PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

The Archaean Craton of the North Atlantic Region

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The Archaean craton of the North Atlantic region

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[Plate 7]

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The North Atlantic Archaean craton, exposed in parts of Greenland, Labrador and northwest Scotland, is a high-grade gneiss terrain which contrasts with Archaean granite–greenstone-belt terrains such as those of southern Africa. The tonalitic to granitic banded or agmatitic gneisses which occupy most of the craton are considered to be derived largely from granitic bodies emplaced within the crust. Early granitic gneisses of this type in Godthåbsfiord are at least 3800 Ma in age and it is suggested that a granitic basement of similar age extended over much of the craton. Most of this early basement was reworked and interleaved with metamorphosed supracrustal rocks, with layered anorthositic complexes and with abundant tonalitic gneisses derived from younger intrusions. Identifiable metavolcanics and metasediments, forming narrow belts in the gneisses, occupy less than 20% of the craton; they include highly-metamorphosed basic, ultrabasic and intermediate-acid volcanic rocks with associated intrusions and predominantly chemical sedimentary rocks. Clastic sediments are preserved in the lower part of the Isua supracrustal belt where they are overlain by banded ironstones and metavolcanics.

All these rocks suffered profound deformation and metamorphism which destroyed their primary relationships and culminated in the development of fold interference patterns without linear grain and in granulite or amphibolite-facies metamorphism ending at about 2800 Ma. Tectonic and metamorphic episodes over the next thousand million years were more localized and served to differentiate the Archaean craton from border-zones of early Proterozoic mobility.

1. Regional setting

The opening of the North Atlantic Ocean in Phanerozoic times fragmented and dispersed portions of an important Archaean province which had been defined as a cratonic geological entity some 2500 Ma ago. The object of this paper is to consider as an integral unit the remnants of this ancient craton which are now located along the Labrador coast of Canada, in East and West Greenland and in northwest Scotland. When regrouped (figure 1) they are seen to constitute a roughly triangular massif with sides 600 km in length which is enclosed by mobile belts of early Proterozoic age. Major parts of the mobile belts surrounding the old craton (for example the Baffin island 'Hudsonian', the Nagssugtoqidian of Greenland and the Laxfordian of Scotland) are composed of reworked Archaean material suggesting that the features now

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preserved in the old block may have been much more extensive than they are at present (Bridgwater & Windley 1972).

The central Archaean craton is dominated by gneisses of amphibolite or granulite facies and in many respects contrasts markedly with provinces of similar age, such as the nearby Superior province of Canada, which are dominated by an association of massive granitic rocks with weakly-metamorphosed supracrustal greenstone belts. In spite of the very high grades of metamorphism attained, the early history of the North Atlantic province can be established in some detail and in west Greenland this history can be taken back to 3800 Ma. Tectonic, igneous and metamorphic activity continued over almost the entire province and its border-regions

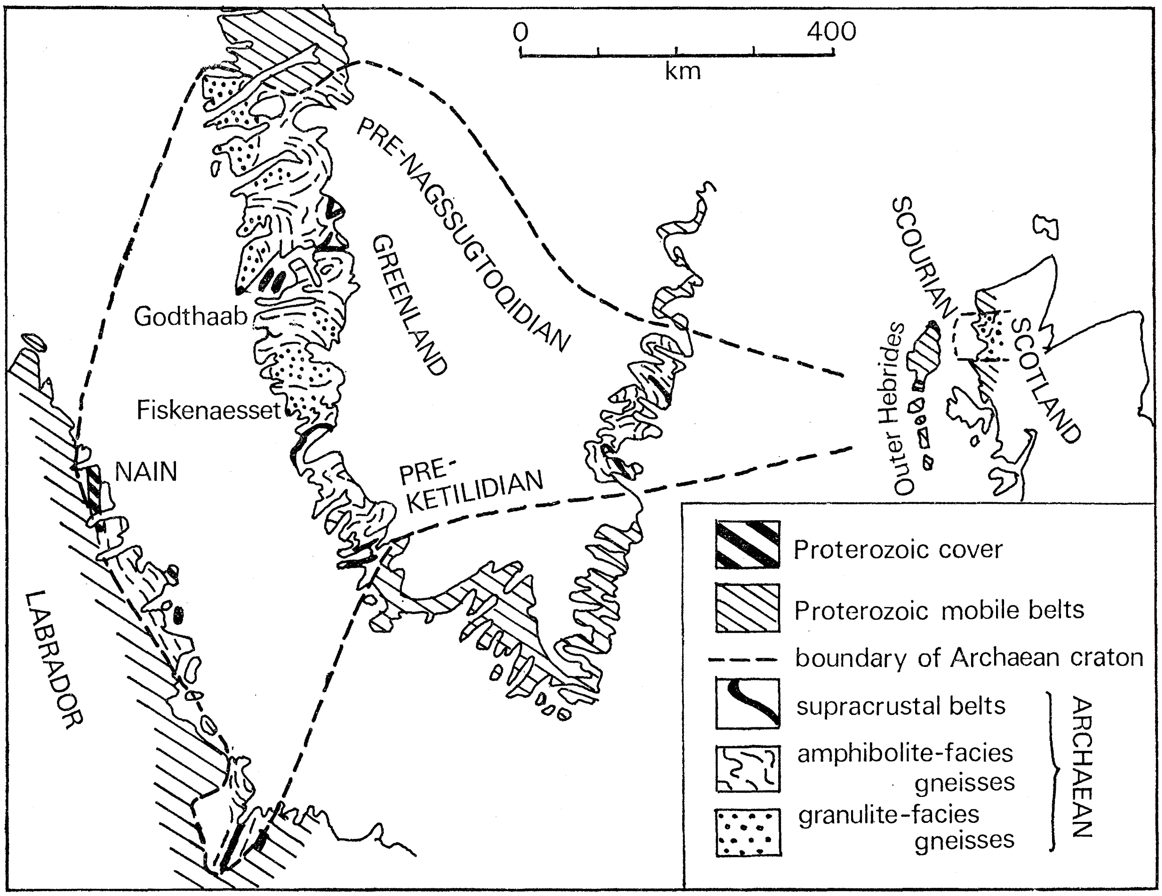

FIGURE 1. Outline map of the Archaean craton of the North Atlantic.

down to about 2600 Ma, when large areas became effectively stabilized. Activities were continued or renewed for about the next 1000 Ma in the border-zones which behaved in a different manner from the central Archaean craton over this time-span.

Our principal objects in this paper are to summarize the information concerning the early history of the craton, to provide an account of its geological components and of the tectonic and metamorphic styles displayed to serve as a basis for comparison with Archaean provinces of granite–greenstone-belt type, and to examine briefly the evidence relating to the stage at which the craton became differentiated from its border-zones.

2. Outline of geological history

The history of repeated deformation, metamorphism, igneous intrusion and accumulation of supracrustal groups recorded in the craton spanned a period of nearly 1500 Ma. The sequences of events established by field geologists from the relationships of the principal components, and some fixed points dated by isotopic methods are summarized in table 1. The early rock-groups and structures are best known in the Godthåbsfjord area of west Greenland which escaped the full effects of high-grade metamorphism at a later date (see McGregor, this volume). An early basement of deformed granitic rocks in this area (table 2) has yielded a Rb/Sr isochron age of 3980 ± 170 Ma and an Pb/Pb whole rock age of 3760 Ma (O.I.G.L. & McGregor 1971 – amended to 3750 Ma).

Metamorphosed supracrustal rocks are shown to be younger than these very ancient gneisses and are in turn older than a variety of gneisses of intrusive origin. 100 km to the south the Fiskenaesset meta-igneous complex with prominent anorthosite layers is seen to be intrusive into amphibolitic horizons believed to represent supracrustal rocks similar to those of the Godthåbsfiord region. If one accepts the tentative model age of 3600 Ma obtained from these rocks as the date of their intrusion (Evenson, Murthy & Windley, in prep.) then the supracrustals were probably deposited at some time between 3600 and 3790 Ma.

Broadly similar sequences of early events can be made out for many widely separated parts of the ancient craton (tables 1 and 2) and there is no reason to believe that Godthåbsfjord was in any way unique (see McGregor, this volume). Whether or not the various lithological units such as supracrustal belts and anorthosites can be correlated even over short distances is a matter of conjecture which can only be resolved by a combination of detailed field mapping and isotope studies. At present it seems reasonable to regard some of the younger events, for example the formation of large amounts of granitic material around 3000 Ma, as events which occurred throughout the craton and to leave correlation of older events such as the deposition of widely separated supracrustal groups more open. A valuable time marker recognized in every part of the massif is provided by a 'blanket' metamorphism of granulite or high amphibolite grade affecting all the rocks mentioned above. Dates for the late stages of this regional event fall about 2900 to 2800 Ma with a scatter down to about 2500 Ma which may reflect slow cooling and the local injection of granitic rocks. We regard this 2800 Ma high-grade metamorphic event as representing a turning point in the history of the Archaean massif after which structural and metamorphic effects became localized in specific areas. Scattered relics of low-grade supracrustal rocks apparently deposited on a high-grade basement but yielding radiometric ages in excess of 2500 Ma were incorporated in the craton during this late stage and numerous calc-alkaline intrusions and some carbonatites were emplaced in the general period 2000 to 2800 Ma ago (table 1). Between 2600 and 1900 Ma ago the craton was intruded by numerous swarms of basic and ultramafic dykes represented throughout east Labrador, west and east Greenland and the Precambrian of northwest Scotland. Extensive faulting occurred within the craton at this time. Some of the ancient faults have been reactivated by Cainozoic movements.

eastern Labrador	Ma		Greenland	Ma	northwest Scotland	Ma
Regional swarms of dolerite dykes. Faulting in craton. Possible late Archaean–early Proterozoic orogenic activity in area east of Labrador trough, west of coastal Archaean block	> 1800 < 2500	12	Regional swarms of dolerite and ultrabasic dykes. Faulting, unstable conditions in the areas to north and south of craton	2000–2600	Dolerite and ultrabasic dykes. Local metamorphism and deformation	2000–2400 2200–2500
—		11	Local calc-alkaline and carbonatitic activity in southeast Greenland	> 2000 < 2600	Pegmatites tonalitic granites and minor calc-alkaline intrusions	2400–2600 2600
Emplacement of granites, widespread pegmatites retrogression of granulite facies rocks. Extensive break up of older structures in southern part of Archaean coastal strip	< 2500	10	Emplacement of granites, widespread pegmatite swarms, infolding and greenschist facies metamorphism of late supracrustal sequences, retrogression of granulite facies rocks	> 2500 < 2800		
—		9	Deposition of supracrustal sequences (mainly basic and acid volcanic sequences) ?Retrogression	> 2500 < 2800	Deposition of supracrustal sequence (Loch Maree series). Local retrogressive metamorphism.	
Cordierite granulite facies metamorphism preserved in northern part of block	not dated (stages 1–8)	8	Culmination of cordierite granulite or amphibolite facies metamorphism, emplacement of andesine-anorthosite hypersthene-monzonite complexes. Widespread tectonic activity forming interference patterns	2800–2900	Granulite or amphibolite grade metamorphism	2900
Intrusion of granitic-tonalitic suite to form sheets in high grade gneisses		7	Emplacement of major calc-alkaline suites probably over extended time interval. Widespread mobilization of earlier rocks with major phase of formation of migmatite complexes. Intrusions of Nûk gneiss suite Godthåbsfjord	> 2800–? < 3300 3100	Tonalitic intrusions? Anorthosites (Hebrides) and basic and ultrabasic intrusions	
—		6	Tectonic interleaving of all earlier rocks (probably by a variety of processes and in more than one event)			
—		5	Intrusion of layered igneous complexes characterized by presence of chromite-bearing calcic anorthosites	?3600		
Deposition of supracrustal rocks, basic and ultrabasic volcanics, aluminous pelites, thin quartzites and impure calc-silicate horizons. Possibly some acid volcanics		4	Deposition of supracrustal sequences (largely basic ultrabasic and intermediate volcanic rocks in southern part of craton, possibly higher proportion of pelitic material further north)		Deposition of supracrustal sequences – mainly sediments with ? volcanic components including ultrabasic rocks	
—		3	Basic dykes (Ameralik dykes) } demonstrable in Godthåbsfjord district. Inferred elsewhere			
Presumed older basement now forming one of the components in the gneiss complex		2	Deformation and metamorphism	3800	Presumed early basement	
—		1	Emplacement of granitic rocks with inclusions of basic material			

Stages 5 and 6 and 11 and 12 probably overlapped or may be

Underlined ages Pb/Pb, Pb/U or Rb/Sr isochron determina-

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Table 2. Events recorded at three localities in Greenland

	(A) *Godthåbsfjord and immediate surroundings (modified from McGregor* 1972)	(B) *Fiskenaesset and northern Frederikshåb district (after Dawes* 1970 *and recent mapping by the Geological Survey of Greenland*)	(C) *Southeast Greenland (from Bridgwater & Gormsen* 1968, 1969; *Andrews* et al. 1971 *and Andrews* et al. *in prep.*)
12	Shearing with local loss of radiogenic argon *ca.* 1800 Ma	Local shearing causing sporadic loss of radiogenic argon *ca.* 1800 Ma	Local intrusions of carbonatite, appinite and calc-alkaline plutons 2000–2600 Ma
11	Dolerite dykes, some slightly metamorphosed > 1800 < 2600 Ma	Dolerite dykes (3 or more generations) K/Ar determination on ENE dyke 2428 Ma (Bridgwater 1971)	Dolerite dykes
10	Regional closure of K/Ar and Rb/Sr mineral systems *ca.* 2500 Ma regional pegmatite swarms, intrusion of granites	Regional uplift and closure of K/Ar systems *ca.* 2500 Ma. Some problematical earlier K/Ar ages	Regional uplift ages 2300–2700 Ma. Widespread slight alteration
9	Intense local deformation	Retrogression, probably major period of granite emplacement particularly in the south of the area	Retrogression of granulite facies rocks leaving small relics. Possibly some of granites under (6) below belong to this suite
8	High grade metamorphism. Granulite facies in areas to north *ca.* 2800 Ma metamorphism apparently continued after major folding	High-grade metamorphism. Granulite facies in northwest, amphibolite facies to the south *ca.* 2800 Ma	High-grade metamorphism. Emplacement of norite anorthosite and hypersthene granite suites at Skjoldungen and Angmagssalik probably during major period of folding.
7	Complex folding	Complex folding	Regional formation of interference patterns
6	Intrusion of syntectonic calc-alkaline suites (rocks now forming the Nûk gneisses). Rb/Sr whole rock system set at 3050 Ma	Granitic activity, migmatization of anorthosites and supracrustal units injection of granite sheets	Major emplacement of granite–granodiorite–diorite suite, varying between syntectonic to late tectonic. Locally affected by granulite facies metamorphism (?9, above). Anorthosites severly broken up
5	Emplacement of anorthosites	Emplacement of anorthosites and associated igneous bodies	Emplacement of anorthosite sheets and associated more basic rocks. ? Some ultrabasic bodies
4	Thrusting to form alternating units of supracrustal rocks and gneisses emplacement of ultrabasic lenses	—	Thrusting to form concordant layers of gneiss and supracrustal rock (particularly well seen in relics of Archaean rock near Angmagssalik
3	Deposition of basic lavas and sediments (Malene supracrustals)	Deposition of supracrustal units (mainly basic lavas) well preserved on Ravns Storø and on the nunataks. Correlation uncertain between different groups	Deposition of supracrustal units – mainly basic to the south, more aluminous to the north. Some ultrabasic rocks in sequences
2	Injection of basic dykes	Basic dykes pre-dating supracrustal units on the nunataks – mainly synkinematic types proven. Possibly some normal dolerites now metamorphosed. Granitic gneisses with inclusions of basic and ultrabasic material interpreted as earlier supracrustal rocks	Basic dykes – particularly in northern part of the area
1	Deformation of original granitic suite to form Amîtsoq gneisses Rb/Sr whole rocks isochron at 3750 Ma. Inclusions of small basic and ultrabasic masses		Granitic rocks forming early gneisses. Contain migmatitic inclusions of basic and ultrabasic material interpreted as older supracrustal rocks

The correlation between the oldest parts of the above sequences of events is clearly difficult and relies on lithological units such as supracrustal layers which are probably not unique to any one time. The columns are placed side by side to give an impression of the complexity of the Archaean and to suggest that no one single model can be used for the whole block

3. Early crustal components (> 3000 Ma)

The oldest components of the province – indeed the oldest dated rocks of the Earth's crust – are the Amîtsoq gneisses of the Godthåb district which escaped extreme deformation and granulite-facies metamorphism in later times (table 2). They are mainly banded gneisses of granitic to granodioritic composition which sometimes carry megacrysts of potash feldspar. McGregor considers (O.I.G.L. & McGregor 1971) that the Amîtsoq gneisses were formed mainly by recrystallization and flattening of an originally more uniform granitic suite. The Amîtsoq gneisses contain enclaves of basic and ultrabasic material now represented by inclusions of amphibolite, hornblendite, dioritic gneiss, micaceous gneiss and quartzose gneiss carrying either magnetite or iron silicates. No inclusions of rocks of proven supracrustal origin occur in these gneisses and in their published account the O.I.G.L. & McGregor consider that the Amîtsoq gneisses may represent primordial granitic crust.

The stratigraphical position of the Amîtsoq gneisses relative to other units in the Godthåb district was established by McGregor from field evidence concerning the distribution of a swarm of basic dykes (the Ameralik dykes, see below) which cut, and are deformed with, Amîtsoq gneisses but do not enter younger supracrustal groups or intrusive gneisses. The radiometric age of the Amîtsoq gneisses is shown by isotopic studies at Oxford University referred to above which indicate that they date back to at least 3800 Ma ago.

According to V. R. McGregor (personal communication and this volume) the type Amîtsoq gneisses occur as part of the gneiss complex over an area of at least 130 × 25 km. Outside this area in which the presence of the Ameralik dykes clarified field relations, the presence of rocks of equivalent age is less easy to demonstrate, partly because of lack of detailed mapping, partly because of the intensity of later metamorphic effects and, perhaps most importantly, because of the lack of amphibolite dykes in sufficiently large numbers to allow the methods used by McGregor in Godthåbsfjord to be applied. Local sequences of events in the Archaean gneisses throughout the craton show patterns similar to that described by McGregor, however, and in our opinion rocks similar in age to the Amîtsoq gneisses make up an appreciable part of the whole block. In Labrador the amphibolite-facies Hopedale gneisses on Ford island (to the east of Nain, 56° 30′ N) show a history of metamorphism and deformation before the injection of amphibolitic basic dykes which were themselves later metamorphosed. In the Fiskenaesset area south of Godthåb (table 2) rare amphibolite dykes are found in gneisses regarded by one of us (B. F. W.) as a basement into which the meta-igneous complex was intruded at Fiskenaesset (see below). However, amphibolite dykes are seen to cut supracrustal rocks and the anorthosite complex (J. Myers, personal communication 1972).

In the Dalagers Nunatak region southeast of Fiskenaesset, Dawes (1970), has recorded a sequence of events (table 2) which is at least as complex as that recorded from Godthåbsfiord and which could well prove as interesting geochronologically. The oldest rocks in that area are acid and basic gneisses which were deformed, cut by a variety of basic dykes, overlain by a supracrustal succession consisting dominantly of basic volcanics, metamorphosed under amphibolite facies conditions and intruded by granites in the period before 2500 Ma ago. Dawes tentatively correlates the major supracrustal sequences with the Ravns Storø schists of the Fiskenaesset district now thought to be older than the 2800 Ma-old granulite facies metamorphism in the areas to the north (Kalsbeek 1972). This would place his older gneisses in the same relative position in the regional sequence of events as the Amîtsoq gneisses of

Godthåbsfjord. Dawes interprets the basic and ultrabasic material in his oldest group of rocks as of possible volcanic origin, an interpretation followed by many of the geologists working in the Frederikshåb area to the south (see, for example, Kalsbeek & Leake 1970; Andrews, in press).

In southeast Greenland thin amphibolite dykes are found in gneiss units which appear to have passed through a more complex history than the major supracrustal belts in the same area. This relationship (which is particularly clearly seen in the remnants of Archaean rocks preserved in the Angmagssalik area) has been interpreted in terms of a series of basement slices thrust together with younger cover rocks (Bridgwater & Gormsen 1969). Many of the gneisses interpreted as basement in southeast Greenland are agmatitic and contain numerous inclusions of amphibolite, dioritic material and ultrabasic (peridotite and olivine-orthopyroxene) rocks. In contrast to the interpretation favoured by O.I.G.L. & McGregor for the primeval origin of the Amîtsoq granitic gneisses, Windley & Bridgwater (1971) regard this arrangement as possible evidence of still earlier events involving the break-up of supracrustal material by intrusive granitic material broadly equivalent in age to the Amîtsoq gneisses.

In the Outer Hebrides of western Scotland, and possibly also in the Scottish mainland, a similar distinction between banded gneisses, largely of tonalitic or granodioritic composition and units representing an ancient cover-series can be drawn (Coward *et al.* 1969, see also Dearnley & Dunning 1968). While it remains to be seen whether any of these possible basement assemblages will turn out to be as old as the Amîtsoq gneisses, it does seem reasonable to infer that remnants of a gneiss complex pre-dating both the earliest important supracrustal groups and the earliest anorthosites are distributed across almost the full width of the Archaean massif.

These remnants, some or all of which are at least 3600 Ma in age, are broadly granitic and, although the majority are tonalitic or granodioritic, it is of interest to note that potash feldspar is conspicuous in the Amîtsoq gneisses which locally verge on a truly granitic composition. These gneisses (O.I.G.L. & McGregor 1971) bear no resemblance to lunar materials and equally do not resemble oceanic crustal materials. The extent of granitic gneisses in the North Atlantic Archaean suggests the existence of considerable areas of continental crust before the accumulation of the earliest dated greenstone-belts. The survival of folds and foliations predating the Ameralik dykes, and the preservation at some localities of the primary structural relationships of these dykes show that regeneration of basement complexes at least as old as 3800 Ma could be achieved without loss of coherence, that is without wholesale remelting.

The Ameralik dykes of Godthåbsfjord represent the oldest well-documented dyke-swarm yet recognized. The swarm, which now has a general north-northwest trend, contains hundreds of amphibolized dykes up to a few metres in width. Primary discordances, apophyses, chilled edges and anorthositic inclusions are well preserved where later deformation has been slight; but many dykes have been rotated into parallelism with the gneiss foliation, folded, boudinaged or migmatized by granitic veins extending from the gneiss. Little or no evidence remains as to their primary textures and minerals.

Intercalated conformably with the Amîtsoq gneisses of Godthåbsfjord are belts of supracrustal rocks up to 1 km in breadth (the Malene supracrustals) which include amphibolites, mica-schists and less common marbles and quartzites. As these supracrustal units contain no amphibolite dykes McGregor suggested in his earlier papers that they represent a cover deposited on an earlier gneiss basement and subsequently interleaved tectonically with reworked gneisses and dykes. In his most recent publication a second hypothesis is offered as an alternative in which the relationship is explained in terms of the interleaving of continental and oceanic crust with no proven age relationships to one another.

The Malene supracrustals are representatives of an assemblage which recurs in units of much the same scale, character and range of variation at many points throughout the craton. These units are seldom much more than 1 km broad and are generally, though not always, sufficiently clearly defined to be mapped out from the adjacent gneisses. Almost all contain a high proportion of basic material (amphibolites, hornblende-gneisses, basic granulites) which appears to be of igneous origin. Some of these basic rocks were undoubtedly volcanic as they exhibit pillow-structures. Geochemical studies of amphibolites from the Frederikshåb area of West Greenland led Kalsbeek & Leake (1970) to an interpretation in terms of an assemblage of basic lavas and tuffs. Pods of dunite, harzburgite and serpentinite (sometimes with layers of chromite) commonly occur in the basic units or in the gneisses immediately adjacent to amphibolite layers. We interpret most of these as associates of the original supracrustal sequence, although some have clearly been moved tectonically as pips during later deformation. The ultrabasic rocks frequently preserve more of their primary textures and mineralogy than other rocks in the sequence, presumably because their physical properties allowed them to respond to deformation by sliding along their contacts rather than by recrystallization.

Many of the supracrustal sequences contain garnet–amphibole–quartz–feldspar rocks of intermediate composition some of which include fragments of granitic material and which are thought to have been derived from andesitic or dacitic tuffs and agglomerates. A variety of feldspathic gneisses which lack distinctive features may be capable of a similar interpretation. Demonstrable metasediments form a comparatively small part of the successions. Siliceous layers found in conjunction with ultrabasic and basic rocks have been interpreted as derived from cherts; aluminous units commonly consisting of biotite, sillimanite or kyanite, garnet, quartz and feldspar with minor amounts of graphite and sulphide have generally been interpreted as derived from pelitic sediments (Coward *et al.* 1969) though a volcanic origin is not impossible. Calc-silicate layers probably represent impure limestones or oozes. Major quartzitic units are apparently absent from the typical supracrustal successions – thin quartz-rich layers often with magnetite, sillimanite, garnet or iron-rich silicates are widespread as minor components of the successions. No primary clastic structures have been noted from the majority of the supposed metasedimentary rocks which can be interpreted as chemical precipitates or volcanic tuffs rather than detrital sediments. A major exception to this is found in the Isua belt of supracrustal rocks from Godthåbsfjord (Keto 1969) which differs from the majority of successions preserved in that the lower part of the succession consists of quartzites and metagreywackes. These are overlain by garnet-chlorite schists and banded ironstones including both oxides and carbonates. The top of the succession consists of a greenschist series interpreted as derived from basic volcanics. The total succession is up to 2 to 3 km thick – that is considerably more than the majority of the supracrustal successions. It is metamorphosed under upper greenschist to amphibolite facies conditions. The age of the Isua successions is controversial. They, and the rocks surrounding them, have yielded K/Ar ages varying from 1800 to 3500 Ma. Their comparatively low metamorphic grade has been used to suggest that they are younger than other supracrustal successions but this criterion is no longer regarded as reliable (see, for example, the revised position of the Ravns Storø succession). If the typical supracrustal successions preserved in the Archaean block are regarded as having been formed under oceanic or at least deep water conditions then the Isua supracrustals appear to be more in the nature of shelf deposits.

The supracrustal assemblages referred to above have something in common with those which characterize the greenstone belts of the Superior province, the Yilgarn block of western Australia and the Rhodesian and Kaapvaal cratons. The range of lithological types is broadly equivalent and the dominance of basic material is common to most assemblages. So far, however, rocks with the distinctive chemistry of the komatiites (Anhaeusser *et al.* 1969) or major units comparable with the clastic Moodies or Shamvaian sediments of the southern African supracrustal belts have not been recognized. The supracrustal belts of the North Atlantic province are narrow (figure 1) and form only a small proportion of the gneiss complex. Their rocks are strongly deformed (often lacking any primary structures), highly metamorphosed and at present have not shown the gold–quartz mineralization of the major greenstone belts. As a working hypothesis Windley & Bridgwater (1971) suggested that many of these differences can be explained by regarding the North Atlantic craton as revealing a deeper crustal section than that exposed in Archaean provinces of the granite-greenstone type. A second possibility – not necessarily in opposition to the first – is that we are dealing in the North Atlantic craton with a slightly earlier phase of crustal evolution (either in time or in stage of development). Major greenstone belts of the Barberton–Superior province type may characterize a phase when the crust had differentiated into areas of continental and oceanic type and was sufficiently stable to bear thick successions of basic and ultrabasic rock. The thinner supracrustal belts of the high-grade terrains could have formed at a stage in crustal development when proto-continents and proto-oceanic crust had only separated on a small scale. It is possible that the smaller remnants of highly-metamorphosed supracrustal rocks recorded from the granitic terrains bordering the major greenstone belts – for example those recorded from Swaziland (Hunter 1970) and Rhodesia (Stowe 1968) which are considered by these authors to be older than the neighbouring major belts – may provide appropriate material for comparison with the amphibolite belts of the North Atlantic craton.

The make-up of the North Atlantic craton confirms the evidence from other provinces that groups resembling greenstone-belts in lithology and relationships continued to form over a very long period. The oldest belts in the craton may be as old as 3500 to 3600 Ma (Evenson, Murthy & Windley 1972). The youngest – the Tartoq belt of West Greenland (Higgins 1968) and the Loch Maree Series of northwest Scotland – are thought to post-date the 2900 Ma metamorphic event and are probably not older than about 2600 Ma (table 1).

Anorthositic rocks are widespread throughout the massif and in its reworked border-zones; the only region where Archaean anorthosites have not yet been found is Labrador. In west Greenland, metamorphosed and folded anorthositic layers with a strike-length of at least 500 km (Windley 1969) are remarkably continuous. In East Greenland (Bridgwater & Gormsen 1969) and in the Outer Hebrides, anorthosites occur mainly in pods up to a few kilometres in length associated with basic and ultrabasic bodies which together probably represent the disrupted remnants of stratified igneous complexes. Although the primary igneous stratigraphy of these remnants has been greatly modified, the resemblance of individual fragments to recognizable units within the better-preserved bodies is close enough to suggest that the suites developed under similar conditions. Individual anorthositic gabbro pods now less than 1 m in diameter may retain the original igneous textures remarkably well (figure 3, plate 7).

In the Fiskenaesset region of West Greenland, calcic anorthosites form part of a metamorphosed layered igneous complex up to 2 km thick and 200 km along the strike. The complex is bordered conformably along much of its outcrop by layers of amphibolites (interpreted as metavolcanics) associated with minor marbles and mica-schists which are flanked in turn by gneisses carrying deformed rare remnants of the amphibolitic dykes which were mentioned above. Many of the smaller anorthositic bodies both in Greenland and in Scotland are similarly bordered by metamorphosed supracrustal assemblages and it is inferred that the igneous complexes to which they belong were emplaced along zones of tectonic weakness such as the interface between slices of original basement gneiss and younger cover rocks. Indeed in the absence of widespread equivalents to the Ameralik dykes the characteristic occurrence of meta-anorthosites in zones separating gneisses of unknown origin from supracrustal rocks is one of the most useful indications of the possible presence of an older pre-supracrustal gneissose basement in many parts of the craton.

In the Fiskenaesset complex, magnetite-bearing ultramafic rocks (dunites, peridotites, pyroxenites) are succeeded towards the original top by a lower layered series of mafic rocks, by mafic gabbros, leucogabbros with marked cumulate textures, and by anorthosites, chromitites and garnet-anorthosites. This layered structure represents a gravity-differentiated sequence, the fractionation trend of which is well preserved despite subsequent metamorphism (Windley, Herd & Bowden, in the press).

The next important additions to the crust were tonalitic and dioritic rock-masses emplaced within pre-existing units as pods, sheets or more irregular intrusions. In the Godthåb area, the deformed and flattened derivatives of these bodies make the Nûk gneisses which are interleaved conformably with the older Amîtsoq gneisses and Malene supracrustals. The type Nûk gneisses have yielded a Rb/Sr isochron age of 3084 Ma (see McGregor, this volume). McGregor estimates that over 50% of the rocks exposed in the area mapped in detail around Godthåb is made up of Nûk gneiss. Elsewhere in the craton the amount of gneiss formed from rocks intruded after the formation of the early supracrustal belts and anorthosites is known with less certainty. Over large areas of southeast Greenland many of the gneisses show intrusive contacts against the local supracrustal units and it has been estimated that up to 80% of the gneiss around Tingmiarmiut may have been derived from rocks which were intruded between the formation of the local supracrustal belts and the period of high-grade metamorphism around 2900 Ma. Probably more than one event is represented by these rocks since they range from syn- or pre-tectonic sheets of gneissified diorite and granodiorite which only locally preserve their intrusive contacts to major cross-cutting bodies which break up the structures preserved in the supracrustal rocks and the earlier post-supracrustal intrusives. The youngest phases, which include large bodies of norite, andesine-anorthosite and mangeritic-charnockitic members, appear to have been emplaced as late- or post-tectonic intrusions around the peak of high amphibolite and granulite facies metamorphism dated at 2800 to 2900 Ma ago. Some of the intrusive rocks are massive, free of foreign inclusions, show no sign of local derivation and are thought to represent a major addition to the crust at the level exposed. Other more nebulitic bodies and many of the agmatitic gneisses of the east coast of Greenland probably represent remobilized basement, partly remobilized rocks from the supracrustal successions and perhaps early members of the post-supracrustal intrusive suite remobilized by later metamorphism. So far we have seen little evidence which suggests to us that major parts of Archaean gneisses were formed by *in situ* recrystallization of supracrustal rock of appropriate composition such as acid volcanic or greywackes and we regard the post-supracrustal suite as essentially intrusive in origin.

Reviewing the lithological constitution of the whole massif a few general points may be worth commenting on. Perhaps the most important is the evidence that continental crust was in existence 3800 Ma or more ago and is older than any proven supracrustal sequences. The very old ages obtained from the Amîtsoq gneisses as well as the survival of primary intrusive relationships in the Ameralik dykes shows that although the basement underwent repeated reworking this did not involve wholesale remelting of the crust throughout the craton. In this respect, the gneissose craton differs markedly from the areas immediately surrounding the typical greenstone belts in southern Africa, Canada and Australia where the majority of granitic rocks show clear intrusive relationships with the low-grade greenstone belts and where there is seldom any isotopic evidence for the presence of an older basement. It gives support to workers such as Hunter (1970) and Stowe (1968) who have suggested that older basements underlie the well-preserved greenstone belts in southern Africa, and that the contact relationships have been modified by later granite injection and thrusting. However, in our opinion the fact that sialic material was already present 3800 Ma or more ago does not necessarily indicate the presence of a primordial granitic crust. It seems rather unlikely that rocks formed some 700 Ma after the formation of the Earth should be regarded as primordial.

We regard rocks such as those of the lower parts of the Barberton mountainland volcanics as models for crust of oceanic type formed some 1000 Ma after the formation of the Earth, and perhaps approaching primordial basalts in chemical character, and the Amîtsoq gneisses as models for early (but not necessarily primitive) granitic crust of continental type. It would perhaps be reasonable to assume that the oldest rocks likely to be preserved would be granitic, since in unstable environments the denser rocks might be rapidly returned to the mantle and recycled, but this does not mean any granitic rocks we see now are primordial. For a type of crust which could predate differentiation into oceanic and continental régimes perhaps we should look to the agmatitic gneisses which are common in both the North Atlantic craton and the granitic gneisses surrounding the major greenstone belts. We would not expect these to be primordial – nor necessarily to contain older crustal elements than are seen in the more clearly-defined granitic and greenstone terrains; they may, however, give an indication of what the earliest crust was like before it stabilized sufficiently to allow the differentiation of major continental and oceanic areas.

A second point of interest concerns the relatively small contribution, in terms of area of outcrop, made to the massif by rocks of proven supracrustal origin. Much of the complex, as noted above, consists of gneisses which we consider were largely derived from granitic rocks emplaced within the crust, while rocks of obvious supracrustal derivation form a relatively small part of the craton. Clearly the proportion of the various components may be expected to vary from area to area, but taking the areas mapped in detail (for example the Outer Hebrides, the Frederikshåb and Fiskenaesset areas of southwest Greenland and the Godthåbsfjord area), we would suggest that an average of 10 to 15 % of the craton is made up of demonstrable supracrustal material (table 3). Areas where the proportion of obvious supracrustal material is lower than 10 % are generally those where massive granitic activity at a late stage in the local development of the craton has both diluted the proportion of supracrustal rocks present and partially destroyed the evidence of their origin.

When the recognizable supracrustal groups and the intrusive bodies in the high-grade complex have been accounted for, large areas of banded gneisses which appear to have lost almost all diagnostic primary structures remain. In the Lewisian complex of northwest Scotland, for example, such undistinctive gneisses occupy over 70 % of the outcrop; most are of tonalitic or granodioritic composition, but mafic and ultramafic pods and granitic layers are widespread (see, for example, Watson 1965). Sheraton (1970) and Bowes, Barooah & Khoury (1971) have favoured a volcanic origin, on account of geochemical considerations and of the characteristic banding; such a suggestion implies the dominance of andesitic-dacitic volcanism over basic volcanism on a regional scale. An alternative suggestion favoured by some workers in both Scotland and Greenland (e.g. Kalsbeek 1970; Andrews 1972) is that the gneisses are derived from the recrystallization *in situ* of sedimentary rocks of appropriate composition.

Table 3. Components of some Archaean complexes

	southwest Greenland						
	Godthåbsfiord area	Fiskenaesset area	Frederikshåb area	Fiskefiord area	northwest Scotland	Rhodesian craton	Canadian Archaean craton
percentage area of	(1)	(2)	(3)	(4)	(5)	(6)	(7)
(*a*) supracrustal sequences < 2900 Ma	—	—	5	—	2	—	30–40
(*b*) supracrustal sequences > 3000 Ma with associated basic-ultramafic intrusives	11	11	11	19	7–12	18	
(*c*) gneisses demonstrably older than (*b*)	39						} 60–70
(*d*) gneisses and granites later than (*b*) and > 2400 Ma	50 } 89	85	83	81	85	82	
(*e*) anorthositic and associated complexes	—	4	—	—	2	—	—
map area (km^2)	200	3000	1350	1800	4400	190 000	2×10^6

(1) From map, McGregor, this volume.
(2) From information supplied by F. Kalsbeek (see Kalsbeek *et al.* 1972). Figures for (*b*) refer to amphibolite layers in gneiss.
(3) From map compiled by J. Escher (1971).
(4) From a sketch-map published by Windley & Bridgwater (1971). Figures for (*b*) refer to amphibolite and pyribolite layers in gneiss.
(5) From maps of Institute of Geological Sciences, Coward *et al.* (1969) and others.
(6) From Phaup (1971).
(7) From Stockwell (1968).

As we have stated above, our own views are strongly against accepting a sedimentary or acid volcanic origin for granitic gneisses of this kind without direct evidence. Our preferences arise partly from the fact that many Archaean gneisses formerly accepted as supracrustal have been shown to have originated either as a basement older than undoubted supracrustal associates or as later intrusive granitic bodies. In younger mobile belts such as the Caledonides or the Alps, where the level of erosion might favour the preservation of rocks of supracrustal origin, surprisingly small proportions of the gneisses present appear to have been formed from the geosynclinal successions deposited in the period before the main tectonism and metamorphism; recent remapping and geochronological studies, again, suggest that the proportions of regenerated basement are higher than was formerly thought. Geochemical evidence is difficult to interpret for several reasons; rocks of volcanic origin cannot be distinguished with confidence from rocks of intrusive origin by geochemical criteria; supracrustal rocks converted to gneisses in a single cycle cannot easily be distinguished from reworked supracrustal rocks in a polycyclic basement; and the geochemical effects of the 'blanket' high-grade metamorphism affecting the gneisses still remain to be established. Field evidence is also usually inconclusive, since authentic primary structures are virtually absent. The banding of the gneisses and the interlayering of gneisses with undoubted supracrustal rocks are largely the results of repeated deformation (p. 506). The transitional contacts which have been described from areas where small supracrustal remnants are enclosed in gneisses (see e.g. Coward *et al.* 1969) undoubtedly indicate local transformation of supracrustal parent-rocks to banded gneisses but the scale of the phenomenon does not, in our view, justify the conclusion that such a transformation has taken place on a regional scale; there is an analogy with the transitional contacts of xenoliths and aureole-rocks associated with certain granite plutons, which a few decades ago were cited as evidence that the plutons were products of large-scale granitization but which are now generally accepted as marginal phenomena.

With these considerations in mind, we consider it is now more realistic to suggest a granitic origin for the majority of granitic gneisses of unknown parentage than to invoke a direct derivation from volcanic or sedimentary materials. The easiest way to produce a granitic or tonalitic gneiss is to deform and recrystallize a granite, a tonalite or an earlier gneiss and in our opinion the demonstration in this volume by McGregor that banded gneisses of the type so prevalent in high-grade Archaean complexes have been produced in this way represents a major contribution to basement geology.

4. Structural and metamorphic history

Deformation and metamorphism recurring over a time-span of more than a 1000 Ma have affected the Archaean province and the resulting structures are complex. It may be helpful to group the episodes concerned rather loosely into four deformational-metamorphic 'events', using the relationships of supracrustal belts and igneous bodies as markers:

(1) Events older than the emplacement of the Ameralik dykes in the early basement.
(2) Events associated with the interleaving of basement and cover.
(3) Events which occurred during the regional event of *ca.* 2900 Ma.
(4) During the initial stages of stabilization.

(1) The effects of the earliest episodes can only be distinguished where little-deformed Ameralik dykes cut folds and foliations in the Amîtsoq gneisses and their equivalents. McGregor considers that the banded Amîtsoq gneisses cut by the dykes were formed by metamorphic differentiation from originally more homogeneous granitic rocks and recognizes augen gneisses formed by flattening of rocks containing potash-feldspar megacrysts. The modifications envisaged by McGregor suggest deformation in a high-grade metamorphic environment at least 3600 Ma ago.

(2) Throughout the Archaean massif, as in other high-grade Archaean provinces, the contacts between adjacent rock-units are characteristically conformable (figure 2, plate 7). It is clear that this parellelism of lithological boundaries on all scales does not reflect a primary stratigraphical arrangement but is the result of tectonic and metamorphic modifications imposed on assemblages of very different ages. In the Godthåbsfjord area units of the early basement of Amîtsoq gneisses, distinguished by McGregor by their relationships with Ameralik dykes, are conformably interleaved with belts of Malene supracrustals and with units of Nûk gneisses

derived from still younger intrusive bodies. No angular discordances are seen at the borders of the Amîtsoq gneisses although the Ameralik dykes invading these gneisses do retain discordant contacts at a few localities where effects of post-dyke deformation are exceptionally slight.

Concordant belts of metamorphosed supracrustal rocks broadly similar to the Malene supracrustals in thickness, metamorphic state and lithological range are, as noted above, distributed through most of the Archaean terrains in Labrador, Greenland and Scotland, in association with gneisses considered to include both younger intrusive rocks and an older basement. The conclusion follows that cover/basement units were interleaved tectonically in such a way that their internal structures were brought into parallelism with their contacts both on a regional and on a local scale. Evidence as to whether the interleaving was achieved by downfolding of the cover and subsequent flattening of the synclines so formed, to produce parallel-sided belts, or by the trapping of cover slices on dislocations between moving slabs of basement is conflicting and both processes may have occurred. Symmetrical arrangements of horizons within the supracrustal belts which would favour a synclinal interpretation have only rarely been recognized (for example in the Sagleq area of Labrador where the supracrustal units form an isoclinally repeated succession). The Ravns Storø supracrustal belts and the Grydefjeldet belt of respectively southwest and southeast Greenland show possible bilateral symmetry, but its significance remains to be established. The layered rocks of the Fiskenaesset meta-igneous complex, which lies mainly within a supracrustal belt, are commonly arranged in isoclinal synclines which could have been formed simply by flattening of an initially basin-shaped complex.

TABLE 4. TRACE ELEMENT ABUNDANCES IN ARCHAEAN GNEISSES OF NORTHWEST SCOTLAND

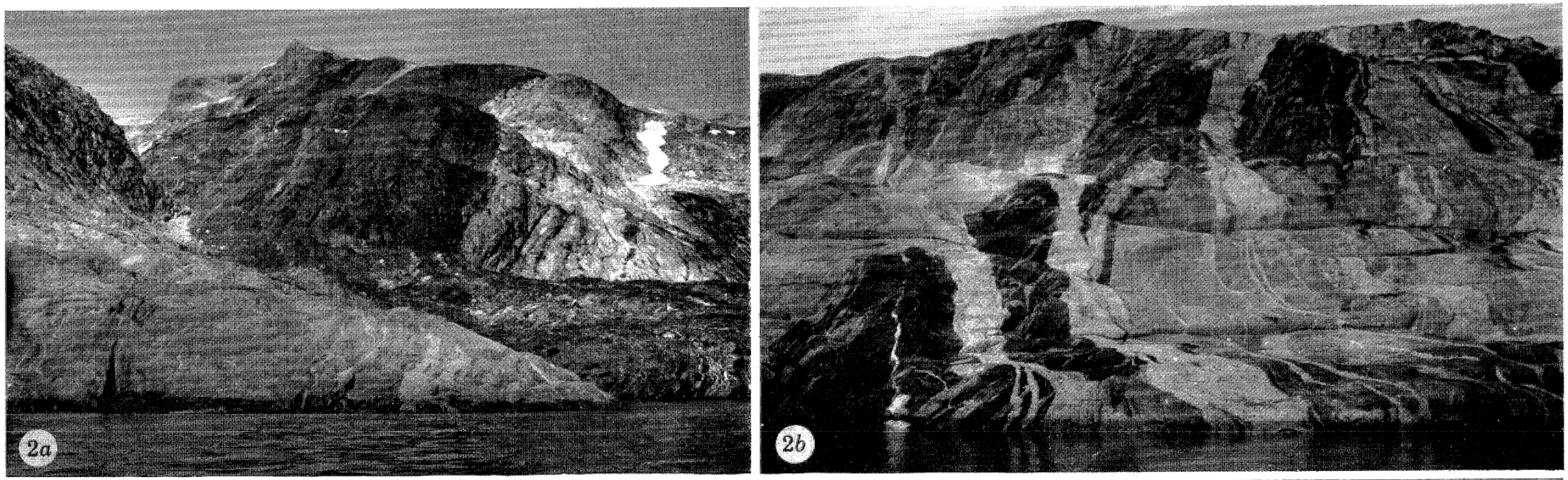
element	no. of samples	average		crustal average of Taylor (1964)	
uranium†	24	0.24	parts/10^6	2.7	parts/10^6
rubidium‡	254	11.00	parts/10^6	9.0	parts/10^6
thorium‡	254	1.00	parts/10^6	9.6	parts/10^6
yttrium‡	254	9.00	parts/10^6	33.0	parts/10^6
K/Rb‡	254	763.00		230.0	
K/Rb§	—	1500.00		—	

† From Moorbath, Welke & Gale (1969).
‡ From Sheraton (1970).
§ From Holland (1965).

The samples studied include charnockitic Scourian gneisses affected by the 2900 Ma event and a variety of amphibolized gneisses thought to have been derived from similar parent rocks.

The degree of flattening seen in the supracrustal belts and in the meta-igneous complexes where primary structures remain is less than that which might be expected to accompany the very large reduction in width of the sequences measureable in the field, and it appears that simple shear may have played a major part in the early deformation of the Archaean block. Many of the gneisses contain vertical zones of highly sheared rocks which vary from a few metres to a kilometer or more in width. Some at least of these zones of high deformation appear to have developed early in the history of the block since the deformed rocks can be mapped as lithological units around later structures.

Evidence for interleaving basement and cover by the thrusting together of a series of cover/basement slices is presented by McGregor (this volume) and thrusting certainly played a large part in the early intercalation of Archaean metasupracrustal rocks and older basement in the Angmagssalik area (Bridgwater & Gormsen 1969).



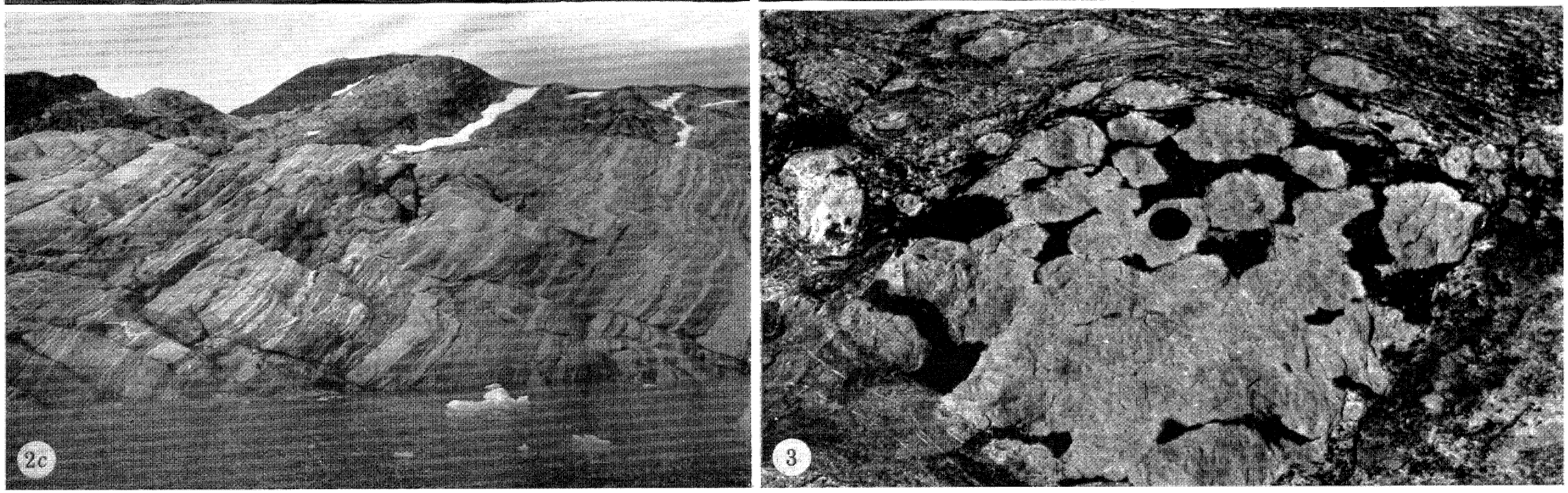


FIGURE 2. (*a*) Typical Archaean amphibolite belt probably of supracrustal origin flanked by quartzo-feldspathic gneisses, Grydefjelet, near Tingmiarmiut, southeast Greenland. The amphibolites contain a thin central pelitic layer.

(*b*) Archaean amphibolite belt flanked by quartzo-feldspathic gneisses and penetrated by several generations of granites and pegmatites which post-date the main phases of deformation but pre-date regional metamorphism of granulite facies 2800 Ma (same locality as (*a*)).

(*c*) Strongly deformed banded gneisses at margin of amphibolite belt incorporating fragments of the belt, later granite veins and, possibly, reworked basement. All the components have been rotated into parallelism (same locality as (*a*)).

FIGURE 3. Anorthosite gabbro fragment in which a primary igneous texture defined by the large feldspars is still recognizable despite fragmentation during both Archaean and early Proterozoic deformation: Kitaq Island near Angmagssalik, East Greenland.

(*Facing p.* 506)

Whatever the mechanism, it is clear that the interleaving of basement and cover took place at an early stage, since the supracrustal belts behave as parallel-sided layers in the structural 'succession' which defines the interference patterns discussed below. Furthermore, the intrusion of the post-supracrustal igneous suites (including perhaps in some areas the anorthosite complexes) appears to have been partly controlled by the tectonic intercalation of supracrustal rocks with older basement. There seems also little doubt that the conformable layering produced at this early stage has been accentuated by penetrative deformation which was broadly homogeneous when considered on a regional scale. The obliteration of unconformities on a regional scale is matched by the obliteration of discordant intrusive contacts, as between Ameralik dykes or Nûk gneisses and their country rocks and by the almost complete loss of primary structures (apart from a few examples of very strongly elongated pillow-structures) from the supracrustal rocks. Such changes must clearly have taken place while the rocks were ductile, that is, in a metamorphic environment.

(3) The last stages of deformation whose effects are regionally displayed are those which were broadly contemporaneous with the 'blanket' high-grade metamorphism which terminated at some time after 2900 Ma and before about 2700 Ma. Over much of the central Archaean massif in Greenland the most widespread structural patterns and the dominant metamorphic assemblages date from these episodes and similar patterns and assemblages are preserved as remnants far out in the reworked marginal tracts – for example, within the Laxfordian belt of northwest Scotland and within the Nagssugtoqidian in west Greenland.

In West Greenland, where the structures developed during and before the 2900 Ma event are preserved over a tract several hundred kilometres in length, the tectonic pattern is characterized by fold interference structures on a scale of a few kilometres to several tens of kilometres and is remarkable for the absence of a linear 'grain' (see, for example, Berthelsen 1960). Dome and basin forms and refolded folds are outlined by steeply dipping foliations, the relative scarcity of gentle dips suggesting that the domes and basins have peaked rather than broad closures. Where structures of comparable age survive in Scotland there is a similar absence of linear grain but the dips are predominantly low, suggesting a broader and flatter type of interference-pattern. Small-scale interference-patterns visible in single outcrops sometimes, though not very often, mimic the structures displayed on a regional scale. Such minor structures are displayed even by chromitite layers in anorthosites, a phenomenon that suggests a remarkable ductility at the time of deformation.

The distinctive tectonic pattern developed in the North Atlantic craton at or soon after 2900 Ma resembles that seen in several other provinces dominated by high-grade gneisses, notably in the Limpopo belt of southern Africa (Mason 1972, this volume, p. 463). If the high-grade craton presents a deep section beneath an original 'roof' of granitic domes and greenstone-belts, the pattern might be indirectly related to the gravitational rise of the granitic domes, since such a movement could create a constrictional stress with a vertical extension direction consistent with the forms of the steep-sided interference structures.

The characteristic metamorphism shown by the rocks displaying these complex patterns is of high amphibolite or granulite facies, the rocks being predominantly gneissose, coarse grained and often lacking in strong mineral fabrics. Assemblages of cordierite granulite facies are widely distributed, occurring in Labrador and West and East Greenland. In the central part of the outcrop on the Scottish mainland, the gneisses have charnockitic affinities. Relict granulite-facies assemblages partly replaced by assemblages of amphibolite facies are perhaps even more widespread and suggest that a large part of the craton may have approached granulite grade at the height of the metamorphism.

Some original variations can be recognized, however; there is no evidence that the region of Godthåbsfjord, where the rocks are now of amphibolite facies, has suffered retrogression and, as has been seen, this region provides a 'window' through which early events in the history of the complex can be recognized. The southern part of the Hopedale gneisses in Labrador, the southern Fiskenaesset area and the Frederikshåb area in southwest Greenland give no evidence of having passed through granulite facies conditions (Kalsbeek 1970, personal communication 1972). In southeast Greenland granulite facies rocks are only locally developed and where they are found show clear evidence of developing from earlier amphibolite-facies rocks (Bridgwater & Gormsen 1969; Andrews *et al.* 1971) either as local hot spots or as large-scale marginal phenomena in areas surrounding the late Archaean leuco-norite-charnockite complexes of Skjoldungen and Angmagssalik. The granulite facies metamorphism appears in southeast Greenland to have taken place essentially statically without the disruption of the structures developed under amphibolite facies conditions, a conclusion also reached by V. R. McGregor (this volume) for the development of granulite facies conditions in the Nordland area to the north of Godthåb. Similar 'windows' which escaped the most profound metamorphism and remained in amphibolite facies may exist in the southern part of the Archaean outcrop on the Scottish mainland and the northern part of the Outer Hebrides, though in both regions the picture has been complicated by early Proterozoic reworking. In the Glenelg region of the Scottish mainland, assemblages including eclogites and kyanite-garnet gneisses occurring in the basement of the Caledonides are probably of similar age but have not, so far, been securely dated: kyanite which occurs, but without true eclogites, in the Outer Hebrides and east Greenland may have formed during Proterozoic deformation.

The 'blanket' metamorphism dated at 2900 or 2850 Ma in West Greenland (Evenson *et al.* in press and O.I.G.L. & B. F Windley, in preparation, respectively), 2800 Ma in southeast Greenland (Gulson & Krogh 1972) and at 2900 Ma or somewhat later in Scotland (Moorbath, Welke & Gale 1969; Pidgeon & Bowes 1972), was imposed on all rock types mentioned in the previous section, blotting out much of the geological and isotopic evidence relating to the earlier history. Since it affects supracrustal rocks which must initially have been at low temperatures as well as older gneisses containing dyke swarms one can infer that the metamorphism reflected an actual rise in crustal temperature in the section of the crust now available for study. This would suggest that the period of high-grade metamorphism had a definite beginning as well as an end at the crustal level now exposed and that it was preceded by a period of lower temperatures. Whether these lower temperatures coincided with a period of crustal stability or whether the crust remained essentially mobile throughout the period before 2900 Ma remains to be established, as does the real significance and duration of the high regional temperatures attained during the 'blanket' metamorphism.

Since Ramberg (1951) suggested that a massive change in the bulk composition of the lower parts of the crust might accompany granulite facies metamorphism there have been various attempts to relate the relative abundances of mobile elements to the metamorphic history of the rocks in the craton. The granulitic Scourian gneisses of the Scottish mainland were shown by Holland (1965), Sheraton (1970) and Moorbath *et al.* (1969) to be low not only in potassium (a feature they share with many gneisses in other parts of the craton) but also in uranium, thorium, yttrium and rubidium, a character ascribed by some authors to depletion during metamorphism in which the more mobile elements moved upwards (cf. table 4). However, interpretation of the available results is far from simple since most studies have been carried out on complexes made up of different proportions of rocks of very different ages and possibly very different pre-metamorphic characters. For example, the ancient Amîtsoq gneisses of West Greenland have lead isotope ratios indicating early U/Pb ratios lower than those of any known terrestrial rock (O.I.G.L. & McGregor 1971), but relatively high rubidium and potassium contents. On the other hand, the much younger Nûk gneisses in the same area have low potassium contents like many granitic rocks formed in other parts of the crust before 3000 Ma ago. Regional geochemical studies on terrains containing an unknown mixture of these two gneiss groups involved in later metamorphism could easily be interpreted incorrectly and it seems that much more information is required about the primary composition of identifiable rock units within the complex before the effects of regional metamorphism can be interpreted. The fact that Rb/Sr and whole-rock lead studies give reasonable isochrons from gneisses in various parts of the complex shows there must have been some migration of material around 2700 to 2900 Ma ago and it would be absurd to assume that such a migration and homogenization was restricted to the elements used in age-determination studies. However, so far, individual studies on the bulk chemistry of rock groups within the complex have shown surprisingly little change in composition which could be attributed to the massive migration of material. The primary differentiation trends of the Fiskenaesset meta-igneous complex do not appear to have been strongly affected by the periods of heavy deformation and metamorphism through which the body has passed (Windley *et al.* in press). Ultrabasic lenses throughout the complex show very little alteration except for a marginal rim of biotite or phlogopite suggesting that water and potassium penetrated into these bodies for a few centimetres only. Preliminary rock-staining studies on granulite facies gneisses from Sukkertoppen in West Greenland and the Tingmiarmiut area of southeast Greenland have shown the high-grade rocks to contain large amounts of potassium feldspar, while the much more comprehensive studies of Kalsbeek, Ghisler & Thomson (1972) have shown no statistical differences in the proportions of potassium feldspar and plagioclase in sands derived from granulite-facies and amphibolite facies terrains in the Fiskenaesset district. If migration of major elements has occurred then it does not appear to have been on the scale envisaged by earlier writers.

5. Stages of stabilization

Until the ending of the 2900 Ma metamorphic event, there appear to have been no very consistent differences between the central craton of the North Atlantic region and the enveloping zones which later became parts of the early Proterozoic mobile belt (figure 1) either in terms of rock-types, or in terms of tectonic and metamorphic styles. Small massifs and remnants of Archaean gneisses which escaped wholesale Proterozoic reworking occur well within the Nagssugtoqidian and Laxfordian belts while reworked Archaean rocks form the greater part of these belts. Allowing for the effects of reworking, it can be inferred that soon after 2900 Ma a complex of gneisses of granulite or amphibolite facies incorporating narrow supracrustal belts and anorthosites not only existed at depth throughout the present Archaean craton, but also extended at least some hundreds of kilometres into the border zones: no limit can yet be set to the original extent of this complex.

The geological events which took place over the next thousand million years, 2700 to

1700 Ma, served collectively to differentiate the central massif from its surroundings: whereas the tectonic and metamorphic patterns already established were modified only to limited extents in the massif, they underwent extensive reworking in the border regions where several major episodes of deformation and metamorphism took place. Most of these episodes were Proterozoic, affecting dyke-swarms emplaced at about 2600 to 1900 Ma as well as earlier rocks, but some appear to date from the closing stages of the Archaean and in both Greenland and Scotland several workers have suggested that the areas which later marked the border-zone between the Archaean block and the mobile belts to the north and south, had been areas which either remained unstable from about 2600 Ma onwards or which were reactivated at a very early stage in the Proterozoic (see Bridgwater, Escher & Watterson, this volume, p. 513). In Scotland a period of metamorphism and deformation giving rise to a number of steep movement-zones in the Archaean gneisses has been called the Inverian episode and has been dated at around 2200 to 2400 Ma (Evans 1965).

The sedimentary and igneous rocks added to the crust after the 2900 Ma event fall into two principal categories, those of the first resembling earlier contributions in composition and relationships, those of the second being distinctive in both respects. In the first category, two assemblages are important. A few groups of supracrustal rocks and associated intrusives, dominated by basic material but including acid volcanics and pelitic and calcareous metasediments, appear to have accumulated after the 2900 Ma event. These groups, which show metamorphism of low grades but which are strongly deformed and interleaved with their basement, include the Tartoq belt of southwest Greenland (Higgins 1968) and the Loch Maree series of northwest Scotland (table 1). Small intrusions of tonalites, diorites and granites with minor carbonatites and appinites bearing some resemblance to the more widespread tonatitic suite emplaced before the main episode of high-grade metamorphism are common in southeast Greenland and occur more locally in northwest Scotland; examples of this suite have yielded ages of 2600 Ma in the southern Outer Hebrides (Francis, Moorbath & Welke 1971) and 2200 Ma in southeast Greenland (Bridgwater 1970). Local developments of granulite-facies metamorphism are seen in the vicinity of some of these intrusions.

New rocks in the second category are represented by swarms of basic dykes, mostly tholeiitic (Dearnley 1962; Chadwick 1969), but including a variety of other basic and ultrabasic (picritic) types (Berthelsen & Bridgwater 1960). These swarms were developed on a regional scale – the Scourie dyke swarm of northwest Scotland, for example, is not less than 250 km across the strike direction – and although only a few examples have so far been accurately dated it seems clear that very large numbers of dykes were emplaced in one or more phases after about 2600 and before about 2000 Ma. This period in which mantle material was tapped and steep crustal fractures opened not only in the central massif but also in many parts of the marginal belts was marked by a style of geological activity conspicuously different from that of earlier periods. Dykes emplaced in the craton tend to have simpler forms than those of the bordering zones some of which (e.g. the Kangamiut dykes in West Greenland) appear to have been emplaced during phases of movement (Windley 1970). Some dykes show partial or complete recrystallization to assemblages of amphibolite or even granulite facies which have been variously attributed to emplacement in hot country rocks (by, for example, O'Hara 1961; Moorbath & Park 1972; Tarney 1972) and to subsequent reheating (Dearnley 1962).

Basic dykes emplaced near the margin of the craton were partly amphibolized and deformed by Proterozoic activity.

Faulting affected the craton during its last stages of stabilization. A network of several generations of faults traverses the crystalline basement displacing many of the basic dykes. Some areas have undergone more complex faulting than others. The Fiskefjord area of West Greenland has a prominent set of northeast trending faults with displacements up to 1.5 km (Berthelsen & Bridgwater 1960) and there is an important northeast trending fault at least 200 km long in West Greenland with a lateral displacement of up to 2 km (Windley, 1972).

Some faults movements took place under sufficiently deep-seated conditions to be responsible for recrystallization of the wall rocks. The Fiskefjord faults (Berthelsen & Bridgwater 1960) and some faults in Amitsuarssuqasuaq fiord in West Greenland have caused amphibolization of dolerite dykes. In one example, 30 cm of amphibolite was produced by a fault with a displacement of 10 m (Windley, 1972). Larsen (1971) has recorded a K/Ar age of 1865 Ma from one such amphibolized dyke. This may indicate that movement on the deep-seated faults cutting the Archaean basement took place at approximately the time at which regional deformation was affecting the Proterozoic mobile belts to the north and south.

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References (Bridgwater *et al.*)

Andrews, J. 1972 Stratigraphic, structural and metamorphic features of Archaean (pre-Ketilidian) rocks in the Frederikshåb area in *The early Precambrian of Scotland and related rocks of Greenland*. University of Keele (in the Press).

Andrews, J., Bridgwater, D. B., Gulson, B. & Watterson J. 1971 Reconnaissance mapping of south-east Greenland between 62° 30′ N and 60° 30′ N. *Rapp. Grønlands geol. Unders.* **35**, 32–37.

Berthelsen, A. 1960 Structural studies in the Precambrian of western Greenland Pt 2, Geology of Torqussap Nuna *Meddr Grønland* **123**, 1–223.

Berthelsen, A. & Bridgwater, D. 1960 On the field occurrence and petrography of some basic dykes of supposed Precambrian age from the southern Sukkertoppen district, Western Greenland. *Meddr Grønland* **123**, 1–42.

Bowes, D. R., Barooah, B. C. & Khoury, S. G. 1971 Original nature of Archaean rocks of northwest Scotland. *Spec. Publ. geol. Soc. Austr.* **3**, 77–92.

Bridgwater, D. 1970 A compilation of K/Ar age determinations on rocks from Greenland carried out in 1969. *Rapp. Grønlands Geol. Unders.* **28**, 47–55.

Bridgwater, D. 1971 Routine K/Ar determinations on rocks from Greenland carried out for G.G.U. in 1970. *Rapp. Grønlands Geol. Unders.* **35**, 52–60.

Bridgwater, D. & Gormsen, K. 1968 Precambrian rocks of the Angmagssalik area, East Greenland. *Rapp. Grønlands Geol. Unders.* **15**, 61.

Bridgwater, D. & Gormsen, K. 1969 Geological reconnaissance of the Precambrian rocks of south-east Greenland. *Rapp. Grønlands Geol. Unders.* **19**, 43–49.

Bridgwater, D. & Windley, B. F. 1972 Anorthosites, post-orogenic granites, acid volcanic rocks and crustal development in the North Atlantic shield during the mid-Proterozoic '*Granite* 71' *Symposium, Geol. Soc. S. Afr.* (in the press).

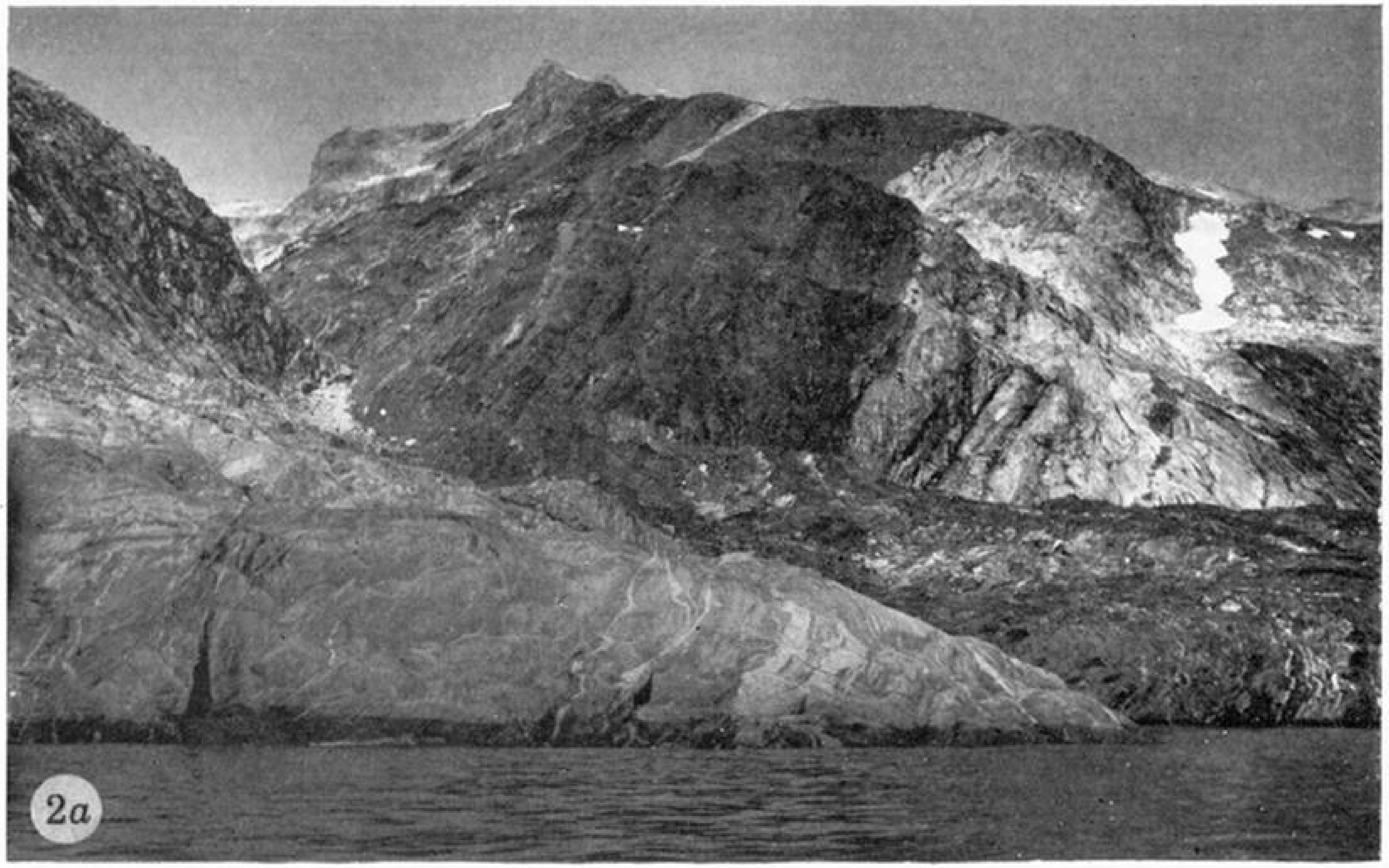
Chadwick, B. 1969 Patterns of fracture and dyke intrusion near Frederikshåb, south-west Greenland. *Tectonophysics* **8**, 247–264.

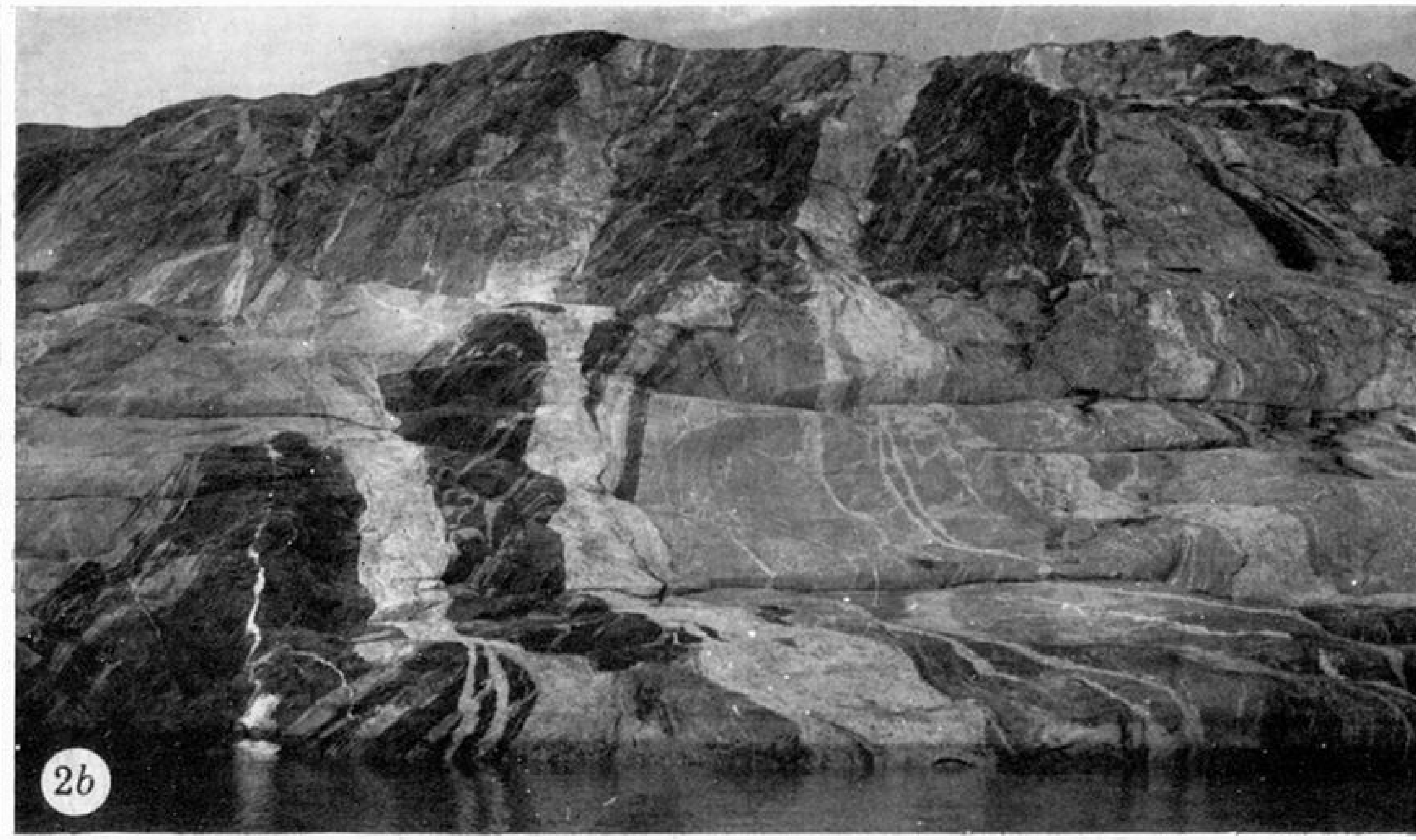
Coward, M. P., Francis, P. W., Graham, R. H., Myers, J. S. & Watson, J. 1969 Remnants of an early metasedimentary assemblage in the Lewisian complex of the Outer Hebrides. *Proc. geol. Ass.* **80**, 387–408.

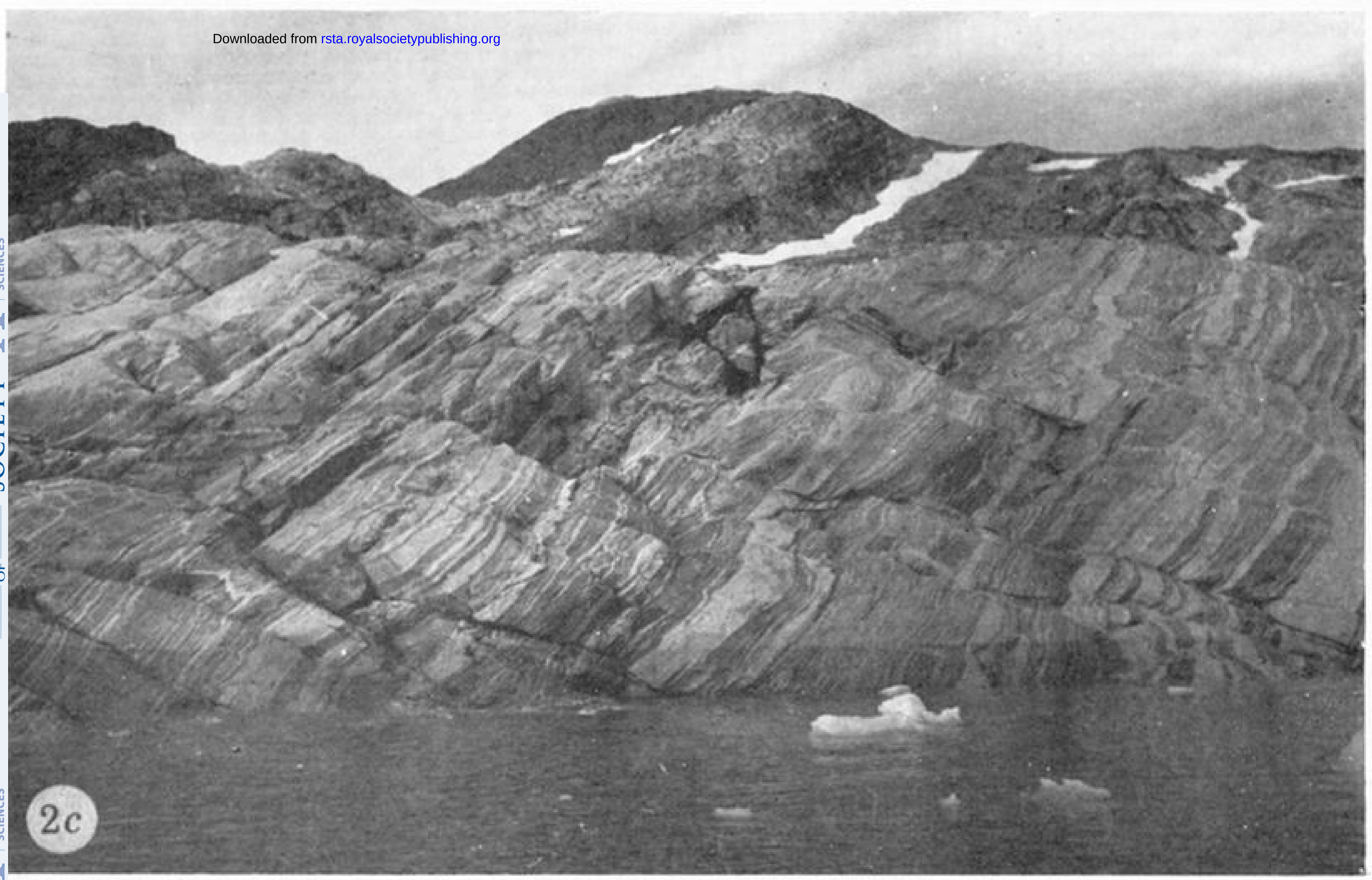
Dawes, P. R. 1970 Bedrock geology of the nunataks and semi-nunataks in the Frederikshåbs Isblink area of southern West Greenland. *Rapp. Grønlands geol. Unders.* **29**, 1–60.

Dearnley, R. 1962 An outline of the Lewisian complex of the Outer Hebrides in relation to that of the Scottish mainland. *Q. Jl geol. Soc. Lond.* **118**, 143–176.

Dearnley, R. & Dunning, F. W. 1968 Metamorphosed and deformed pegmatitic and basic dykes in the Lewisian complex of the Outer Hebrides and their geological significance. *Q. Jl. geol. Soc. Lond.* **123**, 353–378.
Escher, J. C. 1971 The geology of Akuliaq. Doc es Sci. Thesis, Lausanne University.
Evans, C. R. 1965 Geochronology of the Lewisian basement near Lochinver, Sutherland. *Nature, Lond.* **207**, 54–56.
Evenson, M. M., Murthy, V. R. & Windley, B. F. In prep. Rb–Sr dating of Fiskenaesset complex, West Greenland.
Francis, P. W., Moorbath, S. & Welke, H. J. 1971 Isotopic age data from Scourian intrusive rocks on the Isle of Barra, Outer Hebrides, north-west Scotland. *Geol. Mag.* **108**, 13–22.
Gulson, B. L. & Krogh, T. E. 1972 U/Pb zircon studies on the age and origin of post-tectonic intrusions from South Greenland. *Rapp. Grønlands geol. Unders.* **45**, 48–53.
Higgins, A. K. 1968 The Tartoq Group on Nunaquqortoq in the Itlerdlak area, south-west Greenland. *Rapp. Grønlands geol. Unders.* **17**, 1–17.
Holland, J. G. 1965 Geochemical studies in the Lewisian. Thesis for D. Phil. Oxford.
Hunter, D. R. 1970 The ancient gneiss complex of Swaziland. *Trans. geol. Soc. S. Afr.* **73**, 107–150.
Kalsbeek, F. 1970 The petrography and origin of gneisses, amphibolites and migmatites in the Qasigialik area, south-west Greenland. *Bull. Grønlands geol. Unders.* **83**, 1–70.
Kalsbeek, F. 1972 Field work in the Fiskenaesset area, southern west Greenland. *Rapp. Grønlands Geol. Unders.* **45**, 22–24.
Kalsbeek, F. & Leake, B. E. 1970 The chemistry and origin of some basement amphibolites between Ivigtut and Frederikshaab, south-west Greenland. *Bull. Grønlands Geol. Unders.* **90**, 1–36.
Kalsbeek, M., Ghisler & Thomsen, B. 1972 The composition of sands from the Fiskenaesset region, south-west Greenland. *Bull, Grønlands geol. Unders* (in prep.).
Keto, L. 1969 Järnmalmfyndigheten vid Isua, Väst Grönland. *Abst. IX Nord. Geol. Vintermøde Lyngby*, 1970.
Larsen, O. 1971 Reconnaissance K/Ar dating of samples from West Greenland between Søndre Stromfjord and Frederikshaab Isblink. *Rapp. Grønlands geol. Unders* **35**, 44–48.
Mason, R. 1973 The Limpopo mobile belt – southern Africa. *Phil. Trans R. Soc. Lond.* A **273**, 463–485 (this volume).
McGregor, V. R. 1973 The early Precambrian gneisses of the Godthåb district, West Greenland. *Phil. Trans. R. Soc. Lond.* A **273**, 343–358 (this volume).
Moorbath, S., Welke, H. & Gale, N. H. 1969 The significance of lead isotope studies in ancient, high-grade metamorphic basement complexes as exemplified by the Lewisian rocks of north-west Scotland. *Earth Pl. Sci. Lett.* **6**, 245–256.
Moorbath, S. & Park, R. G. 1972 The Lewisian chronology of the southern region of the Scottish mainland. *Scott. Jl Geol.* **8**, 51–74.
O'Hara, M. J. 1961 Petrology of the Scourie dyke, Sutherland. *Min. Mag.* **32**, 848–865.
Oxford Isotopic Geology Laboratory & McGregor, V. R. 1971 Isotopic dating of very early Precambrian amphibolite facies gneisses from the Godthaab district, West Greenland. *Earth Pl. Sci. Lett.* **12**, 246–259.
Phaup, A. E. 1971 Provisional map of the granitic rocks of the Rhodesian craton. Excursion guide-book 'Granite 71' Symposium, *Geol. Soc. S. Afr.*
Pidgeon, R. & Bowes, D. R. 1972 Zircon U–Pb ages of granulites from the central region of the Lewisian, north-west Scotland. *Geol. Mag.* **109**, 247–58.
Ramberg, H. 1951 Remarks on the average chemical composition of granulite facies and amphibolite or epidote–amphibolite facies gneisses from the Godthaab district, West Greenland. *Medd. Dansk geol. Foren.* **12**, 27–34.
Sheraton, J. W. 1970 The origin of the Lewisian gneisses of north-west Scotland, with particular reference to the Drumbeg area, Sutherland. *Earth Pl. Sci. Lett.* **8**, 301–310.
Stockwell, C. H. 1968 Geochronology of stratified rocks of the Canadian shield. *Can. J. Earth Sci.* **5**, 693–698.
Stowe, C. W. 1968 Intersecting fold trends in the Rhodesian basement south and east of Selukwe. *Geol. Soc. S. Afr.* annexure to **71**, 53–78.
Tarney, J. 1972 The Scourie dyke suit in Assynt in *The early Precambrian of Scotland and related rocks of Greenland.* University of Keele (in the press).
Taylor, S. R. 1964 Abundance of chemical elements in the continental crust. *Geochim. et cosmochim. Acta* **28**, 1273–1285.
Watson, J. 1965 Lewisian, in *The geology of Scotland* (ed. Craig) Oliver & Boyd.
Windley, B. F. 1969 Anorthosites of southern West Greenland. *Mem. Am. Ass. Petrol. Geol.* **12**, 899–915.
Windley, B. F. 1970 Primary quartz ferro-dolerite/garnet amphibolite dykes in the Sukkertoppen region of West Greenland. In *Mechanism of igneous intrusion* (ed. G. Newall and K. Rast) **6**, 79–92. (Also *Geol. J.*, sp. issue no. 2.)
Windley, B. F. 1972 Regional geology of early Precambrian high-grade metamorphic rocks in West Greenland. Pt. 1. Kangnaitsoq to Ameralik fjord. *Rapp. Grønlands geol. Unders*, **46**, 1–46.
Windley, B. F. & Bridgwater, D. 1971 The evolution of Archaean low- and high-grade terrains. *Spec. Publ. Geol. Soc. Aust.* **3**, 33–46.
Windley, B. F., Herd, R. K. & Bowden, A. A. The Fiskenaesset complex, West Greenland, Pt. 1. A preliminary study of the stratigraphy, petrology and whole-rock chemistry. *Bull. Grønlands geol. Unders.* (in the press).







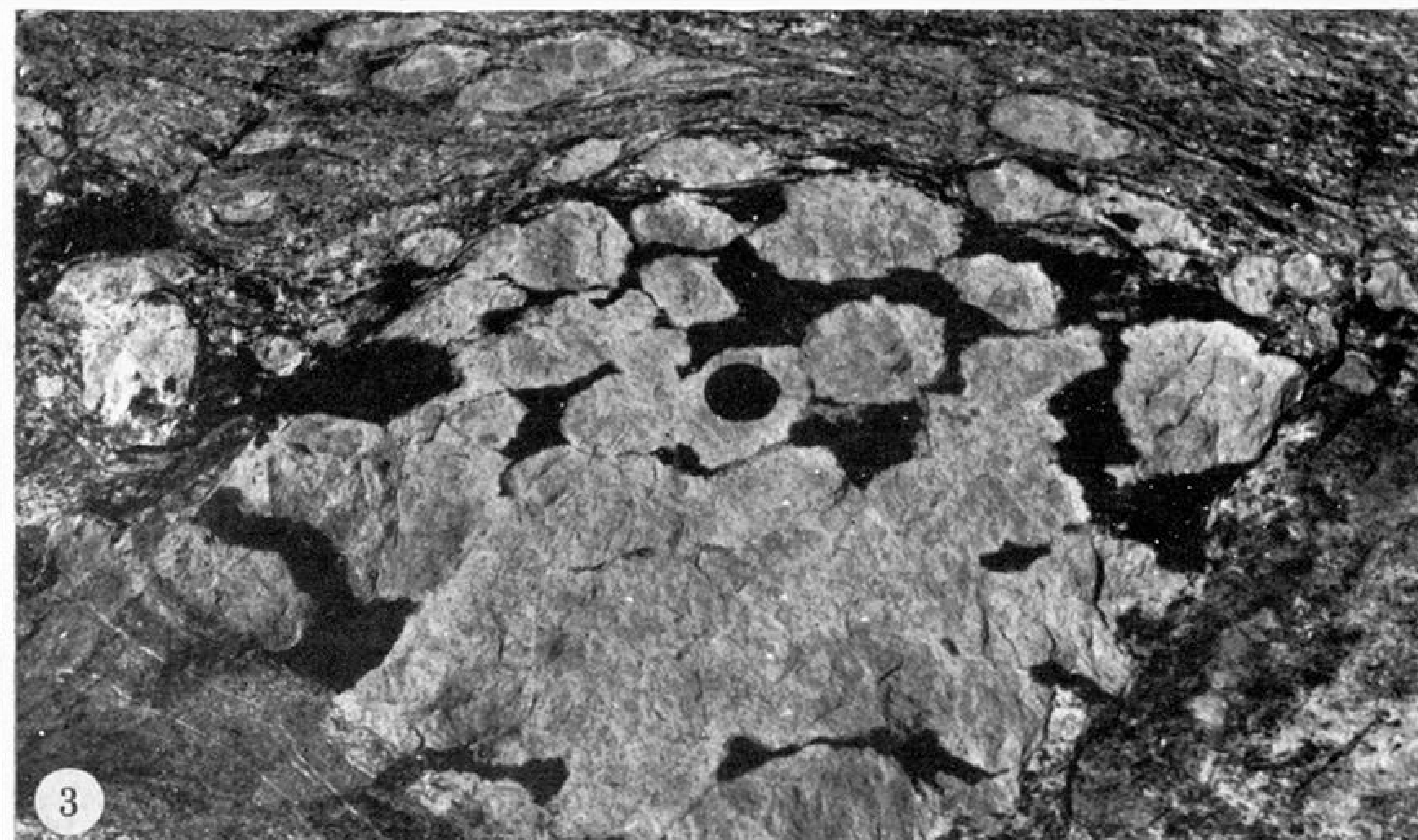


FIGURE 2. (*a*) Typical Archaean amphibolite belt probably of supracrustal origin flanked by quartzo-feldspathic gneisses, Grydefjelet, near Tingmiarmiut, southeast Greenland. The amphibolites contain a thin central pelitic layer.

(*b*) Archaean amphibolite belt flanked by quartzo-feldspathic gneisses and penetrated by several generations of granites and pegmatites which post-date the main phases of deformation but pre-date regional metamorphism of granulite facies 2800 Ma (same locality as (*a*)).

(*c*) Strongly deformed banded gneisses at margin of amphibolite belt incorporating fragments of the belt, later granite veins and, possibly, reworked basement. All the components have been rotated into parallelism (same locality as (*a*)).

FIGURE 3. Anorthosite gabbro fragment in which a primary igneous texture defined by the large feldspars is still recognizable despite fragmentation during both Archaean and early Proterozoic deformation: Kitaq Island near Angmagssalik, East Greenland.