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Early Tertiary flood basalts from Hareøen and western Nûgssuaq, West Greenland

by

Niels Hald

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Abstract

In central West Greenland flood basalts were erupted in the Early Tertiary. On Hareøen and western Nûgssuaq the upper part of the volcanic sequence predominates reaching a thickness of more than 3 km.

In these two areas tholeiitic, olivine porphyritic basalts and picritic basalts are followed by tholeiitic basalts with plagioclase as the dominant phenocryst. The content of incompatible elements in the plagioclase porphyritic basalts is low in the early stages, as is the case in most of the older olivine porphyritic lavas in the province; however, after a pause in the volcanic activity, the concentration of these elements is increased by a factor of 3–6. A few thin layers of peralkaline, rhyolitic tuffs are found in the upper part of the plagioclase porphyritic sequence. The tholeiitic lavas are intruded by dykes. Most of these are petrographically the equivalent of the extrusive rocks, but dykes of transitional olivine basalts are presumed to represent a younger magmatic episode from which no lavas are known. The youngest igneous rocks in the area – and perhaps the youngest lavas in all of the West Greenland basalt province – are olivine porphyritic, alumina enriched transitional basalts deposited unconformably on the tholeiitic sequence on Hareøen.

Forty-three new chemical analyses of the magmatic rocks are presented as well as microprobe data on phenocryst and groundmass phases. The diversity of basaltic rocks cannot be explained by low pressure crystal fractionation alone, and it is suggested that the chemical evolution of the lavas and dyke rocks reflect chemical variations in batches of olivine rich magmas injected into the crust from the mantle.

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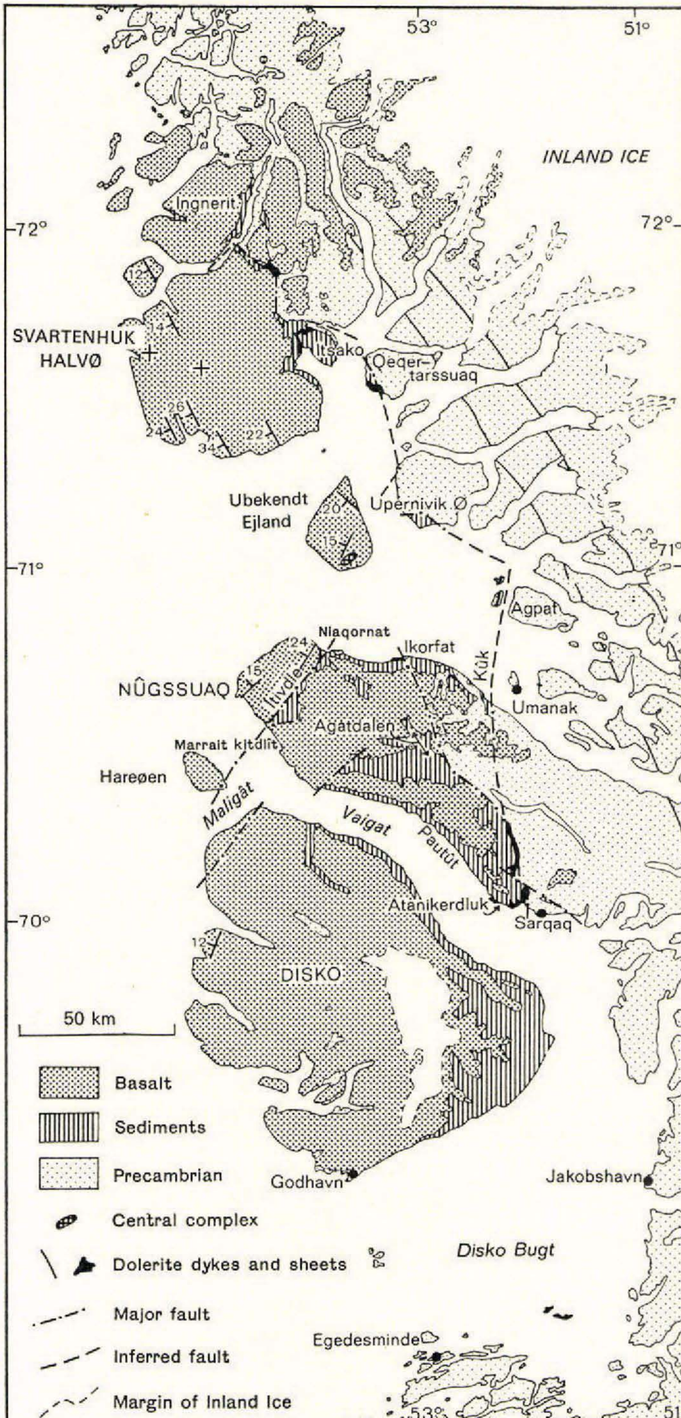

Fig. 1. Geological map of central West Greenland between 68°30′N and 73°00′N. After Rosenkrantz & Pulvertaft (1969).

INTRODUCTION

A sequence of flood basalts was erupted during the Early Tertiary in the central part of West Greenland between latitudes 69° and 73° N. The lavas rest on Precambrian metamorphic rocks and limnic and marine sediments from the Cretaceous and Early Tertiary (Danian) (fig. 1).

Rosenkrantz & Pulvertaft (1969) have summarised the geology of central West Greenland while Munck & Noe-Nygaard (1957) and Clarke & Pedersen (1976) have concentrated on the magmatic rocks. More detailed investigations of the magmatic rocks have been published by Pedersen (1970, 1973) on Disko, by Drever & Game (1948), Drever (1958) and Larsen (in press) on Ubekendt Ejland and by Noe-Nygaard (1942), Munck (1942), Clarke (1970) and Münther (1973) on Svartenhuk Halvø. Rosenkrantz, Münther & Henderson have compiled a geological map of the larger part of Nûgssuaq at a scale of 1 : 100 000 (Agatdal, 70 V.1 N).

The volcanic activity was initiated by eruptions of tholeiitic basalts rich in olivine. As the area in the early stages was partially covered by water, the oldest extrusive rocks have usually developed as pillow breccias. This lower formation, the Vaigat Formation, is overlain by the Maligât Formation, which mainly consists of tholeiitic, plagioclase porphyritic flows poor in olivine. On Hareøen the tholeiitic sequence is followed by transitional basalts with phenocrysts of olivine (Hareøen Formation). On Ubekendt Ejland picritic basalts and olivine basalts from the Vaigat Formation are followed by basic, intermediate and acid tuffs and lavas often with alkaline affinities, as yet not correlated with the lavas on Nûgssuaq and Svartenhuk Halvø. Gabbroic and granophyric intrusives found on Ubekendt Ejland are probably related to these younger volcanic rocks.

The total thickness of the extrusive sequence is about 3 km on Disko and possibly up to 10 km on Ubekendt Ejland and Svartenhuk Halvø.

A basaltic lava from Ubekendt Ejland has been dated by the K-Ar method to 57–70 m.y. (Tarling & Otulana, 1972, citing Mitchell & Evans). Rb-Sr dating of the Sarqâta qáqâ complex also on Ubekendt Ejland gave an age of 65 $\pm$ 5 m.y. whereas biotite from gabbro in the same intrusion has been dated to 55 $\pm$ 2 m.y. by the K-Ar method (Beckinsale *et al.,* 1974). The youngest pre-basaltic sediments on Disko and Nûgssuaq were deposited during the Upper Danian (Jürgensen & Mikkelsen, 1974; Perch-Nielsen, 1973).

Large fault systems have resulted in a stepwise down-faulting of the rock units towards the west. It is generally agreed that both the extrusion of the Tertiary basalts and the faulting was related to movements of Greenland relative to North America (cf. Rosenkrantz & Pulvertaft, 1969; Clarke & Upton, 1971). Models for the opening of Baffin Bay have been put forward by e.g. Le Pichon *et al.* (1971) and Keen *et al.* (1972), but still the evolution of the sea between Greenland and Canada is disputed. Evidence from the Labrador Sea suggests that a change in the pattern of movements took place 60 m.y. ago. As mentioned by Le Pichon *et al.* (1971) this change corresponds in time with the intense volcanic activity in West Greenland.

The main object of this paper is to present an account of the igneous geology of Hareøen and western Nûgssuaq (west of the Itivdle valley) with special reference to the younger Maligât and Hareøen Formations.

GEOLOGY

Nomenclature

The basaltic lavas and dykes on Hareøen and western Nûgssuaq are with few exceptions hypersthene normative (table 2); they are defined as tholeiitic according to Yoder & Tilley (1962) and Green & Ringwood (1967). Several of the tholeiitic basalts contain, however, a brownish-violet calcic augite in the groundmass; these are described as transitional. In the normative ol–hy–di triangular diagram the transitional basalts always plot near the ol–di join.

Chronology

A formal lithostratigraphy of the igneous rocks on Hareøen and western Nûgssuaq has been presented by Hald & Pedersen (1975) and Hald (in press) (table 1).

Western Nûgssuaq

The area mapped on western Nûgssuaq is bounded on the east by the broad Itivdle valley, which follows one of the major fault systems.

The lavas generally dip 0–30° WNW or W, the exposed layers thus becoming progressively younger towards the west. As pointed out by Münther (1973) and Henderson (1973) western Nûgssuaq is cut by numerous normal faults striking N–S or NNE–SSW. Movements along a system of normal faults immediately

Table 1. Stratigraphy of western Nûgssuaq and Hareøen

		Western Nûgssuaq	Hareøen
Hareøen Formation	Talerua Member		Transitional basalts with phenocrysts of olivine and microphenocrysts of plagioclase
	Aumarûtigssâ Member		Arenaceous and argillaceous sediments with coal seams
Maligât Formation	Kanísut Member	Microporphyritic zone: Tholeiitic basalts with microphenocrysts of plagioclase, olivine and augite Porphyritic zone: Tholeiitic basalts with phenocrysts of plagioclase, olivine and augite	Tholeiitic basalts with phenocrysts of plagioclase, olivine and augite
	Ifsorisok Member	Coarse-grained basaltic talus sediments. Minor arenaceous and argillaceous sediments with coal seams	
	Nûluk Member	Tholeiitic basalts with phenocrysts of plagioclase, olivine and augite	Tholeiitic basalts with phenocrysts of plagioclase, olivine and augite
Vaigat Formation		Tholeiitic basalts, usually rich in olivine phenocrysts	Tholeiitic basalts, usually rich in olivine phenocrysts

west of the Itivdle valley resulted in a downthrow to the west and west-north-west with consequent loss of sections of the lava sequence. Further to the west faults which are antithetic to the main system in the Itivdle valley have resulted in downthrow to the east and east-south-east thus giving a repetition of parts of the Maligât Formation. This is particularly noticeable east of Nûluk on the north coast (fig. 2).

Vaigat Formation

Lavas from the Vaigat Formation are exposed in the area around Sangmissoq on the north coast, along the west side of the Itivdle valley and south of Nûlûp qâqai on the south coast. The lavas are separated from the older sediments as well

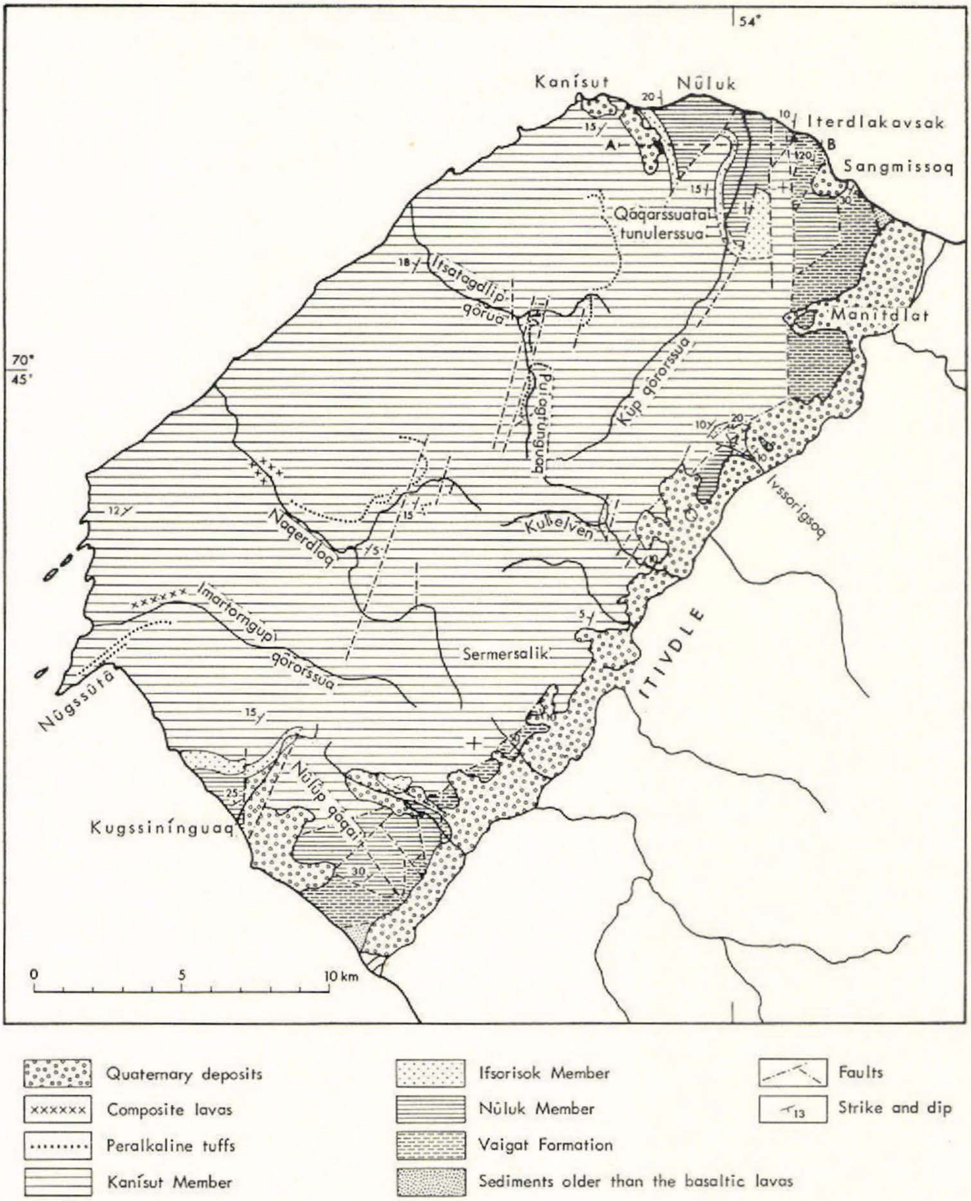

Fig. 2. Geological map of western Nûgssuaq. Based partly on the 1 : 100 000 GGU map sheet Agatdal.

as from the younger volcanic rocks by faults. They appear typically as 1–3 m thick pahoehoe flows of fine-grained, vesicular olivine porphyritic basalt or picritic basalt. The flows often contain coarse-grained, strongly vesicular basaltic segregation veins up to 10 cm wide. Flow groups consisting of very fine grained olivine porphyritic basalt or picritic basalt of pahoehoe or aa type often occur. In these lavas, which are 5–10 m thick, segregation veins are absent.

No continuous profiles have been obtained across the boundary between the Vaigat and the Maligât Formations. It is generally observed that the lavas from the older formation dip towards the west with a higher angle than neighbouring younger lavas. It is therefore supposed that western Nûgssuaq was tilted towards the west prior to the extrusion of the Maligât lavas.

Maligât Formation

The oldest lavas from the Maligât Formation found on western Nûgssuaq have been defined as the Nûluk Member. Owing to the faulting pattern mentioned above the lower boundary is not exposed. The thickness is more than 750 m. The member is characterised by rather thin tholeiitic flows (generally 5–10 m) with a distinct yellowish-brown weathering (see also Henderson, 1969), and with usually rather thin top layers of scoria; plagioclase is the dominant phenocryst.

The extrusion of the lavas of the Nûluk Member was followed by a period of volcanic quiescence. During this interval tilting of western Nûgssuaq took place and the area was concomitantly cut by normal faults. The movements have resulted in a considerable topographic relief as the Nûluk lavas are overlain by a sequence of clastic sediments more than 200 m thick consisting of angular fragments of basalt, up to 0.5 m in size in a fine-grained matrix (Ifsorisok Member). Overlying the coarse-grained sediments, beds of sand, light coloured tuffs, mudstone and coal are locally found, e. g. at Nûluk on the north coast and Kugssinínguaq near the south coast (Nordenskiöld, 1871; Steenstrup, 1883; Koch, 1964) suggestive of a quieter depositional environment.

When the volcanic activity was again initiated, 10 to 20 m thick tholeiitic aa flows now showing reddish-brown weathering overflowed the upper surface of the Ifsorisok sediments. These flows make up the younger, more than 2000 m thick Kanísut Member, which is divided into a lower zone dominated by basalts with plagioclase phenocrysts, 1–10 mm in size (porphyritic zone), and an upper zone consisting mainly of microporphyritic basalts (microporphyritic zone).

Both in the Nûluk and in the Kanísut Members subalkaline rhyolites – mainly tuffs – are found; acid rocks however make up only about one per cent of the total Maligât Formation. Transitional and alkaline magmas were erupted a few times. A transitional olivine basaltic lava rich in segregation veins has been noted in the gully of Ítsatagdlip qôrua surrounded by tholeiitic microporphyritic basalts; and two thin layers of acid, peralkaline, welded tuffs are found near the contact between the porphyritic and microporphyritic zones (fig. 2).

A series of arenaceous and argillaceous, coal bearing sediments, generally less than 30 m thick, is found locally, approximately 50 m below the peralkaline tuffs. These sediments, mentioned by Koch (1964) from Puiagtúnguaq (a tributary to Itsatagdlip qôrua), provide the only evidence suggestive of major interruptions in the volcanic activity during the formation of the Kanísut Member. No angular unconformities have been observed within the member, but the whole sequence (with the exception of some areas near the Itivdle valley) has later been tilted towards the west or west-north-west and cut by normal faults. Structural comparisons with Hareøen suggest that at least some of these crustal movements took place when the volcanism was still active in the province.

Dykes

The lavas of the Vaigat and the Maligât Formations have been intruded by basaltic dykes with trends from N–S to NNE–SSW parallel to the larger faults. An exception to this is found in the area around Nûlûp qáqai where most of the dykes and some faults strike NW–SE parallel to the south coast of Nûgssuaq. Basaltic olivine bearing dykes are dominant in the Vaigat Formation. In the Maligât Formation tholeiitic, mainly plagioclase porphyritic dykes and transitional olivine microporphyritic dykes are found. Tholeiitic dykes are dominant in the Nûluk Member while the two types are evenly distributed in the younger Kanísut Member.

Hareøen

Lavas from the Vaigat Formation are found on the eastern promontory, Niaqua, and in small areas along the north-east coast (fig. 3). The lavas consist of olivine porphyritic basalts resembling the flows from the Vaigat Formation on Nûgssuaq; they are separated from the younger lavas by faults. The Maligât Formation is built up of tholeiitic plagioclase porphyritic basaltic lavas, divided into the lower Nûluk Member and the upper Kanísut Member in accordance with the stratigraphy of western Nûgssuaq. Neither angular unconformities nor sedimentary deposits have, however, been found between the two members on Hareøen. Acid lavas and tuffs are found in a subordinate amount.

The lavas on Niaqua dip 30–40° W. The tholeiitic lavas from the Maligât Formation form a weakly developed anticline, the layers on the north-western part of the island dipping 10° WNW, while the layers elsewhere dip 5–20° ESE.

On the south-eastern part of Hareøen the tholeiitic lavas are overlain by arenaceous and argillaceous sediments with thin coal seams (Aumarûtigssâ Member) mentioned by Giesecke (1910), Steenstrup (1883) and Koch (1964).

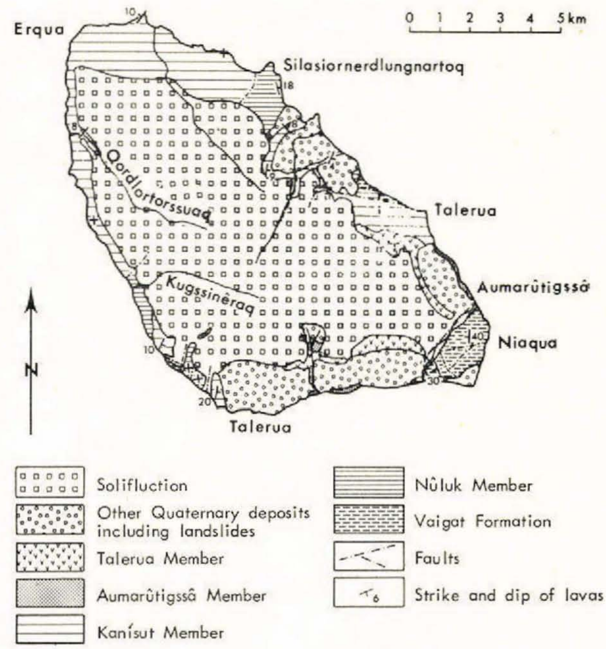

Fig. 3. Geological map of Hareøen.

These sediments are followed by subhorizontal, olivine porphyritic, transitional basalts (Talerua Member) described by Pedersen (1970). The flows are rarely more than 10 m in thickness and the thinner flows, in particular, are strongly vesicular; horizontal segregation veins are common. Thus morphologically the lavas resemble rather closely the olivine porphyritic lavas in the Vaigat Formation. Mineralogically and chemically, however, they differ markedly from these and from the transitional dykes cutting the lavas of the Maligât Formation.

Also the dykes show a close relationship between Hareøen and western Nûgssuaq. Tholeiitic olivine bearing dykes are dominant in the Vaigat Formation whereas transitional dykes dominate in the Maligât Formation. No dykes cutting the transitional basalts from the Talerua Member have been found. The dykes generally strike NNE–SSW parallel to the normal faults which cut the lavas and often show a vertical displacement of several hundred metres.

PETROGRAPHY

A large number of rock samples representing the igneous sequence have been examined in thin section. In addition feldspars, olivines and pyroxenes from 30 samples of the Maligât and Hareøen Formations have been partially analysed using an electron microprobe (groundmass feldspars: Hitachi XMA-5B Scanning Elec-

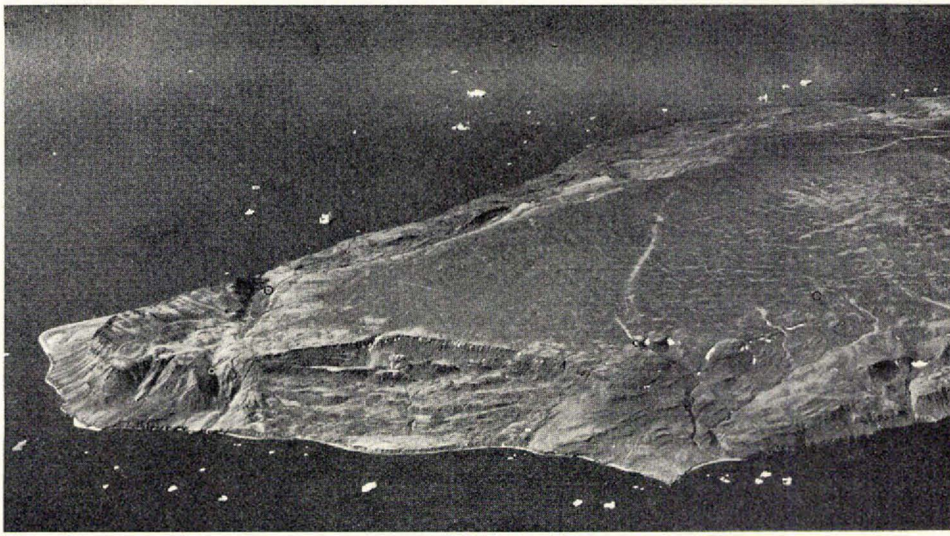

Fig. 4. Aerial photograph showing the north-east coast of Hareøen between Niaqua (left) and Talerua (right). Niaqua, at the south-east end of the island, consists of steeply dipping lavas from the Vaigat Formation. Above Talerua tholeiitic lavas from the Kanísut Member are overlain by transitional lavas from the Talerua Member with an angular unconformity. Sediments from the Aumarûtigssâ Member are exposed in the low cliffs along the coast between Niaqua and Talerua. Copyright Geodetic Institute, Denmark (A. 649/72).

tron Microanalyser, Univ. of Copenhagen; other phases: ARL, EMX, Technical University of Denmark). Natural minerals were used as standards. The analyses have been corrected according to Springer (1967).

Vaigat Formation

As an investigation of the sequence of igneous rocks from the Vaigat Formation on Nûgssuaq is in progress only the thin olivine porphyritic flows which dominate the formation on Hareøen and western Nûgssuaq will be discussed briefly here.

Phenocrysts of olivine are generally less than 1 cm in size; cubic, opaque inclusions, presumably of picotite, are common. Small phenocrysts of basic plagioclase up to 2 mm long are present in some of the lavas. In the groundmass plagioclase, olivine, pyroxene and opaque minerals are found. The strongly vesicular segregation veins consist of a more coarse grained basalt composed of plagioclase, pyroxene and opaque minerals, the latter with skeletal development; olivine is sparse. The olivine porphyritic lavas are generally somewhat altered, especially in fault zones, where olivine is often totally replaced by secondary minerals.

Maligât Formation

The tholeiitic lavas and dykes in the Maligât Formation are fine-grained rocks with doleritic texture. The phenocryst assemblage is most often plagioclase-olivine-augite, less commonly plagioclase-olivine. Only in a few of the basalts neither fresh nor altered olivine has been found.

Nûluk Member

Plagioclase is the dominant phenocryst mineral in the Nûluk Member. Microporphyritic lavas (lath-like phenocrysts up to 1 mm in length) are most common; in some places they alternate with basalts exhibiting a large concentration of phenocrysts, 5 to 10 mm in size. The phenocrysts are zoned from bytownite to andesine and the groundmass plagioclase from basic labradorite to andesine (fig. 5).

Phenocrysts of augite less than 1 mm in size are found in subordinate amount relative to plagioclase. Plotted on the Mg–Fe–Ca triangular diagram (fig. 6) the trend of compositional variation of the groundmass augites is parallel to the trend of groundmass augites from the basic Thingmuli lavas (Carmichael, 1967); the Nûluk trend has, however, shifted somewhat towards the Ca-corner. Using the microprobe a few grains of pigeonite have been found in basalts from Nûgssuaq.

Small olivine phenocrysts are most often replaced by secondary alteration

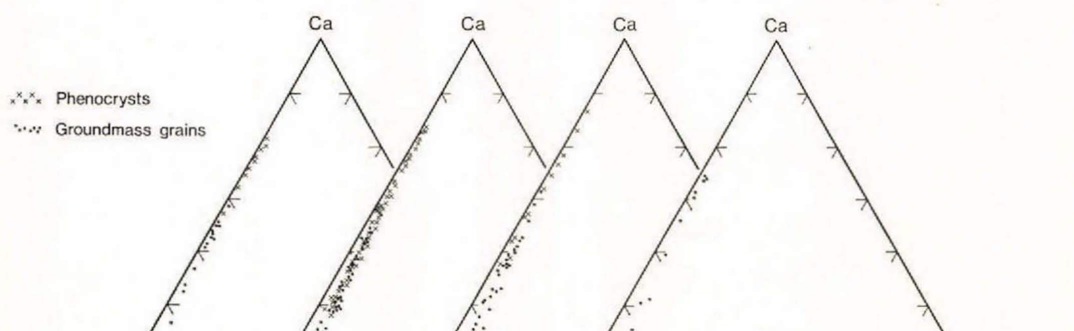

Fig. 5. Plot of partial feldspar microprobe analyses. Atomic proportion. *a*. Nûluk Member; *b*. Kanísut Member; *c*. Transitional dykes; *d*. Talerua Member.

products. Titanomagnetite, ilmenite and apatite are found only in the groundmass together with brown glass or aggregates of brown or green 'chlorite'.

Kanísut Member

Also in the basaltic lavas from the Kanísut Member plagioclase is the dominant phenocryst mineral. Basalts with phenocrysts, 1–10 mm in size, are dominant in the lavas on Hareøen and in the lower part of the lava sequence on Nûgssuaq; microporphyritic flows are, however, common. On Nûgssuaq microporphyritic basalts become dominant approximately 1000 m above the base of the Kanísut Member. The phenocrysts often show a distinct oscillatory zoning. The cores have bytownitic or labradoritic compositions, the sodium content generally being highest in the more differentiated basalts. The groundmass plagioclase is a labradorite; like the phenocrysts it is zoned to andesine. Compared to the Nûluk Member the plagioclase is rich in the orthoclase component corresponding to the larger content of K_2O in the rocks (fig. 5 and table 2).

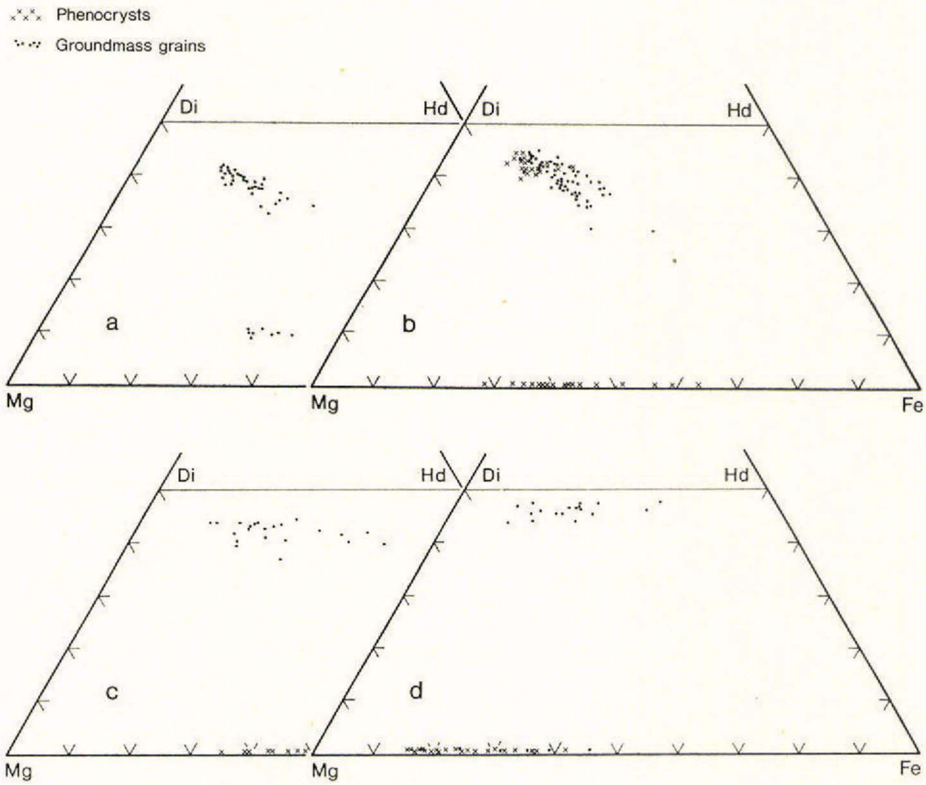

Fig. 6. Plot of partial olivine and pyroxene microprobe analyses. Atomic proportion. *a*. Nûluk Member; *b*. Kanísut Member; *c*. Transitional dykes; *d*. Talerua Member.

Augite is present as phenocrysts rarely more than 1–2 mm in size and occurs as the only pyroxene of the groundmass; there appears to be no systematic difference in calcium between the two pyroxene generations. Compared to the lavas of the Nûluk Member the variation trend is displaced towards more calcium rich compositions (figs 6 and 7).

Olivine phenocrysts (Fo_{70} zoned to Fo_{35}) are less than 0.25 cm in size. Unlike the olivines in the Nûluk Member, these phenocrysts are often well preserved.

Titanomagnetite, ilmenite and apatite occur only in the groundmass together with interstitial glass or 'chlorite'.

Intermediate and acid lavas and tuffs

Intermediate and acid lavas and tuffs make up only a small part of the volcanics in the Mal:gât Formation. Composite lavas of tholeiitic affinity are found on the east coast of Hareøen and at Imartorngup qôrorssua on Nûgssuaq. At both localities the lavas are formed by a lower aphyric, grey, basaltic andesite (table 2, no. 124368) and an upper whitish rhyolite (table 2, no. 124344) with phenocrysts of andesine (An_{30} Ab_{66} Or_4), apatite, altered opaque minerals and ferromagnesian pseudomorphs. The composite lava at Imartorngup qôrorssua is overlain by a dark coloured, glassy lava of rhyolitic composition (table 2, no. 124441) with phenocrysts of andesine (composition as above), augite (Ca_{38} Mg_{41} Fe_{21}), apatite and altered opaque minerals.

A few thin layers of green or yellow, sometimes welded, peralkaline tuffs (table 2, no. 124420) are found on western Nûgssuaq. The phenocryst assemblage is anorthoclase together with aenigmatite or green hedenbergite. In a few rocks all three minerals are found together. The anorthoclase phenocrysts (Ab_{65} Or_{35}) are calcium-poor (0.4 % An) and compare well with the anorthoclase from the Pantellarian pantellerites described by Carmichael (1962). Angular inclusions of basic and acid fine-grained rocks often make up an important part of the tuffs. The grain size generally increases towards the south, and it is presumed that the area

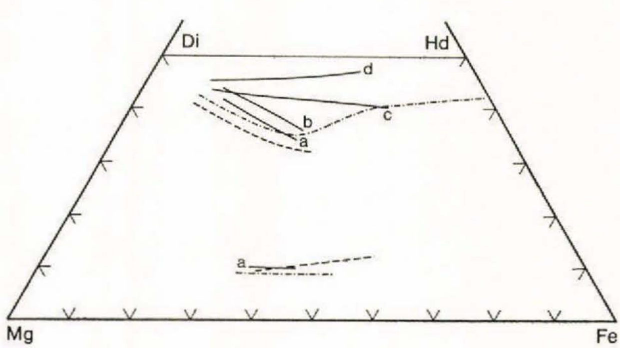

Fig. 7. Trends of pyroxenes and olivines from Nûluk Member (a), Kanísut Member (b), transitional dykes (c) and Talerua Member (d) compared with the trends from the Skaergaard Intrusion –·–·– (Brown & Vincent, 1963) and Thingmuli – – – – – (Carmichael, 1967).

Fig. 8. Photomicrograph. Transitional basalt from dyke. The groundmass consists of olivine, plagioclase and augite. Interstitial material with skeletal augite is seen. Plain polarised light. (× 45).

of eruption was located in the south-western part of Nûgssuaq or in the sea between Nûgssuaq and Hareøen.

Dykes

The tholeiitic dykes cutting the Maligât Formation are generally porphyritic in plagioclase, olivine and augite. In thin section they resemble the tholeiitic lavas and will not be treated further.

The transitional dykes are fine-grained basaltic rocks with doleritic texture and with microphenocrysts of olivine and usually also plagioclase (fig. 8). The composition of the euhedral to subhedral microphenocrysts of olivine is Fo_{65}. They show transitions in size to groundmass olivines zoned from Fo_{65} to Fo_{35}. The plagioclase phenocrysts are bytownites. They are about 1 mm in size and make up less than 1 vol. per cent of the rocks. Groundmass plagioclases have labradoritic cores, the outer rims consisting of andesine.

Pyroxene is found only in the groundmass: a brownish violet calcic augite with increasing colouring of the grains towards the rims. Regarding the Mg:Fe:Ca ratio the cores of augites from the dykes and from the younger tholeiitic lavas have nearly identical compositions. However, the trend of the former is almost parallel to the diopside–hedenbergite join in the Mg:Fe:Ca triangular diagram thus resembling augites from certain alkaline basaltic rocks, e.g. the Shiant Island Sill (Gibb, 1973).

Ilmenite, titanomagnetite and apatite are also restricted to the groundmass. Late crystallised residual material makes up 5–10 per cent of the rocks: skeletally developed grains of plagioclase, calcic augite, ilmenite, apatite and (rarely) olivine surrounded by carbonates, zeolites and 'chlorite'.

Hareøen Formation

The lavas of the Talerua Member are fine-grained poikilitic rocks of basaltic composition with phenocrysts of olivine and scattered microphenocrysts of plagioclase (fig. 9).

Euhedral to subhedral magnesium rich olivine phenocrysts (Fo_{85} in cores), 1–2 mm across, make up 5–10 vol. per cent of the rocks. Cubic grains of picotite are common as inclusions. In the groundmass olivine is present as subhedral grains zoned from Fo_{75} to Fo_{55}. Scattered microphenocrysts of bytownitic plagioclase (less than 1 vol. per cent) are found in most of the lavas. The feldspar laths in the groundmass are likewise bytownites; they are strongly zoned and often surrounded by sodium rich sanidine. Late crystals consist exclusively of alkali feldspar. Pyroxene, which poikilitically surrounds the feldspar laths, is a brownish-violet augite; the colour intensity increases towards the rims. With respect to the Mg:Fe:Ca ratio the pyroxene is a typical calcic augite similar to the augites occurring in Shonkin Sag (Nash & Wilkinson, 1970). Ilmenite, developed in tabular form, equidimensional titanomagnetite and prismatic apatite is like the augite

Fig. 9. Photomicrograph. Transitional basaltic lava from Talerua Member. Phenocrysts of olivine are found in a poikilitic groundmass with feldspar and augite. Plain polarised light. (× 20).

restricted to the groundmass. The lavas are rich in interstitial material ('chlorite' and zeolites).

CHEMISTRY

Fifteen rocks from Hareøen and western Nûgssuaq have been analysed at the Department of Earth Sciences, University of Leeds. Major elements except Na were analysed with XRF on glass discs. Na was determined by flame photometry, Fe^{++} by wet chemistry and H_2O^+ by the Penfield method. Trace elements were analysed by XRF on powder pellets.

Twenty-eight rocks were later analysed for major elements by the Geological Survey of Greenland in Copenhagen. The same analytical methods were used except for Mg, which was determined by complexometric titration. A number of samples from various parts of Greenland, previously analysed at Leeds, were reanalysed for control between the two sets of measurements.

The tholeiitic lavas all have rather high Fe_2O_3/FeO ratios (0.75 on average). This suggests a post-eruptional oxidation as is also shown by the Fe-Ti oxides. To diminish the influence of this oxidation the normative mineral compositions have been calculated with Fe_2O_3 = 1.5 % as proposed by Coombs (1963).

Total water in the tholeiitic lavas and in the transitional dykes ranges from 0.80 % to 3.12 % and in the transitional lavas from the Talerua Member between 1.72 % and 6.52 %. The high content of water makes it likely that the rocks have gone through post-eruptional alteration besides oxidation of the opaque minerals. However, no correlation has been found between H_2O or Fe_2O_3/FeO and major element composition within a stratigraphical unit.

In most of the analysed tholeiitic lavas and dykes the content of any phenocryst mineral is 5 % or less; the only exceptions are 124355, 124385 and 134874 with 14 %, 6 %, and 6 % plagioclase respectively. In the transitional dykes phenocrysts are always sparse whereas olivine phenocrysts make up 5–15 % of the transitional lavas listed in table 2.

The flows from Nûgssuaq and Hareøen belonging to the Nûluk Member (table 2 and fig. 10) are chemically very similar. The oldest lavas in the Maligât Formation on Nûgssuaq as well as on Hareøen are tholeiitic basalts characterised by rather low concentrations of potassium. The content of K_2O varies between 0.10 % and 0.26 % with an average of 0.17 % for 20 lavas from Nûgssuaq, including 14 basalts only analysed for K_2O, while on Hareøen the content of K_2O varies from 0.13 % to 0.33 % with an average of 0.21 % for 8 lavas including 6 basalts only analysed for K_2O. Also the concentration of Rb, Sr, Ba, Zr and Nb are low in these rocks (124424 and 124470).

On Nûgssuaq the composition of the tholeiitic lavas changes from the Nûluk

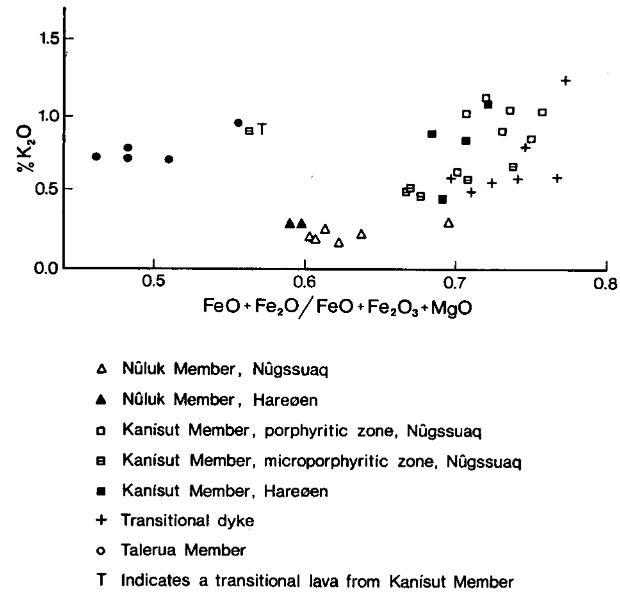

Fig. 10. Plot of potassium in basaltic lavas and dykes against $FeO + Fe_2O_3/FeO + Fe_2O_3 + MgO$ (water free composition recalculated to 100 %; $Fe_2O_3 = 1.50$ %).

Member to the Kanísut Member. The lavas of the Kanísut Member are more 'evolved' with lower MgO, CaO and Ni and with higher total iron, TiO_2, Na_2O, K_2O, P_2O_5, Rb, Sr, Ba, Zr and Nb. The concentration of K_2O is three to six times greater in the porphyritic zone (0.96 % on average) and two to three times greater in the microporphyritic zone (0.54 % on average) as compared to the older basalts of the Maligât Formation. Along with the increased potassium content in the younger tholeiitic lavas the K_2O/Na_2O has increased. At the same time the concentration of Al_2O_3 and SiO_2 seems on the average to be lower in the Kanísut Member than in the Nûluk Member. Although the Kanísut Member on Nûgssuaq has been divided into a 'porphyritic' and a 'microporphyritic' zone it should be noted that microporphyritic basalts in the lower zone (134863 and 135104) have the same general chemistry as the surrounding porphyritic basalts.

Also on Hareøen the lavas from the Kanísut Member are 'evolved' compared to the older basalts; the average K_2O content is 0.82 %. The variation of potassium among the lavas is large; 124345 with only 0.43 % K_2O was collected from a sequence of almost aphyric basalts. This suggests that it may be possible to subdivide the Kanísut Member according to the same criteria as used on Nûgssuaq.

The three-fold subdivision of the Maligât lavas is also exemplified by the alkali–silica diagram (MacDonald & Katsura, 1964). The three tholeiitic lava types cluster around three different variational trends (fig. 11). Although not well defined these trends seem to be more or less parallel to the trends of the tholeiitic basalts from Hawaii (MacDonald & Katsura, 1964) and Thingmuli (Carmichael, 1964). The older, potassium poor, tholeiitic lavas plot in the tholeiitic field relative to the

Table 2. Chemical analyses of rocks

Nûluk Member, Nûgssuaq

	124424	124462	124465	124470	134815	134871	134874
SiO_2	49.2	71.9	48.1	48.2	49.6	48.0	46.5
TiO_2	2.49	0.33	1.90	2.04	1.77	1.80	1.61
Al_2O_3	13.0	12.9	14.7	14.0	14.1	14.0	14.4
Fe_2O_3	3.70	2.89	5.51	5.35	3.23	3.94	4.61
FeO	10.54	0.07	6.53	7.25	8.12	7.70	7.21
MnO	0.24	0.02	0.25	0.20	0.19	0.22	0.24
MgO	6.13	0.13	6.62	7.43	7.36	7.16	7.46
CaO	10.6	0.70	11.4	11.7	11.5	11.7	11.8
Na_2O	2.79	4.05	2.16	2.47	2.28	2.34	2.34
K_2O	0.23	4.24	0.23	0.12	0.21	0.24	0.18
P_2O_5	0.24	0.03	0.31	0.21	0.26	0.42	0.39
H_2O^+	0.69	1.29	1.12	1.04	1.05	1.11	1.64
H_2O^-	0.41	0.65	0.92	0.69	0.66	1.32	1.48
	100.26	99.20	99.75	100.70	100.33	99.95	99.86
Trace elements (ppm)							
Rb	4	121		–			
Cu	303	3		278			
Sr	198	88		179			
Ba	143	565		34			
Zr	186	980		126			
Nb	7	117		3			
Co	44	7		42			
Ni	70	6		85			
C. I. P. W. norms (Fe_2O_3 = 1.5 %)							
Q		30.51			0.29		
C		0.45					
or	1.36	25.06	1.36	0.71	1.24	1.42	1.06
ab	23.61	34.27	18.28	20.90	19.29	19.80	19.80
an	22.27	3.28	29.74	26.76	27.62	26.99	28.26
ne							
ac							
di	11.91		11.50	14.37	13.66	13.66	13.40
he	11.99		8.94	10.21	9.08	9.60	9.38
ln	8.14	0.32	10.95	6.52	12.00	8.36	4.26
fs	9.41		9.77	5.31	9.14	6.74	3.42
fo	1.12		0.15	3.73		2.20	5.68
fa	1.43		0.14	3.35		1.96	5.03
mt	2.17		2.17	2.17	2.17	2.17	2.17
il	4.73	0.19	3.61	3.87	3.36	3.42	3.06
hm		2.89					
ap	0.57	0.07	0.73	0.50	0.62	0.99	0.92
ru		0.23					

from Maligât and Hareøen Formations

Hareøen		*Kanísut Member, porphyritic zone, Nûgssuaq*						
123929	123961	124385	124390	124819	134859	134863	135104	135107
47.0	47.2	48.3	47.9	48.9	47.9	48.6	47.3	46.5
1.46	1.48	3.13	3.05	4.05	3.11	3.08	3.29	4.12
15.1	14.0	14.2	13.5	12.6	13.5	13.7	12.9	12.7
5.63	5.28	4.22	5.37	2.51	6.45	6.77	4.19	6.89
5.56	6.46	9.16	8.76	12.60	7.14	6.39	10.63	7.81
0.17	0.20	0.20	0.23	0.23	0.16	0.17	0.21	0.21
7.50	7.63	5.44	5.87	5.01	4.69	4.63	4.68	5.50
11.7	11.8	10.1	10.5	9.33	10.4	10.4	10.4	9.83
2.02	2.34	3.06	2.82	2.83	2.69	2.74	2.96	2.75
0.28	0.28	1.02	0.60	0.88	1.02	0.89	1.05	1.14
0.28	0.29	0.40	0.36	0.53	0.55	0.41	0.56	0.51
2.43	1.82	0.77	0.94	1.06	1.53	1.27	0.74	1.08
0.26	0.35	0.46	0.61	0.12	0.73	0.25	0.32	1.10
99.39	99.13	100.46	100.51	100.65	99.87	99.30	99.23	100.14
		20	6					
		236	157					
		366	340					
		347	405					
		264	231					
		36						
		41	47					
		44	49					
				0.36		0.37		
1.65	1.65	6.03	3.55	5.20	6.03	5.26	6.20	6.74
17.09	19.80	25.89	23.86	23.95	22.76	23.18	25.05	23.27
31.31	26.87	22.00	22.41	19.08	21.75	22.45	18.81	18.94
12.44	14.55	10.80	11.54	8.99	10.27	10.55	10.52	11.05
7.96	9.88	10.36	11.15	10.87	11.65	11.51	13.92	10.97
8.32	4.65	2.53	4.73	8.31	5.87	6.64	1.54	3.10
6.11	3.62	2.78	5.24	11.53	7.64	8.31	2.34	3.53
3.22	5.33	4.21	3.18		0.74		3.67	3.84
2.60	4.57	5.11	3.88		1.06		6.13	4.81
2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17
2.77	2.81	5.94	5.79	7.69	5.91	5.85	6.25	7.82
0.66	0.69	0.95	0.85	1.26	1.30	0.97	1.33	1.21

Table 2. Chemical analyses of rocks

Kanísut Member, microporphyritic zone, Nûgssuaq

	124420	124440	124441	124444	134879	135192	135194
SiO_2	69.5	70.6	68.6	48.5	42.3	46.8	48.1
TiO_2	0.43	0.80	0.75	2.30	2.48	3.11	2.44
Al_2O_3	9.86	13.9	13.4	14.0	14.4	12.7	14.0
Fe_2O_3	4.92	3.06	2.56	4.31	4.85	8.61	5.65
FeO	0.95	0.27	1.56	8.36	7.88	6.67	6.69
MnO	0.15	0.04	0.17	0.22	0.17	0.18	0.20
MgO	0.73	0.28	0.40	6.09	9.62	5.17	5.70
CaO	0.64	1.00	1.51	11.3	9.85	10.7	11.7
Na_2O	3.34	4.71	4.35	2.87	2.15	2.70	2.54
K_2O	4.13	3.74	3.85	0.52	0.84	0.64	0.45
P_2O_5	0.07	0.09	0.15	0.33	0.46	0.47	0.33
H_2O^+	4.36	0.97	2.20	0.68	3.27	1.13	0.88
H_2O^-	1.11	0.13	0.35	0.12	1.61	0.82	0.46
	100.19	99.59	99.85	99.60	99.88	99.70	99.14
Trace elements (ppm)							
Rb	179		119	8			
Cu	4		5	206			
Sr	19		104	237			
Ba	14		576	196			
Zr	130		921	162			
Nb	179		116	15			
Co	18		10	42			
Ni	7		7	58			
C. I. P. W. norms (Fe_2O_3 = 1.5 %)							
Q	32.72	26.59	25.34				
C		0.50					
or	24.41	22.10	22.75	3.07	4.96	3.78	2.66
ab	27.72	39.85	36.81	24.28	14.29	22.85	21.49
an		4.37	5.67	23.78	27.16	20.64	25.47
ne					2.11		
ac	0.47						
di	2.12		0.66	13.39	9.86	11.09	13.43
he				11.52	5.38	13.48	11.74
en	0.84	0.70	0.69	3.52		3.69	6.18
fs				3.47		5.15	6.20
fo				3.81	13.59	2.83	1.25
fa				4.14	9.36	4.36	1.38
mt	2.30		3.41	2.17	2.17	2.17	2.17
il	0.82	0.66	1.42	4.37	4.71	5.91	4.63
hm	3.17	3.06	0.21				
ap	0.17	0.21	0.36	0.78	1.09	1.11	0.78
ru		0.45					

from Maligât and Hareøen Formations (cont.)

		Kanísut Member, Hareøen					
135196	135198	123934	123991	124344	124345	124355	124368
47.1	46.0	48.0	48.0	69.4	47.1	50.0	53.1
2.45	3.43	2.93	3.49	0.84	2.96	3.30	2.76
14.4	12.7	14.6	13.5	13.7	13.8	14.9	13.8
5.91	6.47	5.41	5.44	3.04	6.03	5.82	6.42
7.09	8.44	7.89	8.34	0.90	8.43	5.20	6.10
0.20	0.24	0.21	0.21	0.10	0.21	0.18	0.24
6.19	5.94	5.34	5.18	0.96	6.23	4.93	3.77
11.6	10.5	10.7	9.87	0.97	10.6	9.88	7.97
2.53	2.51	3.00	2.87	4.77	2.89	3.36	3.69
0.52	0.57	0.83	1.09	3.72	0.43	0.94	1.25
0.35	0.40	0.42	0.48	0.13	0.31	0.40	0.37
1.09	1.54	0.71	0.76	0.99	1.15	0.98	0.76
0.73	1.10	0.44	0.71	0.53	0.81	0.84	0.43
100.16	99.84	100.48	99.94	100.05	100.95	100.73	100.66
		15	24		4	15	18
		184	275		299	277	237
		356	327		247	346	225
		203	358		165	299	314
		240	312		179	268	351
		31	40		18	35	39
		43	40		44	37	39
		62	59		56	46	23
				24.31		0.01	3.30
				0.37			
3.07	3.37	4.90	6.44	21.98	2.54	5.55	7.39
21.41	21.24	25.38	24.28	40.36	24.45	28.43	31.22
26.40	21.70	23.92	20.73	3.96	23.41	22.80	17.40
12.76	11.46	11.11	10.42		11.57	11.34	7.32
11.11	11.64	10.83	10.44		10.95	8.05	9.20
2.90	4.42	2.02	5.02	2.34	2.31	7.02	6.00
2.89	5.15	2.26	5.77		2.51	5.72	8.65
4.63	3.55	4.29	2.14		5.50		
5.09	4.56	5.29	2.71		6.57		
2.17	2.17	2.17	2.17	0.79	2.17	2.17	2.17
4.65	6.51	5.56	6.63	1.60	5.62	6.27	5.24
				2.49			
0.83	0.95	0.99	1.14	0.31	0.73	0.95	0.88

Table 2. Chemical analyses of rocks

Transitional dykes

	123966	123970	124312	124413	134850	134166	134188
SiO_2	46.8	46.6	46.1	46.0	47.3	46.5	46.1
TiO_2	3.45	3.35	4.03	3.20	3.47	2.79	3.82
Al_2O_3	12.6	12.5	13.0	12.9	13.3	13.5	11.8
Fe_2O_3	4.67	4.14	4.52	5.59	3.80	2.11	2.84
FeO	11.46	11.32	9.91	9.11	11.40	11.89	14.07
MnO	0.24	0.23	0.20	0.23	0.27	0.21	0.25
MgO	5.99	5.28	4.82	6.19	4.43	5.69	5.09
CaO	10.7	10.7	10.9	10.4	9.50	11.4	10.7
Na_2O	2.80	2.78	3.00	2.57	3.77	3.12	2.78
K_2O	0.55	0.57	0.79	0.56	1.24	0.50	0.58
P_2O_5	0.37	0.45	0.50	0.43	0.50	0.36	0.50
H_2O^+	0.67	1.02	0.86	1.43	0.82	1.18	0.68
H_2O^-	0.32	0.38	0.29	1.16	0.32	0.22	0.13
	100.62	99.32	98.92	99.77	100.12	99.47	99.34
Trace elements (ppm)							
Rb	12						
Cu	354						
Sr	233						
Ba	160						
Zr	266						
Nb	18						
Co	46						
Ni	51						
C.I.P.W. norms (Fe_2O_3 = 1.5 %)							
Q							
C							
or	3.25	3.37	4.67	3.31	7.33	2.95	3.43
ab	23.69	23.52	25.14	21.75	25.93	22.86	23.52
an	20.19	19.95	19.67	22.01	15.71	21.35	18.01
ne			0.13		3.24	1.92	
ac							
di	11.94	11.25	12.16	11.22	9.70	13.22	10.96
he	13.50	14.04	13.84	11.03	14.00	14.14	15.81
en	1.60	2.62		3.88			1.57
fs	2.07	3.74		4.38			2.60
fo	5.45	3.73	4.46	4.44	4.58	5.64	4.22
fa	7.79	5.87	6.42	5.52	8.36	7.62	7.70
mt	2.17	2.17	2.17	2.17	2.17	2.17	2.17
il	6.55	6.36	7.65	6.08	6.59	5.30	7.26
hm							
ap	0.88	1.07	1.18	1.02	1.18	0.85	1.18
ru							

from Maligât and Hareøen Formations (cont.)

Hareøen Formation

123940	124337	124341	124363	124360
45.3	45.1	44.7	44.8	46.9
1.31	1.12	1.10	1.24	1.45
14.7	14.9	15.0	14.7	15.6
2.43	3.91	3.99	1.82	3.00
7.03	5.96	5.65	8.47	6.93
0.17	0.17	0.16	0.18	0.17
7.48	11.2	10.1	9.86	10.5
10.6	9.49	9.98	10.0	10.4
1.91	2.04	1.79	1.98	2.45
0.89	0.70	0.74	0.69	0.75
0.33	0.26	0.28	0.26	0.24
5.92	4.21	5.12	4.31	1.44
0.60	0.38	0.61	0.30	0.28
98.67	99.44	99.22	98.61	100.11
				21
				63
				476
				405
				122
				35
				36
				195
5.26	4.14	4.37	4.08	4.43
16.16	17.26	15.15	16.75	20.61
28.91	29.43	30.71	29.19	29.35
				0.06
11.44	9.32	9.75	10.36	12.04
6.08	3.54	3.96	4.83	4.64
7.23	3.93	6.16	3.88	
4.41	1.71	2.87	2.08	
4.27	13.77	10.14	11.12	14.42
2.87	6.61	5.21	6.56	7.03
2.17	2.17	2.17	2.17	2.17
2.49	2.13	2.09	2.36	2.75
0.78	0.62	0.66	0.62	0.57

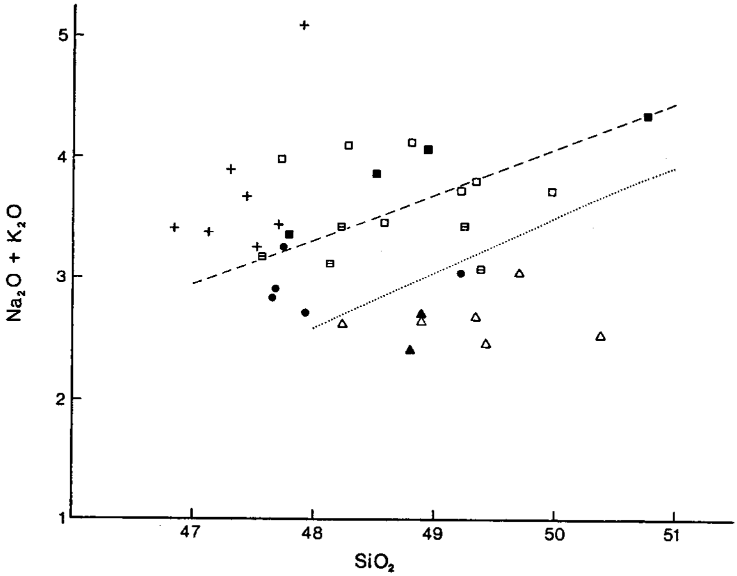

Fig. 11. Plot of total alkalies versus silica (water free compositions recalculated to 100 %; Fe_2O_3 = 1.50 %). Dashed line shows the position of the Hawaii dividing line and the dotted line the position of the Thingmuli trend (Carmichael, 1964). See fig. 10 for other symbols.

Hawaii dividing line, whereas most of the K-enriched tholeiitic lavas from the porphyritic zone on Nûgssuaq and from the Kanísut Member on Hareøen plot in the alkaline field. The K-enriched, tholeiitic lavas from the microporphyritic zone on Nûgssuaq occupy a position intermediate between the two older lava types.

Although many of the lavas plot in the alkaline field of the alkali–silica diagram, they are all hypersthene-olivine normative or hypersthene-quartz normative (for Fe_2O_3 = 1.5 %; when analysed values for Fe_2O_3 are used all lavas except 124385, 134874 and 135104 are quartz normative). Fig. 12 illustrates that the position in the normative quartz–hypersthene–olivine–diopside double tetrahedron is approximately the same for the lavas from the Nûluk Member and from the Kanísut Member.

In spite of the difference in mineralogy between the plagioclase-olivine-augite porphyritic tholeiitic lavas from the Kanísut Member and the younger olivine-plagioclase porphyritic dykes the difference in chemical composition is rather small. The dykes are higher in titanium, manganese and total iron and lower in silica and aluminium compared to the lavas. The dykes are either hypersthene–olivine normative or nepheline-olivine normative (also when analysed values for Fe_2O_3 are used). In the olivine–hypersthene–diopside–nepheline double triangular diagram they are grouped around the olivine–diopside join; in accordance with the average composition the dykes are termed transitional.

Also the youngest rocks in the area investigated, the transitional lavas from the Talerua Member, are relatively high in K_2O, P_2O_5, Rb, Sr, Ba, Zr and Nb. In other

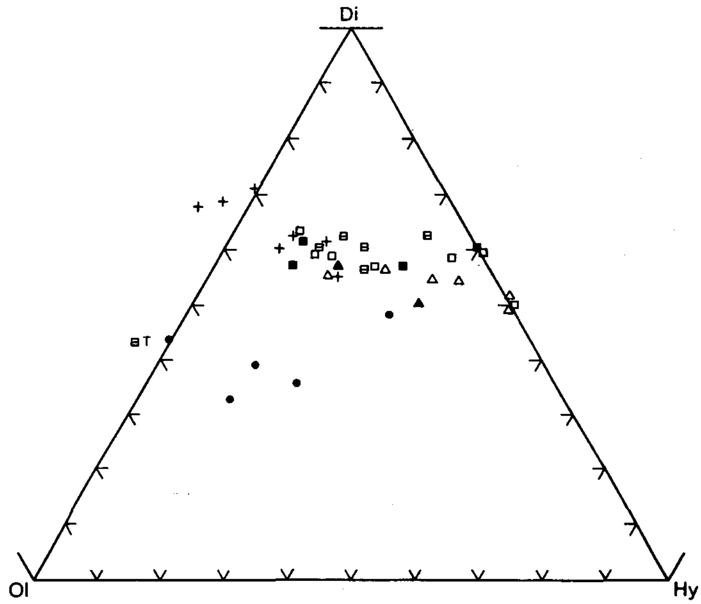

Fig. 12. Normative compositions expressed as the ratios between ne, ol, hy, Q and di. Fe_2O_3 = 1.50 %. See fig. 10 for symbols.

respects the lavas are more primitive. They are rich in MgO and Ni and poor in total iron and TiO_2 when compared to the rocks of the Maligât Formation and thus show some resemblance to the olivine porphyritic lavas from the Vaigat Formation as described from Svartenhuk Halvø by Clarke (1970). The lavas from the Talerua Member are exceptional with respect to the high content of Al_2O_3. They are generally hypersthene-olivine normative, but one of the analysed rocks, 124360, contains less than 0.1 % normative nepheline.

DISCUSSION

The low concentrations of potassium, phosphorous and incompatible elements like Rb, Ba, Zr and Nb and also the low K_2O/Na_2O ratio make the tholeiitic basalts from the Nûluk Member comparable to ocean ridge basalts. Also except for some low values of Na_2O, the range of major oxides lies inside the chemical spectrum of ocean ridge basalts as given by Kay *et al.* (1970) and Shido, Miyashiro & Ewing (1971).

After the pause in the volcanic activity during the deposition of the sediments forming the Ifsorisok Member the composition of the tholeiitic basalts on Hareøen and western Nûgssuaq changes and now becomes comparable in chemistry to the so-called 'FETI' or 'plume' basalts characterised by high concentrations of iron- and titanium relative to ocean ridge basalts. Lavas from the microporphyritic zone compare well to 'FETI' basalts from Iceland (Jakobsson, 1972) and the Faeroes

(Rasmussen & Noe-Nygaard, 1969) whereas the lavas from the porphyritic zone are higher in titanium as well as in potassium than most Caenozoic tholeiitic basalts from the North Atlantic area (table 3).

Table 3. Average compositions of basaltic rocks from Hareøen and western Nûgssuaq

	1	2	3	4	5	6	7	8	9
SiO_2	49.3	48.8	48.9	48.5	49.0	47.4	48.1	50.0	49.7
TiO_2	1.98	1.52	3.47	2.82	3.22	3.51	1.31	2.14	2.40
Al_2O_3	14.3	15.1	13.6	13.9	14.4	13.1	15.9	14.77	14.02
Fe_2O_3	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50	1.50
FeO	10.75	9.99	12.53	12.01	11.42	13.82	8.75	10.57	12.01
MnO	0.22	0.20	0.20	0.22	0.20	0.23	0.18	0.23	0.21
MgO	7.19	7.85	5.22	5.97	5.50	5.47	10.40	6.67	5.99
CaO	11.7	12.2	10.3	11.4	10.4	10.8	10.7	10.84	10.80
Na_2O	2.45	2.26	2.90	2.70	3.08	3.03	2.15	2.79	2.72
K_2O	0.20	0.29	0.96	0.55	0.83	0.69	0.79	0.25	0.42
P_2O_5	0.32	0.30	0.48	0.39	0.41	0.45	0.29	0.24	0.23

Water free compositions recalculated to 100 %. Fe_2O_3 = 1.50 %

1. Nûluk Member, Nûgssuaq
2. Nûluk Member, Hareøen
3. Kanísut Member porphyritic zone
4. Kanísut Member microporphyritic zone (134879 not included)
5. Kanísut Member, Hareøen
6. Transitional dykes
7. Talerua Member
8. Ocean Ridge Tholeiite (recalculated from Shido, Miyashiro & Ewing, 1971, Table 7: Group of PL–Tholeiites, FeO/MgO = 1.70–1.89; Fe_2O_3 = 1.75 %; H_2O^+ = 0.47 %; H_2O^- = 0.06 %)
9. 'FETI' basalt (recalculated from Jakobsson, 1972, Table 1: Saturated tholeiite, Veidivötn; Fe_2O_3 = 2.15 %; H_2O = 0.42 %).

The average compositions of the three tholeiitic lava types from the Maligât Formation define a chemical trend with increasing TiO_2, total iron, Na_2O, K_2O and P_2O_5, with decreasing MgO and CaO and with constant or slightly decreasing SiO_2 and Al_2O_3. The two extreme compositions are contributed by the Nûluk Member and the porphyritic zone of the Kanísut Member respectively whereas the microporphyritic zone of the Kanísut Member – highest in the stratigraphical column – takes up an intermediate position.

Calculations using least squares approximations demonstrate that low pressure fractionation of the phenocrysts present in the lavas: olivine, plagioclase and augite, cannot explain the chemical differences between the mean compositions of the three

Table 4. Least square approximation to the average Nûluk Member basalt on Nûgssuaq

	Nûluk Member, observed	1 Calculated	2	3
SiO_2	49.4	49.4	47.6	49.4
TiO_2	1.98	2.68	0.79	3.44
Al_2O_3	14.3	14.4	16.3	14.5
FeO	12.1	12.0	7.5	11.5
MnO	0.23	0.17	0.10	0.23
MgO	7.21	7.35	11.8	7.58
CaO	11.7	11.7	13.6	11.6
Na_2O	2.46	2.49	1.58	1.39
K_2O	0.20	0.72	0.18	0.17
P_2O_5	0.32	0.36	0.07	0.07
Derived liquid (%)		73.3	15.0	15.0
Percentage of fractionating phenocrysts				
Olivine (Fo_{30})		4.1	15.9	21.1
Plagioclase (An_{77})		12.1	41.0	34.2
Augite ($En_{45}Fs_{12}Wo_{43}$)		10.8	27.6	21.2
Hypersthene ($En_{74}Fs_{24}Wo_2$)				41.3
Titanomagnetite ($Fe_{71}Ti_{29}$)				9.4
Sum of squares of residuals		0.83	54.7	3.9

The approximations are calculated as the average basalt from the Kanísut Member, porphyritic zone (Nûgssuaq) + fractionating crystals. Concentrations of minor elements in the fractionating phases are estimated.

1. Best approximation with olivine, plagioclase and augite as fractionating minerals.
2. Best approximation with olivine, plagioclase and augite as fractionating minerals assuming 15 % residual liquid.
3. As 2 but including hypersthene and titanomagnetite (both with estimated compositions) among the fractionating phases.

Computer program, LSQ, written by T. S. Petersen, Institute of Petrology, University of Copenhagen.

tholeiitic lava types (table 4). The best fit shows fractionation of approximately 12 % plagioclase, 4 % olivine and 11 % augite (i. e. 27 % crystallisation) from a magma with the composition of the average Nûluk basalt to give the average 'porphyritic' basalt of the Kanísut Member (table 4, no. 1). However, the variation of K_2O demands half to two–thirds crystallisation of the average Nûluk basalt to give the average 'microporphyritic' basalt of the Kanísut Member and a further third to half crystallisation to give the average 'porphyritic' basalt, assuming that no potassium is incorporated in the fractionating plagioclase. Considering also the variation of Rb and Nb a fractionation percentage of 85 from the Nûluk basalts to the 'porphyritic' basalts is more realistic. Table 4 no. 3 demonstrates that 85 % fractionation of the phenocrysts (best fit: 16 % olivine, 41 % plagioclase and 28 % augite) is impossible if a major element basaltic composition is to be retained. Especially the Fe/Mg ratio of the derivative liquid will be too high. Furthermore fractionation of 15 % olivine is unacceptable due to the small differences in Ni between the Nûluk basalts (80 ppm) and the 'porphyritic' basalts (50 ppm) in connection with the high olivine/liquid partition coefficient for this element (about 15, Häkli & Wright, 1967).

Clarke (1975) has proposed a model for fractionation of the plagioclase porphyritic lavas in West Greenland involving hypersthene as well as olivine, plagioclase and clinopyroxene at pressures between 5 and 8 kbar. Therefore hypersthene has been included among the fractionating phases in the least square approximations. Also included is titanomagnetite which as microphenocrysts, now hidden in the groundmass of the lavas, may have taken some part in the fractionation process. The sum of residuals is considerably lowered (from 55 to 4) when these two minerals with estimated compositions are incorporated among the fractionating phases (table 4 no. 3). The Fe/Mg ratio of the derivative liquid is within the range found in basaltic rocks, but the ratio has only been obtained by assuming almost 10 % fractionation of titanomagnetite although distinct phenocrysts of opaque minerals have not been found. Alternatively a higher Fe/Mg ratio of the ferromagnesian minerals fractionating in the intermediate pressure range can give a better fit in the least square calculations. Neither hypersthene nor reversely zoned phenocrysts of olivine and clinopyroxene have, however, been observed in the lavas of Hareøen and western Nûgssuaq.

The assumption that the differences between the tholeiitic lava types are not due entirely to fractionation of the present phenocryst phases plus hypersthene and titanomagnetite is supported by a consideration of the ratio between K_2O and P_2O_5, two elements both of which can be considered as incompatible during the crystallisation of these lavas. This ratio is 0.63 in the Nûluk Member, 2.00 in the porphyritic zone of the Kanísut Member and 1.41 in the microporphyritic zone; K_2O/P_2O_5 generally remains constant or decreases slightly with increased crystal fractionation of basaltic magmas as long as apatite is not present as a phenocryst phase (Thingmuli: Carmichael, 1964 and Skaergaard Intrusion: Wager, 1960).

The rejection of the low or intermediate pressure crystal fractionation mechanism emphasises the relationship to ocean ridge basalts and 'FETI' basalts respectively. According to some authors, as for instance Flower *et al.* (1975), variations in pressure and degree of melting in the mantle may explain the basic differences in chemistry between lavas from the southern part of the Reykjanes Ridge and the

'FETI' basalts erupted on Iceland. It seems, however, to be more widely accepted that the two magma types are generated from two mantle sources with different chemical compositions (Schilling, 1973 a & b). Some of the more important arguments in the discussion are based on rare earth concentrations and on variations in lead and strontium isotope ratios. As neither rare earth nor isotope data are available for the Maligât lavas it seems questionable to choose between these theories when discussing the chemical variability between the three tholeiitic lava types.

Associations of 'FETI' basalts and basalts chemically related to ocean ridge basalts have earlier been described from the neovolcanic zone of northern Iceland (Sigvaldason, 1974) and also from the Faeroe Islands (Schilling & Noe-Nygaard, 1974) where the chemical variations between the two types are ascribed to changes in the intensity of a mantle plume. In the Baffin Bay area different degrees of mantle plume influence may explain the variations in chemical composition between the picritic basalts on Baffin Island (poor in incompatible elements) and on Svartenhuk Halvø (richer in incompatible elements) (Keen & Clarke, 1974).

It can be concluded that at least the lavas of the Kanísut Member have not been in equilibrium with mantle material, irrespective of whether the various lava types of the Maligât Formation were generated from a homogeneous or a heterogeneous mantle. The basalts from the porphyritic zone have olivine phenocrysts with core compositions in the range Fo_{72} – Fo_{65} compared with an assumed mantle olivine composition of Fo_{86} – Fo_{88} (Carter, 1970). No olivine phenocrysts have been analysed from the basalts from the microporphyritic zone of the Kanísut Member or from the Nûluk Member. According to the relationships between Fe/Mg ratios in olivine and liquids found by Roeder & Emslie (1970) the composition of olivine in equilibrium with 124444 – the least oxidised basalt analysed from the microporphyritic zone – should be Fo_{81}. Regarding the basalts from the Nûluk Member the calculated composition of olivine in equilibrium with 134815 (Fo_{84}) is only slightly richer in iron than the assumed mantle olivine composition.

The derivative nature of the lavas from the Maligât Formation is supported by an investigation of the lavas from Svartenhuk Halvø 100 km north of Nûgssuaq by Clarke (1970). He concludes that the plagioclase porphyritic lavas, which show resemblance to the basalts of the Nûluk Member on Nûgssuaq, have been derived by low to intermediate pressure crystal fractionation of olivine porphyritic, basaltic magmas formed by partial melting (or equilibration) at about 30 kbar followed by olivine fractionation.

The magmatic evolution on Hareøen and western Nûgssuaq during the tholeiitic volcanic activity is thus considered in two steps: (1) formation in the mantle of three magnesium rich magma types of (slightly) different chemical compositions and especially with different levels of incompatible elements; (2) later fractionation of each of the three magma types during their ascent to the surface. This fractionation is responsible for the chemical variations of the lavas belonging to the same stratigraphical unit as illustrated by the three fractionation trends almost parallel to the Thingmuli trend (Carmichael, 1964) in the alkali–silica diagram (fig. 11).

The chemical similarities between the transitional dykes and the younger tholeiitic lavas have already been mentioned. According to the petrogenetic grid for mantle derived basaltic rocks described by Green (1971) the slightly more undersaturated character of the dykes may be caused by a lower degree of partial melting of mantle material. This agrees with the stratigraphical position of the dykes which may be considered as terminating the Kanísut Member volcanism.

With the eruption of the lavas of the Talerua Member the character of the basaltic rocks changed drastically. The flows show morphological resemblance to the olivine porphyritic lavas of the Vaigat Formation. The phenocryst assemblage, abundant olivine and minor plagioclase, and also the low Fe/Mg ratios in olivine phenocrysts and total rocks compared to the lavas of the Maligât Formation emphasise the similarity to the Vaigat lavas (cf. Pedersen, 1970).

But the chemical differences between the two types of lavas are also conspicuous. The lavas from the Talerua Member have higher concentrations of K_2O, Rb, Sr, Ba, Zr and Nb; enrichment factors of 5 – 10 are found for these elements. Also the K_2O/Na_2O ratios are considerably higher. The low Fe/Mg ratio of the lavas restrict the degree of olivine and pyroxene fractionation. Therefore the parent magma is considered to be a picrite enriched in incompatible elements compared to the picrites on Svartenhuk Halvø as was also envisaged for the tholeiitic basalts from the Kanísut Member.

The lavas from the Talerua Member also differ from the early olivine rich lavas by a higher content of aluminium and a lower content of calcium and total iron for the same level of MgO (table 3), a relationship which is also known for high alumina and tholeiitic basalts from Japan (Kuno, 1960). Following the theories put forward for the genesis of high alumina basalts by Green & Ringwood (1967) it is assumed that the picritic magma parental to the lavas of the Talerua Member differentiated towards a more alumina-rich composition via pyroxene–olivine fractionation at intermediate pressure. No deep seated phenocrysts have, however, been found in the transitional lavas to show the composition of the fractionating phases.

SUMMARY AND CONCLUSIONS

More than 3 km of lavas were erupted on Hareøen and western Nûgssuaq starting with olivine rich tholeiitic basalts and picritic basalts (Vaigat Formation) followed by plagioclase porphyritic, tholeiitic basalts with only minor olivine (Nûluk and Kanísut Members). On Hareøen the tholeiitic sequence was capped by olivine porphyritic, transitional basalts (Talerua Member). Rhyolitic extrusives –

mostly tuffs – are found only in the feldspar-phyric sequence; but even here the acid rocks constitute only 1 % of the eruption products.

Major sedimentary units are found above the Nûluk Member on Nûgssuaq (Ifsorisok Member) and above Kanísut Member on Hareøen (Aumarûtigssâ Member). The pause in the volcanic activity during the formation of the Ifsorisok Member marks an important change in the chemistry of the rocks from basalts with affinity to ocean tholeiites to basalts of the 'FETI' type.

It has proved impossible to explain the variability of the plagioclase porphyritic, tholeiitic lavas by means of low pressure crystal fractionation. It is suggested that the chemical variations between the different units of tholeiitic as well as transitional rocks reflect variations in batches of olivine rich magma injected from the mantle. The basic differences in chemistry between the lava types may be explained by variations in the activity of a mantle plume with a composition different from the surrounding mantle as proposed by Schilling & Noe-Nygaard (1974) for the Faeroe Islands. Otherwise the composition of the lavas may reflect varying conditions during high pressure fractionation.

Further differentiation of the magmas erupted as lavas or injected as dykes have taken place during the ascent towards the surface. It should be noticed that there is no direct correlation between lava chemistry and the thickness of the lava pile.

No connection between magma chemistry and tectonic style has been found. Earth movements dominated by tilting and normal faulting were active before and after the eruption of the Nûluk Member and before the eruption of the basalts from the Talerua Member; and even these are cut by faults. Tilting and displacement of peneplaned surfaces on Nûgssuaq and Hareøen show that the tectonic movements went on a long time after the eruption of the lavas exposed in the area.

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