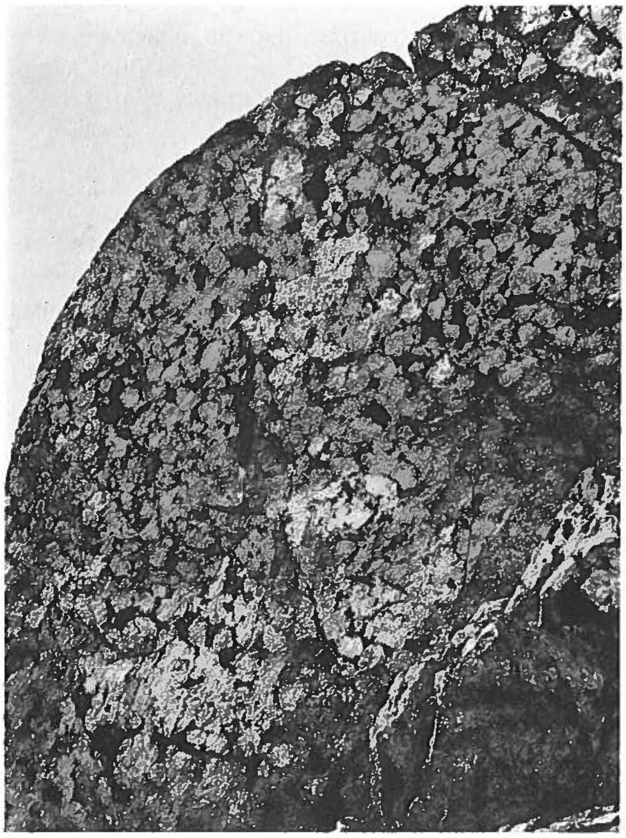
increase in Fe/Mg ratio is less marked than in the samples from Qeqertarssuatsiaq (fig. 43 *a*).

From electron microprobe analyses of individual minerals, Windley & Smith (1974) concluded that the metamorphic plagioclase composition increases upwards from An_{80} to An_{96} in Windley's zone 3 and then decreases to An_{80} in zone 8, with high values in chromite-bearing horizons. A more detailed study of both igneous and metamorphic plagioclases from the Majorqap qâva outcrop (R. G. Platt, personal communication) has showed that most igneous plagioclases are zoned from cores of An_{86} to rims of An_{78} and that, except in the gabbro unit where plagioclase compositions are An_{90-98}, there is no major stratigraphic variation in plagioclase composition. Windley & Smith (1974) also concluded that the MgO/FeO weight ratio of metamorphic amphiboles on Qeqertarssuatsiaq increases upwards from Windley's zones 3 to 5 and then decreases to zone 8 (fig. 44).

Deformation and metamorphism

Rocks of the anorthosite complex have been repeatedly intruded by granitic (now gneissose) material, deformed and metamorphosed, but because of their composition, they were generally more competent than gneisses and amphibolites and have locally escaped the strong deformation which most other rocks of the Archaean complex suffered.

Fig. 40. Typical coarse-grained meta-leucogabbro in the upper part of the upper leucogabbro unit of the Majorqap qâva outcrop.



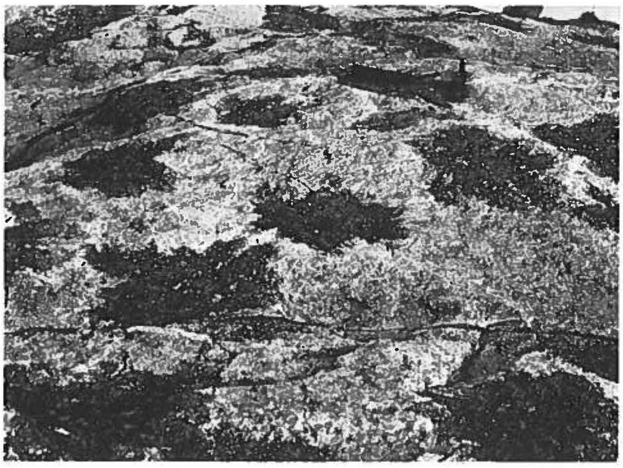


Fig. 41. Little deformed meta-anorthosite with irregular shaped patches of leucogabbro. The anorthosite unit of the Majorqap qâva outcrop.

Fig. 42. Strongly deformed meta-anorthosite with oblate ellipsoidal schlieren of leucogabbro (right and centre) passing (left) into irregular shaped, little deformed, leucogabbro patches in the neutral zone of a tight fold. Anorthosite unit of the Majorqap qâva outcrop.

The anorthosite complex was first folded into nappe-like, recumbent isoclinal folds (fig. 35), associated with thrusting, sub-parallel with igneous layering. In many places thrusting was accompanied by the intrusion of granitic sheets. As a result, parts of the original stratigraphy were cut out or duplicated and split up by sheets of gneiss. In many places the intrusion of large amounts of granitic material left only thin strips or trains of inclusions of the original succession. In some places, inclusion trains of different lithologies of anorthosite still lie in their original stratigraphic order, but individual inclusions

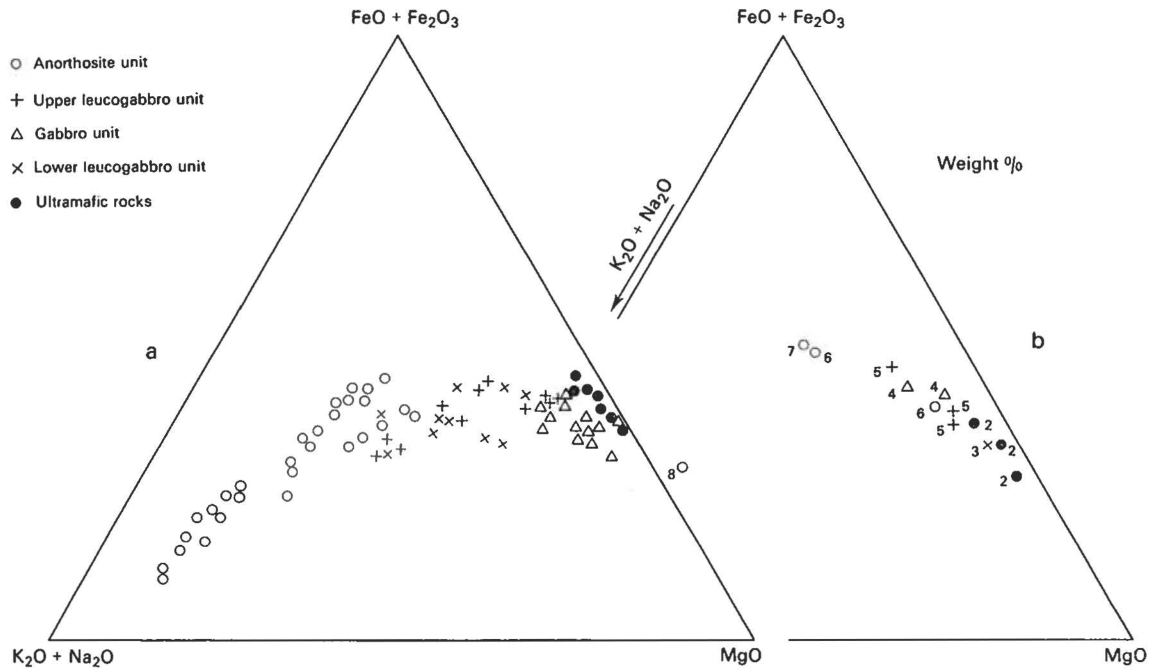
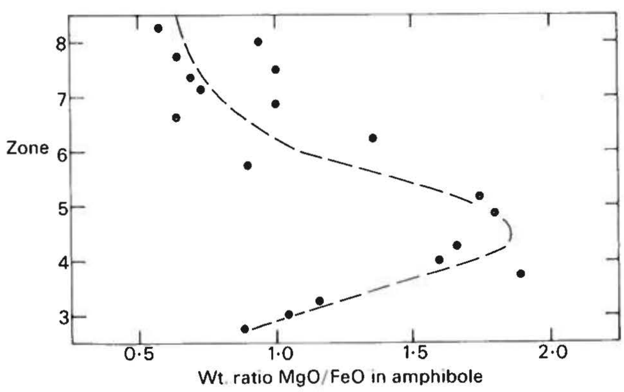


Fig. 43. AFM diagrams of whole rock analyses from the Fiskenæsset complex: *a* at Majorqap qâva (after Myers, 1975), *b* on Qeqertarssuatsiaq (after Windley *et al.*, 1973). Numbers indicate zones named on Table 2.

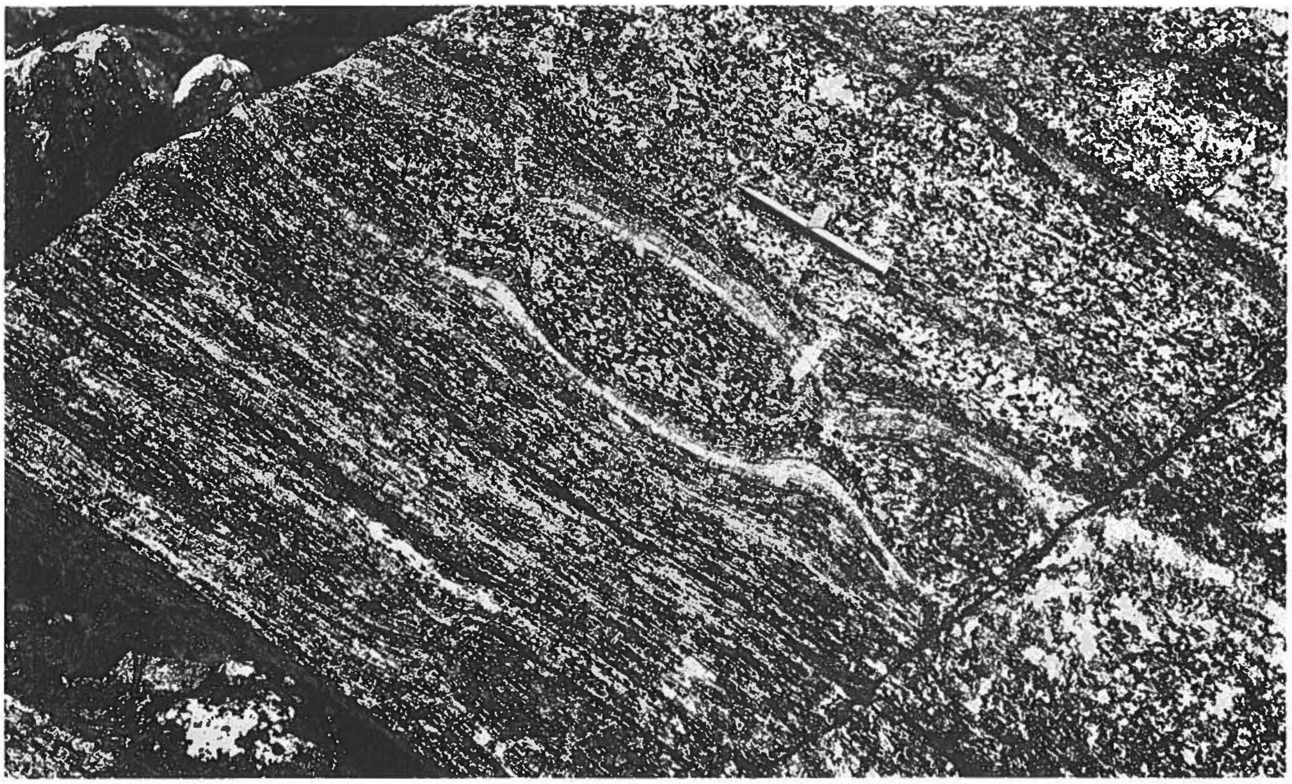
are generally disorientated. Metasomatic effects appear to have been slight during the intrusion of the massive amounts of granitic material which now form the main gneisses of the Fiskenæsset region, as most contacts between gneiss and anorthosite are very sharp.

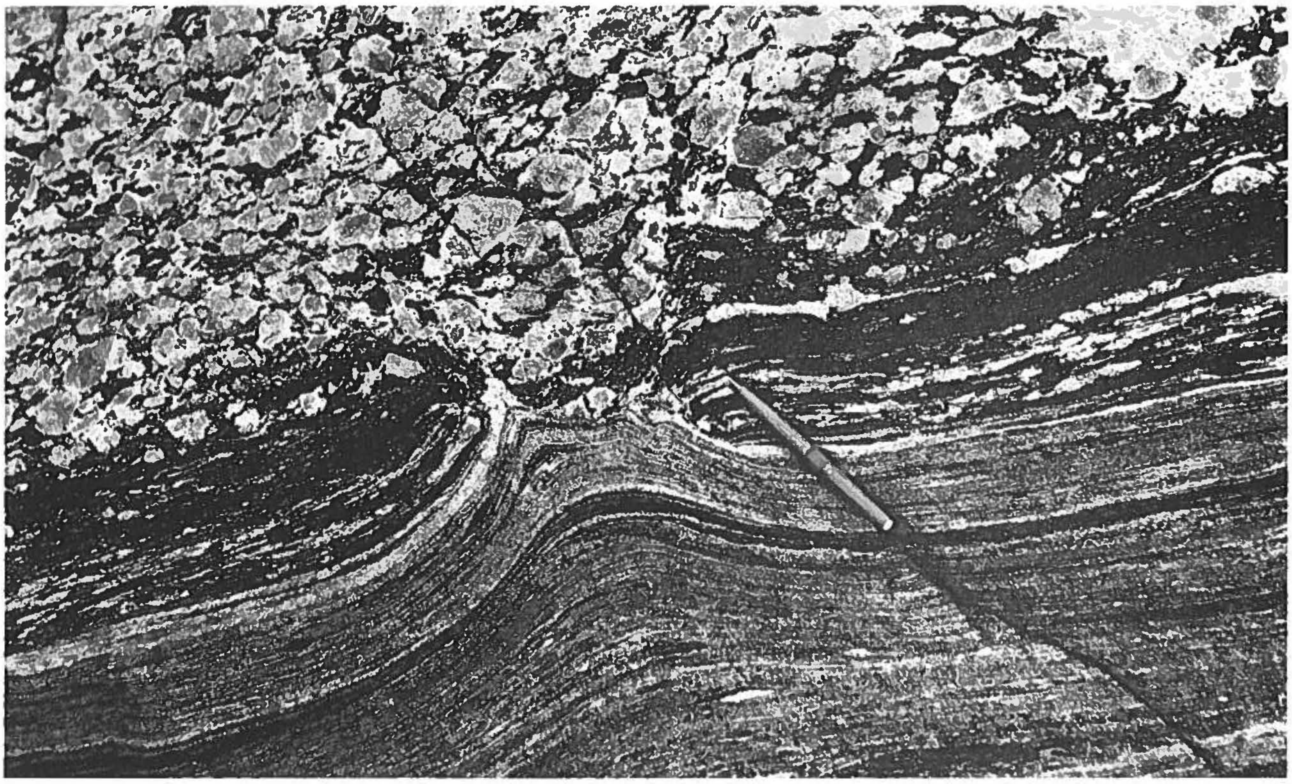
Igneous textures are more widely preserved than igneous minerals in the anorthosite complex. In some cases the rocks recrystallised without being deformed whereas in most cases deformation was accompanied by recrystallisation. In general both deformation and recrystallisation reduced the primary grain sizes and deformation accentuated igneous layering and created new layering. Different types and stages of deformation are illustrated by the sequence of figs 45–51 from the Majorqap qâva outcrop, which show the conversion of leucogabbro with initially equant plagioclase crystals into leucogabbro schist. The anorthosite complex provides more strain markers than most units of the Archaean complex because most primary plagioclase crystals were equant and sub-spherical. But deformation both within the anorthositic rocks and between anorthosite and gneiss was generally very heterogeneous and it is difficult to relate local strain conditions to regional tectonics.

Fig. 44. Variation of MgO/FeO in amphiboles from the Qeqertarssuatsiaq outcrop of the Fiskenæsset complex, after Windley & Smith (1974). The zones refer to those shown in Table 2.



In general in the Fiskenæsset region there appears to have been little change in bulk composition of the anorthositic rocks during metamorphism (Bowden, 1970; Windley *et al.*, 1973). Changes of whole rock composition have only been found on a scale of a few tens of centimetres (Rivalenti, 1973). In this case the anorthosites gained Si, Na, K and possibly Zr so that calcic plagioclase was replaced by more sodic feldspar, muscovite and epidote while hornblende was replaced by biotite and epidote. The composition of individual minerals also appears to have been little changed during early stages of recrystallisation. In some parts of the Majorqap qâva outcrop, igneous plagioclase recrystallised





Figs 45 and 46. Heterogeneous deformation of originally uniform leucogabbros of different grain sizes, in which deformation was concentrated in planes parallel with the larger scale layering of the complex and formed schistose layers. During subsequent deformation the non-schistose layers were boudinaged whilst internal deformation was concentrated in the schistose layers, and further accentuated the schistosity. In fig. 46 conjugate fractures developed in the non-schistose layer during boudinage of an adjacent more mafic layer.

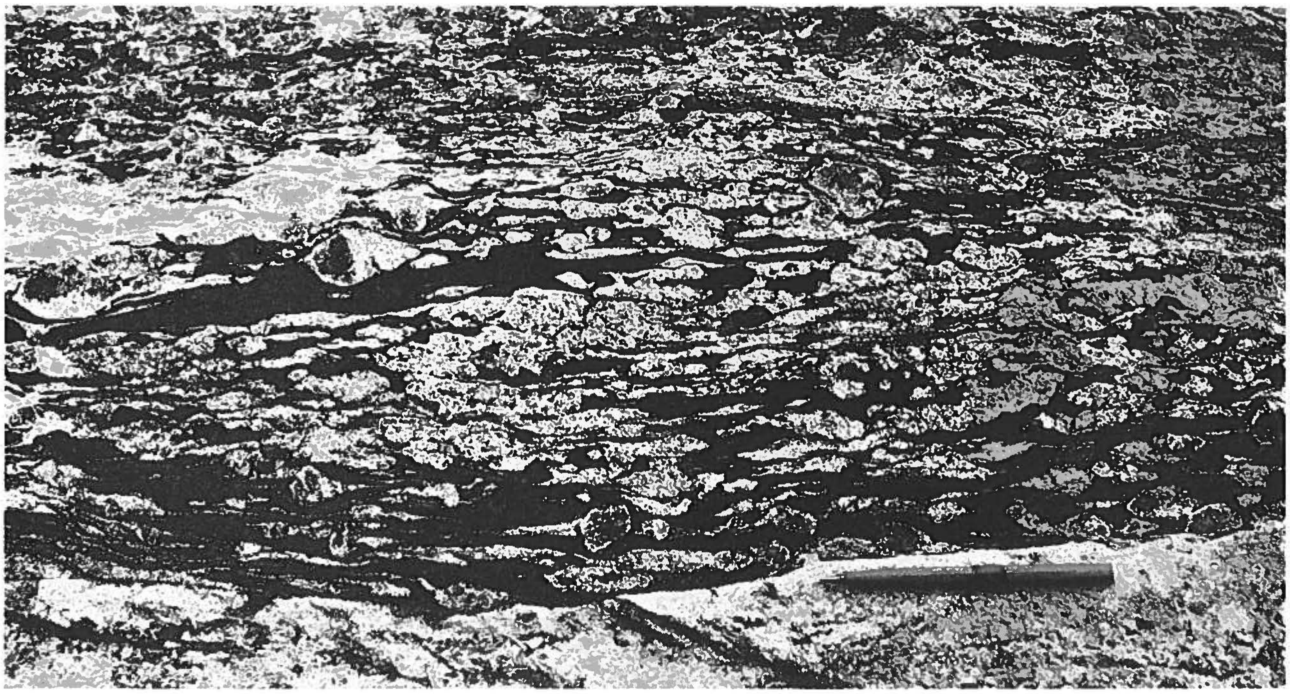


Fig. 47. Heterogeneous deformation of leucogabbro with partly recrystallised igneous plagioclase. During early stages of deformation only the outer rims of the igneous plagioclases recrystallised and this material migrated to form tails to the igneous crystals in strain shadows. The figure shows a more advanced stage of the same process in which some igneous plagioclase crystals have been completely recrystallised and streaked out to form a schlieren layering.

with identical composition and preserved relict igneous zoning (R. G. Platt, personal communication). In samples from Qeqertarssuatsiaq, Windley & Smith (1974) also showed that the MgO/FeO ratio in recrystallised amphiboles preserved their igneous differentiation pattern (fig. 44).

However, in some other parts of the Archaean region there were marked changes in mineral assemblages and compositions during metamorphism (Ellitsgaard-Rasmussen & Mouritzen, 1954; Kalsbeek, 1970; Henriksen, 1969a; Nunes *et al.*, 1974). Henriksen records that plagioclase aggregates in the anorthosites of the Ivigtut area change from bytownite rimmed by grains of andesine and labradorite to entirely clear andesine as the anorthosites became increasingly deformed and metamorphosed in the Ketilidian mobile belt. Similarly the composition of plagioclase in pods of gabbroic anorthosite which occur near the edge of the Nagssugtoqidian mobile belt vary from labradorite and bytownite in the centre of the pods where primary textures are preserved, to oligoclase and andesine at the highly deformed margins (Nunes *et al.*, 1974).

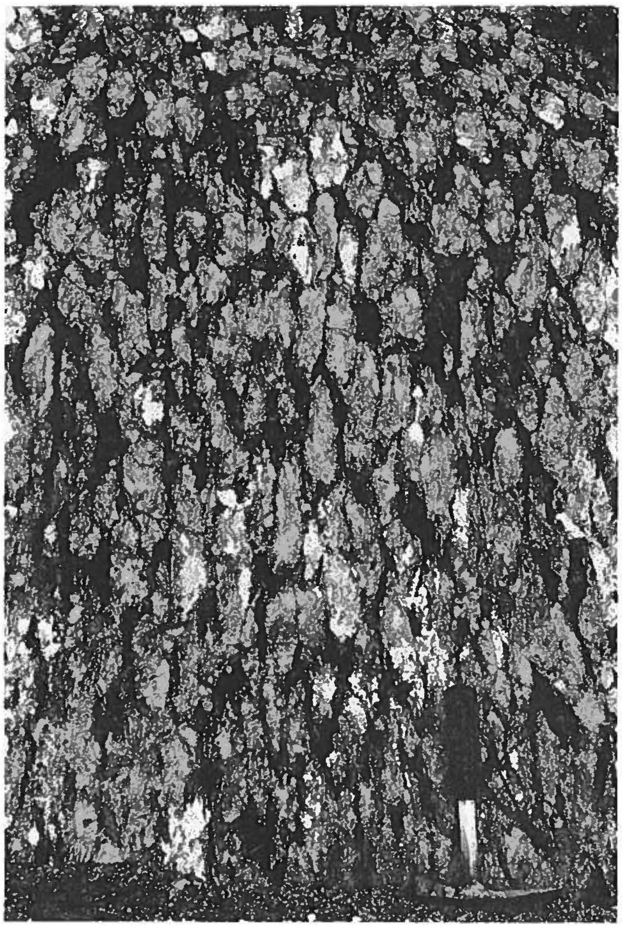


Fig. 48. The first of a series of three photographs to illustrate various stages of homogeneous deformation of coarse grained leucogabbro in which the igneous plagioclase crystals have been completely recrystallised. In this figure the relict igneous plagioclase crystals form constriction type ellipsoids (k = 1.5) with principal extension ratios 9:4:2.

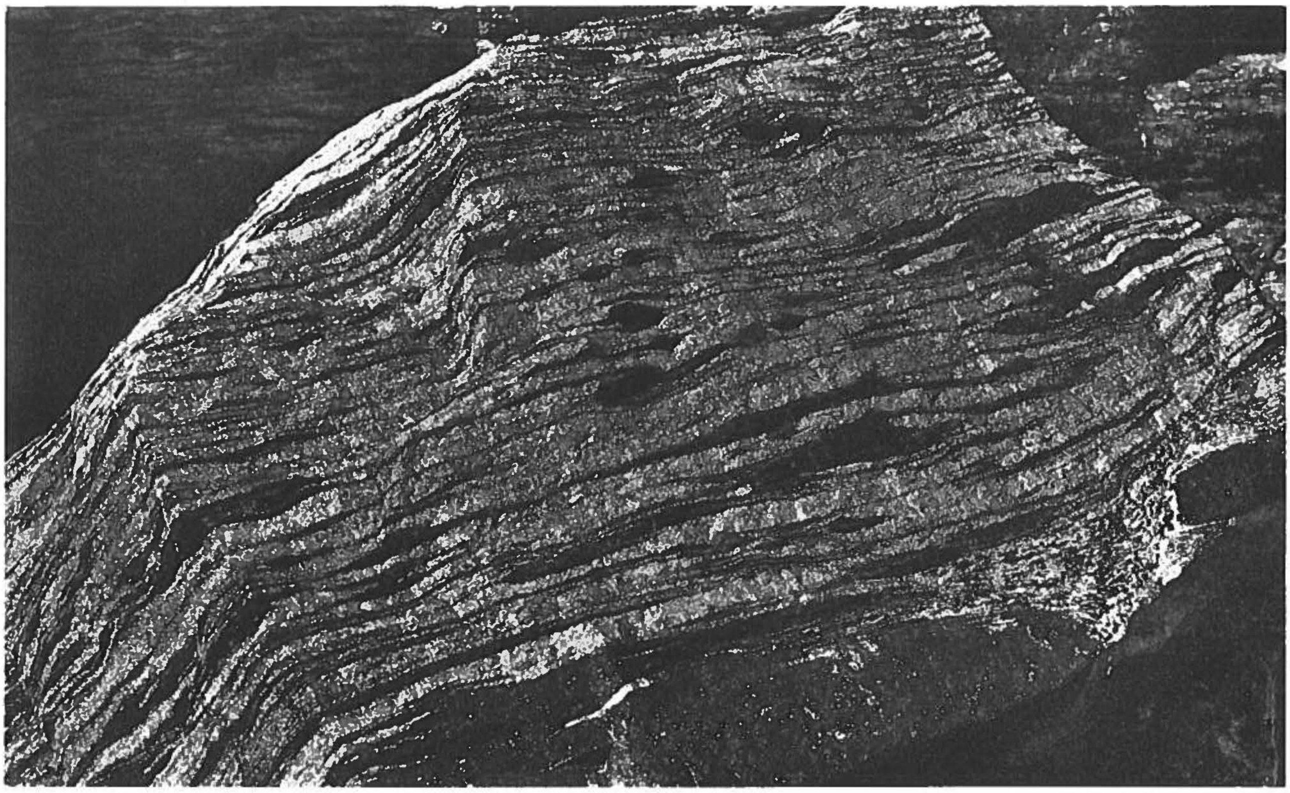


Fig. 49. Further deformation has almost obliterated the outlines of the relict igneous plagioclase crystals which are now flattening type ellipsoids ($k = 0.02$) with principal extension ratios in the order of 70:50:1.

Fig. 50. Deformation has been so intense that the rock has become a leucogabbro schist in which the attenuated relict igneous plagioclase crystals are only recognisable in a few places.

Fig. 51. Adjacent to fig. 50, the schistosity itself has been folded.

Origin

Various opinions have been put forward in the last few years about the origin of the highly calcic anorthosites found in the Archaean gneiss complex: they have been compared to lunar anorthosites (Windley, 1970b), to the Great Dyke of Rhodesia (Windley, 1971), and to the Bushveld complex (Windley, 1969b). They have been regarded as possible thrust slices of Archaean upper mantle or lowermost crust (Windley, 1969a; Banerjee, 1971), as sills intruded between metavolcanics and a gneissose basement (Windley *et al.*, 1973), and recently they have been equated with modern deep ocean floor ophiolites (Sutton & Windley, 1974), and interpreted as intrusions into an epicontinental sedimentary environment (Windley, personal communication, 1974).

The following points seem pertinent to their origin:

(1) They were emplaced into volcanic rocks mainly of oceanic tholeiitic composition associated with minor amounts of intermediate volcanics and sedimentary rocks. Both the type of sediments and the chemical character of the volcanics are reminiscent of recent island arcs and near-arc ocean floor.

(2) The anorthosites are parts of major stratified sills, with igneous layering which formed in a more or less horizontal position.

(3) The anorthosites crystallised from a high-alumina basaltic magma under conditions of high vapour pressure (Herd, 1972, 1973; Windley *et al.*, 1973).

(4) There is evidence from the mineral chemistry that the anorthosite complexes originally crystallised at pressures in excess of 7 kb (Herd, 1972, 1973; Platt & Myers, in press). This would suggest that the complexes crystallised at 20–30 km depth.

(5) Highly calcic anorthosites of this type are either restricted to Archaean layered complexes or are at least much more common in Archaean complexes than later in the Earth's history. The nearest modern analogues known to the writers are xenoliths of highly calcic plagioclase brought up in andesites from Japan (Ishikawa, 1951) and other island arc environments.

(6) The emplacement of the anorthosites was followed by widespread calc-alkaline magmatism (the Nûk gneisses).

Nûk gneisses and similar rocks

The informal lithostratigraphic term Nûk gneisses (McGregor, 1973) is applied to all the quartzo-feldspathic gneisses in the Godthåbsfjord region that do not contain Ameralik dykes and that have intrusive relations with the Malene supracrustals, the anorthositic rocks and the earlier Amîtsoq gneisses. It is not known to what extent all the rocks grouped as Nûk gneisses belong to a single, cogenetic suite or to what extent they were intruded during periods of unrelated granitic activity possibly separated by major time intervals.

Rb-Sr whole rock isotope determinations on a suite from a small area on Bjørneøen (Pankhurst *et al.*, 1973 a) gave a well defined isochron of 3040 ± 50 m.y. (initial Sr ratio 0.7026 ± 0.0004) which is regarded as their date of intrusion. The Bjørneøen suite is petrologically typical of the Nûk gneisses which occur over a large part of the Godthåbsfjord area (fig. 11). However, intrusion of granitic material and deformation may have gone on intermittently after emplacement of the anorthosites into the Malene supracrustals before 3040 m.y ago, up to about 2600 m.y ago when the Qôrqut granite was emplaced.

On the northern coast of Godthåbsfjord highly deformed gneisses equivalent to those dated from Bjørneøen can be traced into an area affected by granulite facies metamorphism dated at approximately 2800 m.y. (Black *et al.*, 1973). They are here strongly recrystallised, partly remobilised, and intruded by late to post-tectonic granites thought to have been emplaced under high grade metamorphic conditions (Bridgwater & McGregor, 1974a; Macdonald, 1974). These charnockitic granites are treated separately from the Nûk gneisses, although they may overlap in time with the younger phases of Nûk gneiss intrusion in the rest of the Godthåbsfjord region, which is thought to have remained a belt of tectonic and magmatic activity throughout the period of granulite facies metamorphism in adjacent areas (McGregor, 1973).

Field characters

Nûk gneisses make up more than half the rocks exposed in the Godthåbsfjord region (fig. 11). They occur as deformed sheets varying from a few centimetres to several kilometres in thickness emplaced within the older complex of Amîtsoq gneisses, Malene supracrustals and anorthosites (fig. 24). On a regional scale the sheets are concordant or subconcordant bodies some of which may have been emplaced along originally sub-horizontal thrust boundaries between or within the earlier rock units. Where relatively unaffected by later deformation many of the original contacts of these sheets are transgressive and cut across earlier lithological variations in the country rocks. In some areas several phases of granitic material break up earlier rocks to form agmatites with inclusions of Amîtsoq gneisses, Malene supracrustals or anorthosites together with earlier phases of the Nûk gneisses themselves (figs 52, 53).

Many of the larger complexes of Nûk gneisses, for example those which extend through the Godthåb peninsula, Sadelø and Bjørneøen (fig. 11), contain

Fig. 52. Early phase of coarse-grained Nûk gneiss with migmatised inclusions of amphibolite derived from nearby Malene supracrustals, cut by a later vein of fine grained Nûk gneiss. South coast of Bjørneøen, Godthåbsfjord.

Fig. 53. Migmatised inclusions of banded green and black skarn-amphibolite, lithologically typical of the Malene supracrustals. The amphibolite is enclosed in rafts of an early phase of Nûk gneiss which are themselves enclosed in a younger, paler, more homogeneous gneiss. A late granite dyke cuts all the earlier lithologies in the upper right part of the figure. South coast of Godthåbsfjord, north-west of Lille Malene.

earlier, more basic phases (including diorites and hornblende gabbros) intruded by younger tonalites, granodiorites and adamellites (fig. 54). In the sequence of intrusion, darker phases are almost always cut by paler phases. Commonly, earlier phases are more deformed than later phases (figs 55, 56). This, together with other field evidence suggests that the igneous parents of the Nûk gneisses were intruded syntectonically.

Petrology and chemistry

Most of the Nûk gneisses in the Godthåbsfjord region are a typical sodic calc-alkaline suite of intrusives ranging from minor hornblende gabbros with cumulate ultramafic layers and diorites to major tonalites, granodiorites and adamellites. Some of the less deformed, coarse-grained, basic rocks contain large poikilitic hornblende crystals and locally show igneous composition-graded layering. These basic rocks resemble the appinitic rocks of younger fold belts such as the Ketilidian of South Greenland (Allaart, this volume).

By far the most abundant type is biotite-bearing tonalite or granodiorite commonly with less than 5 per cent potash feldspar. Chemically the Nûk gneis-

Fig. 54. Intrusive relations between an early, dark, tonalitic Nûk gneiss and a younger, paler, granodioritic phase, south coast of Hundeø, just south of Godthåb. A few metres away the same lithologies are strongly deformed and concordant.

ses are similar to more recent calc-alkaline suites (figs 17 b) except for a generally higher sodium-potassium ratio, low uranium content and generally high but variable Th/U ratio. The high K/U and Th/U ratios are common to many of the granitic gneisses of the Greenland Archaean complex whether or not they show field or petrographic evidence of having passed through granulite facies. K/Rb ratios average 330 slightly higher than both the crustal average and the values given by Amîtsoq gneisses of comparable major element chemistry.

Origin

The Nûk gneisses in the Godthåbsfjord region appear to have been derived from calc-alkaline igneous rocks intruded syntectonically as a series of flat-lying sheets into a layered complex of earlier gneisses, supracrustals and anorthosites. The field relations combined with the low initial strontium ratio both suggest that these Nûk gneisses were derived either directly from the mantle or from a crustal source containing considerably less Rb than the country rocks into which they were emplaced. In this region there is no field or isotopic evidence that any major part of the Nûk gneisses were derived by remobilisation of older sialic material *in situ*. Elsewhere, for example south of Godthåb (Chadwick *et al.*, 1974 b), where field evidence suggests that rocks mapped as equivalent to the Nûk gneisses have been contaminated by or derived from older sialic material, the available isotopic data does not show any evidence of a long crustal history. The relatively sodic nature of the Nûk gneisses is compatible (D. B.) with a moderately shallow origin of the calc-alkaline magmas.

Fig. 55. Earlier phase of Nûk gneiss, derived from a relatively coarse-grained parent, cut by a later, fine-grained phase. The first phase was cut by pegmatitic veins and deformed before the second phase was intruded. At nearby localities the same two gneiss lithologies are so strongly deformed that intrusive relations are no longer visible and the rocks are banded gneisses. South coast of Bjørneøen, Godthåbsfjord.

Similar rocks

Over 80 per cent of the Archaean gneiss complex is made up of quartzo-feldspathic gneisses which were deformed before the 2800 m.y. regional granulite facies event. Outside the area between Sermilik and Isua, there is no definite evidence of rocks older than the main supracrustal units and anorthosites. This does not mean that older rocks do not occur but that they are difficult to recognise. However if the supracrustals and anorthosites are regarded as equivalent in age to the Malene supracrustals and anorthosites in Godthåbsfjord, then a very large part (perhaps 70–80 %) of the gneiss complex must have been formed, or at least remobilised, at approximately the same time as the emplacement of the Nûk gneisses.

Suites of quartzo-feldspathic gneisses formed from rocks lithologically similar to the Nûk gneisses of Bjørneøen have been recorded from many localities in the Archaean complex, particularly in areas in which there are moderately well preserved supracrustal belts (for example Ravns Storø – Andersen & Friend, 1973; Tingmiarmiut – Andrews *et al.*, 1971, 1973; the Alángua–Finnefjeld complex – Berthelsen, 1962; and north of Fiskenæsset – Myers, in press b). These show the same variation in lithologies and local evidence for injection under syntectonic conditions as the Nûk gneisses. They intrude the supracrustal belts and are clearly derived from allochthonous magmas.

Many of the quartzo-feldspathic gneisses do not, however, show a marked resemblence to the Nûk gneisses from Godthåbsfjord either because they have passed through a much more pervasive deformation and metamorphism than the Nûk gneisses, or were partly derived from different source material. Several writers have suggested that a large part of the gneiss complex represents very old sialic material (possibly equivalent to the Amîtsoq gneisses) which has been partly remobilised during several periods of thermal activity extending over a long time. Chadwick & Coe (1973) and Chadwick *et al.*, (1974a,b) have suggested that major parts of the Nûk gneisses in the Buksefjorden–Færingehavn area were derived by the large scale assimilation and remobilisation of Amîtsoq gneisses. In this case the assimilated material contains dykes considered to be Ameralik dykes which range from moderately well preserved amphibolite dykes clearly discordant to an earlier foliation, to wisps and fragments of basic material.

In the southern part of the Fiskenæsset region there are numerous sheets of granodiorite which Hopgood (1973) considers were formed by selective granitisation of certain horizons of gneiss after they had been folded four times. Zircons from this granodiorite gave a U-Pb concordia age of 3030 ± 20 m.y. (Pidgeon, 1973), similar to the age of Nûk gneiss on Bjørneøen.

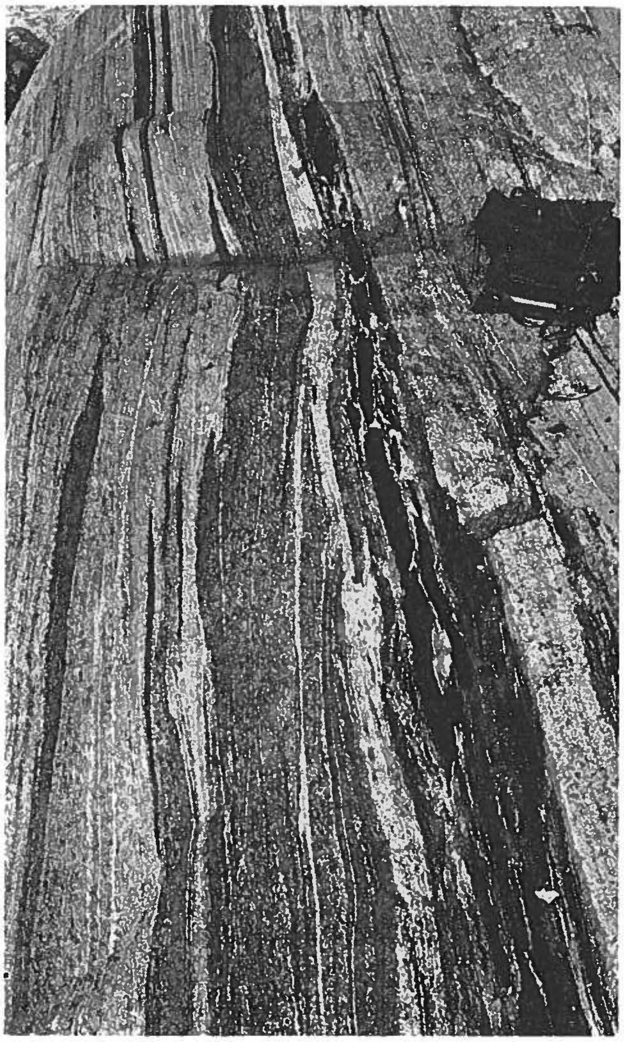


Fig. 56. Strongly deformed Nûk gneisses, possibly the same lithologies as in fig. 54. The younger, paler phase contains strongly attenuated rafts of an earlier darker phase, which in turn contains broken-up fragments of Malene amphibolite. South-west of the centre of the town of Godthåb.

On the south-east coast of Greenland Bridgwater & Gormsen (1969) and Andrews *et al.*, (1973) note the widespread occurrence of agmatites. These could be regarded as the penultimate stage in the regional digestion of older dioritic and acid gneiss to form new granitic rocks during the same general period of thermal activity as the intrusion of the Nûk gneiss suite in Godthåbsfjord. There is, however, no proof that the gneissose fragments were derived from much earlier rocks and the agmatites could be interpreted as formed from several different generations of intrusive granitic material all of which were emplaced later than the adjacent supracrustal and anorthositic units.

Late granites and associated intrusions

This section describes a heterogeneous group of rocks which includes: discrete intrusive bodies of porphyritic granite emplaced before the 2800 m.y. granulite facies metamorphism; diffuse bodies of rock apparently formed by the *in situ* recrystallisation and partial remobilisation of earlier quartzo-feldspathic gneisses during regional high grade metamorphism; discrete intrusive bodies of charnockitic granites and associated norites emplaced under or affected by the 2800 m.y. old granulite facies metamorphism; and late to post-tectonic granite intrusions and pegmatite swarms which post-date the granulite facies metamorphism. One such pegmatite has yielded a Rb-Sr mineral isochron age of approximately 2600 m.y. (Pankhurst *et al.*, 1973 b).

These rocks are not regarded as a cogenetic suite, and the main reason for describing them together is that they were all formed towards the end of plutonic activity in the Archaean craton, in the period after the main regional foliation had been impressed on the gneiss complex, although many of them are affected by one or more phases of younger deformation.

Ilivertalik granite

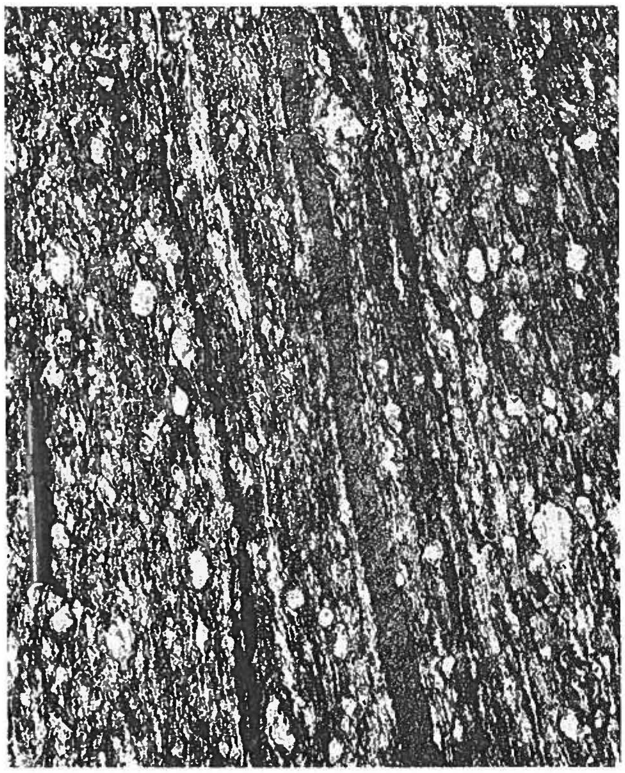
Kalsbeek & Myers (1973) and Myers (in press b) describe an intrusive porphyritic granite complex named after the mountain Ilivertalik north of Fiskenæsset (fig. 33). This consists of a suite of biotite, hornblende and hypersthene-bearing granites characterised by potash feldspar augen 1–2 cm long derived from primary tabular phenocrysts (fig. 57). The granites are associated in time and space with layered sheets of metadiorite and metatonalite which were emplaced into the granites and surrounding country rocks while the former were still partly mobile.

In the area described by Myers (in press b), the Ilivertalik granite forms three thick sheets which are subconcordant with the regional layering in the surrounding gneisses. These thick sheets are accompanied by numerous thinner granite sheets which cut across the foliation in the surrounding gneisses, up to three kilometres away from the contacts of the main bodies. The three main sheets all contain potash feldspar megacrysts set in a biotite-bearing matrix. In two sheets the feldspar megacrysts are densely packed, in the other they are more spread out and set in a coarse-grained matrix. Both sheets contain hypersthene in the western part of the area which has been affected by late granulite facies metamorphism. One sheet with densely packed feldspars is composite with a light and dark facies locally separated by a sharp contact with the lighter facies veining the darker facies. The darker facies contains a few inclusions of a more melanocratic rock, in some places associated with trough-like composition-graded layering in the granite; layers grade from rocks with 50 per cent hornblende to mafic-free layers of quartz and feldspar.

The layered sheets of metadiorite and metatonalite associated with the Ilivertalik granite are up to 100 m thick. They are compositionally layered with variations in the proportion of plagioclase, hornblende, diopside and hypersthene, and in some places relict igneous textures are preserved. Some sheets contain an olivine-hypersthene-magnetite cumulate ultramafic layer near their centre which grades upwards into rusty weathering metadiorite rich in sulphides. The sheets were intruded soon after the emplacement of the porphyritic granite and in some places they are disrupted and back-veined by the granite.

The Ilivertalik granite and associated metadiorite-metatonalite sheets cut sharply across an older gneiss complex with inclusions of amphibolite and anorthosite, and are themselves cut by sheets and irregular shaped masses of younger pegmatites and

Fig. 57. Ilivertalik augen granite and a younger granitic vein. Inner Grædefjord, north-east of Fiskenæsset.



granitic gneiss made up of quartz, plagioclase, potash feldspar and biotite with accessory magnetite, allanite, epidote and apatite. All these intrusions were strongly deformed before the granulite facies metamorphism dated at 2850±100 m.y. (Black *et al.*, 1973). Pidgeon *et al.* (in press) give a U-Pb zircon concordia age of 2835±10 m.y. for a hypersthene-bearing sample of the Ilivertalik granite from the western part of the area affected by granulite facies regional metamorphism.

Qánguartoq gneisses

In the Fiskenæsset region there are numerous small irregular shaped granitic and tonalitic intrusions which cut across deformed quartzo-feldspathic gneisses with inclusions of amphibolite and anorthosite, and across the Ilivertalik granite (figs 57, 58). They have been called Qánguartoq gneisses by Myers (1973 a; in press b) in part of the Fiskenæsset region, where they vary from homogeneous bodies to pegmatite-banded gneiss. They range from granite to granodiorite and tonalite in composition, and are made up of quartz, plagioclase and biotite with variable amounts of potash feldspar and hornblende, and accessory allanite, epidote and apatite. Some of the intrusions are syntectonic with respect to the first major deformation which folded the Ilivertalik granite, and some post-date this deformation. They were all deformed during a later tectonic episode which overlapped in time with early stages of the granulite facies metamorphism dated as 2850±100 m.y. (Black *et al.*, 1973).

Kua granulite

In southern Nordlandet as far north as Qugssuk (fig. 11), highly deformed gneisses (derived mainly from Nûk diorites, quartz diorites and granodiorites) are invaded by veins, sheets and discordant masses of coarse-grained, leucocratic, pyroxene-bearing granites (Macdonald, 1974; Bridgwater & McGregor, 1974a). They outcrop extensively in the western part of southern Nordlandet where they have been called 'Kua granulite' by Macdonald (1974). They are typically coarser grained than the gneiss which they invade and are leucocratic, possess a weak foliation, and contain quartz, feldspar, magnetite, pyroxene and hornblende as the principal constituents. Allanite is an abundant accessory. Both potassic and sodic feldspars occur and are pale pink to lilac and give the rock a characteristic purplish appearance. The 'Kua granulite' outcrops as large masses which are surrounded by a diffuse network

Fig. 58. Deformed veins of tonalitic Qánguartoq gneiss cutting older and more deformed quartzo-feldspathic gneiss with inclusions of banded amphibolite. 40 km north-east of Fiskenæsset.

of veins and migmatites which pervade and brecciate the earlier gneisses over a large part of Nordlandet. This disruption makes subdivision of the earlier gneisses into different lithological groups difficult.

In some places the network of veins associated with the Kua granulite have escaped deformation, but elsewhere they are involved in the regional deformation and were intensely drawn out and sheared and then recrystallised in granulite facies conditions. Late concordant and discordant veins of Kua granulite cut across these tectonic fabrics in zones of later deformation.

Farther north-east along the coast of Godthåbsfjord the highly deformed gneiss complex contains subconcordant sheets varying from a few centimetres to a few tens of metres in width. These are generally coarser grained than the granitic gneisses surrounding them. They are either diffuse and show a less pronounced fabric than the surrounding gneisses, or contain a planar fabric which is discordant to that outside the sheet and is interpreted as a syntectonic crystallisation fabric (cf. Watterson, 1965).

These subconcordant sheets frequently contain diopside rimmed by hornblende, and locally hypersthene. They have a lilac colouration similar to that of the Kua granulite although the surrounding gneisses are commonly white or grey. In contrast to the rocks further west they contain considerable iron-rich biotite. A larger body of the same rock type is found at the head of Qugssuk on the north side of Godthåbsfjord. Late pegmatitic segregation veins associated with these granites contain black feldspar, biotite and bluish quartz.

The Kua granulites and similar rocks to the north-east are thought to have been formed by partial remobilisation of parts of the pre-existing gneiss com-

Fig. 59. Grey dyke, cutting Nûk gneisses on Qugssuk, Godthåbsfjord.

plex towards the end of the youngest regional deformation in the area. Their initial remobilisation preceded the peak of regional granulite facies metamorphism in the area. In areas transitional between granulite and amphibolite facies, such as the north-east coast of Nordlandet, the veins of younger granite frequently show a higher grade mineralogy than the gneisses which they cut. Their formation appears to have occurred during progressive metamorphism of the gneiss complex and to have continued during regional granulite facies metamorphic conditions.

'Grey dykes'

The formation of the Kua granulite was followed by the emplacement of a suite of minor granitic intrusions over a large area of Nordlandet. They are called 'grey dykes' from their characteristic colour in amphibolite facies areas (Macdonald, 1974). They vary from a few centimetres to a few tens of metres in width, and have more sharply defined margins than the Kua granulite (fig. 59). Most are medium to fine-grained granodiorite, some are composite with pegmatitic margins and fine-grained centres or more mafic margins and coarser grained granitic centres. In granulite facies terrains they are locally brown, suggesting they have been affected by high grade metamorphism. However, in contrast to the Kua granulite which may contain higher grade minerals than the surrounding rocks, the 'grey dykes' frequently contain lower grade minerals than the country rocks into which they were emplaced. They are therefore regarded as formed during the waning phases of high grade metamorphism in the area.

Sukkertoppen granulites

Reconnaissance mapping in coastal areas north of Sukkertoppen has demonstrated the widespread occurrence of very homogeneous quartzo-feldspathic gneisses. One type is a leucocratic even-grained rock comprising quartz, andesine, accessory biotite, potash feldspar and hypersthene. A coarser grained variety contains large potash feldspars which grow across an earlier foliation. The latter type is particularly abundant near the margin of the Nagssugtoqidian mobile belt (Escher *et al.,* this volume). Both types have intrusive relations with local supracrustal belts and earlier layered gneisses which locally preserve amphibolite facies mineralogy in enclaves surrounded by granulite facies rocks.

The even grained enderbitic rocks show very little structure except on wave polished surfaces where slight changes in grain size and mafic mineral content occur. These outcrops suggest that the gneisses represent polyphase intrusive bodies, but the general field impression is that they have lost earlier structure through some form of static homogenisation. Ramberg (1951) suggested that a regional redistribution of what are regarded as the more mobile components Si, Na, K, O and H_2O could have taken place under granulite facies conditions. This idea is attractive as far as potassium is concerned since it might well explain the general 'sweated out' appearance of the quartzo-feldspathic rocks in the granulite facies areas north of Sukkertoppen. It is possible that the two even-grained types of quartzo-feldspathic rocks might represent rocks from which potassium has been lost, by its migration into rocks with potash feldspar porphyroblasts.

Metanorites south-east of Sukkertoppen

A group of metanorites occur as a series of irregular pods up to 4 km long in the area mapped by Kryolitselskabet Øresund between Fiskefjord and Søndre Isortoq (fig. 60). They are younger than the quartzo-feldspathic gneisses but older than deformation which formed the major interference patterns of the area and before the 2800 m.y. peak of granulite facies metamorphism.

Skjoldungen and Angmagssalik complexes

These composite masses occur in South-East Greenland and are elongated parallel to the main structural grain of the surrounding country rocks (fig. 4). The Skjoldungen complex is little known (Bridgwater & Gormsen, 1969; Andrews *et al.*, 1973) but appears to be dominated by quartz monzonites and leucocratic hypersthene granites with comparatively small amounts of hypersthene diorite and norite. The basic rocks mainly occur as thin sub-concordant sheets which cut the lithological layering in the country rocks but which have locally been deformed by renewed movements along the same planes. The Angmagssalik complex is dominated by leuconorite – andesine anorthosite, and occurs in that part of the Archaean gneiss complex which was reworked by the Nagssugtoqidian mobile belt (Bridgwater & Gormsen, 1968; Andrews *et al.*, 1973; Wright *et al.*, 1973).

Both complexes appear to have been emplaced under granulite facies conditions after the main tectonic events which produced the layered structures in the surrounding gneisses but before the end of active tectonism. Their emplacement was accompanied by widespread remobilisation of the surrounding country rocks and the formation of garnet-bearing granitic gneiss along the border zones. The latter grades from slightly recrystallised gneiss of the same general character as the country rocks into inhomogeneous intrusive rocks which carry inclusions of less remobilised material and vein the earliest parts of the main igneous bodies.

The age of these igneous complexes is unknown. The Skjoldungen complex intrudes high grade supracrustal rocks of Malene type and is affected by the high grade metamorphism regarded as having occurred approximately 2800 m.y. ago. The Angmagssalik complex is cut by post-tectonic granites which have given Rb-Sr mineral ages of about 2000–1800 m.y. (Wager & Hamilton, 1964), but could be younger than the regional swarm of dykes emplaced into the main Archaean gneiss complex.

Post-tectonic granites

The Archaean gneiss complex remained an area of metamorphic and igneous thermal activity for at least 300 m.y. after the end of granulite facies metamorphism. The gneisses over large areas recrystallised

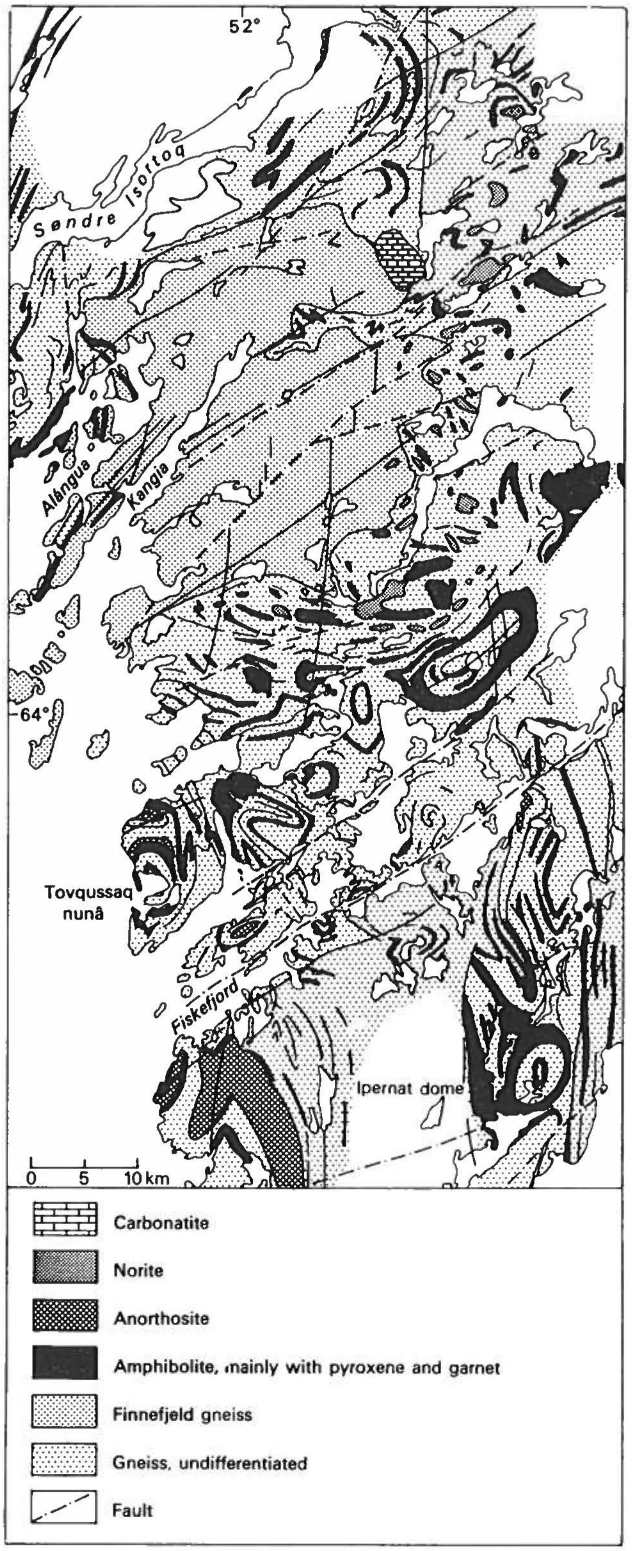


Fig. 60. Simplified map of the Fiskefjord–Alángua area, based on mapping by Kryolitselskabet Øresund and GGU. Note the fold interference patterns outlined by the amphibolite layers and the distribution of norite bodies in a belt to the south and east of the Finnefjeld gneiss. The Finnefjeld gneiss contains a much smaller proportion of amphibolite and pyribolite layers than the other gneisses and is interpreted as a major body of granitic material which has been mobile at a comparatively late stage in the history of the area. See fig. 3 for aerial photograph of the Ipernat dome.

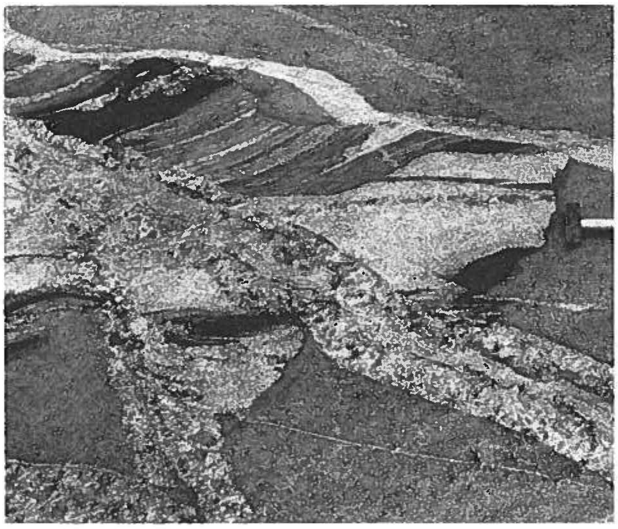


Fig. 61. Inclusions in the Qôrqut granite, Godthåbsfjord.

either under static conditions (as in the southern part of the Fiskenæsset area) or in distinct linear belts (as in Godthåbsfjord). Granitic intrusions ranging from major bodies such as the Qôrqut granite to pegmatites and minor dioritic plugs a few hundred square metres in outcrop were emplaced during this period of final stabilisation of the Archaean craton.

Qôrqut granite

The Qôrqut granite (McGregor, 1973) forms an elongate body, parallel to the regional structure, 50 km long and up to 18 km wide (fig. 11). It appears to have been emplaced in the core of a broad NNE–SSW trending antiform, and a Rb-Sr mineral isochron from a pegmatite associated with the granite indicates an age of emplacement of about 2600 m.y. (Pankhurst *et al.,* 1973 b). The eastern border of the granite fingers out into the country rocks as a number of gently dipping sheets, whereas the western contact is steep and discordant. To the south-west, the granite is fringed by a large number of gently dipping granite and pegmatite sheets which extend for 50 km south-westwards until their outcrop is cut off by the sea at Færingehavn (Chadwick *et al.,* 1974 a).

Large areas in the central part of the pluton consist of homogeneous granite, but elsewhere there are complex migmatites containing many rotated and partly granitised rafts and inclusions of country rocks (fig. 61). At many places in its southern part, the granite consists of two phases in addition to pegmatites, a grey phase richer in biotite, cut by a paler, coarser grained phase. The grey granite formed large, homogeneous masses before it was intruded by the pale granite. A network of gently dipping sheets of granite and pegmatite cut the country rocks around the granite. They are most conspicuous near its roof, exposed on the north coast of Ameralik and on the high peaks inside the eastern boundary (fig. 62). These sheets increase in density and thickness downwards, the rafts of country rock between them retaining their original orientation well down into the granite.

The Qôrqut granite is thus a complex body, which is relatively finer grained and richer in potash feldspar than most of the other rocks in the Godthåb area. It has a relatively restricted range of composition with equal amounts of quartz, plagioclase and microcline, and minor biotite.

South-East Greenland

In South-East Greenland Bridgwater & Gormsen (1969) noted the presence of late to post-tectonic granodiorite-granite complexes on the north coast of Umîvik and close to Tingmiarmiut weather station (fig. 4). These complexes are intrusive into the banded gneisses and appear to be later than the granulite facies metamorphism which locally affects the layered rocks. They locally have nebulitic margins with the surrounding gneisses which show a gradual loss of structure as the contacts are approached. Away from the contacts the intrusions are seen to be made up of several cogenetic phases between which contacts are cuspate (fig. 63). The Umîvik body is associated with a thin sheet of oligoclase-epidote-muscovite rock with corundum phenocrysts (plumasite). The body is clearly intrusive into the earlier banded gneiss which it cuts at a high angle to the foliation

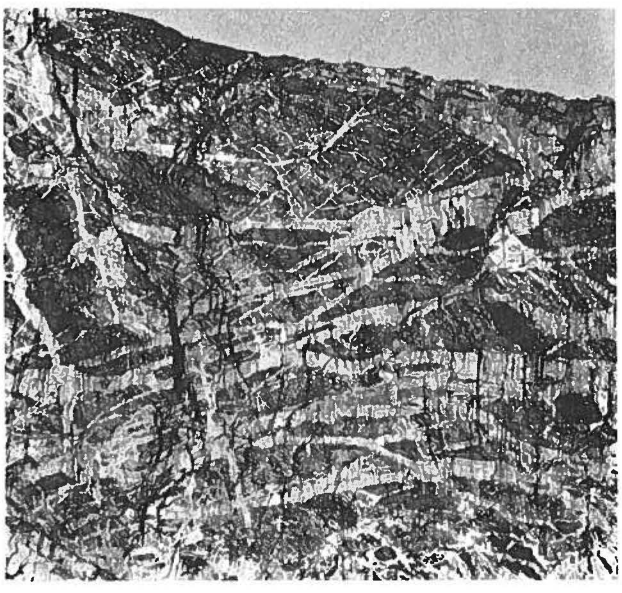


Fig. 62. Gently dipping sheets of granite and pegmatite above the roof of the Qôrqut granite. Godthåbsfjord.

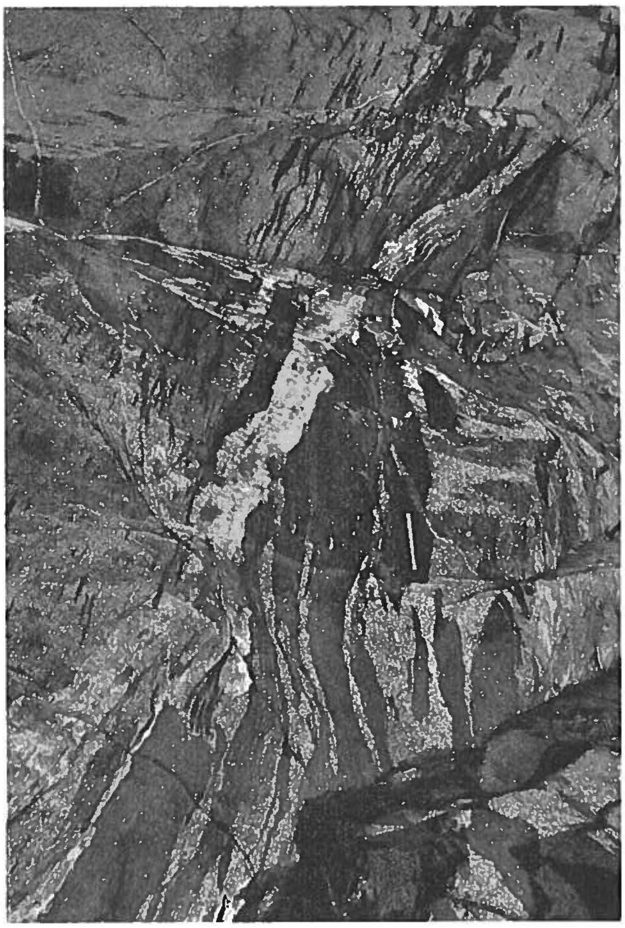


Fig. 63. Sheared basic enclaves in a late tectonic Archaean granite, Umîvik, South-East Greenland.

Tartoq Group and Sarfartûp nunâ supracrustals

Tartoq Group

The Tartoq Group are upper greenschist to low amphibolite facies greenschists and outcrop on either side of Sermiligârssuk between Ivigtut and Frederikshåb (figs 4, 65) (Higgins & Bondesen, 1966; Higgins, 1968; Berthelsen & Henriksen, 1975). They occur as refolded synforms and slices locally repeated by isoclinal folding, and over 2 km thick, interlayered with Archaean gneisses which had already passed through a complex structural and metamorphic history (fig. 66).

Contacts with the surrounding gneisses are highly deformed and have been the site of considerable granitic intrusion. They are enclosed by a zone of migmatites and agmatites, locally several kilometres wide, in which inclusions of the Tartoq Group occur within a quartzo-feldspathic matrix. The boundary was also complicated by later deformation, which impressed a foliation on the migmatites and rendered them difficult to distinguish from the surrounding gneiss complex. Slices of the supracrustals and the marginal migmatites were also detached by thrusting and interleaved with the surrounding gneisses.

No isotopic age determinations are available from the Tartoq Group. The granitic activity and meta-

(fig. 64). The marginal 10 cm are finer grained than the centre and do not contain corundum phenocrysts. The origin of this extremely aluminous intrusive body is unknown.

Smaller bodies of diorite and granodiorite postdating the regional foliation but cut by dolerite dykes are reported from many areas within the craton suggesting that plutonism continued over a wide area after the end of major deformation.

Pegmatites

Major swarms of pegmatites were injected throughout the Archaean complex, many of them probably during the same period of activity as the emplacement of the Qôrqut granite. In Nordlandet Macdonald (1974) has distinguished four distinct generations which all cause local retrogression of the granulite facies rocks, and are locally associated with shear zones.

Fig. 64. Discordant sheet of corundum bearing plagioclase-muscovite-epidote rock (plumasite) cutting Archaean gneisses. Nansens Bugt, Umîvik, South-East Greenland.

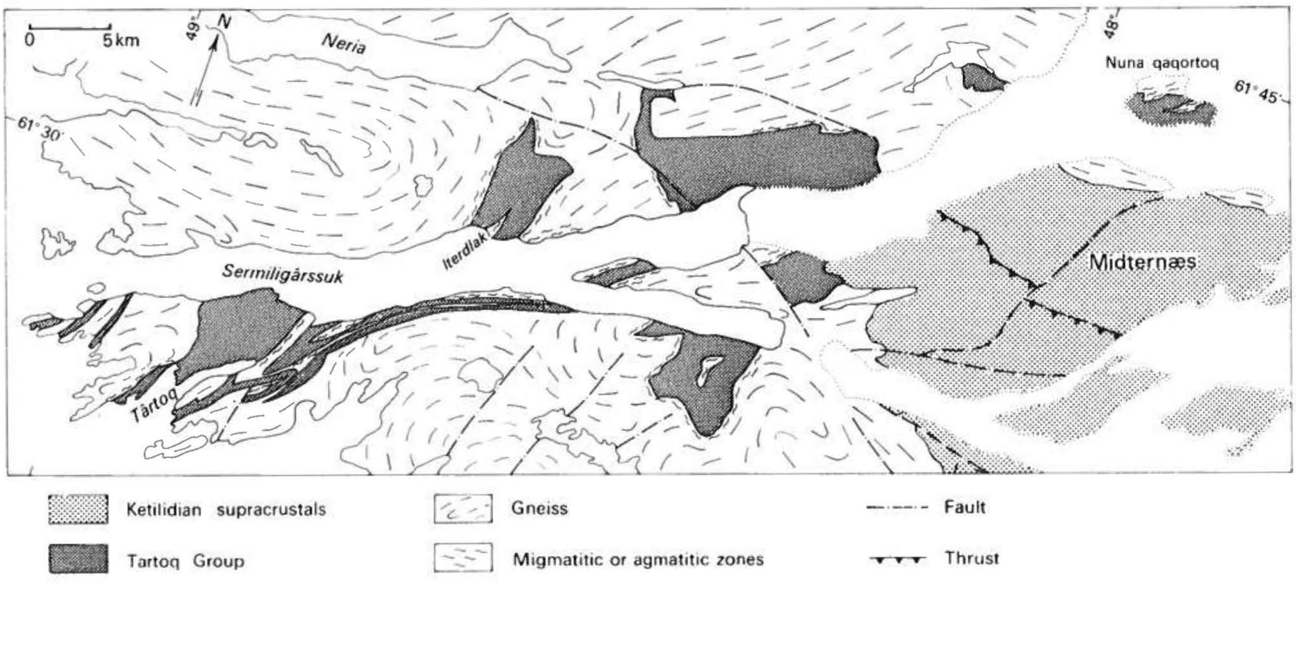
morphism affecting them has a minimum (K-Ar) age of approximately 2500 m.y. The group is cut by basic dykes which are affected by Ketilidian (*c.* 1800 m.y.) metamorphism and is overlain by Ketilidian sediments and lavas (see Allaart, this volume). It was considered that these supracrustal rocks were younger than the majority of gneisses which surround them because of their relatively low metamorphic grade. This would imply that the Tartoq Group was deposited at some time between 2500 m.y. and 3000 m.y. ago. However, it is also possible that the Tartoq Group is an allochthonous sequence of low grade rocks of any age older than 2500 m.y. which had been thrust over complexly folded gneisses.

The Tartoq Group consists largely of basic volcanic rocks interlayered with quartzitic units, with minor calcareous layers and ultrabasic bodies. Because of the fragmented nature of the outcrops a complete stratigraphy has not been worked out. Berthelsen & Henriksen (1975) describe a type section of the group 2000 m thick, on the south side of Sermiligârssuk near Târtoq fjord. There the structurally lower 1000 m of the succession consists of quartz-rich schists intercalated with basic volcanic units. This is overlain by a dominantly basic unit 1000 m thick with locally well-preserved quartz tholeiitic pillow lavas. The shape of the lava pillows locally suggests that the succession is the right way up.

The quartz schists include rusty brown weathering calcareous schists containing talc and chlorite as well as carbonate and quartz, and pale coloured and sometimes banded micaceous or talc-bearing quartzites. Individual units may form layers up to 60 m broad but many thin out laterally to form lenses. Similar units are described by Higgins (1968) from north and east of Sermiligârssuk. Here the quartzitic rocks are locally associated with calcareous units including one thin layer of almost pure dolomite, and with a highly deformed conglomerate with quartzite pebbles (fig. 67). The quartzitic rocks are interpreted as derived from siliceous sediments and tuffs possibly interlayered with acid volcanic flows and shallow intrusives. Relict primary textures suggest that the basic rocks represent a mixed suite of pillow lavas, tuffs, pyroclastics and some gabbroic sills. Ultrabasic rocks occur as sills up to 25 m thick and as rows of lenses and pods. The contacts are generally concordant but in places can be seen to cut across earlier structures in the surrounding greenschists. They are regarded as igneous bodies emplaced within the supracrustal rocks before they were deformed (Weidmann, 1964).

Some of the quartzitic units contain augen of feldspar and quartz set in a matrix of quartz, feldspar, chlorite, muscovite and epidote. Other quartzitic schists described by Higgins lack the augen structures and consist largely of quartz with some biotite, muscovite, epidote and a little tourmaline. The basic rocks show a range in mineral assemblages from one area to another. The main mineral assemblages reported are: epidote–chlorite–actinolite–sphene–sodic plagioclase–quartz; hornblende–epidote–biotite–almandine–plagioclase–quartz; hornblende–chlorite–biotite–calcite–sphene–epidote–plagioclase–quartz. Apatite, opaque minerals, muscovite, allanite and tourmaline are found as accessories.

Fig. 65. Sketch map showing distribution of the Tartoq Group in the Sermiligârssuk–Midternæs region (modified after Higgins, 1968).



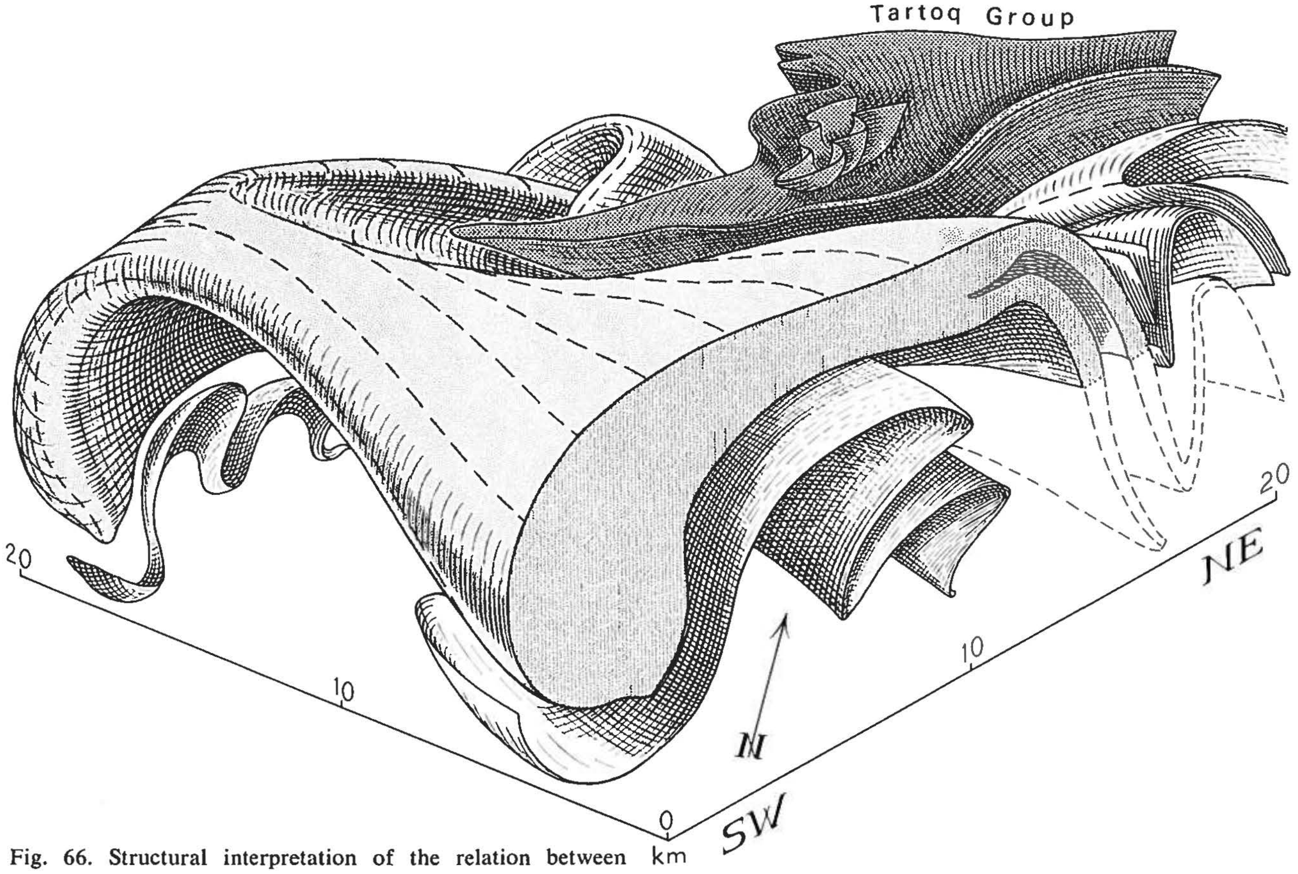


Fig. 66. Structural interpretation of the relation between the Tartoq Group and the underlying early Archaean gneisses (modified from Berthelsen & Henriksen, 1975).

The ultrabasic rocks are all serpentinised with serpentine, talc, chlorite, carbonates and oxides. Primary igneous layering is locally preserved outlined by concentrations of magnetite in distinct layers. Reaction zones are found along the contacts of the ultramafic bodies with the formation of talc-actinolite and biotite.

Sarfartûp nunâ supracrustals

This group of late Archaean supracrustal rocks occurs at Sarfartûp nunâ, 8 km north of Sukkertoppen ice cap, 15 km north-west of the southern margin of the Nagssugtoqidian belt (Diggens & Talbot, 1974). They are greenschist to low amphibolite facies schists and occur in an east–west trending synformal basin 15 km² in area overlying Archaean gneisses which are modified by Nagssugtoqidian shearing. The succession is a layered sequence of actinolite schist, actinolite-chlorite schist, tremolite-calcite schist and chlorite-muscovite phyllite, with sills and dykes of garnet amphibolite. A large metamorphosed ultrabasic sill up to 200 m thick occurs at or near the base of the succession. The succession is repeated by several low-angle thrust faults. Diggens & Talbot suggest that the original thickness of the units preserved was about 300 m.

The actinolite schists outcrop as lensoid bodies and locally show relict pillow lava structures. They interfinger with actinolite-chlorite schists which possess relict pillow breccia structures. Interbedded tremolite-calcite schists and chlorite-muscovite phyllites locally preserve primary tuffaceous textures, and, al-

Fig. 67. Deformed quartzititic pebbles in the Tartoq Group.

though frequently less than 5 m thick, individual layers can be traced for over 1 km.

The supracrustal rocks are cut by two generations of garnet amphibolite dykes. The earlier suite appears to be partly coeval with some of the metavolcanic horizons, and at several localities dykes of coarse-grained garnet amphibolite can be seen to turn into sills (locally with igneous compositional banding). These in turn merge laterally into actinolite schists with pillow lava structures.

The outcrop of supracrustal rocks is interpreted by Diggens & Talbot as a complex refolded klippe resting on a sole thrust and made up of nine individual thrust slices of metavolcanic rock. The klippe has been refolded with the underlying higher grade basement. Both are preserved as a less deformed eye structure within the marginal shear belts of the Nagssugtoqidian mobile belt (see Escher *et al.*, this volume). The age of these supracrustal rocks is unknown but they are tentatively regarded as younger than the regional deformation which produced the layered nature in the Archaean gneisses and younger than or contemporaneous with the Kangâmiut dykes.

Structural history

The structural evolution of the Archaean block can be divided into four main stages:

(a) early vertical movements;
(b) sub-horizontal movements (nappes and thrusts);
(c) formation of dome and basin interference patterns, and straight belts;
(d) late shear movements and faulting.

Locally stages (b) and (c) can be subdivided into different episodes of deformation. The effects of individual episodes vary markedly from area to area and from one lithological unit to the next, so that rocks which preserve evidence of the earliest stages in the structural development of the complex are found adjacent to gneisses in which all evidence of the early structures has been obliterated by later movements. Zones of intense deformation once established show a tendency to be reworked during subsequent deformation episodes. Correlation of individual episodes of deformation, or even the major stages, can be problematical in the same way as there are uncertainties in making regional lithological correlations.

Early vertical movements

The earliest major structures which survive occur at Isua. The largest structure is a partial dome of Amîtsoq gneiss rimmed by a semicircular belt of steeply dipping supracrustal rocks (fig. 6). Steeply plunging linear features in the belt suggest that major movements were vertical and the structures are regarded as similar to those described from other early Archaean terrains such as in Rhodesia (MacGregor, 1951). Structures of this type may be produced when masses of granite (either reactivated basement or newly derived sialic material) move upwards into horizontal layered rocks.

The Isua area is unique in that it is the only known part of Greenland to have escaped major deformation after the injection of the Ameralik dykes. There is no evidence of the formation of similar structures later in the history of the Greenland Archaean, between, for example, the Malene supracrustal suite and either Amîtsoq gneisses or early phases of the Nûk granitic suite. It is possible that structures of this type may have been more widespread but have been destroyed by younger deformation of the type described below.

Sub-horizontal movements (nappes and thrusts)

The main structural feature of the Greenland Archaean gneiss complex, which is apparent on regional maps (figs 33, 60), single outcrops and in the majority of hand samples, is the predominance of layered rocks. Layering occurs on all scales from discontinuous millimetre thick lamellae to alternating lithologies over a kilometre thick. Most of the layering may be a result of interleaving of rocks of different age and geological provenance by a combination of magmatic injection and major tectonic transport (fig. 24), or the result of intense deformation of original inhomogeneities in the rocks such as pillow lava structures (figs 26, 27, 29), large igneous crystals (figs 15, 16, 45–51), inclusions (figs 41, 42, 53, 63) pegmatites and cross-cutting veins and dykes (figs 14, 21), which were streaked out into concordant attenuated lenses and layers. Alternatively it may be due to rapid changes in the degree of deformation from place to place and within one outcrop (figs 45, 46), so that originally homogeneous rocks become layered gneisses in which deformation was concentrated in distinct zones, leaving septa of much less highly deformed material between them. Once established tectonic layering of this kind generally controlled the lines of metamorphic segregation and the injection of pegmatites, which further emphasised the tectonic layering.

Most rocks of the Archaean gneiss complex are very strongly deformed and direct evidence for the formation of the layering by a combination of thrusting and nappe tectonics is recorded from many parts of the complex. In the Godthåbsfjord region McGregor (1973) distinguished between an early phase of sub-horizontal thrusting which intercalated Malene supracrustal units of various lithologies with Amîtsoq gneisses, separated from a later phase of nappe formation and the injection of sub-horizontal granite sheets. The main evidence for the early formation of thrusts is that individual units of Amîtsoq gneiss and Malene supracrustals wedge out laterally and so on a regional scale contacts are commonly discordant to lithologies. Similar arguments to those put forward by McGregor apply to many parts of the Archaean gneiss complex although direct evidence for individual thrust planes is generally lacking. Contacts between supracrustal rocks and gneisses in the Angmagssalik area (Andrews *et al.*, 1973; Wright *et al.*, 1973) are often regionally discordant to lithologies in the supracrustal rocks. In many places in the Fiskenæsset region the detailed stratigraphy of the anorthosite complex can be seen to be cut out or repeated by thrusts subparallel with the igneous layering.

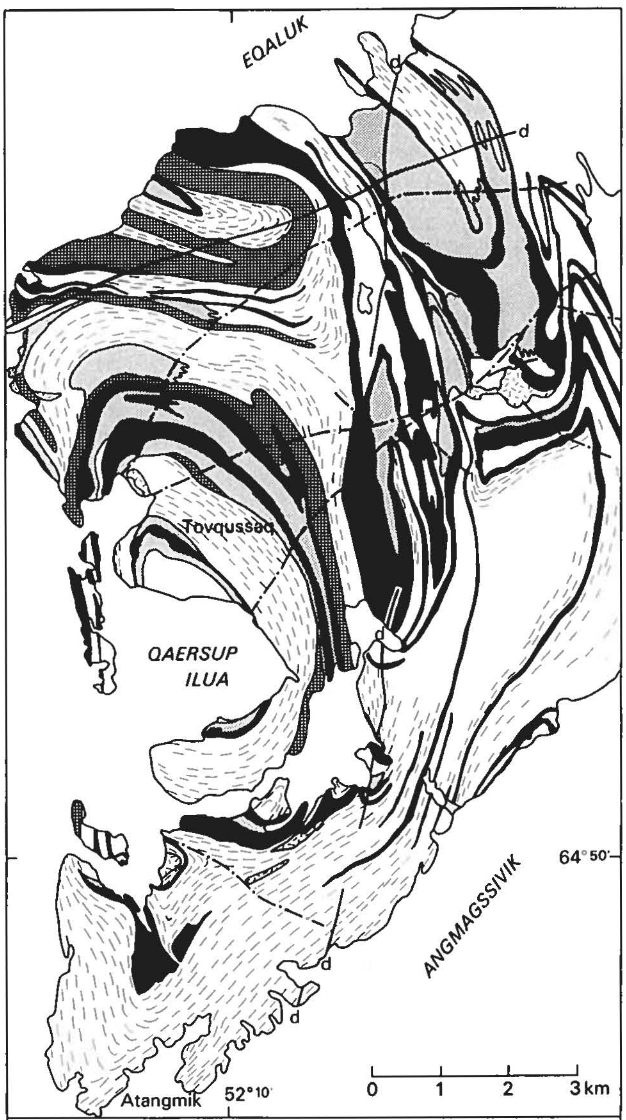
There is widespread evidence of the formation of major recumbent isoclinal folds or nappes during or directly after the injection of the Nûk gneisses and similar rocks. In the Godthåbsfjord region the Amîtsoq gneisses, Malene supracrustals, anorthosites and Nûk gneisses were all folded together as a single layered sequence in a series of recumbent folds (McGregor, 1973) (fig. 13). Many of the resultant folds are extremely attenuated. Fold limbs defined by tracing individual layers of Malene supracrustal rocks can be followed for several tens of kilometres. Elsewhere in the gneiss complex the earliest major structures recognisable are a series of recumbent isoclinal folds, which may have originated as nappes (Berthelsen, 1960, 1972; Berthelsen & Henriksen, 1975; Kalsbeek & Myers, 1973; Chadwick *et al.*, 1974b).

Dome and basin interference patterns and straight belts

The widespread formation of thrust sheets and nappes which preceded and followed the intrusion of the Nûk gneisses and their equivalents about 3000 m.y. ago, led to formation of a gneiss complex with dominantly horizontal layering. This was subsequently refolded twice by folds with axial surfaces at high angles to each other and formed dome and basin interference patterns over wide areas (figs 3, 33, 60, 68). This sequence is most clearly seen in the Fiskenæsset region (Kalsbeek & Myers, 1973) where the primary way up of the anorthosite layers enables the facing directions of the first formed nappe-like, recumbent isoclinal folds to be determined (figs 33, 35).

In most areas at least two major phases of upright folding are recognised after the formation of the regional flat-lying structures. In general the earlier phase is characterised by a more plastic style of deformation than the later. No strict correlation of the

Fig. 68. Map of the Tovqussaq dome (from Berthelsen, 1960, plate 4), at Tovqussaq nunâ (fig. 60).



individual fold phases producing the interference patterns in different parts of the gneiss complex is possible, partly because regional mapping is not yet complete and partly because the axial directions of individual fold phases change markedly from area to area even when they are not seen to have been affected by later fold phases. Variations in competence may give rise to two types of structures formed essentially at the same time: (1) dome and basin type of interference patterns seen in the Nordlandet and north-west Fiskenæsset areas (figs 33, 60), and (2) 'straight belts' of extreme deformation which can be followed along strike for tens of kilometres. The latter occurs in the Godthåbsfjord and Buksefjorden regions (McGregor, 1973; Chadwick *et al.,* 1974a), and near Skjoldungen in South-East Greenland (Andrews *et al.,* 1973) where a particularly marked linear structure trends at approximately 120° parallel to the main fjord direction (fig. 4). These 'straight belts' vary from a few centimetres to 5–10 km wide. Lineations and elongated inclusions found within the belts are commonly sub-horizontal. Many of the belts of high deformation occur in steep limbs of folds which are the youngest of the two sets which formed the regional interference patterns. Most major 'straight belts' trend either NE or SE.

The deformation which gave rise to the interference patterns and the formation of the major 'straight belts' occurred some time after the emplacement of the Nûk granite suite but before or locally during the culmination of regional metamorphism at about 2800 m.y. ago. In a few places in the Fiskenæsset region the formation of the two main phases of folding which gave rise to the interference patterns was accompanied by growth of hypersthene parallel to the fold axes, but most tectonic fabrics associated with those folds are in amphibolite facies and are older than the 2800 m.y. old granulite facies metamorphism which affected a small area close to Fiskenæsset.

The change from a plastic type of deformation seen in the formation of the nappe-like, recumbent isoclinal structures, to deformation in distinct zones, some of which show signs of more brittle deformation styles, may represent a gradual drying out of the gneiss complex as granulite facies conditions were reached. This can be seen during the last major fold episode in the Fiskenæsset region where ductile folds in amphibolite facies are replaced westwards by shear zones and then by faults in the granulite facies area near Fiskenæsset (Myers, in press b).

Late shear movements and faulting

This section includes shear zones and faults which post-date the 2800 m.y. old granulite facies metamorphism. Many of these movements took place within NE and SE trending belts of high deformation whose position had been established before the granulite facies event. In the Godthåbsfjord region movements probably continued within the belt of amphibolite facies rocks extending north-east from Godthåb town at the same time as the rocks in Nordlandet 10 km across strike were recrystallising under essentially static granulite facies conditions. Late deformation continued to emphasise older regular strikes and strong sub-horizontal linear fabrics in the area around Godthåb itself. Movement is thought to have continued along this zone until the intrusion of the Qôrqut granite about 2600 m.y. ago. In Nordlandet intermittent movements, separated by different phases of granite injection and remobilisation, continued in zones parallel to the regional NE strike both during and after the granulite facies metamorphism. In southern Nordlandet late movements along these structures resulted in retrogression of the granulite facies gneisses (Macdonald, 1974). Elsewhere, movement in NE trending belts of high deformation led to the formation of plutonic mylonites (Watterson, 1968 b).

The NE and SE trending zones of weakness established before 2800 m.y. ago remained dominant zones of wrench faulting after the end of plutonic activity in the Archaean gneiss complex. The faulting was accompanied by the local growth of upper greenschist facies minerals in the fault zones (Berthelsen & Bridgwater, 1960), suggesting that the gneiss complex remained at a moderately high temperature for some considerable time after the end of the major plutonic events. The general pattern of late movements within the Archaean block is similar to that seen in the Nagssugtoqidian mobile belt to the north and it is probable that the major tectonic control was the same for both areas.

Intrusions cutting the Archaean complex

The Archaean gneiss complex was intruded by at least eight regional swarms of basic dykes. The dyke swarms were emplaced in the period after the end of regional plutonic activity at about 2700–2500 m.y. ago but before major plutonic and tectonic activity in the Nagssugtoqidian and Ketilidian mobile belts, respectively to the north and south of the Archaean complex. The dykes have been used as markers separating Archaean and Proterozoic plutonic activity (see A. Escher *et al.*, 1975; Allaart, this volume). No strict correlation of the major swarms throughout the craton has yet proved possible; firstly because there are comparatively large areas only mapped during reconnaissance work, and secondly because individual swarms die out or change direction along the strike. Scattered swarms of later Precambrian and Phanerozoic dykes have been identified from the Archaean gneiss complex of both South-West and South-East Greenland.

Direct isotopic measurements of the age of intrusion of the late Archaean – early Proterozoic basic dyke swarms are so far unreliable because of considerable excess argon (Bridgwater, 1970). This problem is thought to be connected with the slight regional metamorphism recorded from many parts of the craton at about 1700 m. y. (Rb-Sr mineral determinations; Pankhurst *et al.*, 1973 b). Many of the dykes show signs of slight recrystallisation which may either be due to a late metamorphism about 1700 m. y. ago or possibly due to continued high temperature gradients throughout the late Archaean – early Proterozoic.

Early Proterozoic dykes between Ivigtut and Fiskefjord ('MD' dyke swarms)

The basic dyke chronology in the southern part of the Archaean craton in West Greenland is well documented and the main mineralogical and chemical features of individual dykes have been studied (Henriksen, 1969b; Rivalenti & Sighinolfi, 1971; Williams, 1973). As a group they are younger than the 2600 m.y. Qôrqut granite and older than the oldest Ketilidian supracrustal rocks recognised from this part of Greenland. Towards the southern part of the Archaean block they show the progressive effects of Ketilidian metamorphism (Bondesen & Henriksen, 1965) and they have been collectively given the name 'MD' (metadolerite) in many reports, even from areas in which the dykes are not metamorphosed.

Four main sets of basic dykes have been recognised between Ivigtut and Fiskefjord; correlations between the dyke sets are well established south of Godthåbsfjord but further north they are more tentative.

Early east–west dykes

The earliest post-tectonic dykes recognised in West Greenland are a sporadic group of E–W dolerite dykes which occur singly in the Ivigtut area around Tigssalûp ilua (Henriksen, 1969b), in the coastal part of the Frederikshåb area (Preston, 1969), and to the north of Fiskefjord (Berthelsen & Bridgwater, 1960).

The Ivigtut dykes vary between 10 and 50 m wide while those from the Frederikshåb area are thinner. Most of the suite are recrystallised and no chemical or mineralogical details are available. In the Fiskefjord area these dykes can be traced for at least 30 km along strike, they vary between 7–10 m and 20–25 m wide and show many *en echelon* and *en bayonet* features (Berthelsen & Bridgwater, 1960). The dykes show major differences in bulk composition due to highly variable contents of mafic minerals as phenocrysts. The chilled contact of one dyke contains approximately 75 per cent mafic minerals, mainly clinopyroxene. Orthopyroxene is locally present. Both plagioclase and olivine are commonly full of small 'dusty' inclusions.

North–south dykes (MD_1)

Olivine dolerite dykes which trend from 150° to 010° form a remarkably persistent but scattered swarm in West Greenland. Individual dykes can be traced for many tens of kilometres, and vary in thickness from a few metres to 150 m. The swarm as a whole may extend for 500 km along strike if correlations are accepted between Fiskefjord and areas further south. Dykes with similar trends, position in the local chronology, and petrological peculiarities have also been noted from South-East Greenland (Andrews *et al.*, 1973).

The MD_1 dykes were emplaced along shear zones (Chadwick, 1969) which have locally been reactivated after dyke injection. Many dykes bifurcate and rejoin, sometimes filling a pre-existing fracture pattern as a series of individual small dykelets which can be traced as a more or less continuous straight line (Berthelsen & Bridgwater, 1960). Most have sharp chilled contacts.

The MD_1 dykes show considerable variation in textures, mineralogy and bulk composition near Fiskefjord. They range from ultramafic with 90 per cent orthopyroxene, olivine and clinopyroxene phenocrysts, to dolerite with augite and pigeonite as the main mafic minerals.

The variations in composition are controlled by two factors: the amount of mafic material present as phenocrysts at any one point in the dyke and the degree of differentiation which the surrounding material had reached at the time of solidification. The marked variations in the amount of early mafic minerals present from one dyke to another largely control the bulk chemistry of the rocks. Available analyses (Henriksen, 1969b; Rivalenti & Sighinolfi, 1971; Williams, 1973; GGU unpublished data), show that the suite as a whole is characterised by marked iron enrichment, and generally low potassium and titanium contents, which increase markedly in rocks containing a high proportion of late crystallising fractions. They are regarded as continental tholeiites which have undergone considerable crystallisation prior to and during their injection.

NE-trending dykes (MD_2)

The suite of MD_2 dolerite dykes contains more than one generation of intrusion and shows considerable variation in its dominant trend, both regionally and within comparatively small areas, and locally may become sill-like bodies with low dips. MD_2 dykes in any one area may fan out with trends varying from almost north–south to east–west (Jensen, 1962).

There is no evidence that all the dykes described as MD_2 dolerites were emplaced during the same period of magmatism. However, they are grouped together because they show the same relation to the major faults cutting the Archaean block and broadly similar petrological features.

The MD_2 dykes range from a few centimetres wide to major gabbroic intrusions over 300 m across which can be traced for tens of kilometres along strike (Rivalenti & Rossi, 1972). In some regions they occur in pairs or parallel networks (Chadwick, 1969), in others they occur singly or *en echelon* with a large number of smaller dykes leaving the main bodies where they terminate or change direction abruptly. Large dykes may be discontinuous when followed along their trend but are often joined by a network of smaller intrusions.

The MD_2 dykes post-date wrench movements on major faults such as the Fiskefjord fault and the wrench faults affecting the earlier MD_1 dykes in the Frederikshåb area. They are locally sheared by renewed activity along these earlier fault planes and may be displaced by later movements along the larger faults (for example the Kobbefjord fault near Godthåb (figs 11, 13) (McGregor, 1973).

Most of the MD_2 dykes are ophitic or subophitic and contain augite as the main mafic mineral with subordinate olivine in the chilled margins and rarely hypersthene or pigeonite rimmed by augite. They locally contain calcic labradorite megacrysts or aggregates sometimes concentrated in the centres or along one margin. Many of the dykes are slightly altered and appear green in outcrop. This contrasts with the earlier MD_1 dykes from the same areas and appears to be a late magmatic phenomenon. Analyses of the MD_2 dykes (Rivalenti & Sighinolfi, 1971; Henriksen, 1969b; Williams, 1973) show them to be tholeiitic with marked iron enrichment differentiation trends and moderately low potassium and high titanium contents compared to present day continental tholeiites. Where affected by the faults the dykes are recrystallised with greenschist facies or even low amphibolite facies mineral assemblages.

SE-trending dykes (MD_3)

The youngest regional swarm of late Archaean to early Proterozoic basic dykes generally trends between 090° and 140°. These dykes cut the earlier MD_2 dykes and are petrologically identical with them. MD_3 dykes in the Ivigtut and Frederikshåb areas locally contain major accumulations of plagioclase phenocrysts (Bondesen & Henriksen, 1965). Chemically the MD_3 dykes are mainly continental tholeiites with marked iron enrichment trends. They possibly show slightly more advanced stages in differentiation than the MD_2 swarms (Rivalenti & Sighinolfi, 1971).

Early Proterozoic dykes in the Sukkertoppen – Søndre Strømfjord area (Kangâmiut dyke swarm) and equivalents in South-East Greenland

The northern part of the Archaean block in both East and West Greenland is cut by a closely spaced basic dyke swarm which extends as far south as Sukkertoppen on the west coast and the southern shore of Gyldenløves Fjord on the east coast (Bridgwater, this volume). Two main generations have been recognised on the west coast: south of the Nagssugtoqidian boundary an early, sparsely distributed E–W swarm of olivine norites and a younger much more abundant swarm trending approximately NNE. The relations between the Kangâmiut dyke swarm and the MD dyke swarm south of Godthåb is uncertain. It is assumed in this account that all the major doleritic dyke swarms were emplaced after the intrusion of the Qôrqut granite and are thus younger than 2600 m. y. There is some evidence, particularly near the northern boundary of the Archaean block, that the dykes were emplaced under high grade metamorphic conditions (Bridgwater *et al.*, 1973a, b; Watterson, 1974). If this metamorphic event corresponds to the regional 2800 m.y. granulite facies metamorphism found in the Archaean block, this correlation would no longer be satisfactory and the major dyke swarms north of Fiskefjord would then be older than the Qôrqut granite (Bridgwater & McGregor, 1974 a).

East–west Kangâmiut dykes

The oldest set of Kangâmiut dykes correspond petrologically with olivine and hypersthene-bearing dykes from the Fiskefjord area and are tentatively correlated with them. Comparable mafic-rich dykes are abundant in the border zone of the Nagssugtoqidian mobile belt in South-East Greenland.

NNE Kangâmiut dykes

The main NNE-trending Kangâmiut dyke swarm which is a spectacular feature of the geology along the border of the Nagssugtoqidian mobile belt (Escher *et al.*, 1975; this volume) was emplaced during active shear movements along fractures trending parallel to the dykes. These movement zones are thought to belong to the same wrench fault system as the Fiskefjord and Kobbefjord faults to the south (figs 11, 60) (Berthelsen & Bridgwater, 1960, fig. 2).

The NNE Kangâmiut dykes are younger than scattered dykes trending at 160° north of Sukkertoppen, which Berthelsen & Bridgwater (1960) regard as the possible northern continuation of the Fiskefjord MD_1 swarm. Most of the dykes range between 10 and 50 m wide, a few measure over 100 m in width. Many can be traced for tens of kilometres along strike. Individual dykes may show sudden changes in strike, and intersections between different generations within the same set are common. Many of the dykes send out apophyses into the surrounding country rock. Petrologically the dykes of the NNE swarm all appear to have crystallised from wet basaltic magmas but show a considerable range in composition. The main factors controlling these variations appear to be the relative timing of injection and speed of crystallisation compared to the timing and amount of movement along the dyke fissure during crystallisation.

Three main varieties of NNE dykes are distinguished in the field.

(1) *Normal dolerites or hornblende dolerites* with a marked ophitic texture and little or no internal structure. Compositionally these are water-rich, potassium-poor tholeiites or quartz tholeiites with moderately high titanium contents compared to the MD_2 swarms further south. Locally these dolerites contain pockets or small irregular patches of more leucocratic material with biotite, quartz and garnet. They appear to be earlier than varieties (2) and (3) described below.

(2) *Layered garnet amphibolites.* The Kangâmiut dykes exposed near Sukkertoppen show multiple intrusion features. They have outer margins of ophitic hornblende dolerite with microliths of plagioclase, hornblende and pigeonite with small scattered garnets in the groundmass, and inner margins of subophitic hornblende-quartz dolerite with a little biotite and slightly more garnet than in the chilled margins. The margins are similar to many of the hornblende dolerites of group (1). The centres of the dykes consist of a variety of alternating layers ranging from weakly to highly foliated hornblende-rich quartz dolerite, and from homogeneous to highly foliated garnet amphibolite.

There is a marked increase in garnet, biotite and quartz from marginal to central zones, and a complementary decrease in the proportion of pigeonite compared to hornblende present reflected by a very strong enrichment in iron from margin to centre (Windley, 1970a) which is even more marked than that seen in the MD dykes further south.

(3) *Composite dykes* with quartz-albite-biotite-garnet centres. North of Sukkertoppen several of the major Kangâmiut dykes show a very marked zoned structure. The margins of these composite intrusions consist of hornblende dolerite followed by interlayered amphibolite and hornblende dolerite of the type described above. These are followed in turn by major units of quartz-albite-biotite-garnet-hornblende rocks or quartz-albite-biotite rocks. The central albite granitic zones may be over 20 m wide and fill half the dyke fissures. They range from homogeneous rocks to rocks with marked foliation and strong fissility parallel to the margins of the dykes. Contacts between the outer more basic rocks and the leucocratic rocks of the central zones are generally abrupt and irregular. The leucocratic centres in individual dykes persist for a considerable distance along strike and in many dykes the total volume of albite-quartz rock exposed is at least as great as the basic margin. There is no sign of the quartzo-feldspathic material being derived from rheomorphism of the surrounding country rocks (at least at the present erosion level) and the centres are regarded as cogenetic with the margins. If some form of filter-press action is invoked to produce the leucocratic rocks during the syntectonic injection of the dykes (cf. Watterson, 1968 a) then it must be assumed that more ultrabasic rocks occur at depth.

Early Proterozoic diorites, carbonatites and olivine lamprophyres (c. 1900 m.y.)

The gneiss complex immediately north of the boundary of the Ketilidian mobile belt in South-East Greenland was intruded by a suite of minor intrusions which post-date at least two generations of basic dykes representing the local equivalents of the MD dyke swarms, but are themselves affected by the marginal effects of the Proterozoic plutonic activity to the south.

The carbonatites in the suite are considerably variable in mode of occurrence and appearance. Near to Tingmiarmiut weather station they outcrop in gneiss as brown coloured areas a few metres across in which the original structures are preserved while the quartz and feldspar have been partially or completely replaced by carbonate. These carbonate-rich areas contain irregular masses of diopside, scapolite and magnesium olivine. The carbonatites also occur as thin, regular sills of buff, almost pure, carbonate rock, and as irregular, carbonate-rich masses associated with coarse-grained, hornblende-rich sheets (appinites) between 2 and 5 m wide often with marked crystal layering parallel to the margins. Associated lamprophyres are biotite-rich and contain olivine phenocrysts or pseudomorphs after olivine.

The age of these bodies is not known. They are probably related to the major appinitic intrusions within the Ketilidian mobile belt (Allaart, this volume) the nearest of which has given a U-Pb diffusion zircon age of 1845 m.y. (Gulson & Krogh, 1972).

Later intrusions

The 120° feldspar-phyric dykes (1650–1350 m.y.) The 120° trending dykes in the Frederikshåb–Ivigtut area can be followed as a well defined swarm approximately 9 km wide of fairly closely spaced thin dykes for over 120 km. In South-East Greenland equivalent dykes trending 150–180° are more widely spaced and individual dykes occur up to 50 m wide. They outcrop from as far north as Angmagssalik to Kap Farvel. Both sets of dykes are tholeiitic, contain scattered feldspar phenocrysts and are commonly slightly altered, particularly when they outcrop within the areas affected by Ketilidian metamorphism. They are thought to have been emplaced during the final phase of cooling in the Proterozoic mobile belts. K-Ar ages from these dykes in areas unaffected by Proterozoic thermal activity range from 1650 to 1350 m.y.

Gardar dykes (c. 1200 m.y.)
Gardar dykes form swarms of NE to ENE trending dolerite dykes, individually up to 100 m thick, as far north as 62°30′ in both South-West and South-East Greenland. They commonly show a characteristic brown weathering similar to that seen in the main Gardar dyke swarms further south (Emeleus & Upton, this volume). However, available chemical and mineralogical studies suggest that they are not so markedly alkaline as the Gardar basic rocks exposed in the type area of Gardar magmatism between Ivigtut and Julianehåb.

Phanerozoic kimberlites and associated carbonatites (c. 600–140 m.y.)
Kimberlites and associated carbonatite intrusions are found as sporadic swarms cutting the Archaean complex in West Greenland. They are particularly abundant near the Nagssugtoqidian boundary in West Greenland (Escher & Watterson, 1973). A large carbonatite ring dyke complex at Qaqarssuk south-east of Sukkertoppen has been mapped by Kryolitselskabet Øresund (fig. 60; Nielsen, this volume). A carbonatite-bearing fault fissure associated with this complex has yielded an upper Palaeozoic fossil (Poulsen, 1966). Further details of the chemistry and mineralogy of the kimberlites are given by Andrews & Emeleus (this volume). Isotopic age determinations vary between about 600 m.y. and 130 m.y. It is thought likely that these ages reflect the presence of more than one period of injection although there are considerable difficulties in obtaining a reliable age from any one intrusion.

Mesozoic and Tertiary dolerite dykes (160–50 m.y.)
A major swarm of alkali dolerites occurs in the southern part of the Archaean block in South-West Greenland. They are parallel to the coast and are probably related to the opening of Baffin Bay. These can be traced approximately 250 km from north of Frederikshåbs Isblink to Julianehåb (Watt, 1969). K-Ar ages from these intrusions range between 160 and 130 m.y. Scattered Tertiary basic dykes have been noted from Godthåbsfjord and near Tingmiarmiut in South-East Greenland (Bridgwater, 1970). The Godthåbsfjord dykes commonly show deuteric alteration and appear to be controlled by late movements along parallel trending faults.

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