Tertiary volcanic province of West Greenland

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Fig. 322. Thin greyish weathering picrite lavas covered by thick flows of feldspar-phyric basalts, looking north-west, near Kûgánguaq, northern Disko with Hareøen in the background. A NW–SE striking dyke swarm is seen. Route 515 D-V no. 12301. Copyright Geodetic Institute.

Introduction

The Tertiary volcanic province of West Greenland is geographically divisible into four main areas, namely Svartenhuk Halvø, Ubekendt Ejland, Nûgssuaq and Disko. Other smaller exposures of Tertiary igneous rocks include Schades Øer, Hareøen, Grønne Ejland and probably parts of Upernivik Ø and Qeqertarssuaq (figs 323, 324). The areal extent of the province including recently discovered offshore extensions, is roughly 55 000 km² and has maximum onshore dimensions of 125 km in width by 370 km in north–south length (fig. 323).

This volcanic area has already become widely known for its occurrences of native iron bearing basalts and the production of enormous volumes of picrites and olivine basalts. In addition, the volcanics are now recognised as a key factor in interpreting tectonic evolution in the Baffin Bay – Labrador Sea region.

History of investigation

Some of the earliest recorded investigations in this area were by Giesecke (1823, 1910) and Rink (1853), but it remained for Steenstrup (1883) to produce the first comprehensive geological map. Except for general papers by Munck & Noe-Nygaard (1957), Rosenkrantz & Pulvertaft (1969), Brooks (1973) and Noe-Nygaard (1974), later workers concentrated on small areas of interest within the province.

For *Svartenhuk Halvø*, Rosenkrantz *et al.* (1942) provide a general account of the geology, and Noe-Nygaard (1942) gives the most detailed petrography of the lavas available. Recent work includes that by Pulvertaft & Clarke (1966), Clarke (1970) and Münther (1973).

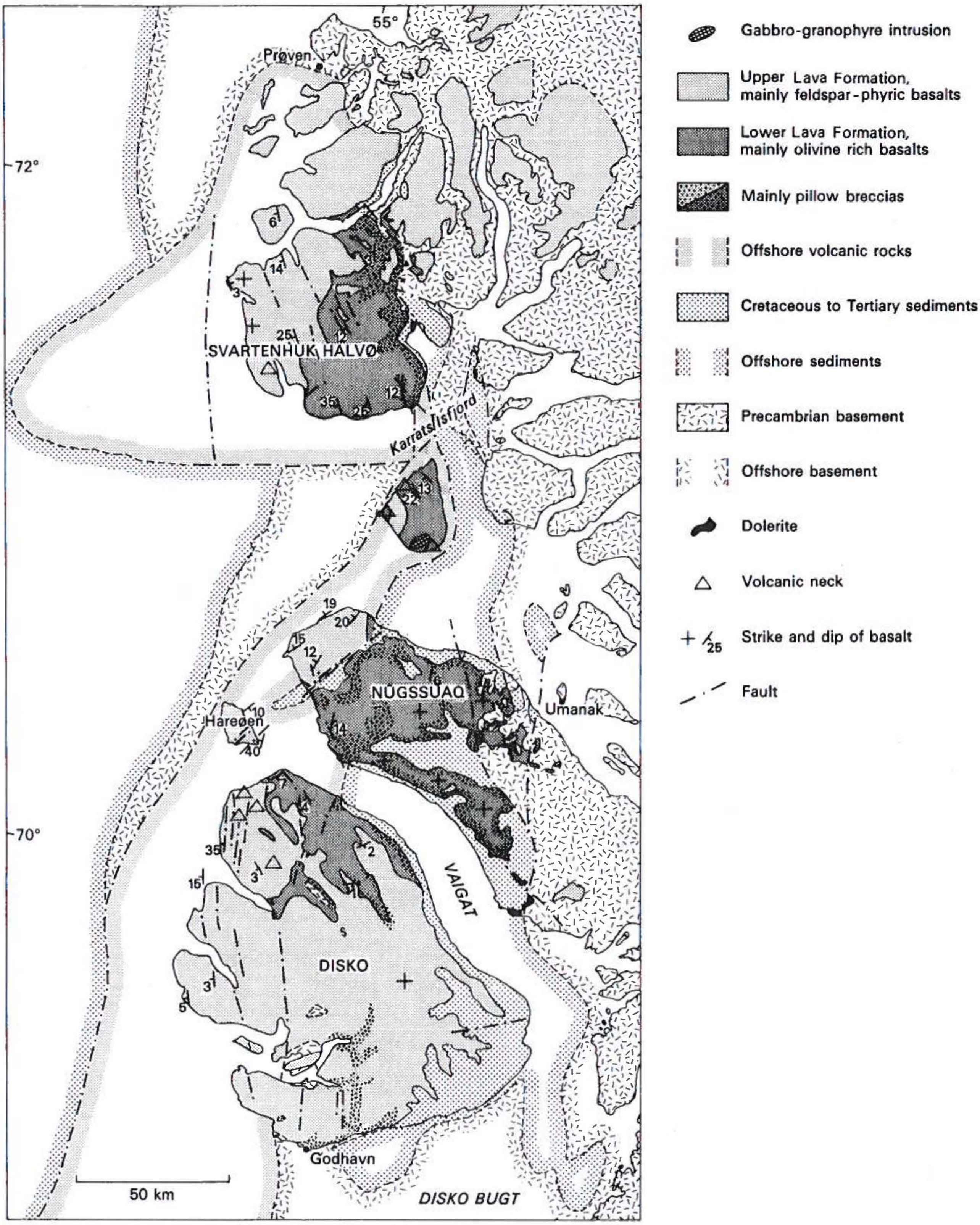


Fig. 323. Simplified map showing offshore and onshore parts of the volcanic province of West Greenland. Offshore geology after Denham (1974).

For *Ubekendt Ejland,* a brief review of results has been given by Drever & Game (1948) and Drever (1958). Detailed mapping and petrochemical work on the late-stage igneous rocks of south-west Ubekendt Ejland has been initiated by D. B. Clarke and J. G. Larsen (Clarke, 1973).

For *Nûgssuaq,* published information deals mostly with the picritic and doleritic intrusives, e. g. Heim (1910), Drescher & Krueger (1928), Drescher (1933), and Munck (1945). General information on the volcanic sequence is scarce but some data may be found in Drever & Livingstone (1948), B. E. Koch (1959), Henderson (1969, 1973) and Rosenkrantz (1970), while detailed investigations have been made by Hald (1973, & personal communication) on western Nûgssuaq. Most of the geology has been compiled on the 1:100 000 geological map sheets of Agatdal and Qutdligssat.

For *Disko,* a bibliography of about 80 papers dealing with the telluric iron and sulphides is given in Bøggild (1953). More recent works include those of Pauly (1958, 1969), Lovering (1964), Melson & Switzer (1966) and Fundal (1975). Again, general information on this volcanic sequence is rare except for the early work by Steenstrup and contributions from Krueger (1928), Drever & Livingstone (1948) and Münther (1952). Recent work has been done by Pedersen (1969, 1970, 1973, 1975 a, b). The geology of northern Disko has now been compiled on the 1:100 000 geological map sheet Qutdligssat.

Structure

The principal structural elements of the province have been discussed by Rosenkrantz & Pulvertaft (1969) and Henderson (1973) and are summarised in fig. 323. A boundary fault system (dashed line) forms the eastward limit to Cretaceous–Tertiary sedimentation and the early phases of volcanic activity. Several of the minor picritic and major doleritic intrusions discussed under eruptive rocks are related to this fault system. A brief discussion of the structure of each major area follows.

Svartenhuk Halvø. Post-volcanic subsidence south-west of a line running from Schades Øer to Skalø has tilted the volcanic pile towards the south-west. North-east of this flexure the basalts are horizontal or nearly horizontal. South-west of the flexure the lavas dip at angles from 12° to 37° to the south-west.

Ubekendt Ejland. The structure here is generally that of a westerly plunging syncline, and thus it forms a link between the dominantly NW-trending strikes on Svartenhuk Halvø and the NE-trending structures in Nûgssuaq.

Nûgssuaq. In Nûgssuaq a major fault system runs through the Itivdle valley down-dropping the north-western block so that the base of the volcanic section is both below sea level and tilted to the north-west, with dips in the range 0 to 30°. South-east of the

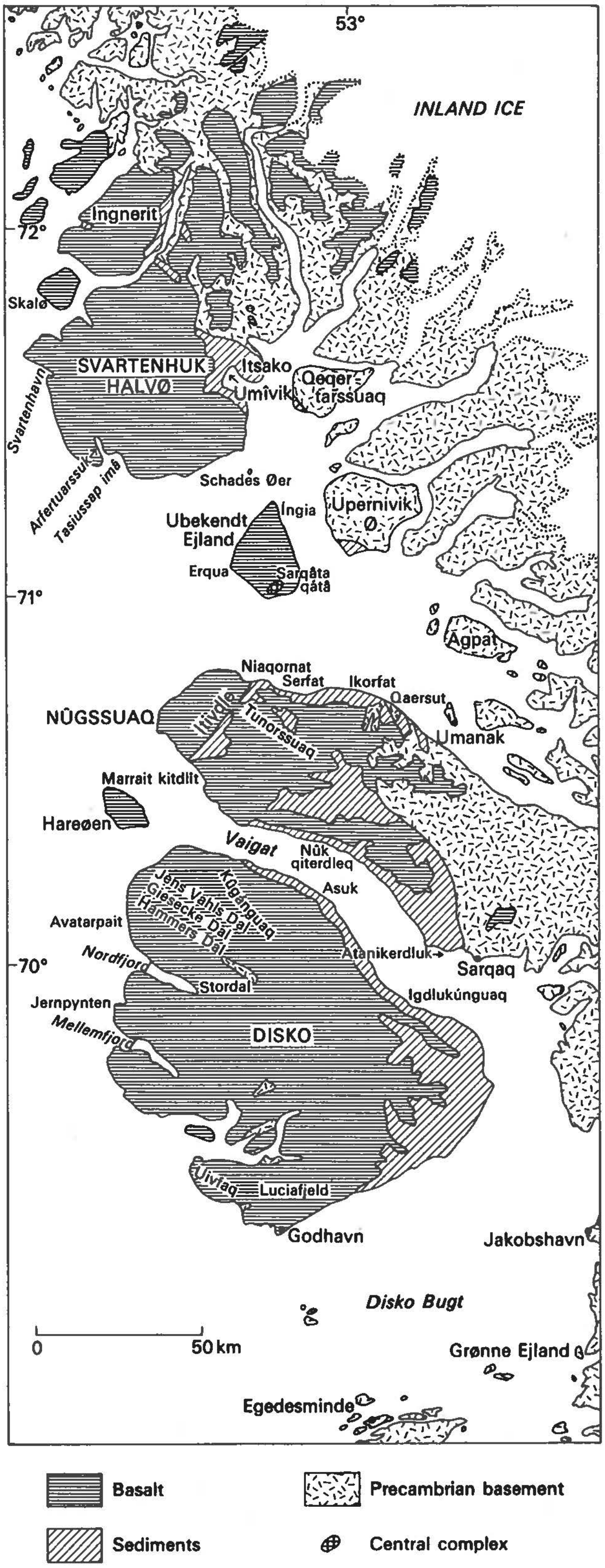


Fig. 324. Simplified map showing places mentioned in the text.

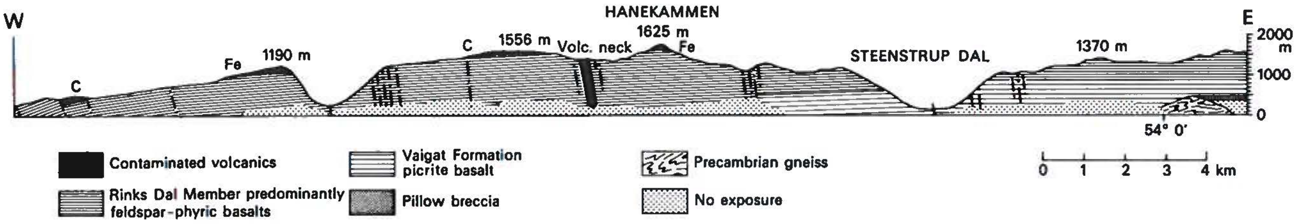


Fig. 325. A section from north-western Disko showing the structure along the western margin of the province, facing Baffin Bay. (After Pedersen, 1975 a).

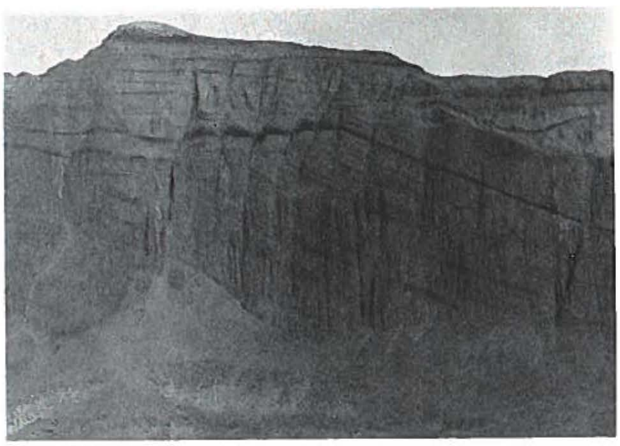
Itivdle fault, the volcanics have remained horizontal or sub-horizontal (but one broad syncline with a N–S axis is present).

Hareøen. The Itivdle fault continues through the south-eastern corner of Hareøen. South-east of the fault the basalts dip obliquely toward it; north-west of the fault the basalts form an anticline with its axis parallel to the fault.

Disko. The eastern part of Disko forms a sub-horizontal plateau in which slow basin movements can be detected. West of a N–S gneiss ridge through Disko the plateau has been affected by regional down-warping, and the lavas dip westwards at angles of 3 to 40° with extensive repetition by faulting (fig. 325). In the north-west, a zone of down-warping runs NE–SW and lavas dip from 0 to 10° toward the south and south-east.

Recent regional work on the offshore structures is given by Keen *et al.* (1972) and Denham (1974) (fig. 323).

Fig. 326. Cross-bedded picritic breccias south-west of Ikorfat, more than 600 m thick, covered by thin picritic lavas. A dark brown lava horizon enters the old shore and can be followed as a number of breccia beds down to the base of the breccias. Also shown in fig. 328 and figured by Henderson (1973, fig. 4).



The pre-volcanic tectonic setting

Rosenkrantz & Pulvertaft (1969) and Henderson (1973) have given a detailed account of the tectonic evolution of the West Greenland Cretaceous–Tertiary province and more information may be found in Henderson *et al.* (this volume). Briefly, the pre-basalt topography was rugged, including such features as large scarps in the vicinity of the boundary fault zone, a basement gneiss ridge running north–south through central Disko and, in other places, deeply eroded sections through the Cretaceous marine and non-marine sediments. Where the volcanics rest on the Precambrian basement, the gneisses frequently had developed a kaolinised weathering cap several metres thick. Where the pre-basaltic floor is not exposed, its nature is often revealed by the occurrence of abundant xenoliths in some of the flows and dykes, especially on Ubekendt Ejland and Disko.

Eruptive rocks

For the purposes of the following discussion, the volcanic section has been somewhat arbitrarily subdivided as follows:

(1) the early subaqueous breccia, mainly of picritic composition;

(2) the subaerial picrites and olivine basalts, a generally uniform sequence of olivine tholeiites in the northern part of the province, but may include other compositions in the south;

(3) a transition zone marked by interbasaltic, non-marine sediments in some places, and by a lithological boundary between olivine basalts and feldspar-phyric basalts in others;

(4) aphyric and feldspar-phyric basalts of the upper part of the section, but may include occasional olivine basalts;

(5) olivine porphyritic transitional basalts resting unconformably on feldspar-phyric basalts;

(6) late stages of volcanic activity including inter-

mediate to acid lavas and pyroclastics of limited geographical extent.

Early subaqueous breccia

In Svartenhuk Halvø, Nûgssuaq and parts of Disko, the first eruptions are represented by subaqueous, picritic, pillow breccias.

A detailed description of some of these breccias has been given by Munck (1942). The outcrop pattern of the breccias is irregular because they filled up depressions in the pre-basaltic topography. Since source areas for clastic sediments are known to have been present, the general absence of sedimentary material in the breccia sequence indicates a rapid growth of the breccia pile.

Usually the breccia units are several hundred metres thick, the thickness being less than or equal to the depth of water into which the magma was erupted or flowed. Most units show a prominent giant cross-bedding with well-developed, steeply-dipping foreset beds. Frequently a normal subaerial flow can be traced laterally into a brecciated foreset bed, usually from 1 to 10 m thick (fig. 326). The dip direction of the foresets is directly opposite to the direction of provenance, and thus the cross-bedding gives important information about the local positions of magma source areas. Most breccia units appear to have been derived from sources lying to the west but reversals can be found in some localities, as for example close to the Ikorfat fault in central Nûgssuaq (Henderson, 1973, fig. 5) and locally along the south coast of Nûgssuaq.

The foresets are composed of an assortment of pillows with glassy margins, fragmented pillows and angular holocrystalline blocks in a matrix of basaltic fragments and glass shards. Much of the glass is fresh, isotropic sideromelane but various degrees of palagonitisation and zeolitisation have taken place in most instances. The basaltic material is usually picritic in composition and is characterised by large numbers of olivine microphenocrysts, usually less than 1 mm in size and often exhibiting skeletal growth patterns. Minor amounts of picotite, less than 0.05 mm in diameter, and small amounts of plagioclase constitute the only other phenocryst phases (fig. 327). A chemical analysis is given in Table 6, analysis 2.

On Svartenhuk Halvø the subaqueous breccias form the base of the volcanic sequence except for some minor older tuffs mentioned by Gry (1942). In the south-east the breccias were deposited discordantly on marine upper Turonian to lower Cenomanian sediments. The eastward extent of the breccias was

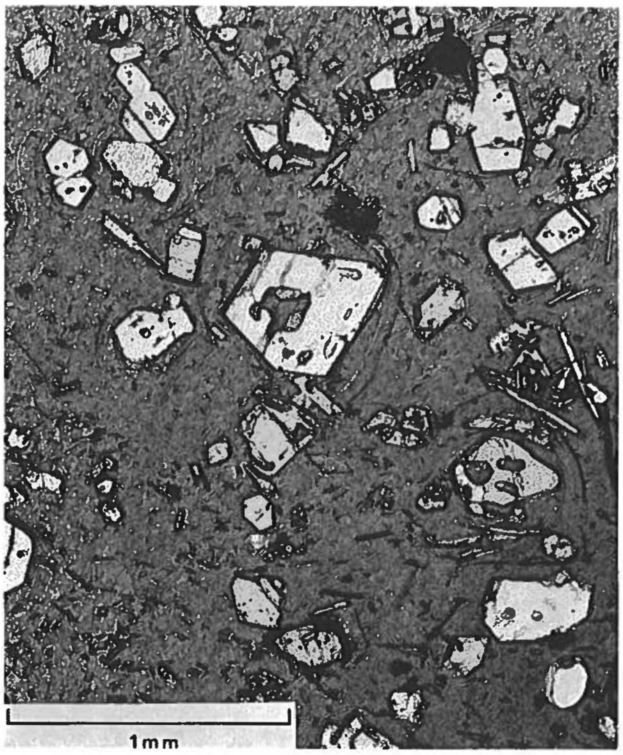


Fig. 327. Olivine microphenocrysts in glass. Picritic basalt pillow margin of the early subaqueous breccias.

limited by the north to north-west striking fault zone which also controlled the deposition of the pre-volcanic sediments. The breccias are readily eroded resulting in obscure contact relations with older rocks over large distances; nevertheless the breccias themselves are nearly continuously exposed for a distance of some 70 km. The westward extent beneath the subaerial basalt pile is unknown. The thickness of the breccia unit is highly variable because of the control by the relief in the pre-basalt topography but in places exceeds 1 km in thickness.

Munck (1942) recognised a lower brown breccia unit, rather olivine-poor, and characterised by large proportions of holocrystalline basaltic material. The brown breccia is overlain by a grey breccia which is olivine-rich and is characterised by much more glass, palagonite and finely comminuted basaltic material. Both of these units show giant cross-bedding which indicates a source area to the west or south-west.

On Schades Øer subaqueous breccias of olivine basalt composition have been found. Petrologically they appear to correlate with the brown breccias on Svartenhuk Halvø. In this area there may be some intercalated subaerial lava flows as well as the breccias.

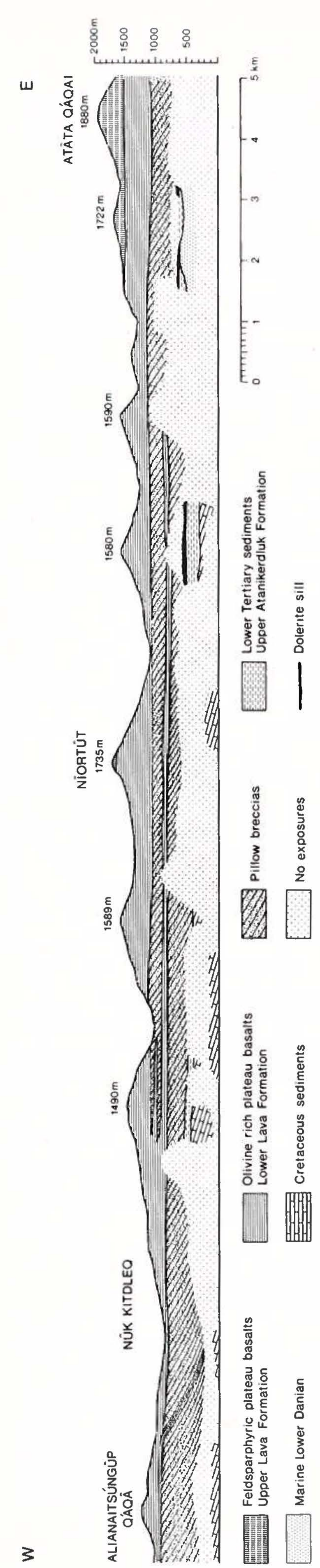
On Nûgssuaq the early pillow breccias are exposed only east of the Itivdle valley fault zone which has

Table 6. Analyses of West Greenland igneous rocks

	1	2	3	4	5	6	7	8	9	10
SiO_2	41.60	43.90	48.50	48.30	48.51	44.60	48.00	42.27	53.20	63.80
TiO_2	0.70	1.11	1.62	3.12	3.99	1.69	1.52	1.41	1.12	0.81
Al_2O_3	5.50	9.80	14.08	13.60	12.38	12.70	16.50	15.81	14.90	15.80
Fe_2O_3	3.20	3.60	4.68	7.50	4.24	3.10	3.66	3.99	1.22	4.40
FeO	8.00	7.70	6.86	7.10	10.83	7.50	4.99	3.74	7.40	0.70
MnO	0.17	0.17	0.18	0.20	0.23	0.19	0.15	0.17	0.17	0.13
MgO	30.60	19.40	7.80	5.30	4.33	12.30	8.15	7.32	8.49	0.70
CaO	5.10	10.00	12.60	10.70	8.64	13.40	9.53	12.05	8.89	1.50
Na_2O	0.60	1.20	2.05	2.64	2.82	1.20	2.21	3.84	2.16	6.15
K_2O	0.18	0.06	0.12	0.32	1.18	0.79	1.55	2.43	0.56	4.75
P_2O_5	0.09	0.12	0.21	0.35	0.57	0.55	0.37	0.56	0.15	0.24
H_2O	3.24	2.39	1.31	0.77	1.27	1.97	2.87	4.18	0.98	0.57
CO_2	–	–	–	–	–	–	–	1.81	0.52	–
	98.98	99.45	100.01	99.90	98.99	99.99	99.50	99.58	99.76	99.55
C.I.P.W. norms										
Q	–	–	2.18	6.72	4.32	–	–	–	5.95	7.29
or	1.11	0.36	0.72	1.91	7.13	4.76	9.48	15.07	3.35	28.35
ab	5.30	10.46	17.57	22.53	24.41	10.35	19.35	7.34	18.00	52.58
an	12.30	21.82	29.22	24.51	18.04	27.47	31.57	19.62	29.67	1.49
ne	–	–	–	–	–	–	–	14.47	–	–
di	10.66	22.60	26.19	21.11	18.17	29.29	11.76	21.36	8.64	3.45
hy	10.04	6.93	13.61	5.44	12.51	0.56	15.91	–	28.39	0.16
ol	54.13	29.99	–	–	–	18.39	2.54	7.58	–	–
mt	4.85	5.38	6.88	10.96	6.29	4.58	5.49	6.06	1.79	0.33
il	1.39	2.17	3.12	5.98	7.75	3.27	2.99	2.81	2.16	1.56
hm	–	–	–	–	–	–	–	–	–	4.21
ap	0.22	0.29	0.51	0.84	1.38	1.33	0.91	1.36	0.36	0.58
cc	–	–	–	–	–	–	–	4.32	1.19	–
Trace elements, in parts per million										
Ba	27	36	31	101	515	706	670	1655	255	1150
Co	–	–	46	–	41	40	37	–	37	–
Cr	2300	2300	413	200	86	799	320	64	616	–
Cu	198	131	201	331	395	67	68	62	26	–
Ga	18	15	–	22	–	–	–	–	–	33
Ni	1200	1500	140	100	37	288	172	93	26	–
Zn	78	67	–	99	136	–	–	65	–	78
Rb	1	2	1	3	25	26	48	65	13	62
Sr	141	170	164	215	322	643	498	1727	179	108
Y	20	14	–	49	45	–	23	–	–	49
Zr	73	78	89	232	319	189	177	335	129	324
Nb	–	–	2	–	39	117	54	206	4	–

1. Picrite flow, Simiútap kûa, Svartenhuk Halvø (GGU 87546).
2. Olivine basalt, south-eastern Svartenhuk Halvø (GGU 87651).
3. Plagioclase and olivine porphyritic basalt from the lower lava formation. Kûgánguaq, Disko (GGU 113337).
4. Feldspar-phyric basalt, Svartenhavn, Svartenhuk Halvø (GGU 87589).
5. Olivine, plagioclase and augite microporphyritic basalt from dyke. Naujánguit, northern Disko (GGU 135978).
6. Olivine porphyritic transitional basalt from the lower lava formation. Manîdtlat kugssinerssuat, Disko (GGU 113254).
7. Transitional basalt, Hareøen (GGU 113482).
8. Monchiquite, Ubekendt Ejland (GGU 138955).
9. Bronzite basalt, Asuk, Disko (GGU 113271).
10. Anorthoclase trachyte, Arfertuarssuk, Svartenhuk Halvø (GGU 87630).

Analyses: Major elements: D. B. Clarke (1,2,4,8,10), G. Hornung (5,6,9), Ib Sørensen (3,7).
Trace elements: D. B. Clarke (1,2,4,8,10), G. Hornung (3,5,6,7,9).



dropped the base of the volcanic pile below sea level on the western side. However, for long distances both on the north and south coasts of Nûgssuaq east of Itivdle the breccias lie on Cretaceous and Danian marine and non-marine sediments. Along the south coast the picritic breccia attains local thicknesses of 600–700 m and the giant cross-bedding generally indicates a westerly provenance (fig. 328). An interfingering pattern between subaerial lavas and breccia beds at the top of this basal unit records how lavas with general provenance from the west gradually filled a continuously sinking basin. In several areas repeated subsidence has given rise to one or more extra breccia units above the thick basal member. These later breccias may rest directly on the basal breccia or may be separated from it by a few subaerial flows.

On Disko the picritic pillow breccias cover a small area on the north coast. The breccias attain a thickness of at least a few hundred metres (base not exposed) and have well-developed giant cross-bedding. As in southern Nûgssuaq breccia units appear higher in the subaerial sequence reflecting periods of further subsidence. Pedersen (1970) has recognised two cycles of eruptive activity in these regions. The upper breccias record a slowly sinking basin being gradually filled by subaerial lavas flowing into the water generally from the west and north-west. In the eastern part of the basin far from the volcanic source subordinate bituminous shales have been deposited. In a few places tuffaceous layers have been deposited by turbidity currents within the shales which were later strongly disturbed by the advancing coarse breccia beds.

Subaerial picrites and olivine basalts

The dominant volcanics in the first phase of subaerial eruption are olivine-rich basalts and picrites. The flows tend to be 3–5 m thick, and rarely exceed 15 m. However, compound flows consisting of numerous, thin, welded pahoehoe tongues also occur and may occasionally exceed 50 m in thickness. Two flow types have been recognised:

Type I. These are massive, dark grey or brown weathering flows. They are characterised by a central massive portion with thin vesicular tops and pipe amygdales at the base. Pahoehoe structures may be present. These lavas are rich in magnesian olivine phenocrysts of about 1 mm in size although occasion-

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Fig. 328. A section along the south coast of Nûgssuaq showing several cross-bedded pillow breccia horizons. The breccia beds indicate a western provenance.

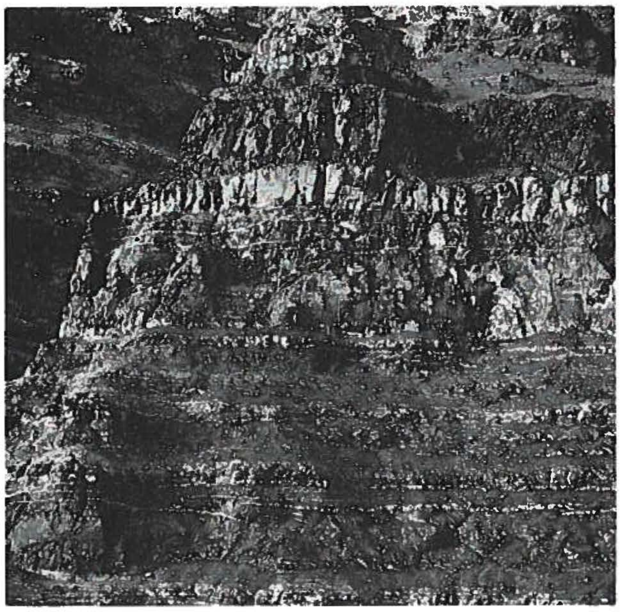

Fig. 329. Sequence of picritic type 2 lavas with regular development of sub-horizontal segregation veins. Zeolite filled vesicles make the veins appear white. Kûgánguaq, northern Disko.

ally they reach a maximum dimension of 25 mm. These phenocrysts often show zones of glass inclusions near their centres and are relatively inclusion-free in the outer portions. Gravitative settling of olivines in these flows is slight or absent. Picotite is invariably present as a microphenocryst phase. Plagioclase may also occur as phenocrysts whereas augite and Fe-Ti oxides are confined to the groundmass.

Fig. 330. Phenocrysts of olivine surrounded by groundmass of ophitic, intergrown augite and plagioclase. Lower part of picritic type 2 flow.

Type II. These are light grey or greenish, easily weathered flows rich in zeolites. They often form small lava domes and show pahoehoe morphology. Autodifferentiation through gravitative settling of the olivine phenocrysts and concentration of volatiles has been important, thus the lower part of the flow is invariably richer in olivine and the upper portion is cut by sub-horizontal veins of olivine-poor or olivine-free, vesicular dolerite. Some of the zeolites in these veins may be of magmatic origin (fig. 329). The autodifferentiation may be attributable to higher volatile contents in these magmas compared with Type I resulting in increased fluidity. These flows may also contain subordinate orthopyroxene or pigeonite (Disko only) in the groundmass as well as augite, Fe-Ti oxides and possibly some zeolites (fig. 330). A chemical analysis is given in Table 6, analysis 1.

The picrites and olivine basalts were erupted from widely scattered, and sometimes randomly oriented, thin dykes. The small volume of each flow (estimated at usually less than 0.1 km^3), restricts its lateral extent and, in areas where the lavas are only of this composition, a detailed stratigraphy is difficult to establish.

Although picritic compositions are known to be easily weathered, and the climate during the volcanic period was warm and temperate (B. E. Koch, 1964), these flows were generally not weathered before being covered by a subsequent eruption. Horizons of red bole are not common in this part of the volcanic pile and their scarcity would seem to indicate intense volcanic activity and rapid accumulation of the sequence. A similar conclusion was reached for the rate of accumulation of the breccias.

On Svartenhuk Halvø olivine basalts and picrites of Type I and II outcrop over a large area of the peninsula and probably extend beneath the cover of feldspar-phyric basalts in the west and south-west. In the north a few flows have extended beyond the fault zone, which limited the sediments and breccias previously, and lie directly on the Precambrian basement.

Unfortunately the lower part of the lava pile on Svartenhuk Halvø consists entirely of the thin, nondescript olivine basalt and picritic flows and so is devoid of usable stratigraphic horizons. No major faults can be seen in the section along the south coast. Thus without stratigraphic markers it cannot be established whether there is a very thick accumulation of lavas (up to 10 km, Noe-Nygaard, 1942) or whether hidden faults in the river valleys have caused repetition, as suggested by Clarke (1968) and Münther (1973). In the northern part of Svartenhuk Halvø the thickness of subaerial olivine basalts between the underlying breccias and overlying interbasaltic horizon is less than 2 km.

On Ubekendt Ejland the base of the volcanic pile is not exposed. Here the lowermost rocks belong to the subaerial picrite and olivine basalt stage, and the absence of weathered flow tops suggests this pile accumulated rapidly. There is good exposure of this sequence, especially along the east coast.

Recent detailed investigations by J. G. Larsen (personal communication) have only revealed minor faulting and, although the stratigraphic markers are poor, Drever's (1958) estimated thickness of about 5 km has generally been confirmed.

On Nûgssuaq, as mentioned previously, there is no abrupt change from subaqueous breccias to subaerial flows. However, the lavas which eventually replaced the breccias were usually the subaerial compositional equivalents, namely flows of Types I and II. The thickness of subaerial flows plus interbasaltic breccias is 400–900 m in southern and central Nûgssuaq, whereas in northern Nûgssuaq the subaerial flows alone total 1200 m.

The simple picture of monotonous accumulation of picrites as on Svartenhuk Halvø and Ubekendt Ejland begins to change on Nûgssuaq. The generally picritic subaerial section now includes some relatively thick, columnar-jointed, resistant, grey flows which have been mapped as limited stratigraphic markers by G. Henderson. Brecciated equivalents of these flows have also been found. Petrographically these flows are either:

(a) fine-grained basalts with microphenocrysts of plagioclase, augite and occasionally olivine; or

(b) nearly aphyric pigeonite-rich basalts or bronzite-phyric basalts, similar to rocks found on Disko.

A thin, but unusual, tuff sequence is found in the sediments of the Abraham Member of the Agatdal Formation (Munck & Noe-Nygaard, 1957; Rosenkrantz, 1970 and Henderson *et al.* this volume).

Recent work by A. K. Pedersen has shown the tuffs to include both basaltic and intermediate compositions. The intermediate tuffs, being orthopyroxene porphyritic, are associated with graphite, mullite, spinel, cordierite and corundum and are remarkably similar in chemical composition to the native iron bearing volcanic rocks of Asuk on northern Disko.

A native iron bearing lava rich in graphite occurs at Nûk qiterdleq on the south coast of Nûgssuaq. The flow lies among some olivine-rich lavas between the basal breccia and an interbasaltic breccia horizon.

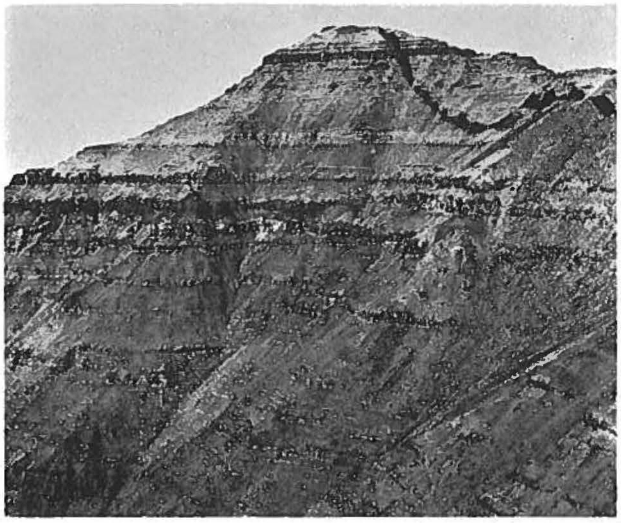

Fig. 331. Thin picritic lavas of type 2 cut by a basaltic dyke. The erosion resistant flows in the centre of the photograph are picritic type 1 lavas covering a bronzite basaltic lava sequence. Kûgánguaq, northern Disko.

The tuffs are correlated with the iron-bearing rocks mentioned above, belonging to an early but not initial phase of the volcanism. Determination of coccoliths from sediments just underlying these tuffs by Perch-Nielsen (1973), and by Jürgensen & Mikkelsen (1974) on a fossiliferous conglomerate found among picritic lavas and breccias at Marrait kitdlît, tie this stage to the NP-3 zone of Martini (1971) implying a Lower Paleocene (Upper Danian) age.

On the eastern corner of Hareøen are some olivine-rich lavas which are separated from the rest of the volcanic pile by a major fault. Several sequences of light brownish weathering olivine-poor lavas are found within these olivine basalts (N. Hald, personal communication).

On Disko, Pedersen (1970) has recognised two cycles of magmatic activity in the predominantly picritic and olivine basaltic stage.

Cycle I begins with the early basal breccia already discussed. Then follows several hundred metres of Type I and II basaltic flows as described, except that some Type I flows contain dunite nodules 1–2 cm in diameter as well as some olivine-chromite gabbro xenoliths, and the Type II flows generally contain either orthopyroxene or pigeonite or both as minor constituents. The last few hundred metres of this cycle (fig. 331) consist of olivine-rich basalts and locally interlayered variable suites of bronzite-bearing or nearly aphyric, pigeonite-rich basalts (Table 6, analysis 9) and intermediate rocks, some

Fig. 332. Orthopyroxene phenocryst showing skeletal growth in marginal zone. From native iron bearing intermediate rock quenched when flowing into water. Asuk, Disko.

of which are rich in sedimentary xenoliths and may contain native iron and sulphides (fig. 332). At the classic locality of Asuk, Steenstrup (1882) first described native iron from a lava belonging to one of these suites and clearly demonstrated the telluric origin of the iron.

The top of the first cycle is defined by a suite of nearly aphyric massive flows with columnar jointing, which are well-defined in north-eastern and central Disko but thin out towards the north-west. Chemically these lavas are similar to the feldspar-phyric and aphyric basalts found in the upper lava formation but differ from them in being more primitive with respect to the incompatible minor and trace elements (Table 6, analysis 3). In one locality in north-east Disko black shales with plant fossils overlie these basalts.

Cycle 2 begins with subaqueous picrite basaltic pillow breccia or subaerial picritic flows depending on the locality. This cycle is dominated by olivine-rich lavas of Type I and II.

In north-eastern Disko there occurs a sequence of olivine porphyritic lavas (slightly nepheline normative alkali basalts, and transitional basalts and picrites*) characterised by greatly enriched amounts of incompatible elements (Table 6, analysis 6).

They cover an area of more than 300 km² and have been mapped as a lava marker horizon, which can be traced into subaqueous breccia facies (Pedersen, 1973). Some of these rocks carry microphenocrystic salite besides olivine and approach ankaramites in chemical composition. With an erupted volume estimated at about 15 km³ these lavas are the first major occurrence of alkaline and transitional basalts in the province.

Further south a few bronzite basalts with native iron have been mapped.

This cycle came to an end either by evolving into the overlying feldspar-phyric basalts or by being abruptly covered by them. Palaeomagnetic work by Athavale & Sharma (1975) covers the lower lava formation and a few hundred metres of the overlying feldspar-phyric basalts. Their study indicates an age around 63 m. y. for the oldest picritic volcanics, in accordance with the palaeontological evidence.

Interbasaltic stage and transition zone

Although it is poorly defined at present in most areas of the province, there is a stage in the volcanic activity which does not fit neatly into either the predominantly olivine-rich basaltic stage or the feldspar-phyric basalt stage. In some parts of the province there is a pronounced break in the volcanic activity after the eruption of the olivine-rich basalts, and this break may or may not be marked by deposition of non-marine sediments. In other areas the volcanic activity appears to have been continuous from the olivine basalts to the feldspar-phyric basalts, and is characterised by the eruption of nearly aphyric, brown-weathering flows.

In northern Svartenhuk Halvø and Ingnerit, the olivine basalts are overlain by non-marine sediments including unconsolidated sands, and coal seams. These sediments vary in thickness from a few metres to several tens of metres depending on the locality, and are directly overlain by the massive feldspar-phyric basalts. In southern Svartenhuk Halvø, in the vicinity of Tasiussap imâ, a complete section exists from picrites through aphyric flows to the feldspar-phyric basalts.

On Ubekendt Ejland the situation is rather differ-

*The terms transitional basalts and picrites are used here for olivine-normative basalts with a slight to moderate content of normative hypersthene and only one pyroxene (salite) often zoned to titanaugite.

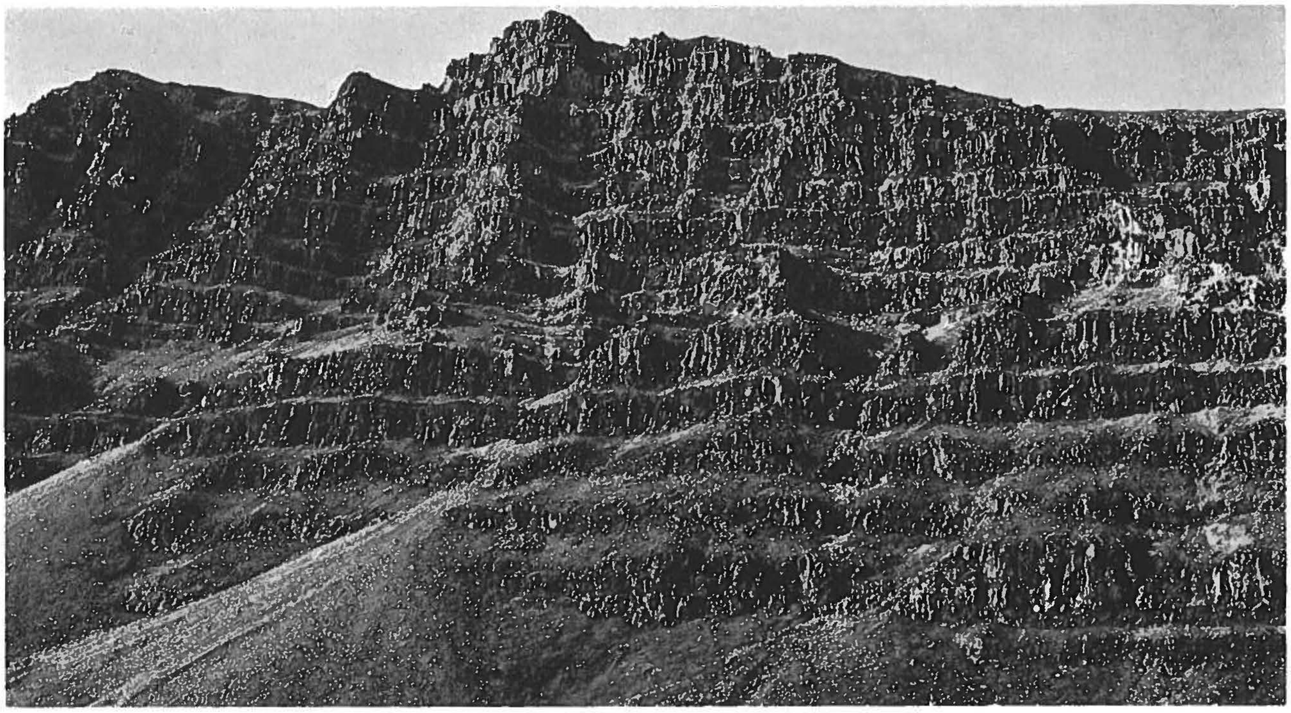

Fig. 333. Typical sequence of feldspar-phyric basalt lavas from the upper lava formation. South-west coast of Disko.

ent from the rest of the province. Here the typical feldspar-phyric basalts characteristic of Svartenhuk Halvø, Nûgssuaq and Disko are poorly represented and hence the transition zone as described by Drever (1958) is an intermediate stage between the lower olivine basalts and an upper suite of rhyolites, pitchstones, alkali basalts, tuffs and ignimbrites not found elsewhere in the province. In this transition zone are developed some feldspar-phyric basalts which are much coarser grained and very light grey in colour compared with the fine-grained, black, feldspar-phyric basalt elsewhere. Also there are thick sequences of pyroclastics and olivine basalts, and although the sediments themselves have not been found, fossilised wood is common in a few localities along the south coast.

On Nûgssuaq the transition zone is disturbed due to faulting west of the Itivdle valley. In central Nûgssuaq feldspar-phyric basalts rest directly on thin picritic basalts or on sediments of the Upper Atanikerdluq Formation.

In the northern part of Disko easily weathering Type II picrite basalts are covered by sequences of: (a) light brownish grey weathering feldspar, augite and olivine porphyritic flows; (b) nearly aphyric flows; and (c) greyish weathering, erosion resistant, olivine-rich flows. In many lavas there are fine to medium-grained 'doleritic' or gabbroic xenoliths. The transition zone lava flows range in thickness from less than 5 to 20 m. Towards the east and south, the transition zone degenerates and a sharp boundary between Type II flows and massive predominantly feldspar-phyric basalts is observed.

Feldspar-phyric basalts

The lavas constituting the top of the section in most places differ from previous eruptions in volume of erupted magma, lava morphology, petrography and chemistry.

Münther (1973) has localised several craters, eruption sites for the feldspar-phyric basalts, and argues that most of the feldspar-phyric basalts erupted from central vents. However, the widespread occurrence of feldspar-phyric dykes of similar composition to the lavas may indicate that fissure eruptions were the dominating eruption form.

The flows have an average thickness of 25–30 m and occasionally units 50 m thick are found, except in the central part of the province where flows are thinner (fig. 333). In contrast to the earlier olivine-rich flows, single flows in this part of the section may be traced for long distances, often in excess of 50 km. These flows often have a well-developed colonnade and entablature and a slaggy top several metres thick. The inner parts of the flows are poor in vesicles and the most common infillings are silica minerals, green sheet silicates and very minor zeolites. Few segregation veins have developed. Layers of red bole are commonly found between the flows and inter-

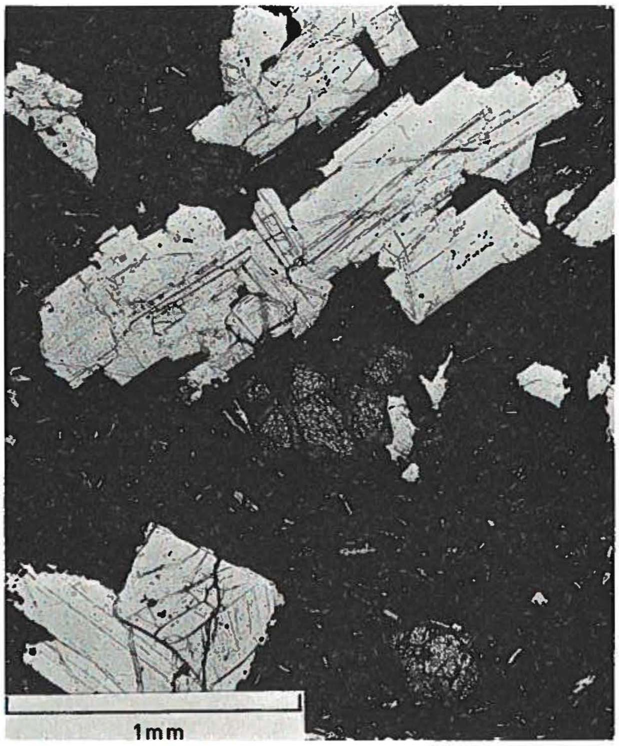

Fig. 334. Phenocrysts of plagioclase, olivine and augite in a fine-grained groundmass. Feldspar-phyric basalt from subaqueous lava tongue. Godhavn, south Disko.

basaltic sediments, indicating prolonged pauses between eruptions.

These lavas contain prominent phenocrysts of plagioclase and usually smaller amounts of augite and pseudomorphed olivine in a fine-grained, black groundmass of plagioclase, clinopyroxene and Fe-Ti oxides. The groundmass pyroxene is usually just augite, but in the southern part of the province pigeonite is a common subordinate phase (fig. 334).

Chemically these basalts are all olivine-poor tholeiites and quartz tholeiites (Table 6, analysis 4). In addition they have greatly increased amounts of the incompatible elements compared to the earlier picritic lavas.

In the north of Svartenhuk Halvø and west of Tasiussaq, the first feldspar-phyric eruptions are subaqueous breccias with giant cross-bedding indicating a southern provenance. East of Tasiussaq the first eruptions were subaerial flows of feldspar-phyric basalt which rest directly on the Precambrian basement. These lavas occupy mountain tops all the way to the Inland Ice.

In south-western Svartenhuk Halvø the feldspar-phyric eruptions lie directly on flows belonging to the transition zone without any interruption in activity. The lavas tend to be very uniform in composition except for the occasional eruption of olivine-poor Type II material.

Ubekendt Ejland, as already mentioned, has apparently not developed a typical, thick section of feldspar-phyric basalts. Occasional flows do occur, and perhaps many of the flows in the central region may be related to the main feldspar-phyric stage, but in general the magmatic evolution here has taken a different course. This will be discussed in the next section.

On Nûgssuaq the feldspar-phyric basalts are exposed on the block west of the valley of Itivdle. The sequence about 3 km thick is complex. Recent detailed work on these lavas by Hald (1973, personal communication) divided the sequence into three units.

The lower one consists of brownish weathering feldspar-phyric basalts, poor in the incompatible elements. Within this unit a few rhyolitic lavas and tuffs have been found. The basalts are covered by a sequence of coarse-grained talus sediments, which may be 200 m thick. The sediments consist of angular basaltic fragments in a fine-grained matrix and are covered by beds of sand, light coloured tuffs, mudstones and coal.

The second unit consists of basalts characterised by phenocrysts of olivine, plagioclase and augite and has been called the porphyritic zone. The basalts of the porphyritic zone are enriched in the incompatible elements compared with all other feldspar-phyric basalts in the province (N. Hald, personal communication) and are nearly identical in composition to basalts dredged offshore Svartenhuk Halvø (Clarke, 1975).

The third unit consists of olivine, plagioclase and augite microporphyritic basalts and has been called the microporphyritic zone. It contains in its lower part composite rhyolite-basalt lavas and also peralkaline acid welded tuffs with phenocrysts of anorthoclase, hedenbergite and aenigmatite. A sequence of coal-bearing sediments, less than 30 m thick represents the only major interruption of the volcanic activity during this stage.

Feldspar-phyric basalts also form the highest tops of the lava pile towards the east of Nûgssuaq, but few details are known. As in other parts of the province these extensive flows transgressed to areas not formerly covered by previous volcanic activity. Thus they are found well inland lying on Precambrian basement east of the Sarqaq–Ikorfat fault zone which had earlier formed the eastern limit of sedimentation.

The western, northern and eastern parts of Hareøen consist of porphyritic and microporphyritic basalts, similar to those of western Nûgssuaq. Acid lavas and tuffs are found in subordinate amount. The basalts are covered by arenaceous and argillaceous sediments with coal seams (Hald, 1971 & personal communication).

In parts of northern Disko, as in northern Svartenhuk Halvø, some of the first feldspar-phyric basalt eruptions were brecciated in a subaqueous environment (figs 335, 336). This is also the case in southern Disko where picrites are absent. Here the oldest part of the lava pile is generally a cross-bedded feldspar-phyric breccia resting on fluviatile and limnic sediments and basement gneiss around the inner part of Disko Bugt and east of Godhavn. The thickness of the breccias varies from a few metres to more than 200 m depending on the pre-volcanic topography.

The breccias are covered by massive subaerial feldspar-phyric flows which lie on the Precambrian basement just west of the breccia zone. Munck & Noe-Nygaard (1957) have described areas where these lavas have flowed into water and have been brecciated. The uniform thickness of these flows in the northern and southern extremities of Disko suggests that their maximum extent in Tertiary times must have been far to the south and west of their present distribution.

In western Disko there occurs a group of lavas and tuffs several hundred metres thick, which have apparently been contaminated by the abundant sandstone and bituminous shale xenoliths they contain (Münther, 1952). Many of these lavas were erupted from several craters south of Giesecke Dal (Münther, 1973) and have been traced at least 50 km southward to the classic localities of Mellemfjord and Jernpynten described by Steenstrup (1882). The rocks include slightly contaminated basalt, strongly contaminated plagioclase-orthopyroxene porphyritic basalts, lavas of intermediate composition containing sulphides and native iron, 'dacites' and rhyolites (Pedersen, 1970; 1975 a, b). Recent work has shown the existence of cognate accumulates of norite in these contaminated lavas suggesting that the crater area forms the surface of several high level magma chambers where contamination and differentiation occurred on a large scale (Pedersen, 1970).

Both within the contaminated sequence, and especially in the few hundred metres of lavas preserved above it, a considerable number of flows carry olivine as the dominant phenocryst phase. Some of these lavas resemble the picritic lavas of the lower lava formation.

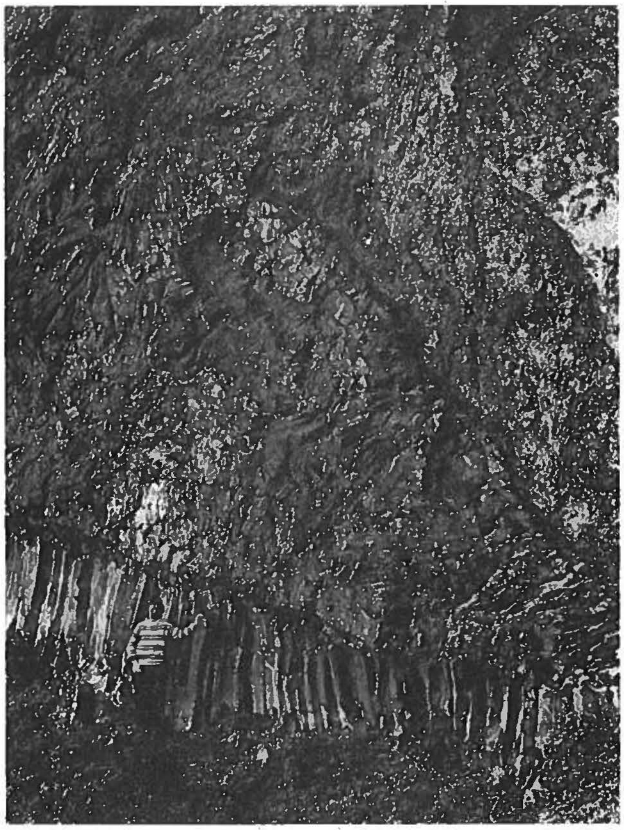

Fig. 335. Subaqueous lava tongue of feldspar-phyric basalt with extremely well developed colonnade and entablature, covered by pillow breccia. Orpît qáqait, south Disko.

Fig. 336. Sideromelane fragments, palagonitised along the margins. Cavity in centre filled by green sheet silicates. Phenocrysts of plagioclase and olivine can be seen. Feldspar-phyric pillow breccia from the upper lava formation. Godhavn, south Disko.

Olivine porphyritic transitional basalts

On Hareøen the youngest volcanics are a sequence of olivine porphyritic transitional basalts, lying unconformably on the feldspar-phyric basalts (Hald, 1971 & personal communication). These lavas, presumably younger than any feldspar-phyric basalts in the province, are petrographically characterised by phenocrysts of magnesian olivine and sometimes subordinate plagioclase in a groundmass of titanaugite, plagioclase, opaque minerals and subordinate late sanidine. Chemically (Table 6, analysis 7) they are olivine and hypersthene or slightly nepheline normative basalts with somewhat higher alumina compared with other picrites and feldspar-phyric basalts in the province (Pedersen, 1970).

On Disko, no equivalent rocks have yet been found. However, Avatarpait, a group of small skerries west of Disko, is composed of alkaline olivine basalt and certainly belongs to this stage. These skerries are probably part of a volcanic neck (Pedersen, 1975 a).

Late stages of eruptive activity

The lavas produced in the closing phases of volcanic activity were highly variable from place to place in the province and generally small in volume. The erupted material was usually intermediate to acid in composition and only in Ubekendt Ejland is any significant amount exposed.

In Svartenhuk Halvø, at the head of Arfertuarssuk, there are outcrops of several trachybasalt flows and two or three trachytic bodies, at least one of which is a flow. The field relations of the largest of these bodies are obscure and it is not known whether it is a flow or a dome. The petrography of this anorthoclase trachyte has been described by Nieland (1931) and Noe-Nygaard (1942). An analysis appears in Table 6, analysis 10.

An $^{40}Ar/^{39}Ar$ age determination on this trachyte gave 58 ± 2 m. y. (Parrott & Reynolds, 1975). This age serves to bracket most of the basaltic volcanism between 63 m. y. and 56 m. y.

On Ubekendt Ejland the last extrusives comprise a highly variable suite of rocks including feldspar-phyric basalt, monchiquitic basalt, trachybasalt, biotite trachyte, rhyolite, pitchstone, ignimbrite, agglomerate, and tuffs with a wide range of compositions forming at least two thick sequences along the south coast (Clarke, 1973). Detailed work on one of the ignimbrites has recently been done by Thompson (1975).

Intrusive rocks

Intrusions in the province include dykes, sills, irregular sheets, cone sheets and central intrusive bodies. Almost all rock types found in the intrusions have extrusive equivalents also represented in the province.

Dykes

Noe-Nygaard (1942) first noted the decreasing concentration of dykes from the bottom to the top of the volcanic pile and concluded that this feature was a consequence of the dykes being feeders to the lavas. In several localities dykes have now been observed directly feeding lava flows (Drever, 1958).

Numerous olivine-rich dykes are found in the early breccias and olivine basalt flows. These dykes are typically less than half a metre to a few metres in thickness, are usually nearly vertical and, in many cases, do not conform to any definite trend. Fewer dykes cut the sequence of feldspar-phyric and aphyric basalt and they are mostly petrographically identical to these lavas. These dykes tend to be thicker than the olivine-rich basaltic dykes.

Dykes of these two types occur throughout the province. Local dyke swarms have been mapped in several areas. The largest dyke swarm in the province has a NW–SE trend from south-west Nûgssuaq and north-west Disko through Disko and can be followed across the sea floor deep into Disko Bugt (Denham, 1973) for more than 175 km.

In the northern part of the zone, the swarm includes both olivine-rich and feldspar-phyric dyke types and seems to have been active for a long period.

A late, widespread dyke generation of olivine and feldspar-phyric basalts, enriched in incompatible elements, similar or related in composition to the porphyritic zone of Nûgssuaq and Dredge Station 6 basalts offshore Svartenhuk Halvø (Clarke, 1975) occurs in Hareøen and western Nûgssuaq. They have a NNE–SSW trend and are described as 'transitional basalts' by Hald (personal communication). Similar dykes can be followed along the entire west and south-west coast of Disko. Some of these may have been feeders, suggesting that lavas of this composition may once have covered large areas in the western part of the province. An analysis is given in Table 6, analysis 5. In addition there are several dykes of unusual composition discussed below.

On Svartenhuk Halvø, near Tasiussap imâ, a late group of carbonate-rich 'dykes' have been intruded.

These dykes are up to several metres wide, are frequently full of basaltic xenoliths, almost certainly derived from the wall-rocks, and are surrounded by zones of alteration comparable in width to the widths of the dykes themselves. Chemically the dykes do not have the trace element characteristics of carbonatites and are probably of hydrothermal origin.

On western Ubekendt Ejland a swarm of perhaps a hundred lamprophyre dykes occurs trending NNW and cutting the late volcanics. These comprise a wide range of compositions including kersantite, camptonite and monchiquite. Several of these dykes contain abundant Precambrian basement xenoliths (significantly no sedimentary xenoliths have yet been discovered), and some dykes also contain clinopyroxene megacrysts, dunite, spinel harzburgite and biotite-pyroxenite xenoliths. An analysis of a typical lamprophyre appears in Table 6, analysis 8. $^{40}Ar/^{39}Ar$ age determinations have been made on three of these dykes and all give ages between 30 and 40 m. y. (Parrott & Reynolds, 1975). If the trachytes of this area represent very late-stage volcanism then there is a gap of at least 15 m. y. before the undersaturated dykes of Ubekendt Ejland were injected.

Also in western Ubekendt Ejland, near the volcanic neck at Erqua, there are some basic–acid composite dykes and some quartz–carbonate veins which are quite different from the carbonate dykes on Svartenhuk Halvø.

In Disko there occur the classic native iron and sulphide-bearing dykes. In southern Disko, at Uivfaq (syn: Ovifak), Nordenskiöld (1871) found blocks of native iron up to 20 tons in weight in an olivine tholeiite. Recently Fundal (1975) has discovered another native iron bearing dyke in southern Disko (fig. 337).

In north-east Disko at Igdlukûnguaq, a basaltic dyke also contaminated by sediments has developed a body of nickeliferous pyrrhotite several tons in weight, described in detail by Pauly (1958).

The largest contaminated intrusives found are volcanic necks and dykes from north-western Disko. North of Hammers Dal a contaminated dyke, up to 45 m wide, can be followed for several kilometres. It is composite and part of the intrusive body displays sediment xenolith flotation and cumulates of native iron and pyrrhotite. A high temperature Ni-pyrrhotite mineralisation occurs in part of the body (Pedersen, 1975 a).

A wide range of minerals formed by pyrometamorphism of sedimentary or gneissic xenoliths or by chemical reaction with the magma include: graphite, native iron, pyrrhotite, Ca-clinopyroxene, orthopyroxene, plagioclase, high-sanidine, cordierite, corundum, rutile, spinel, mullite and tridymite or cristobalite. Quartz is a resistant phase in sandstones and gneisses, and commonly forms xenocrysts (Pedersen, 1970).

Fig. 337. Columnar jointed dyke cutting through feldspar-phyric basalt lavas. The dyke rock is an olivine microporphyritic native iron bearing basalt. Luciafjeld, southern Disko.

Sills and sheets

Most of the sills and irregular sheets in the province are either thick dolerites emplaced close to the boundary fault zone or picritic minor intrusions in the olivine basalt sequence.

In Svartenhuk Halvø a large number of massive doleritic intrusions occur in the valley system trending north-west from Itsako. Some of these, as in Itsako, are emplaced in the pre-volcanic sediments, others in, at or near the contact between the sediments and the overlying breccias. Chemically they appear to belong to the eruptive rocks of the transition zone but otherwise the age of these sills is obscure.

On Ubekendt Ejland a large number of picritic sheets have been described by Drever (1956, 1958) and by Drever & Johnston (1966). Most prominent among these is the Ingia intrusion from the northern part of the island. It was through investigation of these rocks that the first suggestions came of the existence of highly magnesian melts as the parental magma in this province (Drever, 1953, 1956). Globular structures in the Ingia intrusion were interpreted as evidence of liquid immiscibility by Drever

(1960). Drever & Johnston (1966) have also remarked on the highly calcic nature of the aphanitic parts of the picritic sheets.

On Nûgssuaq there are various sills and sheets. Some of the picritic ones are demonstrably younger than the early picritic breccias, whereas the age of others emplaced in the sediments is not known.

A small picrite body with accompanying graphitised shales near Niaqornat was described by Heim (1910). Later investigators mapped this as an intrusion covering an area of at least 80 to 100 km² in the valleys of Itivdle and Tunorssuaq, and found the body to have the form of an irregular branching sheet. The maximum thickness of the body, which is found at the boundary between marine Cretaceous and early Tertiary sediments and picrite basaltic pillow breccia, exceeds 700 m. The rock, which is rich in large (pseudomorphed) olivine phenocrysts, forms easily weathering, crumbly, greyish and greenish masses and sediments are often found as inclusions. However, recent mapping in the area (by G. Henderson map sheet 1:100 000 Agatdal; Philip, 1973) has indicated that apart from some small intrusive bodies, the rest of the formerly mapped unit consists of picritic lavas and breccias affected by hydrothermal alteration related to the numerous faults in the area.

An important group of hydrated alkaline picritic intrusions occur at Qaersut on the north coast of Nûgssuaq where the mineral kaersutite was first described by Lorenzen (1884). This area was later described by Heim (1910), Drescher & Krueger (1928) and Drescher (1933). The principal sill is 50 m thick and is intruded into non-marine Cretaceous sediments. The main rock type is a medium-grained peridotitic rock composed of cumulus olivine poikilitically enclosed in clinopyroxene, plagioclase and sometimes brown monoclinic amphibole. Structures resembling igneous lamination have been described by Drescher & Krueger (1928). Within the sill is a horizontal sheet, one metre thick, of alkali dolerite and elsewhere thinner nepheline-normative, analcime-bearing alkali pegmatite layers and lenses occur. The pegmatite contains such ferromagnesian silicates as titanaugite, aegirine augite, hornblende, kaersutite, arfvedsonite, kataphorite and biotite.

Munck (1945) has described a group of dolerite sills from Serfat on the north coast and Atanikerdluk on the south coast. Like those of Svartenhuk Halvø, these sills were intruded into sediments in the vicinity of the boundary fault zone. These dolerites have undergone *in situ* differentiation to produce leucocratic veins of granophyre.

On Disko thick basaltic and doleritic sills have intruded the sedimentary sequence along the east and north-east coast.

The small group of islands, Grønne Ejland, in Disko Bugt consist, apart from a small area with presumably Mesozoic sediments, exclusively of a large dolerite intrusion (A. Escher, personal communication). It seems to form part of the large group of dolerite sills found along the eastern main fault zone which limited the sedimentary basin.

Central complexes

On Ubekendt Ejland a gabbro-granophyre complex occurs at Sarqâta qáqâ and has been described by Drever & Game (1948), Drever (1958) and Thompson & Patrick (1968). The complex covers an area of about 15 km² and a vertical section of more than 1 km is available for study. The lower unit in the intrusion is an olivine gabbro, parts of which show igneous layering. Slump structures associated with fallen blocks of lava stoped from the roof have been described by Thompson & Patrick (1968). The gabbro is covered by 400 m of granitic rocks and the boundary between the two units is occupied by a hybrid intermediate rock with confusing contact relations. Drever (1958) has suggested multiple intrusion and magma mixing to explain this intrusive body and cites the existence of related composite sheets as evidence for the coexistence of acid and basic magmas. The intrusion has associated with it a sequence of cone sheets and dykes.

Beckinsale *et al.* (1974) have presented isotopic evidence to show that the complex is co-magmatic with the volcanic rocks and evolved without reaction with the underlying Precambrian basement. On the basis of a Rb-Sr age of 65 ± 5 m. y. for the complex as a whole and two K-Ar ages on biotite of about 55 ± 1.5 m. y. they believe that the complex cooled extremely slowly.

Along the west coast of Ubekendt Ejland near Erqua, there are several agglomerate vents consisting of rounded basaltic blocks in a matrix of carbonate. The carbonate is similar in appearance to the 'dykes' on Svartenhuk Halvø and the zones of alteration around the diatremes are similarly extensive. Access to these vents is difficult and, up to the present time, they have not been carefully studied.

On Disko numerous rounded gabbroic xenoliths occur in picritic and feldspar-phyric dykes in a limited area around Jens Vahls Dal in the north-west. Many of the xenoliths are igneous cumulates and demonstrate the existence of a hidden igneous layered complex below sea level in this area (Pedersen, 1973).

Petrogenesis

Two main questions are dominant in any consideration of the petrogenesis of these volcanics. The first question deals with explaining the unparalleled production of hypersthene-normative picrites and deciding on their significance. The second question is concerned with finding an explanation for the diversity of late-stage differentiates, which range from silica-oversaturated granophyres to highly undersaturated monchiquites. These two questions will be treated separately and then a petrogenetic model consistent with current knowledge will follow. The next major thrust of investigation in the province will be of a petrochemical nature, so that the simplicity and possibly the validity of this model will be short-lived.

Hypersthene-normative picrites

The profusion of olivine in the early volcanics of Ubekendt Ejland, combined with textural evidence (Drever & Livingstone, 1948) led Drever (1953) to challenge the limits of olivine solubility in 'basaltic' melts laid down by Bowen (1928). Then Drever (1956) suggested that liquids, from which 25 per cent olivine could crystallise, might be important. Recent experimental work has confirmed the presence of large amounts of normative olivine in high pressure partial melts of peridotites (Cohen *et al.*, 1967; Green & Ringwood, 1967; Kushiro, 1968; O'Hara, 1968).

On the basis of a model proposed by O'Hara (1968), the genesis of the Svartenhuk Halvø basalts, and their relationship to the Tertiary basalts of Baffin Island, was described by Clarke (1968, 1970). Briefly, the rocks most likely to represent the parental magma in the province on the basis of textural evidence and average composition of the olivine basalt pile, have compositions similar to the primary magma produced by partial melting of garnet peridotite at 30 kb. Thus a possible source area for this parental magma is at a depth of 80–100 km. As far as major elements are concerned, the parental magmas in both provinces are very similar but there are certain differences in the concentration of incompatible elements (Ti, K, P, Ba, Rb, Sr, Zr) between the parental magma of Baffin Island and the parental magma of Svartenhuk Halvø. O'Nions & Clarke (1972) have considered these trace element differences both in terms of fractional crystallisation of eclogite in the region of partial melting, and as the result of different degrees of partial melting for the various magma batches. Neither process completely explains the observed variation in early olivine basalt chemistry.

In Disko, Pedersen (in prep.) has found compositional equivalents of both the Baffin Island and Svartenhuk Halvø parental magmas and concludes from trace element studies that either variation in the degree of partial melting or mantle inhomogeneity must be invoked to explain the compositional differences between the two magma types.

In any case, whether the magmas were formed at varying degrees of partial melting or whether the magmas were erupted early or delayed for a while in the source region, they appear to have been erupted quickly enough from that depth to have retained their occult olivine as microphenocrysts. Variation among the early olivine-rich basalts can be explained solely in terms of olivine fractionation. With the possible exception of the early brown breccias of Svartenhuk Halvø which may have suffered an abnormal degree of cooling and fractionation *en route* to the surface through cool country rocks, the early lavas have not been equilibrated at low pressure conditions.

Thus the importance of the enormous volumes of picritic magmas at the beginning of the volcanic activity is two-fold. First it is possible to deduce that at least some of the parental magma for the province was in fact a primary magma, and second, the sheer quantity of magma produced suggests large scale mantle melting and further implies a major tectonic event to effect it.

Transitional basalts, picrites and rocks of more silica-undersaturated compositions

Throughout the province there occur a number of transitional basalts and more silica-undersaturated compositions, probably covering a wide range of genetic conditions of high pressures in the mantle.

Pedersen (1970; in prep.) describes low alumina transitional basalts and picrites from Disko occurring interlayered with the common hypersthene-normative picrites. A few of the transitional basalts may have equilibrated at low pressure, but most have not. Pedersen (in prep.) concludes that the transitional basalts may have formed either by very small degrees of partial melting from a mantle still containing accessories like phlogopite, or alternatively through a complex process like zone refining (Harris, 1957).

The poorly known nepheline-normative olivine basalts of Svartenhuk Halvø may have formed by similar processes, or alternatively, they may have originated through eclogite fractionation of hypersthene normative picrite magma.

According to petrogenetic models of Green &

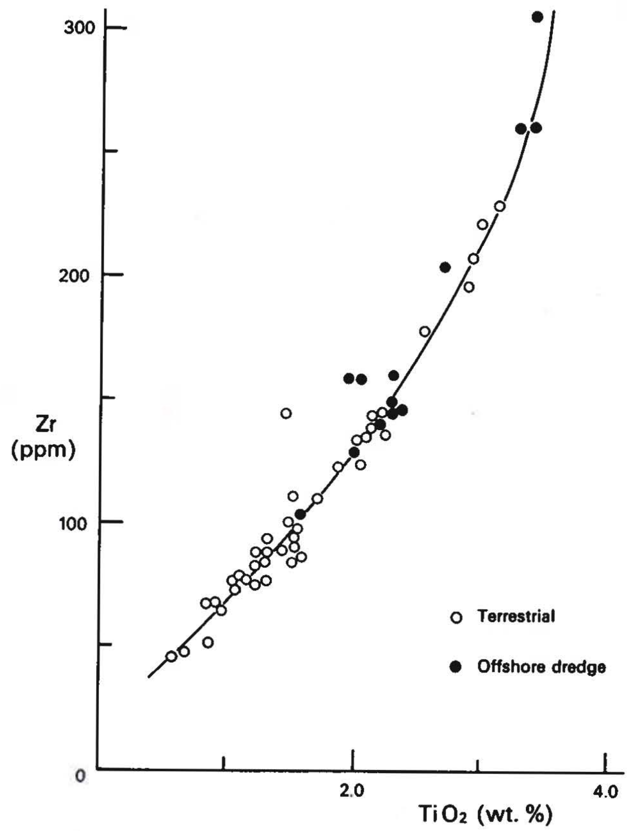

Fig. 338. Zirconium versus titanium in picrites, olivine basalts and feldspar-phyric basalts from Svartenhuk Halvø and in three dredge samples from Baffin Bay, offshore Disko and Svartenhuk Halvø. From Clarke (1975).

Ringwood (1967) and O'Hara (1968) the alumina-enriched transitional basalts of Hareøen may represent compositions equilibrated or formed through melting in the intermediate pressure range of 10 to 20 kb (Pedersen, 1970).

As a representative bulk composition cannot at present be given for the nepheline-normative ultramafic hydrated intrusions from Nûgssuaq, we shall not speculate about their genesis. Whether their water content was derived from the mantle or originated from the Cretaceous sediments is uncertain.

Differentiates

Younger rocks, more highly evolved than the hypersthene-normative picrites, include silica-saturated and silica-oversaturated compositions such as the feldspar-phyric basalts, dolerites, trachytes, granophyres and pitchstones. Of these, the feldspar-phyric basalts, which comprise more than 95 per cent by volume of the final products, lie on continuous chemical trend lines with the picrites (Clarke, 1970) and are considered to be reasonable derivatives of the picrites (fig. 338). It has been suggested by Clarke (1975) that the feldspar-phyric basalt magmas reached their present composition by fractional crystallisation of olivine gabbro from parental picrites in magma chambers near the base of the crust. 'Cognate' xenoliths of olivine gabbro do occur in some of the transition zone basalts of northern Disko.

Hald (in prep.) has discussed the chemical evolution of the feldpsar-phyric basalts of Nûgssuaq and shown that simple crystal fractionation of the observed phenocryst phases; olivine, plagioclase and augite, or these phases plus the non-observed orthopyroxene, cannot explain the evolution from the lower feldspar-phyric basalts to those found in the middle or upper part of the lava sequence. He concludes that pulses of magma from below must have been added to the crystal fractionation regime, and that low pressure crystal fractionation possibly only played a minor role in the evolution of these magmas.

The more silica-rich derivatives of the feldspar-phyric magmas probably evolved in very shallow magma chambers. Proof of the ability of some of these magmas to fractionate to granophyric residua is afforded by the doleritic sills on Nûgssuaq (Munck, 1945). Thus these low-pressure magma chambers could also give rise to the trachytes, rhyolites and pitchstones scattered in small volumes throughout parts of the province. O'Nions & Clarke (1972) have shown that the trachytes and carbonate 'dykes' of Svartenhuk Halvø have the same low $^{87}Sr/^{86}Sr$ ratio as the basalts, suggesting a genetic relationship among all three. Pedersen (1970) has proposed that the transitional basalts of Hareøen with high K_2O/Na_2O+K_2O and high alumina content would be suitable parental material for the trachytes.

The highly silica-undersaturated lamprophyres of Ubekendt Ejland may, since they are more than 15 m. y. younger than the lavas of the province, represent an entirely separate partial melting event. Alternatively, they may have formed from hypersthene normative picrites through high degrees of eclogite fractionation.

Petrogenetic model

With the still limited information available on the chemistry of the West Greenland volcanic rocks, and ignoring for the present various complexities which might be introduced by variations in depth of partial melting and mantle inhomogeneity, a simple petrogenetic model can be proposed:

(1) partial melting of garnet peridotite at 30 kb to

produce a large volume of hypersthene-normative picritic magma;
(2) rapid eruption of most of this magma towards the surface where it is extruded as subaqueous breccias and subaerial flows and intruded as sills in early flows and in pre-volcanic rocks;
(3) some of this magma may fractionate in an intermediate pressure regime (10–20 kb) to become the minor nepheline-normative basalts found in the province;
(3a) alternatively low alumina transitional basalt and picrites and nepheline-normative basalts are formed by very low degrees of partial melting or in areas subject to zone refining;
(4) continued partial melting at depth followed by eruption to magma chambers near the base of the crust (5–8 kb) where olivine gabbro fractionation yields a feldspar-phyric basalt derivative;
(5) new partial melting in the intermediate pressure range, or crystal fractionation of hypersthene-normative picrite magma at this pressure, produces minor amounts of alumina-rich transitional basalt;
(6) further fractionation of feldspar-phyric basalt and alumina-rich transitional basalt in very shallow magma chambers ($<$ 5 kb) produces small volumes of trachytes, and both peraluminous and peralkaline rhyolites and pitchstones;
(7) renewed partial melting produces highly silica-undersaturated lamprophyres;
(7a) alternatively, prolonged eclogite fractionation in the high-pressure regime (30 kb) produces lamprophyres.

The bronzite basalts and native iron bearing basalts are not included in the above scheme. These rocks were formed by reactions between magma and Cretaceous bituminous shales and sandstones rich in sulphur compounds. The processes were complex and involved sulphurisation, desulphurisation and reduction of the magmas and were followed by gravitative fractionation of the dense sulphide and metal phases (Pedersen, 1975 a, b).

In conclusion, a picture is beginning to emerge, not of a homogeneous, monotonous lava pile as formerly believed, but of a highly varied suite of rocks belonging to a major igneous event in the early Tertiary. There is still much to be learned, and as more becomes known, so the model required to explain the variation will become more complex.

Relationship to the Brito-Arctic Province

The West Greenland Tertiary lava province has long been recognised as a part of the Thulean Tertiary basalt province and as such it should be considered in relation to the neighbouring volcanic areas.

Because of their similarity in age and field relations, the Tertiary lavas of West and East Greenland have been considered to be intimately related. Recently Brooks (1973) has compared the East Greenland tholeiitic basalts with the feldspar-phyric basalts of West Greenland and noted their similarity. However, the two provinces which are separated spatially by more than 700 km, display considerable differences. For instance, East Greenland has not produced the large pile of picrite basalts with the low concentrations of minor elements found in West Greenland. On the other hand West Greenland does not display the numerous syenitic and nepheline syenitic plutons nor a prominent coast parallel dyke swarm, so characteristic of the East Greenland province (Deer, this volume). This evidence suggests that the two areas belonged to spatially separate, but roughly contemporaneous, phases of volcanism.

Because of the strong similarities in field relations, petrology and chemistry between the Tertiary lavas of Baffin Island and those of the early eruptives of West Greenland as discussed by Clarke (1970), the two areas should be considered as genetically related. A model for the evolution of the two areas has been presented by Clarke & Upton (1971), who invoke continental rupture and sea-floor spreading to generate the magmas and create the present separation of the two lava provinces respectively. Recent discoveries of offshore extensions of the West Greenland basalt plateau by Park *et al.* (1971) have tended to reinforce this suggestion that the two provinces initially evolved together and have since been separated by sea-floor spreading. The discovery by Barrett *et al.* (1971) and Keen *et al.* (1974) that the crust of Baffin Bay is oceanic lends further weight to this idea. Henderson (1973) has considered in some detail the structural evolution of the eastern half of this continental rupture and has concluded that the evolutionary history of the provinces, including the graben in Melville Bugt, may be much longer than present terrestrial exposures would suggest. Fahrig *et al.* (1971) have also suggested that the development of Baffin Bay may have begun in the Hadrynian, some 600 m. y. ago. If these suggestions are correct, then an interesting picture is emerging of a very sluggish period, in excess of 500 m. y., in which Palaeozoic and Mesozoic sediments accumulated in a slowly subsiding graben. The region of subsidence was then suddenly expanded in the late Cretaceous – early Tertiary, as evidenced by the exposures on both Baffin Island (Paleocene only) and West Greenland of sediments of this age, and culminated shortly thereafter in the massive outpourings of subaqueous breccia and subaerial flows. At this point sea-floor spreading was initiated in which the new sea-floor remained coupled with both continental blocks and the two volcanic areas were soon separated.

It is now clear that the full history of development of the Baffin Bay rift and related volcanics awaits detailed oceanographic work in Baffin Bay and Davis Strait. Several institutions are already engaged in this project.

References

Athavale, R. N. & Sharma, P. V. 1975: Paleomagnetic results on early Tertiary lava flows from West Greenland and their bearing on the evolution history of the Baffin Bay–Labrador Sea region. *Can. J. Earth Sci.* **12**, 1–18.

Barrett, D. L., Keen, C. E., Manchester, K. S. & Ross, D. I. 1971: Baffin Bay – an ocean. *Nature, Lond.* **229**, 551–553.

Beckinsale, R. D., Thompson, R. N. & Durham, J. J. 1974: Petrogenetic significance of initial $^{87}Sr/^{86}Sr$ ratios in the North Atlantic Tertiary igneous province in the light of Rb-Sr, K-Ar and ^{18}O-abundance studies of the Sarqâta qáqâ intrusive complex Ubekendt Ejland, West Greenland. *J. Petrol.* **15**, 525–538.

Bøggild, O. B. 1953: The mineralogy of Greenland. *Meddr Grønland* **149**, 3, 442 pp.

Bowen, N. L. 1928: *The evolution of the igneous rocks.* 334 pp. Princeton U. P.

Brooks, C. K. 1973: Tertiary of Greenland – a volcanic and plutonic record of continental break-up. *Mem. Amer. Ass. Petrol. Geol.* **19**, 150–160.

Clarke, D. B. 1968: Tertiary basalts of the Baffin Bay area. Unpublished Ph. D. thesis, Univ. Edinburgh.

Clarke, D. B. 1970: Tertiary basalts of Baffin Bay: possible primary magma from the mantle. *Contr. Miner. Petrol.* **25**, 203–224.

Clarke, D. B. 1973: New mapping in the western part of Ubekendt Ejland. *Rapp. Grønlands geol. Unders.* **53**, 5–9.

Clarke, D. B. 1975: Tertiary basalts dredged from Baffin Bay, *Can. J. Earth Sci.* **12**, 1396–1405.

Clarke, D. B. & Upton, B. G. J. 1971: Tertiary basalts of Baffin Bay: field relations and tectonic setting. *Can. J. Earth Sci.* **8**, 248–258.

Cohen, L. H., Ito, K. & Kennedy, G. C. 1967: Melting and phase relations in an anhydrous basalt to 40 kilobars. *Amer. J. Sci.* **265**, 475–518.

Denham, L. R. 1973: Marine geophysical survey between 68°30'N and 73°30'N, West Greenland. *Rapp. Grønlands geol. Unders.* **55**, 14–18.

Denham, L. R. 1974: Offshore geology of northern West Greenland. *Rapp. Grønlands geol. Unders.* **63**, 24 pp.

Drescher, F. K. 1933: Zur Kenntnis des Peridotits von Kaersut (Grönland) und seines Ganggefolges. *Mineralog. petrogr. Mit.* **B 43**, 207–270.

Drescher, F. K. & Kreuger, H. K. E. 1928: Der Peridotit von Kaersut (Grönland) und sein Ganggefolge als Beispiel einer Sekretionsdifferentiation. *Neues Jb. Miner. Geol. Paläont.* **BB 57A**, 569–616.

Drever, H. I. 1953: The origin of some ultrabasic rocks: a preliminary survey of the evidence for and against gravity accumulation of olivine. *Meddr dansk geol. Foren.* **12**, 227–229.

Drever, H. I. 1956: The geology of Ubekendt Ejland, West Greenland. II. The picritic sheets and dykes of the east coast. *Meddr Grønland* **137**, 4, 41 pp.

Drever, H. I. 1958: Geological results of four expeditions to Ubekendt Ejland, West Greenland. *Arctic* **11**, 199–210.

Drever, H. I. 1960: Immiscibility in the picritic intrusion at Igdlorssuit, West Greenland. *Rep. 21st int. geol. Congr. Norden* **13**, 47–58.

Drever, H. I. & Game, P. M. 1948: The geology of Ubekendt Ejland, West Greenland. *Meddr Grønland* **134**, 8, 35 pp.

Drever, H. I. & Johnston, R. 1966: A natural high-lime silicate liquid more basic than basalt. *J. Petrol.* **7**, 414–420.

Drever, H. I. & Livingstone, D. F. 1948: Some basaltic rocks from West Greenland. *Proc. R. Soc. Edinb.* **B, 63**, 97–114.

Fahrig, W. F., Irving, E. & Jackson, G. D. 1971: Paleomagnetism of the Franklin diabases. *Can. J. Earth Sci.* **8**, 455–467.

Fundal, E. 1975: The Uivfaq dike and related hybrid dikes from southern Disko, West Greenland. *Meddr Grønland* **195**, 7, 28 pp.

Giesecké, C. [L.] 1823: On the mineralogy of Disko Island. *Trans. R. Soc. Edinb.* **9**, 263–272.

[Giesecke, K. L.] 1910: Karl Ludwig Gieseckes mineralogisches Reisejournal über Grönland, 1806–1813. *Meddr Grønland* **35**, 1–478.

Green, D. H. & Ringwood, A. E. 1967: The genesis of basalt magmas. *Contr. Miner. Petrol.* **15**, 103–190.

Gry, H. 1942: The Cretaceous and Tertiary sediments on Itsako. *Meddr Grønland* **135**, 3, 27–35.

Harris, P. G. 1957: Zone refining and origin of potassic basalts. *Geochim. cosmochim. Acta* **12**, 195–208.

Hald, N. 1971: An investigation of the igneous rocks on Hareøen and western Nûgssuaq, West Greenland. *Rapp. Grønlands geol. Unders.* **35**, 11–13.

Hald, N. 1973: Preliminary results of the mapping of the Tertiary basalts in western Nûgssuaq. *Rapp. Grønlands geol. Unders.* **53**, 11–19.

Hald, N. in prep.: Early Tertiary flood basalts from Hareøen and western Nûgssuaq, West Greenland.

Heim, A. 1910: Über die Petrographie und Geologie der Umgebungen von Karsuarsuk, Nordseite der Halbinsel Nugsuak, W. Grönland. *Meddr Grønland* **47**, 173–228.

Henderson, G. 1969: Field work supplementing photogeological interpretation of Nûgssuaq. *Rapp. Grønlands geol. Unders.* **19**, 18–21.

Henderson, G. 1973: The geological setting of the West Greenland basin in the Baffin Bay region. *Pap. geol. Surv. Can.* **71–23**, 521–544.

Jürgensen, T. & Mikkelsen, N. 1974: Coccoliths from volcanic sediments (Danian) in Nûgssuaq, West Greenland. *Bull. geol. Soc. Denmark* **23**, 225–230.

Keen, C. E., Barrett, D. L., Manchester, K. S. & Ross, D. I. 1972: Geophysical studies in Baffin Bay and some tectonic implications. *Can. J. Earth Sci.* **9,** 239–256.

Keen, C. E., Keen, M. J., Ross, D. I. & Lack, M. 1974: Baffin Bay: small ocean basin formed by sea-floor spreading. *AAPG Bull.* **58,** 1089–1108.

Koch, B. E. 1959: Contribution to the stratigraphy of the non-marine Tertiary deposits on the south coast of the Nûgssuaq Peninsula northwest Greenland. *Bull. Grønlands geol. Unders.* **22** (also *Meddr Grønland* **162,** 1) 100 pp.

Koch, B. E. 1964: Review of fossil floras and nonmarine deposits of West Greenland. *Bull. geol. Soc. Amer.* **75,** 535–548.

Krueger, H. K. E. 1928: Über eine sogenannte Basaltbreccie in der Kreide-Tertiär-Formation von Westgrönland. *Notizbl. Ver. Erdk. Darmstadt* **1927** (5), 270–281.

Kushiro, J. 1968: Compositions of magmas formed by partial zone melting of the earth's mantle. *J. geophys. Res.* **73,** 619–634.

Lorenzen, J. 1884: Undersøgelse af Mineralier fra Grønland. *Meddr Grønland* **7,** 1–31.

Lovering, J. F. 1964: Electron microprobe analysis of terrestrial and meteoritic cohenite. *Geochim. cosmochim. Acta* **28,** 1745–1755.

Martini, E. 1971: Standard Tertiary and Quaternary calcareous nannoplankton zonation. *Proc. 2nd planktonic Conf. Rome 1970,* 739–785.

Melson, W. G. & Switzer, G. 1966: Plagioclase-spinel-graphite xenoliths in metallic iron-bearing basalts, Disko Island, Greenland. *Amer. Miner.* **51,** 664–676.

Munck, S. 1942: The basalt breccia. [Svartenhuk peninsula] *Meddr Grønland* **135,** 3, 43–54.

Munck, S. 1945: On the geology and petrography of the West Greenland basalt province. V. Two major dolerite intrusions of the Nûgssuaq peninsula. *Meddr Grønland* **137,** 5, 61 pp.

Munck, S. & Noe-Nygaard, A. 1957: Age determination of the various stages of the Tertiary volcanism in the West Greenland basalt province. *Rep. 20th int. geol. Congr. Mexico* (1) **1,** 247–256.

Münther, V. 1952: Grafitbasalten i NV-Disko. *Meddr dansk geol. Foren.* **12,** 159 only.

Münther, V. 1973: Results from a geological reconnaissance around Svartenhuk Halvø, West Greenland. *Rapp. Grønlands geol. Unders.* **50,** 26 pp.

Nieland, H. 1931: Beitrag zur Kenntnis der Deckenbasalte von Westgrönland. *Chemie Erde* **6,** 591–612.

Noe-Nygaard, A. 1942: On the geology and petrography of the West Greenland basalt province. III. The plateaubasalts of Svartenhuk peninsula. *Meddr Grønland* **137,** 3, 78 pp.

Noe-Nygaard, A. 1974: Cenozoic to recent volcanism in and around the North Atlantic basin. *In* Nairn, A. E. M. & Stehli, F. G. (edit.) *The ocean basins and margins* **2,** 391–443.

Nordenskiöld, A. E. 1871: Redogörelse för en Expedition till Grönland år 1870. *Öfvers. VetenskAkad. Förh.* **27,** 973–1082.

O'Hara, M. J. 1968: The bearing of phase equilibria studies in synthetic and natural systems on the origin and evolution of basic and ultrabasic rocks. *Earth Sci. Rev.* **4,** 69–133.

O'Nions, R. K. & Clarke, D. B. 1972: Comparative trace element geochemistry of Tertiary basalts from Baffin Bay. *Earth planet. Sci. Lett.* **15,** 436–446.

Park, I., Clarke, D. B., Johnson, J. & Keen, M. J. 1971: Seaward extension of the West Greenland Tertiary volcanic province. *Earth planet. Sci. Lett.* **10,** 235–238.

Parrott, R. J. E. & Reynolds, P. H. 1975: Argon-40/argon-39 geochronology: age determinations of basalts from the Labrador Sea area. *Abstr. geol. Soc. Amer.* **7,** 835 only.

Pauly, H. 1958: Igdlukúnguaq nickeliferous pyrrhotite. *Bull. Grønlands geol. Unders.* **17** (also *Meddr Grønland* **157,** 3) 169 pp.

Pauly, R. 1969: White cast iron with cohenite, schreibersite and sulphides from Tertiary basalts on Disko, Greenland. *Meddr dansk geol. Foren.* **19,** 8–26.

Pedersen, A. K. 1969: Preliminary notes on the Tertiary lavas of northern Disko. *Rapp. Grønlands geol. Unders.* **19,** 21–24.

Pedersen, A. K. 1970: En petrologisk undersøgelse af tertiære vulkanske bjergarter fra det nordlige Disko. Unpublished prize dissertation. Univ. Copenhagen. [Reviewed in *Festskrift Københavns Univ.* **1970,** 379–383].

Pedersen, A. K. 1973: Report on field work along the north coast of Disko, 1971. *Rapp. Grønlands geol. Unders.* **53,** 21–27.

Pedersen, A. K. 1975a: New mapping in north-western Disko 1972. *Rapp. Grønlands geol. Unders.* **69,** 25–32.

Pedersen, A. K. 1975b: New investigations of the native iron bearing volcanic rocks of Disko. *Rapp. Grønlands geol. Unders.* **75,** 48–51.

Pedersen, A. K. in prep.: Petrology of the olivine basalts of northern Disko, West Greenland.

Perch-Nielsen, K. 1973: Danian and Campanian/Maastrichtian coccoliths from Nûgssuaq, West Greenland. *Bull. geol. Soc. Denmark* **22,** 79–82.

Philip, P. 1973: Results of investigation of Tertiary volcanic breccia south of Niaqornat, Nûgssuaq, West Greenland. *Rapp. Grønlands geol. Unders.* **53,** 29–32.

Pulvertaft, T. C. R. & Clarke, D. B. 1966: New mapping on Svartenhuk peninsula. *Rapp. Grønlands geol. Unders.* **11,** 15–17.

Rink, H. 1853: Udsigt over Nordgrönlands Geognosi, især med Hensyn til Bjergmassernes mineralogiske Sammensætning. *K. danske Vidensk. Selsk. Skr.* (5) **3,** 71–98.

Rosenkrantz, A. 1970: Marine Upper Cretaceous and lowermost Tertiary deposits in West Greenland. *Meddr dansk geol. Foren.* **19,** 406–453.

Rosenkrantz, A., Noe-Nygaard, A., Gry, H., Munck, S. & Laursen, D. 1942: A geological reconnaissance of the southern part of the Svartenhuk peninsula West Greenland. *Meddr Grønland* **135,** 3, 72 pp.

Rosenkrantz, A. & Pulvertaft, T. C. R. 1969: Cretaceous–Tertiary stratigraphy and tectonics in northern West Greenland. *Mem. Amer. Ass. Petrol. Geol.* **12,** 883–898.

Steenstrup, K. J. V. 1882: Om Forekomsten af Nikkeljern med Widmannstättenske Figurer i Basalten i Nord-Grønland. *Meddr Grønland* **4,** 113–132.

Steenstrup, K. J. V. 1883: Bidrag til Kjendskab til de geognostiske og geographiske Forhold i en Del af Nord-Grønland. *Meddr Grønland* **4,** 173–242.

Thompson, R. N. 1975: Palaeocene ignimbrite from Ubekendt Ejland, west Greenland. *Lithos* **8,** 9–14.

Thompson, R. N. & Patrick, D. J. 1968: Folding and slumping in a layered gabbro. *Geol. J.* **6,** 139–145.