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TRANSITION FROM LOW POTASSIUM OLIVINE THOLEIITES TO ALKALI BASALTS ON UBEKENDT EJLAND

THE TERTIARY VOLCANIC PROVINCE OF WEST GREENLAND

BY

JØRGEN GUTZON LARSEN

WITH 8 FIGURES, 6 TABLES AND APPENDIX

Nyt Nordisk Forlag Arnold Busck
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Abstract

Five basalt types are distinguished in a 4–5 km thick volcanic pile of the upper formations on Ubekendt Ejland, the Tertiary province of West Greenland. They were erupted in the following order: 1) low potassium olivine tholeiites, 2) transitional basalts with tholeiitic affinity, 3) transitional basalts with alkaline affinity, 4) plagioclase rich alkali basalts, 5) olivine-clinopyroxene porphyritic alkali basalts. A multiparental origin is suggested for type 1–4 and even for rocks belonging to the same type. Possibly slightly different MgO rich magmas represented by the picritic lavas of the province could have formed the basalts of type 1–3 by fractional crystallization at low pressure up to a pressure of about 8 kb. The type 5 basalts were either formed by high pressure fractional crystallization combined with zone refining, or by a small degree of partial melting.

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BIANCO LUNOS BOGTRYKKERI A/S

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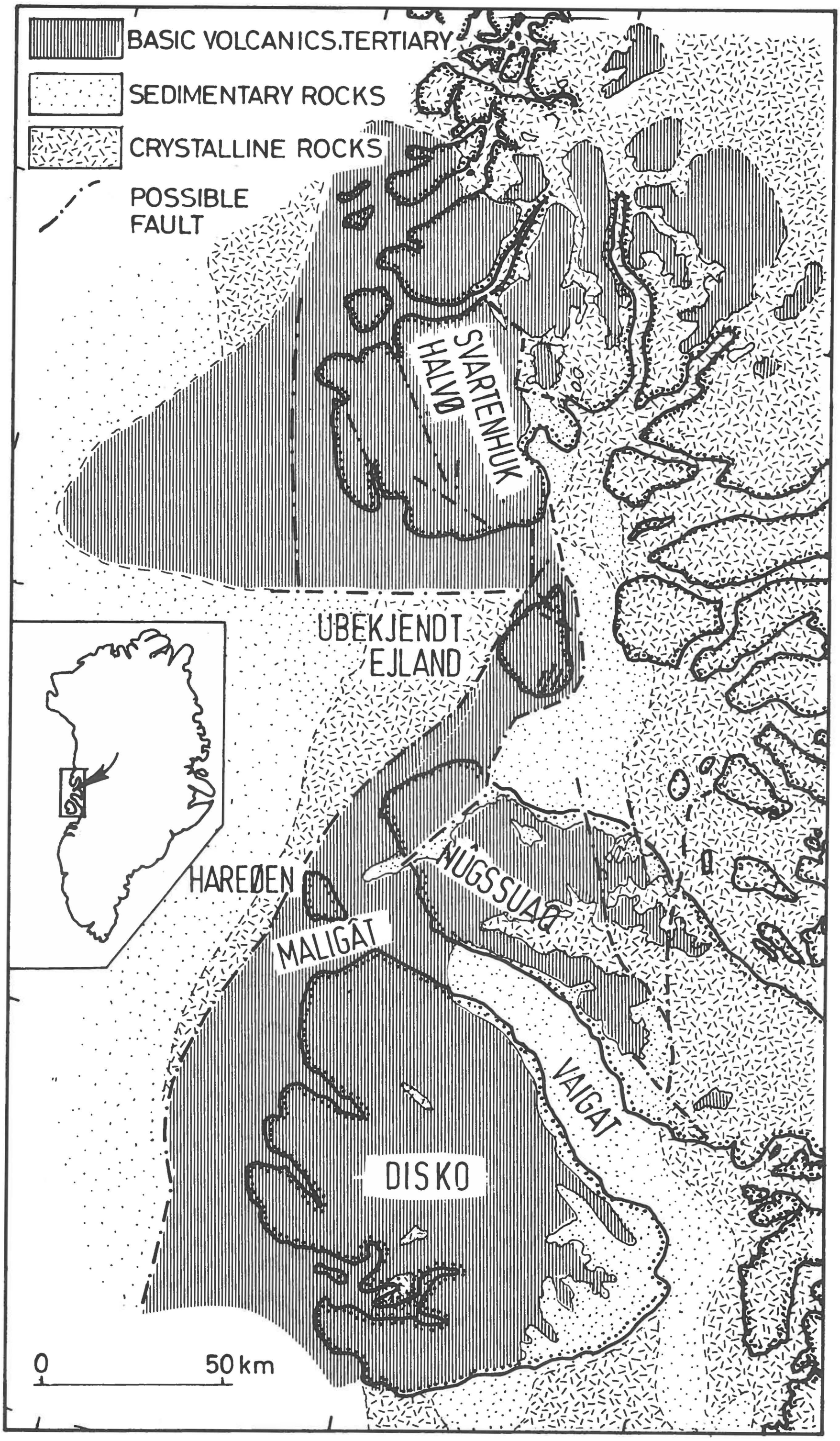

Fig. 1. The Tertiary volcanic province of West Greenland after DENHAM (1974).

INTRODUCTION

Ubekendt Ejland is the only place in the Tertiary volcanic province of West Greenland where alkaline basic rocks were produced in substantial amounts at the end of the magmatic activity (DREVER and GAME, 1948). The present work deals with the early part of this evolution, where the basalts range from low potassium olivine tholeiites and transitional basalts (intercalated with acid pyroclastic rocks) to alkali basalts. A model of fractional crystallization for the province has been presented by CLARKE (1970, 1975), but different degrees of partial melting and zone refining is an alternative possibility (O'NIONS & CLARKE, 1972; CLARKE & PEDERSEN, 1976).

The scope of the present work is partly to demonstrate that a stratigraphic control of the lava pile helps to establish different basalt groups and chemical trends and to discuss such trends on the basis of simple model calculations. These calculations are based on the assumption that the concentration of the incompatible elements is a function of the amount of crystal removal and the approach is rather similar to that of BOWEN (1928, p. 75–78). Least square fit of the phenocryst phases is not used because the phenocrysts in most cases are very small and are presumably crystallized close to the surface. Furthermore the olivine phenocrysts are mostly altered, and the change in composition of the fractionating phases has to be estimated when a high amount of crystal removal is needed.

Regional setting

The Tertiary volcanic province of West Greenland (Fig. 1) has been described by NOE-NYGAARD (1974) and CLARKE & PEDERSEN (1976). The basalts are associated with the development of the Cretatous-Tertiary Basin (ROSENKRANTZ & PULVERTAFT, 1969), which is a part of a large, possibly older graben located along the northwest coast of Greenland (HENDERSON, 1973). Up to 1.5 km of continental sandstone with coal seams and 2 km of marine bituminous shale were deposited (HENDERSON, 1973) before the volcanic activity started in Upper Danian time (MUNCK & NOE-NYGAARD, 1957; PERCH-NIELSEN, 1973; JÜRGENSEN & MIKKELSEN, 1974).

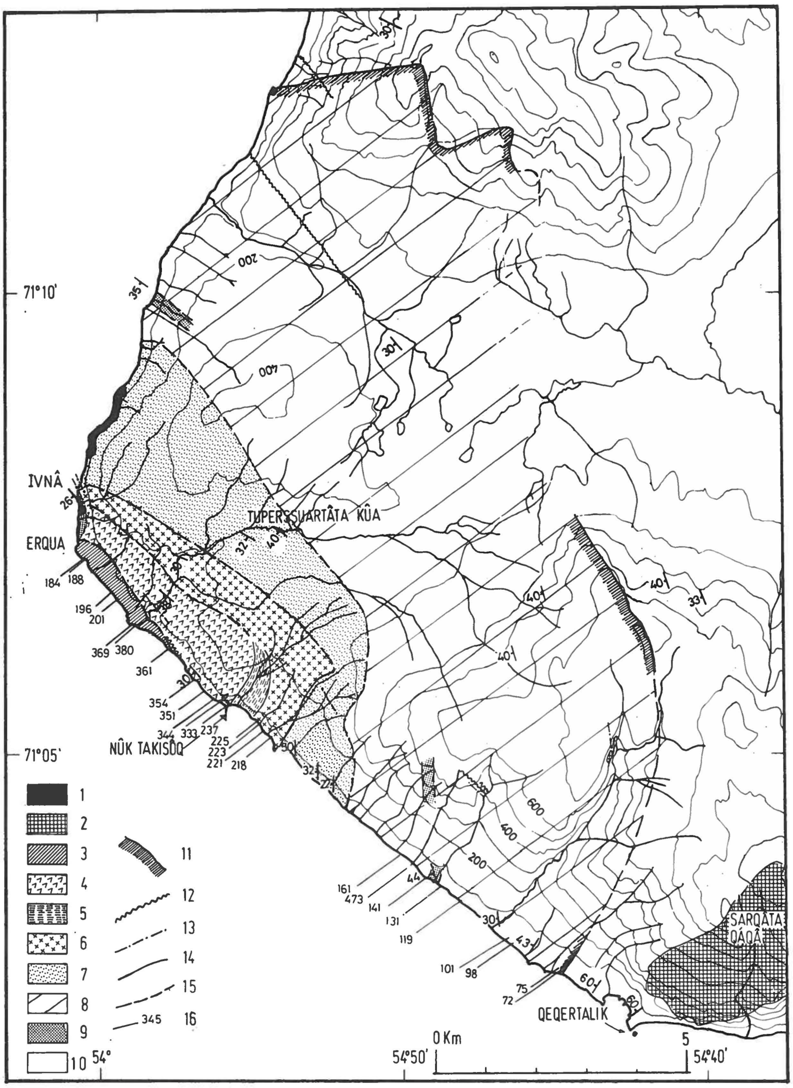

Fig. 2. Geological map of Southwestern Ubekendt Ejland. Symbols: 1. Volcanic vents. 2. Major intrusions. 3. Erqua Formation. 4. Upper part of Nûk takisôq Member. 5. Middel part of Nûk takisôq Member. 6. Lower part of Nûk takisôq Member. 7. Tuperssuartâta kûa Member. 8. Qeqertalik Member. 9. Tuff outside the Tuperssuartâta kûa Member. 10. Picritic basalts of the Vaigat Formation. 11. Olivine poor basalts of the base of Qeqertalik Member. 12. Carbonate zones associated with faults. 13. Faults. 14. Rock boundary 15. Inferred rock boundary. 16. Sample No. and location. Topographic contours in meters.

Table 1. *Stratigraphical summary of the younger volcanics on Ubekendt Ejland.**

	Erqua Formation
ca. 150 m	Porphyritic *alkali basalt* lavas of the aa type, more than 10 m thick, and intercalated with a few thin beds of tuff and sedimentary deposits.
	Maligât Formation
Nûk takisôq Member 400–700 m upper part 200 m	Plagioclase porphyritic *transitional basalts*, and nearly aphyric *hawaiites*. The lavas are of the aa type 2–5 m in thickness. Many vertical carbonate veins cut these lavas and the top scorias are strongly altered.
	Angular unconformity?
middel part 0–300 m	*Acid ignimbrites* composed of five? cooling units. Mostly altered.
lower part 200 m	Plagioclase porphyritic and aphyric *transitional basalt* lavas mostly of the aa type, and mostly less than 10 m in thickness. They are interbedded with clay, which originates from altered lava-tops and tuff beds.
	Angular unconformity
Tuperssuartâta kûa Member ca. 750 m	Altered lapilli tuff and ash beds composed of basaltic and more differentiated rock types.
Qeqertalik Member 3000–3500 m	Olivine porphyritic and olivine-plagioclase porphyritic mostly *low potassium olivine tholeiites*. The lavas are either of a thin (< 5 m) pahoehoe type or of thicker aa type. Except for one 100 m thick tuff bed pyroclastic and clastic deposits are scarce. There is an angular unconformity in the lower part of this member.
Vaigat Formation 5000 ?m	Olivine rich basalts.

* Modified after Larsen (1977).

Paleomagnetic data suggest that the volcanism started 63 m.y. ago (Athavale & Sharma, 1975) in agreement with the palaeontological age. A K-Ar age of 55 ± 1.5 m.y. has been obtained from the late Sarqâta qáqâ intrusion on Ubekendt Ejland (Beckinsale *et al.*, 1974). The latest magmatic activity forming the lamprophyre dykes is 39.5–30.6 m.y. old (Parrot & Reynolds, 1975).

According to Clarke & Upton (1971) the volcanism was contemporaneous and similar in the lower part to that of Baffin Island. They proposed in agreement with Le Pichon *et al.* (1971) that the volcanic activity in this region was connected with the beginning of the break up of North America and Greenland. Thus the basaltic floor occurring beneath the 4 km of sediments in Baffin Bay could be of Tertiary age (KEEN & BARRETT, 1972; PELLETIER *et al.*, 1975). DENHAM (1974) regarded this as unlikely and argued that the sediments could be Cretaceous and even older. ATHAVALE & SHARMA (1975) suggested that Baffin Bay was formed from Jurassic to late Cretaceous time and that the early Tertiary volcanism was associated with minor spreading in Baffin Bay simultaneously with the last spreading in the Labrador Sea.

Stratigraphy

The stratigraphy of the whole province has been formalized by HALD & PEDERSEN (1975) and divided into: *Vaigat Formation* (1500–5000 ? m) composed mainly of olivine rich basalt lavas and hyaloclastites. 2) *Maligât Formation* (1500–3000 m) composed of plagioclase + olivine ± clinopyroxene porphyritic olivine tholeiites. 3) *Hareøen Formation* (300 m) composed of olivine porphyritic transitional basalts. This division is adopted here with the exception that the uppermost basalts on Ubekendt Ejland are considered as an independent formation (Table 1).

The present work deals with the basaltic lavas of the Maligât and Erqua Formations on Ubekendt Ejland (Fig.2) corresponding to the Upper Lava Group of DREVER & GAME (1948) and DREVER (1958). From this group DREVER & GAME (1948) reported the occurrence of olivine-free basalt, monchiquite, trachybasalt and trachyte; rhyolites and pitchstone associated with pyroclastic rocks. THOMPSON (1975) has described one of the ignimbrites.

More detailed descriptions of these volcanics has recently been given by CLARKE (1973) and LARSEN (1977). The stratigraphy is summarized in Table 1. The three lower basalt units are separated by two layers of acid pyroclastic rocks, and one, perhaps two, angular unconformities suggesting that each basalt unit marks a new volcanic episode.

According to DREVER (1958) the volcanic vents on the west coast are associated with the formation of the rocks of the Upper Lava Group.

Younger than the volcanic rocks are dykes, sills, a vent of monchiquitic composition (DREVER, 1958) and faults with associated carbonatization (LARSEN, 1977). The broad synclinal structure in which the Maligât Formation is situated (Fig. 2) is probably caused by this faulting.

Nomenclature

The basalts are divided into olivine tholeiites and alkali basalts after YODER & TILLEY (1962). The olivine tholeiites with $K_2O < 0.30\,\%$ are refered to as *low potassium olivine tholeiites*. Olivine tholeiites, which are enriched in alkalies and plot in the alkaline field of the alkali-silica

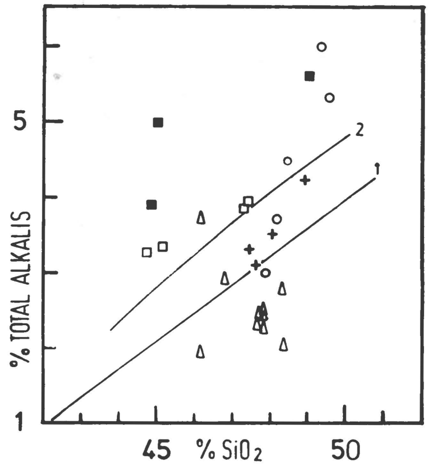

Fig. 3. Alkali-silica variation diagram. 1, Hawaiian division line between the tholeiitic (below) and alkaline basalts (Macdonald & Katsura, 1964). 2. The division line of Irvine and Baragar (1971). △: Qeqertalik Member (mostly low potassium olivine tholeiites). +: Lower part of Nûk takisôq Member (the transitional tholeiitic lineage). ○: Upper part of Nûk takisôq Member (the transitional alkaline lineage). ■: Plagioclase rich alkali basalts of Erqua Formation. □: Olivine-clinopyroxene porphyritic alkali basalts from Erqua Formation.

diagram (Fig. 3) (Macdonald & Katsura, 1964) are called *transitional basalts.*

The alkali basalts have 0.2–6.8 % normative Ne,* and small amounts of modal analcime may occur in the rocks with more than 5 % Ne. These are *basanites* or *basanitoids*, while those with less than 5 % Ne are *alkali olivine basalts* (see Macdonald & Katsura, op. cit.). One rock (No. 369) is Hy-normative but similar in chemistry and mineralogy to the alkali basalts, and it is therefore grouped together with these.

In addition the alkali basalts can be grouped as olivine-clinopyroxene porphyritic alkali basalts and plagioclase rich alkali basalts with $Al_2O_3 > 16\%$. Some of the Ne normative rocks are classified as hawaiites (see Macdonald, 1960).

The monchiquitic basalts of Drever & Game (1948) are probably identical with the olivine-clinopyroxene porphyritic type mentioned above. The reported occurrence of monchiquite? 4 km southeast of Erqua is regarded by the present author to be a calcified basalt. No basalt of the present collection can be termed trachybasalt using the definition of Irvine & Baragar (1971), but one of the alkali olivine basalts has $Na_2O/K_2O < 2$ so this rock belongs to the potassic series.

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* The norms are given as molecular norms (Barth, 1962) calculated with the Fe_2O_3/FeO ratio fixed at 0.15 and on a volatile-free basis, where CO_2 is not combined with CaO to form calcite. These modifications are found to give the best approximation to the modal mineralogy.

PETROGRAPHY

A general description of the analysed samples follows with further information in Table 1A (in appendix). Alteration of the lavas has been caused by the Sarqâta qâqâ intrusion in the southeast, and in the southwestern part of the island extensive carbonatization is associated with the Ivnâ vent and fault zones (Clarke, 1973; Larsen, 1977). In most sample only the olivine is altered, usually to bowlingite, but it is occasionally fresh in lavas from the Erqua Formation.

The low potassium tholeiites and the transitional basalts

The low potassium olivine tholeiites of the Qeqertalik Member have phenocrysts of either olivine or plagioclase or both. The transitional basalts in the overlying Nûk takisôq Member have phenocrysts of plagioclase, and olivine and clinopyroxene microphenocrysts (less than 1 mm in size). A few rocks are aphyric.

The pseudomorphosed olivine phenocrysts are granular 0.5–5 mm in diameter, but in the olivine rich flows (e.g. No. 473) they may be up to 1 cm long and platy.

The plagioclase phenocrysts occur mostly as glomerocrysts a few millimetres in diameter sometimes together with olivine phenocrysts. However, in the transitional basalts of the lower Nûk takisôq Member the plagioclase phenocrysts are up to 2 cm long and platy. Bytownite and basic labradorite are common phenocrysts in the low potassium tholeiites, while labradorites are found in the transitional basalts. Oscillatory zoning is common. Patchy zoning is often associated with chlorite inclusions.

The colourless clinopyroxene phenocrysts in the transitional basalts are from 3 mm to less than 0.5 mm in diameter. The larger ones usually occur together with plagioclase in glomerocrysts.

Ophitic texture is found in fine to medium grained basaltic lavas of the pahoehoe type, and granular or prismatic pyroxene characterize fine-grained basaltic lavas of the aa type. The groundmass is composed of labradorite, clinopyroxene, altered olivine, ores, interstitial chlorite, and small amounts of sphene and carbonate. The chlorite may have formed from interstitial glass. The amount of olivine in the groundmass varies from less than 1 % to ca. 10 % (modally) and there has been no reaction between olivine and groundmass pyroxene. the clinopyroxene is colourless, faintly brownish or yellowish augite. Ca-poor pyroxene was not found, but it has been reported from other parts of the province (Clarke & Pedersen, 1976; Hald, 1976).

The alkali basalts

1. The plagioclase-rich types

These are either plagioclase (An_{76-66}) and olivine (Fo_{77-75}) microporphyritic or plagioclase (An_{81-75}) and clinopyroxene glomerophyric with sparse olivine and partly resorbed magnetite microphenocrysts.

The groundmass is composed of plagioclase grading from laths of microphenocryst size to tiny anhedral plagioclase, prismatic clinopyroxene, altered granular olivine larger than the other groundmass grains, square and rhomb-shaped oxides, and apatite needles. Interstitial biotite and/or brown hornblende are common. Analcime occurs in No. 361. Alkali feldspar has not been identified with certainty.

Partly digested xenoliths less than 1 mm in diameter occur in these rocks. They are composed of sillimanite or mullite, green to pink and opaque spinels and plagioclase. Further some yet unidentified minerals were observed. Similar rock-fragments occurring in lavas on Disko are considered to be pyrometamorphosed shales (MELSON & SWITZER, 1966; PEDERSEN, 1969).

2. The olivine-clinopyroxene porphyritic types

Two types perhaps originating from two individual flows are included in this division: one rich in olivine phenocrysts and one rich in pyroxene phenocrysts. Some few fragmentary plagioclase crystals are believed to be xenocrysts.

Type 1 (No. 196 and 201) has olivine phenocrysts (Fo_{88-85}) 1–2 mm in diameter, and smaller partly resorbed olivine phenocrysts, which are slightly more Fo-rich ($Fo_{\gtrsim 87}$). The partly-altered olivine occasionally contains brown spinel. Less than $1\,^0/_0$ of faint brownish clinopyroxene phenocrysts occurs. Nodules 1–5 cm across of olivine gabbro, serpentinite and spinel-harzburgite are found in this lava. The groundmass is composed of plagioclase laths, brownish, prismatic clinopyroxene, subhedral ores, and interstitial brown amphibole, biotite, chlorite and analcime (the occurrance of the latter mineral is confirmed by X-ray diffraction in No. 196).

Type 2 (No. 369 and 380) contain clinopyroxene phenocrysts up to 4 mm in size, and a smaller generation grading into the groundmass pyroxenes, olivine phenocrysts of Fo_{82} (mostly altered) up to 3 mm in diameter, and partly resorbed titanomagnetite phenocrysts up to 1 mm in diameter. Partly resorped xenocrysts(?) and a few microphenocrysts of plagioclase occur occasionally.

The clinopyroxenes are of two kinds: a greenish salite, rich in the aegirine molecule, and a colourless chromian diposide (Table 2). The salite is found as partly resorbed crystals or aggregates mantled by a

Table 2. *Microprobe analyses of clinopyroxenes from alkali basalt (No. 369)*

	1	2	3
SiO_2	49.08	51.60	49.99
TiO_2	1.23	0.71	1.08
Al_2O_3	4.42	4.39	5.63
Cr_2O_3	n.d.	0.66	0.33
FeO_{total}	14.23	4.23	5.94
MnO	0.45	0,09	0.11
MgO	7.96	15.85	14.42
CaO	20.66	22.11	21.76
Na_2O	1.97	0.32	0.49
K_2O	0.01	n.d.	n.d.
P_2O_5	0.01	n.d.	0.03
Total	100.08	99.96	99.78
Mole percent of end-members mainly after KUSHIRO (1962)			
$CaAl_2SiO_6$	6.1	5.5	8.7
$CaTiAl_2O_6$	3.5	1.9	3.0
$CaCrAlSiO_6$	–	1.9	1.0
$CaFe^{3+}AlSiO_6$	0.6	–	0.1
$NaFe^{3+}Si_2O_6$	14.5	0.1	3.4
$NaAlSi_2O_6$	–	2.2	–
$Mg_2Si_2O_6$	22.5	43.2	39.6
$Fe_2Si_2O_6$	15.1	6.4	7.4
$Mn_2Si_2O_6$	0.7	0.1	–
$Ca_2Si_2O_6$	36.9	38.7	36.6
Numbers of cations on basis of 4 cations (HAMM & VIETEN, 1971)			
Si	1.863	1.887	1.843
Al^{IV}	0.137	0.113	0.157
Al^{VI}	0.061	0.076	0.087
Cr^{3+}	–	0.019	0.010
Ti	0.035	0.020	0.030
Fe^{3+}	0.153	0.001	0.036
Fe^{2+}	0.301	0.128	0.147
Mn	0.015	0.003	0.003
Mg	0.450	0.864	0.792
Ca	0.840	0.866	0.859
Na	0.145	0.023	0.035
K	0.001		
O	6.000	6.000	6.000
$\frac{Mg}{Mg+Fe^{2+}}$	0.60	0.87	0.84

1) Greenish salite core from microphenocryst.
2) Colourless chromian diopside microphenocryst, central part.
3) Faint brownish diopside, mantle on greenish salite.

The analyses were made on an ARL – SEMQ, at 15KV acceleration potential and a sample current of 25nA. The analyses are corrected after BENCE & ALBEE (1968) with correction factors from ALBEE & RAY (1970).

faint brownish clinopyroxene. The colourless clinopyroxenes are mostly euhedral and appear to be in equilibrium with the groundmass.

The groundmass is rather rich in faint brownish clinopyroxene prisms, plagioclase laths, altered olivine and very small ore grains. Interstitial material is composed of brownish glass with dendritic ores, chlorite and small amounts of carbonate. Analcime occur in some amygdales.

Only a brief description of the chemistry of the pyroxenes is given here as a more detailed account on the mineralogy is planned. The greenish salite (1) are characterized by a low $Mg/Mg+Fe^{2+}$ ratio, low Cr content, and a high amount of the aegirine molecule. If the jadeite molecule is calculated before the aegirine molecule then the result would be 6.1% jadeite and 8% aegirine. This is in contrast to the colourless diopside (2) which have a high $Mg/Mg+Fe^{2+}$ ratio (in agreement with the Fo rich olivine phenocrysts) a high Cr content and a small amount of the aegirine molecule. The faint brownish clinopyroxene margin (3), which probably represents the groundmass clinopyroxene, is rather similar in composition to the colourless clinopyroxene. The content of the Ca-Tschermarks's molecule is high in all the three pyroxene types, but highest in the marginal clinopyroxene. Thus it is not possible to use this molecule as a geobarometer in the present case.

The greenish salite has a rather unusual composition similar to sodian augites (Deer *et al.*, 1963, p. 119, anal. no. 29 and 30). Pyroxenes of this type mantled by a more MgO and Cr rich clinopyroxene have been described from other alkali basalts. Frisch & Schmincke (1969) regarded the reverse zoning as a result of increasing fO_2 in the magma chamber, while Brooks & Rucklidge (1973) interpreted their green salites as xenocrysts. It seems unlikely that the same magma could separate a Cr-poor pyroxene before a Cr-rich one, and therefore a xenocrystal origin for salite is assumed.

The hawaiites

The hawaiites of the upper part of the Nûk takisôq Member are aphyric or sparsely porphyritic with phenocrysts of labradorite and titanaugite 1–2 mm in size. The groundmass has a pilotaxitic texture and is composed of less than 0.2 mm long laths of plagioclase (An_{51-47}), granular to interstitial clinopyroxene, altered olivine, magnetite, apatite and interstitial oligoclase, brown amphibole ($2Vz = 80–88°$, $z \Lambda cC = 21°$), biotite and carbonate. Most groundmass clinopyroxenes are faintly yellowish but some have a purplish colour like the phenocrysts. Late stage parallel segregation veins are richer in brown amphibole, biotite and carbonate. The field evidence suggests that the carbonate is secondary.

PETROCHEMISTRY

Introduction

Chemical analyses and molecular norms (BARTH, 1962) are given in Table 2A (in appendix) together with analytical procedures. The average composition of basalts from each stratigraphical unit is given in Table 3. The altered nature of the rocks is indicated by rather high Fe_2O_3/FeO ratios and high H_2O content. Furthermore the CO_2 content is high in some samples (see note p. 9).

Table 3. *Average volatile-free chemical analyses of the basalts from the different stratigraphical units*

	1	2	3	4	5
No. of analyses	8	4	5	3	4
SiO_2	47.82	48.04	48.62	46.33	46.16
TiO_2	1.97	3.01	2.70	2.88	2.22
Al_2O_3	15.22	14.77	14.89	17.23	14.98
Fe_2O_3T*	13.07	13.61	13.73	13.03	11.92
MnO	0.19	0.21	0.21	0.16	0.19
MgO	7.12	5.24	4.91	5.83	8.91
CaO	11.93	11.11	9.91	9.11	11.33
Na_2O	2.31	2.77	3.37	3.36	2.70
K_2O	0.16	0.78	1.13	1.46	0.92
P_2O_5	0.24	0.46	0.52	0.60	0.69
Trace elements in ppm					
Co	41	39	35	37	39
Cu	211	225	44	39	100
Cr	271	103	106	64	450
Ni	116	67	26	55	197
Zn	63	78	72	62	67
Zr	104	226	206	232	226
Nb	8	37	42	64	89
Y	27	36	34	30	28
Sr	233	354	428	693	992
Rb	1**	10	25	34	22
Ba	80	489	1097	1109	2008

* Fe_2O_3T: Total iron as Fe_2O_3.

**) Not detected values are assumed to equal 0.5 ppm.

Averages of:

1) Low potassium olivine tholeiites, Qeqertalik Member.
2) Transitional basalts, lower part of Nûk takisôq Member.
3) Transitional basalts and hawaiites, upper part of Nûk takisôq Member.
4) Plagioclase rich alkali basalts, Erqua Formation.
5) Olivine-clinopyroxene porphyritic alkali basalts, Erqua Formation.

The chemical variation in the basalts from the different members is expressed as a function of $MgO+CaO-Na_2O-K_2O$ in Fig. 4a, b. This index has been chosen, because it is not affected by iron oxide fractionation, and because it is not entirely dependent upon the alkalies, which show no systematic variation in the low potassium olivine tholeiites. The index gives a fair separation of rocks interrelated by subtraction or addition of MgO and CaO rich phases occurring as phenocrysts in these rocks. The covariations of elements like $TiO_2-P_2O_5$, Ba−Rb and Nb−Zr are seen in Figs. 5–7. These graphs together with Fig. 4a and b indicate that basalts from each member tend to have common chemical features best displayed by TiO_2, $Fe_2O_{3\,total}$ Nb, Cu, Y, Sr, Ba and Rb and make up their own chemical trend. With decreasing $MgO+CaO-Na_2O-K_2O$ index the transitional basalts either become enriched in normative hypersthene or become nepheline normative (Fig. 8) and thus form a *transitional tholeiitic lineage* and a *transitional alkalic lineage.* The low potassium olivine tholeiites form an independent group for most elements. This group can possibly be split into a trend towards Hy enrichment and a trend towards Hy depletion (Fig. 8). A chemical distinction between the two types of alkali basalts is also seen from the variation diagrams.

The chemical variation

The low potassium olivine tholeiites are low in K_2O, Rb, Ba and Nb. These elements show no systematic enrichment with decreasing index in Fig. 4 a and b in contrast to $Fe_2O_{3\,total}$, TiO_2, P_2O_5, Zr and Y. CaO, MgO, Cr and Ni decrease and the same tendency is seen for SiO_2 and Al_2O_3. Although these basalts tend to form one coherent group some have individual chemical properties: No. 72 is enriched in incompatible elements similar to the transitional tholeiitic basalts. No. 101 has high CaO content, consistent with a high content of groundmass clinopyroxene. No. 473 is off the trend for $Fe_2O_{3\,total}$ and TiO_2 (Fig. 4a). Although this rock is rich in MgO, it is not correspondingly low in the incompatible elements.

The transitional and alkaline basalts are enriched in incompatible elements relative to the olivine tholeiites, but they are lower in Fe_2O_3 total and TiO_2, and these elements decrease below an index of 10.

In the two transitional basalt lineages many elements behave in a similar way, but Na_2O, Ba and Rb are most concentrated in the transitional alkali lineage, while TiO_2, Cu, Ni, Zr and Y are higher in the transitional tholeiitic lineage. With decreasing index Cu becomes more concentrated in this lineage in contrast to the depletion trend in the transitional alkalic lineage.

Lines have been drawn between the plagioclase rich alkali basalts

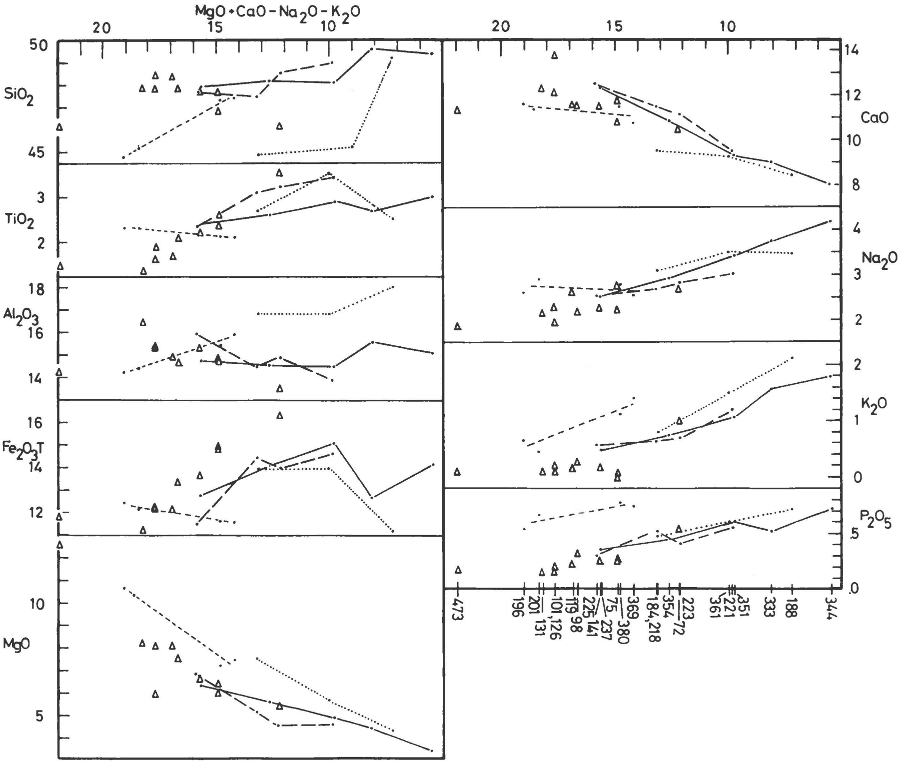

Fig. 4a. Text pag. 17.

and between the olivine-clinopyroxene porphyritic alkali basalts, although the amount of data from these rocks are limited. The former mentioned type is enriched in Al_2O_3, and relative to the transitional lineages these rocks are enriched in Sr, Rb and Nb, but not Ba. The olivine-clinopyroxene porphyritic alkali basaits are characterized by a combination of high Mg, Cr and Ni contents together with high concentrations in incompatible elements especially Ba and Nb. The enrichment "trend" in Sr is different from that found in all the other lineages. The smaller increase in Zr and decrease in Y (with decreasing index) is similar to that found in the plagioclase rich alkali basalts.

Comparative basalt chemistry

The low potassium olivine tholeiites of the Qeqertalik Member show chemical similarities both to the Fe-Ti rich basalts associated with hot spots (BROOKS & JAKOBSSON, 1974) and to the depleted ocean ridge basalts (MELSON & THOMPSON, 1971) (Table 4). Thus in the Qeqertalik basalts $Fe_2O_{3\ total}$, TiO_2 and P_2O_5 show a variation from the first type

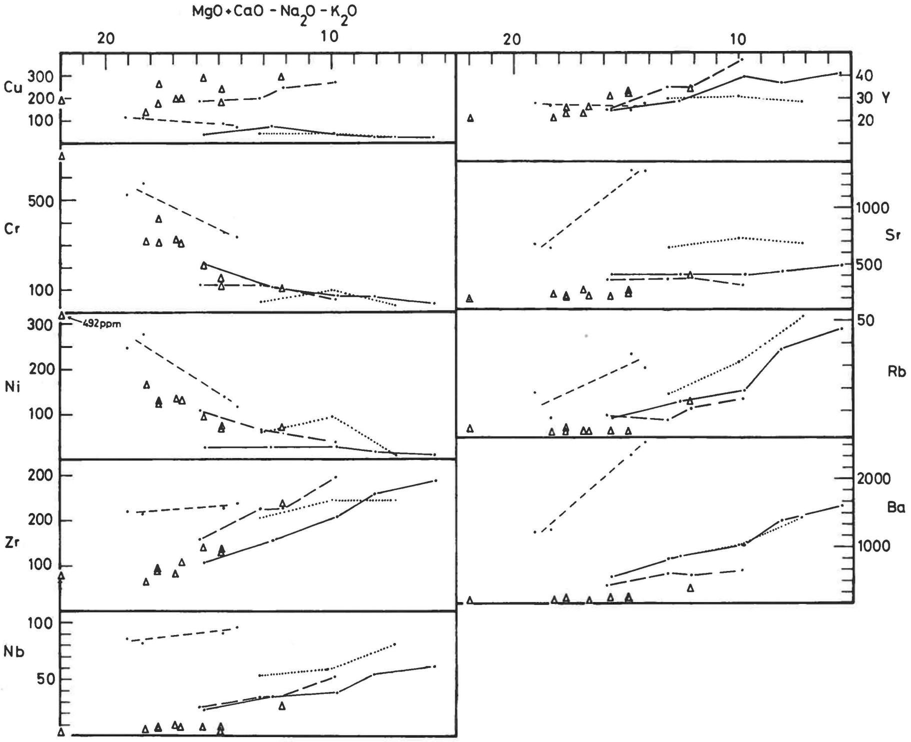

Fig. 4. a and b. The chemical variation against a $MgO+CaO+Na_2O+K_2O$ index. Basalts from Qeqertalik Member (mostly low potassium olivine tholeiites): △. Basalts from the lower part of Nûk takisôq Member (the transitional tholeiitic lineagr): — —. Basalts from the upper part of Nûk takisôq Member (the transitional alkalic lineage): ———. Basalts from Erqua Formation. The plagioclase rich alkali basalts: .... and the olivine-clinopyroxene porphyritic alkali basalts: - - - - -. Analyses are given as dots.

to the other. Ba is somewhat high, but approaches the concentration of the ocean ridge basalts in some samples. Cu is relativly high as found in other parts of the North Atlantic province (Clarke, 1970; Wager & Mitchell, 1951; Bollingberg *et al.*, 1975). Sr is distinctively higher than the range given by Melson & Thompson (1971). The same is probably the case for the $^{87}Sr/^{86}Sr$ initial ratios as indicated by the average of 0.7041–0.7047 for some basic rocks from Ubekendt Ejland (Beckinsale *et al.*, 1974). Ocean ridge basalts have low $^{87}Sr/^{86}Sr$ initial ratios of 0.7027 (Hart, 1970). However, the K_2O content is low and the K/Rb ratio varies from low values similar to Fe-Ti rich basalts to high values often found in the depleted ocean ridge tholeiites (Kay *et al.*, 1970). A somewhat similar variation is found in basalts from Iceland (Sigvaldason, 1974; Sigvaldason *et al.*, 1974) so both types can be produced in hot spot areas. The close chemical similarity between the low potassium olivine tholeiites and the tholeiites from Kohala, Hawaii is seen in Table 4.

The average composition of the lower Nûk takisôq basalts is intermediate between that for tholeiites and alkali basalts from oceanic islands (see Manson 1967). The average for upper Nûk takisôq basalts is closer to the average for alkali basalts. The transitional basalts of Ubekendt Ejland are higher in alkalies than the basalts from the tholeiitic volcanic zones from Iceland, which plot below the division line of Macdonald & Katsura (1964) in the alkali-silica diagram (Jakobsson, 1972; Sigvaldason and co-workers, pers. com.). The transitional basalts can be compared to those from the Aden series and central Afar depression (Gass, 1970), and the transitional olivine tholeiites from Snaefellsnes, Iceland (Sigurdsson, 1970).

The olivine-clinopyroxene porphyritic alkalic basalts are similar in chemistry to the average Hawaiian alkali basalts described by Macdonald & Katsura (1964) (Table 4).

Table 4. *Comparison of volatile-free analyses*

	1	2	3	4	5	6
No. of analyses	8	25	33	11	4	28
SiO_2	47.82	48.79	49.43	48.46	46.16	46.33
TiO_2	1.97	1.80	1.40	2.09	2.22	3.00
Al_2O_3	15.22	13.60	15.88	15.45	14.98	14.60
Fe_2O_3T	13.07	15.19	10.24	12.90	11.92	13.35
MnO	0.19	0.21	0.16	0.17	0.19	0.14
MgO	7.12	6.56	8.57	8.06	8.91	8.17
CaO	11.93	11.13	11.19	10.65	11.33	10.30
Na_2O	2.31	2.29	2.72	1.87	2.70	2.91
K_2O	0.16	0.19	0.26	0.14	0.92	0.84
P_2O_5	0.24	0.24	0.15	0.22	0.69	0.37

ppm	Cu	Cr	Ni	Zr	Y	Sr	Ba
1	211	271	116	104	27	233	80
3	87±26	296±80	123±56	100±42	43±12	123±46	12±8

1) Olivine tholeiites ($K_2O < 0.30$ per cent), Qeqertalik Member.

2) Olivine tholeiites ($K_2O < 0.30$ per cent), Scoresby Sund, East Greenland (Fawcett *et al.*, 1973).

3) Dredged basalts, Mid-Atlantic Ridge (Melson & Thompson, 1971). The standard deviation is given for the trace elements.

4) Tholeiites, Kohala volcano, Hawaii (Macdonald & Katsura, 1964 Table 3 except analyses no. 3 and 13).

5) Olivine-clinopyroxene porphyritic alkali basalts, Erqua Formation.

6) Alkalic basalts, Hawaii (Macdonald & Katsura, 1964).

DISCUSSION

Model calculations

Fractional crystallization within each basalt member is examined by model calculations, where the amount of subtracted solid material is estimated from the concentration factor between the end members of each lineage or group (Table 5). From the work of WATKINS *et al.* (1970) HART *et al.* (1971) and RICHTER & MOORE (1966) it is known that elements like K and Rb may have an uneven distribution within one lava flow, possibly as a result of migration of the last liquid or separation of a volatile phase. Therefore the preferred concentration factor should agree with most of the incompatible elements. Mass balance calculations, recast to reasonable normative components of low or high pressures, have been used to predict the mineral assemblage removed.

These calculations are based on the assumption, that the Fo content in the fractionated olivine is intermediate between that expected in the parental magma and in the residual magma. As the olivine is mostly altered, the Fo content is estimated on basis of the equation of ROEDER & EMSLIE (1970). This is approximate since the Fe_2O_3/FeO ratio has been fixed at 0.15. MYSEN & BOETTCHER (1975) have demonstrated that the Fo content in olivine is dependent on temperature, pressure, P_{H_2O} and f_{O_2}. However with the exception of the f_{O_2}, these effects seem to be small and have been ignored. For simplicity the Mg/Fe^{2+} ratio is assumed equal in olivine and pyroxene. The results of the calculations are given in Table 5.

The calculated crystal cumulates have approximately 50 percent of plagioclase except for the low aluminous Erqua basalts, which will be discussed below. The lineages which go towards the alkaline field, the transitional alkalic lineage and the one branch of low potassium tholeiites, should furthermore fractionate orthopyroxene, clinopyroxene and olivine but the tholeiitic lineages should only fractionate olivine and diopside. The same relation could qualitatively have been obtained from the Ol–Di–Hy/Ne plot (Fig. 8).

It should be expected, that fractional crystallization of plagioclase, olivine, clinopyroxene and oxides would tend to remove elements like Ni, Cr and to a smaller degree Sr and increase the amount of the elements K, Ba, Rb, Cu, Zr and Nb.

The trace elements may be removed by Rayleigh fractionation, by equilibrium crystallization or by a combination of these two processes. The equations for these two models are those given by GAST (1968, p. 1060, eq. 1) and ZIELINSKI (1975, p. 722, eq. 3), and they are used to predict the trace element pattern for Sr, Ni and Cr. The distribution

Table 5. *Calculated fractionates between end-members of the same lineage*

	1	2	3	4	5	
SiO_2	48.02	49.28	46.46	47.33	42.96	
TiO_2	–	–	1.29	2.13	2.49	
Al_2O_3	18.41	18.76	17.74	14.60	13.16	
Fe_2O_3T	7.12	6.13	8.58	12.22	12.85	
MnO	0.08	0.10	0.05	0.15	0.22	
MgO	10.18	11.28	8.87	7.46	13.16	
CaO	13.94	13.01	14.76	13.98	11.87	
Na_2O	2.07	1.28	2.09	1.90	2.89	
K_2O	0.15	0.15	–	–	–	
P_2O_5	0.03	–	0.07	0.22	0.46	
Molecular norms					a	b
Or	0.9	0.9	–	–	–	–
Ab	18.3	11.4	18.8	17.4	Sp 13.7	10.6
An	36.2	44.4	27.7	32.1	Jd 20.6	
Di+He	22.5	15.4	27.3	30.0	44.5	Cpx 65.1
Ca-Tsch	3.0	–	9.1	–	–	
Ol	17.7	10.8	14.3	4.6	13.3	
Hy	–	17.2	–	10.2	5.2	Opx: 16.1
Mt	1.4	–	1.0	2.2	–	5.5
Il	–	–	1.8	3.0	TiO21.7	1.7
Ap	~0	–	~0	0.5	1.0	1.0
An×100/An+Ab	66	80	60	65	–	–
Fo content in Ol	80	78	75	68	67	84
°/₀ subtracted	47.4	41.7	52.4	72.2	54.5	
Conc. factor	1.90	1.72	22.0	3.60	2.20	
R_{Ni}	67	112	22	18	24	51
E_{Ni}	–	–	–	–	100	123
Obs_{Ni}	73	65	39	13	130	130
R_{Cr}	85,170*	198*	20,35*	3,29*	12**	8**
E_{Cr}	–	–	56,68*	62,97*	151**	141**
Obs_{Cr}	101	149	58	42	347	347
R_{Sr}	204	204	372	400	2670	2670
Obs_{Sr}	246	258	313	473	2730	2730

The fractionate which has to be subtracted from:

1) No. 131 to give the most Hy-rich low potassium olivine tholeiite, No. 75.
2) No. 131 to give the Hy-poor low potassium olivine tholeiite, No. 171.
3) No. 225 to give the most differentiated member of the transitional tholeiitic lineage, No. 221.
4) No. 237 to give the most differentiated member of the transitional alkalic lineage, No. 344.
5) The average of No. 196 and No. 201 to give the average of No. 369 and No. 380. Cpx: $Di+He_{58}$ $Ca\text{-}Tsch_5$ $En+Fs_5$ Jd_{32} Opx: $En+Fs_{95}$ $Mg\text{-}Tsch_5$. Sp: Spinel, Jd: Jadeite (including $KAlSi_2O_6$), Ca-Tsch: Ca-Tschermarks molecule $CaAl_2SiO_6$).

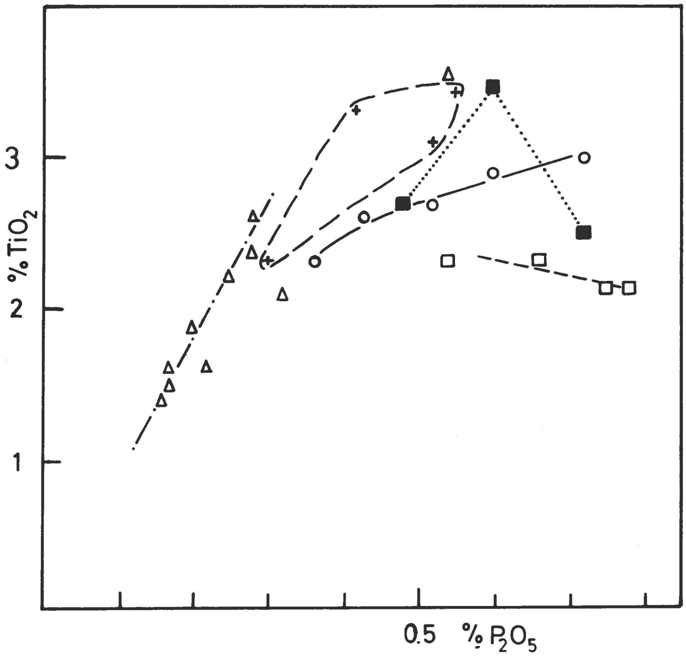

Fig. 5. TiO_2 — P_2O_5 variation diagram. Symbols as in Fig. 3 and tie lines as in Fig. 4.

coefficients used are given with references in Table 3A (in appendix). The uncertainty of distribution coefficients calculated from phenocryst/matrix ratios has been discussed by Albarede & Bottinga (1972) and they concluded that if a model of Rayleigh fractionation is assumed then these distribution coefficients would be too high if they are > 1 and too low if they are < 1. However, the acceptance of either Rayleigh fractionation or equilibrium fractionation is more serious to the predicted trace element concentrations in the differentiates than the uncertainty in the distribution coefficients for Rayleigh fractionation.

The very constant Sr content in all lineages can be explained by the high amount of plagioclase fractionation predicted from the major element chemistry (Table 5). The decrease in Ni and Cr within all the lineages is compatible with Rayleigh fractionation eventually combined with equilibrium fractionation of the approximate amount of olivine, pyroxene and magnetite.

Table 5. Continued

R: Predicted concentration from Rayleigh fractionation.
E: Predicted concentration from equilibrium fractionation.
Obs: Observed concentration in the derived rock.

*) Oxide fractionation is ignored.

**) Low bulk distribution coefficient ($D_{Cr}^{Cpx} = D_{Cr}^{Sp} = D_{Cr}^{Mt} = 7$) is assumed to prohibit the Cr depletion.

The low potassium olivine tholeiites:

The process of fractional crystallization as a general genetic link between the basalts of the Qeqertalik Member cannot be accepted although the calculations give reasonable results. This is due to lack of clear enrichment trends in Na_2O, K_2O and Ba (Rb and Nb are too low to give clues in this respect) with increasing differentiation as seen from Fig. 4. The good correlation between TiO_2 and P_2O_5 (Fig. 5) and between TiO_2 and $Fe_2O_{3\ total}$ indicates that these basalts or their parental magmas are genetically related. Different degree of partial melting from the same source rock more or less depleted in incompatible elements may explain the chemical variation.

If the model of partial melting should work one has to assume that these basalts were in equilibrium with a source rock with an olivine of Fo_{83-75} (the Fe_2O_3/FeO ratio fixed at 0.15), according to the data of Roeder & Emslie (1970). However, mantle olivine has a composition close to Fo_{90} (O'Hara, 1975) and the only way by which these basalts with low $Mg/Mg+Fe^{2+}$ ratios could have been in equilibrium with a mantle olivine is to assume an unlikely high f_{O_2} in the magma (Mysen & Boettcher (1975). For these reasons it is assumed that the low potassium olivine tholeiites were derived from more MgO rich liquids as suggested by Clarke (1970). Only analyses No. 473 could represent a magma, which had been in equilibrium with the mantle.

The transitional tholeiitic lineage:

The phenocryst assemblage in the transitional tholeiitic lineage indicates that fractional crystallization of plagioclase, olivine and clinopyroxene took place. The chemical variation does not seem to preclude such a model, even the incompatible elements are concentrated to the same degree (with a factor 1.8–2.1) between the end members of this lineage. However, the calculations (Table 5) show that the most MgO rich rock in this lineage (No. 225) hardly can be interrelated by fractional crystallization to the other rocks. This conclusion is based on the fact that the An content of the calculated plagioclase is too low (An_{61} compared to An_{83-63} in the phenocrysts) and the Al_2O_3 content of the clinopyroxene is too high in the clinopyroxene (10 cation $^0/_0$) compared to clinopyroxenes in tholeiitic rocks (Deer *et al.*, 1965).

The experimental data of Green & Ringwood (1967) and Thompson (1972, 1974) suggest that clinopyroxenes formed at 8–10 kb dry pressure contain 7–16 cation percent of alumina. These pyroxenes are subcalcic and would force the liquid towards critically undersaturated compositions as opposed to the trend in these rocks. Therefore more than one parental magma should be considered for this lineage.

The transitional alkalic lineage:

Fractional crystallization of plagioclase, clinopyroxene, orthopyroxene, oxides and olivine could explain the chemical variation in the transitional alkaline lineage (Table 5), but the variation in the concentration factors of the incompatible elements cannot be fully explained by this process. Rb is for instance too high relative to K_2O and Ba. This could be explained by late stage liquid migration or volatile transfer as suggested from other studies (Watkins *et al.*, 1970; Hart *et al.*, 1971). The rather low Ni content in this lineage suggests a strong olivine fractionation at an earlier stage. Cu is low and decreases with increasing differentiation. This could be explained by separation of a sulphide phase as in the Skaergaard intrusion (Wager *et al.*, 1957), but there is no evidence for such a process in the present rocks.

The Erqua basalts:

The chemical analyses of the olivine-clinopyroxene porphyritic Erqua basalts probably only represent two flows. One is rich in MgO, Cr and Ni and with a low K_2O/Na_2O ratio, and the other is lower in MgO, Na_2O, Cr and Ni, but higher in K_2O, Rb, Ba and Sr by a factor of 1.5–2.6.

If fractional crystallization has caused this difference between the two flows one would expect that olivine, clinopyroxene and magnetite were dominating phases. Plagioclase fractionation is neither indicated by the phenocryst assemblage nor by the concentration factor for Sr in the less MgO rich lava.

A high pressure origin for these rocks is indicated by the occurrence of ultramafic nodules. The magma of the most MgO rich rock would have been in equilibrium with an olivine of Fo_{88-85}, as indicated by the Fo-rich phenocryst and by comparing the mole percent of MgO and FeO with the experimental data of Roeder & Emslie (1970).

Subtraction calculations (Table 5, no. 5a and b) give reasonable fractionates for assemblages of clinopyroxene olivine, spinel, orthopyroxene, rutile, apatite and magnetite*. However, neither of the two fractionates are attractive, because in no. 5a the Fo_{67} of the olivine is too low compared with Fo_{88-82} in the olivine phenocrysts, and in no. 5b the olivine has disappeared if the $Mg/Mg+Fe^{2+}$ ratio in the silicate minerals is fixed to 0.84 and the FeO excess is oxidized and recalculated into magnetite. In neither case it is possible to explain the high Cr in the residual liquid. Furthermore, the analysed colourless clinopyroxene phenocryst (Table 2) has only a small amount of Na_2O in

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*) An eclogite norm with reasonable mineral components cannot be calculated.

Table 6. *Calculated fractionates based on parental magmas of the Svartenhuk or Baffin Island picrite type* (see Table 4A)

	1	2	3	4
SiO_2	41.41	44.57	44.63	45.31
TiO_2	–	–	0.89	1.16
Al_2O_3	2.87	8.27	8.84	10.25
Fe_2O_3T	11.26	10.66	12.61	12.37
MnO	0.13	0.18	0.18	0.17
MgO	37.53	28.34	22.46	19.32
CaO	6.72	7.71	9.23	9.83
Na_2O	–	0.26	1.07	1.34
K_2O	0.08	0.03	–	0.12
P_2O_5	–	–	0.09	0.12
Molecular norms				
Jd	0.3	–	–	10.0
Ab+Or	–	2.4	9.4	–
An	–	20.3	18.8	–
Di+He	24.7	12.9	20.2	30.0
Ol	69.0	53.7	48.6	24.0
Hy	–	10.7	1.6	0.9
Ap	–	–	0.2	0.3
Il	–	–	1.2	0.8*
Sp	6.0	–	–	–
Gt	–	–	–	33.9
100 × An/An+Ab	–	90	67	–
Fo content in Ol	87	84	78	90
$^0/_0$ subtracted	39.0	60.8	77.8	96.1
Conc. factor	1.64	2.56	4.50	25.6
R_{Ni}	32	11	2	0
E_{Ni}	279	247	240	318
Obs_{Ni}	116	116	107	263
R_{Cr}	77	830	360	~0
E_{Cr}	459	1229	880	309
Obs_{Cr}	271	271	123	556
R_{Sr}	309	310	351	4260
E_{Sr}	306	278	278	2284
Obs_{Sr}	233	233	363	681
R_{Rb}	3	5	9	51
Obs_{Rb}	1	1	8	13
R_{Ba}	82	143	220	1280
Obs_{Ba}	80	80	331	1282

*): TiO_2

The fractionate between a picritic parental magma of:

1) a Svartenhuk type (II) and the average low potassium olivine tholeiites.
2) a Baffin Island type (II) and the average low potassium olivine tholeiites.
3) a Svartenhuk type (II) and the most primitive member of the transitional basalts (No. 225).

contrast to that required in the fractionate. It should be pointed out, however, that fractionation of the the aegirine rich salite, which is regarded as a xenocryst, in fact would be able to explain the decrease in Na_2O, the lower Fe_2O_3/FeO ratio in the evolved rocks than in the more primitive rocks, the relatively low $Mg/Mg+Fe_{total}$ ratio in the calculated fractionate and the relatively slight decrease in Cr in the evolved rocks. But until the genesis of these pyroxenes is clear it is concluded that if the two types of alkali basalt are interrelated it is by different degree of partial melting.

A common parental magma?

The evolution of the basalts on Ubekendt Ejland towards more alkaline types provides an opportunity to discuss the petrogenetic models, which have been proposed by CLARKE (1970), O'NIONS & CLARKE (1972) and CLARKE & PEDERSEN (1976).

According to CLARKE (1970) and CLARKE & UPTON (1971) the volcanics on West Greenland and Baffin Island are very similar in chemistry and morphology and were extruded simultaneously with the early separation of Greenland and Canada. The most K, Rb, Zr and P_2O_5 depleted picrite basalts occurring on Baffin Island were primary melts formed by an extensive partial melting of the mantle at a pressure of 30 kb (CLARKE, 1970). The Svartenhuk picrite basalts, which are enriched in incompatible elements and have higher K_2O/K_2O+Na_2O ratios, were formed from these melts by eclogite fractionation. Equilibrium crystallization of ecolgite or different degrees of partial melting were suggested from the rare earth element data (O'NIONS & CLARKE, 1972). PEDERSEN (in prep., cited from CLARKE & PEDERSEN, 1976) has found picrite basalts of the Baffin Island and Svartenhuk type on Disko, and he favours a process of either different degrees of partial melting or mantle inhomogeneity to explain these differences. Fractional crystallization at 5–8 kb of 1) olivine followed by 2) olivine and plagioclase and 3) olivine, plagioclase, clinopyroxene and orthopyroxene was proposed to explain the formation of the olivine poor basalts (CLARKE, 1970; CLARKE, 1975).

If it is assumed that a picrite basaltic magma of the Svartenhuk or Baffin Island type II (Table 4A) is the parental magma for all the rocks in the province, this can be tested by model calculations (Table 6).

These calculations show that the average Qeqertalik tholeiite can

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Table 6. Continued

4) a Svartenhuk type (II) and the most MgO rich alkali basalts (No. 196 and 201). The garnet (Gt) is composed of $Py_{52\cdot7}$ $Al_{32\cdot3}$ Gr_{15} with a $Mg/Mg+Fe^{2+}$ ratio of 0.62 as in the pyroxenes.

Abrivations: see Table 5.

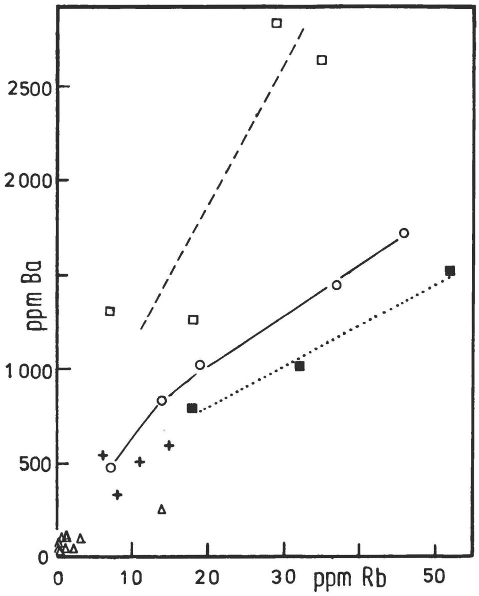

Fig. 6. Ba — Rb variation diagram. Symbgls as in Fig. 3 and tie lines as in Fig. 4.

be formed from an average Svartenhuk picritic magma by removal of olivine (Fo_{88}), clinopyroxene and spinel or from a Baffin Island picritic magma by removal of olivine (Fo_{73}), plagioclase (An_{89}), clinopyroxene and orthopyroxene. Magmas intermediate between these two types would fractionate olivine + plagioclase + clinopyroxene. Clinopyroxene does not occur as phenocrysts in the Qeqertalik tholeiites, but could have separated at some depths, because its stability field expands at higher pressures (O'Hara, 1968). The strong olivine fractionation would deplete the Ni content of the magma completely by Rayleigh fractionation while equilibrium fractionation would leave too much Ni in the residual liquid (Table 6) so that a combination of these two processes can be assumed. Alternatively O'Hara *et al.* (1975) have suggested that the distribution coefficient for Ni in olivine in MgO rich liquids is lower than in basaltic ones. Separation of a Cr rich spinel has to be assumed to explain the low Cr content in the Qeqertalik basalts and this would agree with the occurrence of picotite as phenocrysts in the picritic rocks (Clarke & Pedersen, 1976). The average content of Rb and Sr is too high in the picritic rocks analysed by Clarke (1970) compared with that in the Qeqertalik tholeiites. However, some spread in Rb and Sr is found in the former rocks (Clarke, 1968) and feasible candidates for parental magmas may exist.

O'Hara *et al.* (op. cit.) concluded that fractionation of 50 percent eclogite and 40 percent olivine ($Fo_{87.5}$) from a Baffin Island picrite

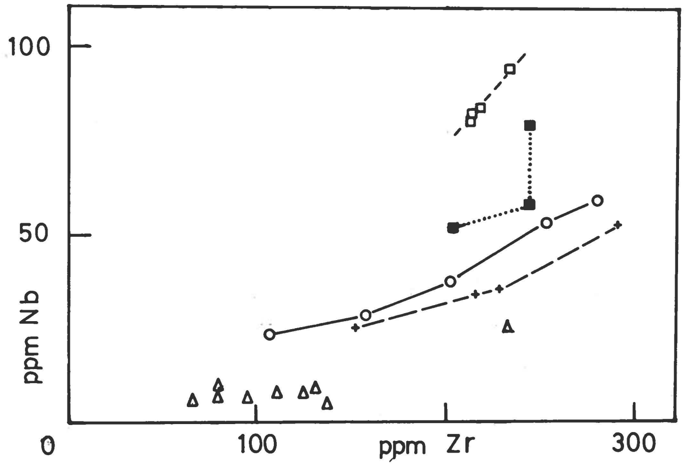

Fig. 7. Nb — Zr variation diagram. Symbols as in Fig. 3 and tie lines as in Fig. 4.

type II would give a basalt with a composition close to the average Hawaiian tholeiite. As seen from the present calculations there is no need for an eclogite fractionation to form the low potassium olivine tholeiite type of magma from the picritic magmas of the province.

The transitional basalts could have been formed by fractionation of olivine (Fo_{78}), plagioclase (An_{67}) and clinopyroxene (picotite removal is inferred from the Cr data). The Mg/Mg+Fe ratio in the normative mafic minerals is reasonable. However, the An content in the normative plagioclase is An_{10} lower than that found in the plagioclase phenocrysts. A better fit could be obtained if the Baffin Island picrite was used instead of the Svartenhuk type, because Na_2O is lower in the former.

A strong enrichment in Ba and Nb relative to the other incompatible elements is found in the alkali basalts (Fig. 6 and 7). Thus Ba (and possible Nb) is concentrated 23–26 times, while Rb and K only 7–4 times compared with the average picrite basalts from Baffin Island and Svartenhuk. Fractional crystallization of eclogite was proposed by O'HARA & YODER (1963, 1967) and O'HARA (1968) as an efficient way to concentrate the incompatible elements. Subtraction calculations for eclogite and olivine are given in Table 6. The forsterite content is assumed to be close to that of the phenocrysts, while the Mg/Fe ratio has to be much lower in the eclogitic minerals in accordance with O'HARA *et al.* (1975, p. 599). However, such a fractionate cannot explain the different concentration factors for Ba, Rb and K mentioned above according to the present knowledge of the distribution coefficients in clinopyroxene, garnet and olivine (GAST, 1968; GRIFFIN & MURTHY, 1969; PHILPOTTS & SCHNETZLER, 1970; HART & BROOKS, 1974; SHIMIZU, 1974). Furthermore it is difficult to explain the relative high Cr and Ni

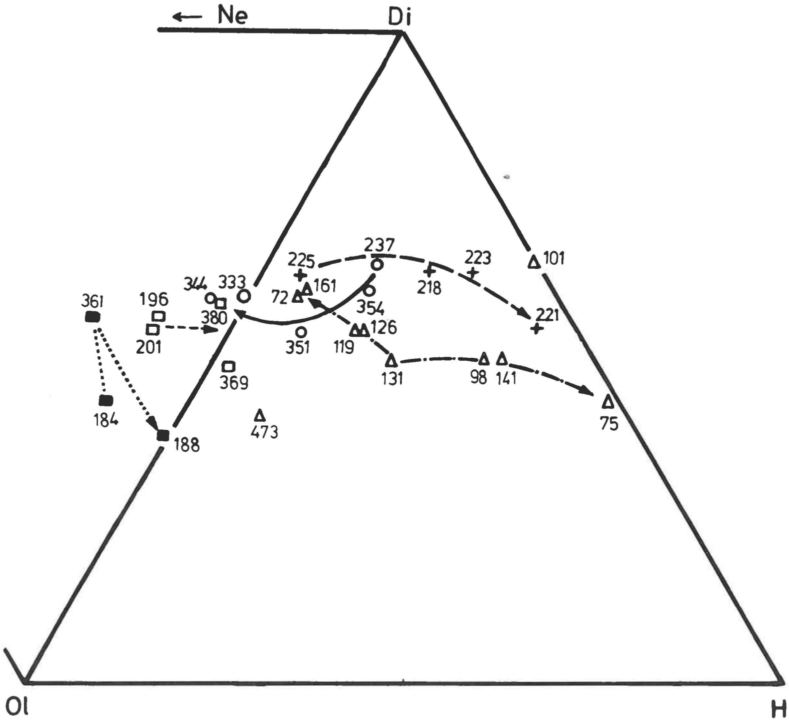

Fig. 8. Ol—Di—Hy/Ne plot (mole percent). Symbols: △: Qeqertalik Member (mostly low potassium olivine tholeiites). +: Lower part of Nûk takisôq Member (the transitional tholeiitic lineage). ○: Upper part of Nûk takisôq Member (the transitional alkaline lineage). ■: Plagioclase rich alkali basalts of Erqua Formation. □: Olivine-clinopyroxene prophyritic alkali basalts from Erqua Formation. Arrows show the direction of increasing differentiation as measured by the $Mg+CaO-Na_2O-K_2O$.

content in the alkali basalts unless equilibrium fractionation is assumed as proposed by O'NIONS & CLARKE (1972). Even such an assumption would deplete the Cr too much (rather low distribution coefficients for Cr has been accepted (see Table 3A).

If fractional crystallization is claimed, it has to be assumed that the parental magma was enriched in Ba and Nb and/or depleted in K relative to the picrites of Baffin Island and Svartenhuk. Picritic rocks with alkaline affinity occur in the province (DRESCHER & KRUEGER, 1928; PEDERSEN, 1973; CLARKE & PEDERSEN, 1976) and these may be potential parental magmas.

Alternatively, fractional crystallization and zone refining (HARRIS, 1957) or low degree of partial melting in an undepleted mantle (GAST, 1968) is proposed for the formation of these rocks.

Evidence for both these two processes may be found in the occurrence of partly resorbed olivine and clinopyroxene crystals in some of the alkali basalts. Furthermore the chemical variation within the olivine and clinopyroxene porphyritic alkali basalts points towards different degrees of partial melting of a spinel lherzolite rather than fractional crystallization.

Both these models have their problems in giving liquids with a Ba/K ratio of 0.28: Complete melting of amphibole and phlogopite would probably not be able to give liquids with a ratio higher than 0.1 as indicated by data from GRIFFIN & MURTHY (1969), PHILPOTTS & SCHNETZLER (1970), PHILPOTTS *et al.* (1972) and MASON & ALLEN (1973). Partial melting of these phases, however, may produce liquids with high Ba/K ratios.

Depth of origin

The magmatic evolution on Ubekendt Ejland from low potassium olivine tholeiites over transitional basalts to alkali basalts resemble that on Hawaii described by MACDONALD & KATSURA (1964). Also, similar basalts occur in both places (Table 3). Fractional crystallization from olivine tholeiitic magmas at increasing depths during the waning phase of volcanic activity has been proposed for the magmatic evolution on Hawaii (GREEN & RINGWOOD, 1967). Although fractional crystallization from one common parental magma is not favoured for the genesis of the basalts on Ubekendt Ejland their change in composition suggests increasing depth of equilibration with time according to the models of GREEN & RINGWOOD (1967) and O'HARA (1968).

The low potassium olivine tholeiites must have equilibrated at pressures from about 8 to less than 5 kb. This is indicated by one trend towards the Ne-normative field and one trend towards the Qz-normative field in Fig. 8.

The basalts of the transitional tholeiitic lineage were equilibrated at low pressures possibly less than 5 kb, where only the olivine gabbro thermal divide exists. This is seen from the trend towards normative hypersthene enrichment in Fig. 8. However, the most MgO rich basalts in this lineage may represent residual liquids formed at pressures close to 8 kb.

Because the transitional alkaline lineage crosses the olivine gabbro thermal divide at least the Ne-normative hawaiites may have formed at pressures above 8 kb. The olivine-clinopyroxene porphyritic alkali basalts possibly formed at pressures of 8–20 kb either by fractional crystallization and zone refining or by small degree of partial melting.

The plagioclase-rich alkali basalts may have inherited their high Al_2O_3 from more primitive melts perhaps similar in composition to the high aluminous basalts from Hareøen described by HALD (1976). According to GREEN & RINGWOOD (1967) such rocks would be generated at intermediate pressures. However, pressure above 8 kb has to be assumed if the Ne-normative composition of the present rocks has to be explained.

CLARKE (1975) proposed that the MgO poor basalts of Svartenhuk, and off shore dredges in the province, represent liquids trapped in the invariant point of ol+cpx+opx+plag+liquid between the thermal divides of olivine gabbro and hypersthene gabbro at 5–8 kb. However, on Ubekendt Ejland this model cannot be applied because the basalts either differentiated towards Ne-normative or Qz-normative compositions. The rhyolites of the island were possibly low pressure residual liquids from magmas belonging to the latter trend.

CONCLUSIONS

Five basalt types erupted in the following order in the younger lavas on Ubekendt Ejland:

1) Low potassium olivine tholeiites (<0.30 percent K_2O) with a strong iron enrichment trend.
2) A transitional tholeiitec lineage, which plots in the alkaline field of the alkali-silica diagram of MACDONALD & KATSURA (1964), but with a trend towards enrichment in normative hypersthene.
3) A transitional alkalic lineage very similar in chemistry to the transitional tholeiitic lineage, but with a trend towards Ne-normative compositions, and lower in Cu, Ni and Zr, and higher in Ba and Rb.
4) Plagioclase rich alkali basalts which contain pyrometamorphosed shales.
5) Olivine-clinopyroxene porphyritic alkali basalts strongly enriched in incompatible elements, and bearing ultramafic and gabbroic nodules.

Acid volcanism and tectonic movements separate the first three basaltic volcanic episodes from one another.

Similar to the petrogenetic evolution of Hawaii proposed by GREEN & RINGWOOD (1967), it is believed that the basalts were formed at increasing depths as the volcanic activity decreased. This similarity would be even better if it could be shown that the uppermost alkaline basalts on Ubekendt Ejland were much younger than the underlying basalts. The less altered nature of the youngest basalts and the age determinations on the lamprophyric dikes (Parrot & Reynolds, 1975) indicate that this may be so.

The concept of one parental magma for the Svartenhuk basalts and Baffin Island basalts (Clarke, 1970) is not accepted for the basalts on Ubekendt Ejland, although it is agreed that most of these basalts represent residual liquids from more MgO rich magmas. It is believed that besides fractional crystallization different degrees of partial melting perhaps in a more or less depleted mantle, or zone refining were important processes in the magmatic evolution on Ubekendt Ejland.

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References

ALBAREDE, F. & BOTTINGA, Y. 1972. Kinetic disequilibrium in trace element partitioning between phenocrysts and host lava. *Geochim. Cosmochim. Acta 36*, 141–156.

ALBEE, A. L. & RAY, L. 1970. Correction factors for electron probe microanalysis of silicates, oxides, carbonates, phosphates and sulphates. *Analytical chemistry 42* (12), 1408–1414.

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.

BARTH, T. F. W. 1962. *Theoretical petrology*, 2nd ed. J. Wiley & Sons. New York.

BECKINSALE, R. D., THOMPSON, R. N. & DURHAM, J. J. 1974. Petrogenic 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 Sarqâta qâqâ Intrusive Complex, Ubekendt Ejland, West Greenland, *J. Petrol. 15*, 525–538.

BOLLINGBERG, H., BROOKS, C. K. & NOE-NYGAARD, A. 1975. Trace element variations in Faeroese basalts and their possible relationships to ocean floor spreading history. *Bull. Geol. Soc. Denmark 24*, 55–60.

BENCE, A. E. & ALBEE, A. L. 1969. Empirical correction factors for the electron microanalysis of silicates and oxides. *J. Geol. 76*, 382–403.

BOWEN, N. L. 1928: *The evolution of igneous rocks.* Princeton University Press.

BROOKS, C. K. & RUCKLIDGE, J. C. 1973. A Tertiary lamprophyre dyke with high pressure xenoliths and megacrysts from Wiedemanns Fjord, East Greenland. *Contrib. Mineral. and Petrol. 42*, 197–212.

BROOKS, C. K. & JAKOBSSON, S. P. 1974. Petrochemistry of the volcanic rocks of the North Atlantic Ridge system, pp. 139–154 in Kristjansson, L. (ed.), *Geodynamics of Iceland and the North Atlantic Area*, D. Reidel Publishing Company, Dordrecht-Holland.

BURRI, C., PARKER, R. L. & WENK, E. 1967. *Die optische Orientierung der Plagioklase*, Birkhauser Verlag, Basel.

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

— 1970. Tertiary basalts of Baffin Bay: Possible primary magma from the mantle. *Contrib. Mineral. and Petrol. 25*, 203–224.

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

— 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 Island: Field relations and Tectonic setting. *Can. J. Earth Sci. 8*, 248–258.

CLARKE, D. B. & PEDERSEN, A. K. 1976. The Tertiary volcanic province of West Greenland, pp. 364–385 in Escher, A. & Watt, S. (eds.). *Geology of Greenland*, Geol. Surv. of Greenland, Copenhagen.

DALE, I. M. & HENDERSON, P. 1972. The partition of transition elements in phenocryst-bearing basalts and the implications about melt structure. *24. Intern. Geol. Congr. 10*, 105–111.

DEER, W. A., HOWIE, R. A. & ZUSSMAN, J. 1963. *Rock-forming Minerals 2, Chain silicates.* Longmans, Green and Co., Ltd., London.

DENHAM, L. R. 1974. Offshore geology of northern West Greenland. *Rapp. Grønlands Geol. Unders. 63*, 1–24.

DRESCHER, F. K. & KRUEGER, H. K. E. 1928. Der peridotit von Kaersut (Grønland) und Seine Ganggefolge. *Neues Jahrb. Mineral. Abhandl. 57 A*, 569–616.

DREVER, H. I. 1958. Geological results of four expeditions to Ubekendt Ejland, West Greenland. *Arctic 11*, 199–209.

DREVER, H. I. & GAME, P. M. 1948. The geology of Ubekendt Ejland, West Greenland, part I, a preliminary review. *Meddr. Grønland 134* (8), 1–35.

FAWCETT, J. J., BROOKS, C. K. & RUCKLIDGE, J. C. 1973. Chemical petrology of Tertiary flood basalts from the Scoresby Sund area. *Meddr. Grønland 195* (6), 1–54.

FRISCH, T. & SCHMINCKE, H. U. 1969. Petrology of clinopyroxene-amphibole inclusions from Roque Nublo Volcanics, Grand Canaria, Canary Islands. *Bull. Volc. 33*, 1073–1088.

GASS, I. G. 1970. Tectonic and magmatic evolution of the Afro-Arabian dome, pp. 285–300 in Clifford, T. N. & Gass, I. G. (eds.), *African Magnatism and Tectonics*, Oliver & Boyd, Edinburgh.

GAST, P. W. 1968. Trace element fractionation and the origin of tholeiitic and alkaline magma types. *Geochim. Cosmochim. Acta 32*, 1057–1086.

GREEN, D. H. & RINGWOOD, A. E. 1967. The genesis of basaltic magmas. *Contrib. Mineral. and Petrol. 15*, 103–190.

GRIFFIN, W. L. & MURTHY, W. R. 1969. Distribution of K, Rb, Sr and Ba in some minerals relevant to basalt genesis. *Geochim. Cosmochim. Acta 33*, 1389–1414.

HALD, N. 1976. Early Tertiary flood basalts from Hareøen and Western Nûgssuaq. *Bull. Grønlands Geol. Unders.* 120, 36 pp.

HALD, N. & PEDERSEN, A. K. 1975. Lithostratigraphy of the early Tertiary Volcanic rocks of Central West Greenland. *Rapp. Grønlands Geol. Unders. 69*. 17–24.

HAMM, H.-M. & VIETEN, K. 1971. Zur Berechnung der krystallchemischen Formel und des Fe^{3+} Gehaltes von Klinopyroxen aus Elektronenstrahl-Mikroanalysen. *Neues Jahrb. Mineral. Monatsh.* 310–314.

HARRIS, P. G. 1957. Zone refining and the origin of potassic basalts. *Geochim. Cosmochim. Acta 12*, 195–208.

HART, S. R. 1970. Ocean floor basalts. *Yb. Carnegie Inst. 69*, 388–405.

HART, S. R. & BROOKS, C. 1974. Clinopyroxene-matrix partitioning of K, Rb, Cs, Sr and Ba. *Geochim. Cosmochim. Acta 38*, 1799–1806.

HART, S. R., GUNN, B. M. & WATKINS, N. D. 1971. Intralava variation of alkali elements in Icelandic basalt. *Am. J. Sci. 270*, 315–318.

HENDERSON, G. 1973. The geological setting of the West Greenland basin in the Baffin Bay Region. *Geol. Surv. Can. Paper 71–73*, 521–544.

HILLEBRAND, W. F. & LUNDELL, G. E. F. 1953. *Applied inorganic analysis*, 2nd ed. J. Wiley and Sons, New York.

IRVINE, T. N. & BARAGER, W. R. A. 1971. A guide to the chemical classification of the common volcanic rocks. *Can. J. Earth Sci. 8*, 523–548.

IRVING, A. J. 1974. Pyroxene-rich Ultramafic Xenoliths in the Newer Basalts of Victoria, Australia. *Neues Jahrb. Mineral. Abhandl.* 120, 147–167.

JAKOBSSON, S. P. 1972. Chemistry and distribution pattern of recent basiltic rocks in Iceland. *Lithos 5*, 365–386.

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

Kay, R., Hubbard, N. J. & Gast, P. W. 1970. Chemical characteristics and origin of oceanic ridge volcanic rocks. *J. Geophys. Res. 75*, 1585–1613.

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.

Kushiro, I. 1962. Clinopyroxene solid solution part I: The $CaAl_2SiO_6$ component. *Japan. J. Geol. Geography 33*, 213–220.

Larsen, J.G. (1977). Fieldwork on Ubekendt Ejland in the Tertiary Basalt Province of West Greenland, 1971 and 1973. *Rapp. Grønlands Geol. Unders. 79*, 35–44.

Le Pichon, X., Hyndman, R. D. & Pautot, G. 1971. Geophysical study of the opening of the Labrador Sea. *J. Geophys. Res. 76*, 4724–4743.

Macdonald, G. A. 1960. Dissimilarity of continental and oceanic rock types. *J. Petrol. 1*, 172–177.

Macdonald, G. A. & Katsura, T. 1964. Chemical composition of Hawaiian lavas. *J. Petrol. 5*, 82–133.

Manson, V. 1967. Geochemistry of basaltic rocks: Major elements, pp. 215–269 in Hess, H. H. & Poldervaart, A. (eds.), *Basalts, the Poldervaart Treatise on Rocks of Basaltic Composition*, J. Wiley and Sons, New York.

Mason, B. & Allen, R. O. 1973. Minor and trace elements in augite, hornblende, and pyrope megacrysts from Kakanui, New Zealand. *New Zealand J. Geol. and Geophys. 16*, 935–947.

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

Melson, W. G. & Thompson, G. 1971. Petrology of a transform fault zone and adjacent ridge segments. *Phil. Trans. R. Soc. Lond. Ser. A 268*, 423–441.

Munck, S. &. Noe-Nygaard, A. 1957. Age determination of the various stages of the Tertiary volcanism in the West Greenland Basalt Province. *20. Intern. Geol. Congr. 20*, 247–256.

Mysen, B. O. & Boettcher, A. L. 1975. Melting of a hydrous mantle: II. Geochemistry of crystals and liquids formed by anatexis of mantle peridotite at high pressures and temperatures as a function of controlled activities of water, hydrogen, and carbon dioxide. *J. Petrol. 16*, 549–593.

Noe-Nygaard, A. 1942. On the geology and petrography of the West Greenland Basalt Province, part III: The plateaubasalts of Svartenhuk Peninsula. *Meddr. Grønland 137* (3) 1–78.

— 1974. Cenozoic to recent volcanism in and around the North Atlantic Basin, pp. 391–443 in Nairn, A. E. M. & Stehli, F. G. (eds.), *The Ocean Basins and Margins*. New York– London, Plenum Publ. Corp.,

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.

— 1975. Is there an Icelandic mantle plume, Nature, 253, 708–710.

O'hara, M. J., Saunders, M. J. & Mercy, E. L. P. 1975. Garnet-peridotite, primary ultrabasic magma and ecologite; interpretation of upper mantle processes in kimberlite. *Phys. and Chemistry of the Earth 9*, 571–604.

O'Hara, M. J. & Yoder H. S. Jr. 1963. Partial melting of the mantle. *Yb. Carnegie Inst. 62*, 66–71.

— 1967. Formation and fractionation of basic magmas at high pressures. *Scott. J. Geol 3*, 67–117.

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.

Padfield, T. & Gray, A. 1971. Major element rock analysis by X-ray fluorescence—A simple fusion method. *Bull. Phillips Analytical Equipment FS35.*

Parrot, 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.

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

— 1973. Report on field work along the north coast of Disko, 1971. *Rapp. Grønlands Geol. Unders. 53*, 21–27.

Pelletier, B. R., Ross, D. I., Keen, C. E. & Keen, M. J. 1975. Geology and geophysics of the Baffin Bay. *Geol. Surv. Can 74–30* (2), 247–258.

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

Philpotts, J. A. & Schnetzler, C. C. 1970. Phenocryst-matrix partition coefficients for K, Rb, Sr and Ba with applications to anorthosite and basalt genesis. *Geochim. Cosmochim. Acta 34*, 307–322.

Philpotts, J. A., Schnetzler, C. C. & Thomas, H. H. 1972. Petrogenetic implications of some new geochemical data on eclogitic and ultrabasic inclusions. *Geochim. Cosmichim. Acta 36*, 1131–1166.

Richter, D. H. & Moore, J. G. 1966. Petrology of the Kilauea Iki Lava Lake, Hawaii. *Geol. Surv. Prof. Paper 537-B*, 26 pp.

Roeder, P. L. & Emslie, R. F. 1970. Olivine-liquid equilibrium *Contrib. Mineral. and Petrol. 29*, 275–289.

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

Shimizu, N. 1974. An experimental study of the partitioning of K, Rb, Cs, Sr and Ba between clinopyroxene and liquid at high pressures. *Geochim. Cosmochim. Acta 38*, 1789–1798.

Sigurdsson, H. 1970. The petrology and chemistry of Setberg volcanic region and the intermediate and acid rocks of Iceland. *Unpubl. thesis, Univ. af Durham.*

Sigvaldason, G. E. 1974. Basalts from the centre of the assumed Icelandic mantle plume. *J. Petrol. 15*, 497–524.

Sigvaldason, G. E., Steinthorsson, S., Oskarsson, N. & Imsland, P. 1974. Compositional variation in recent Icelandic tholeiites and the Kverkfjöll hot spot. *Nature 251*, 579–582.

Sun, C.–O., Williams, R. J. & Sun, S.–S. 1974. Distribution coefficients of Eu and Sr for plagioclase-liquid and clinopyroxene-liquid equilibria in ocean ridge basalts: An experimental study. *Geochim. Cosmochim. Acta 38*, 1415–1434.

Thompson, R. N. 1972. Melting behaviour of two Snake River lavas at pressure up to 35 kb. *Yb. Carnegie Inst. 71*, 406–410.

— 1974. Primary basalt and magma genesis in Skye, North-West Scotland. *Contrib. Mineral and Petrol. 45*, 317–341.

— 1975. Palaeocene ignimbrite from Ubekendt Ejland, West Greenland. *Lithos 8*, 9–14.

Tröger, W. E. 1959. *Optische Bestimmung der gesteinsbildenden Minerale, Teil 1.* Bestimmungstabellen. Schweizerbartsche Verlagbuchhandlung, Stuttgart.

Wager, L. R. & Mitchell, R. L. 1951. The distribution of trace elements during strong fractionation of basic magma—a further study of the Skaergaard intrusion, East Greenland. *Geochim. Cosmochim. Acta 1*, 129–208.

WAGER, L. R., VINCENT, E. A. & SMALES, A. A. 1957. Sulphides in the Skaergaard intrusion, East Greenland. *Econ .Geol. 52*, 855–903.

WATKINS, N. D., GUNN, B. M. & COY-YLL, I. L. 1970. Major and trace element variation during the initial cooling of an Icelandic lava. *Am. J. Sci. 268*, 24–49.

WEAVER, S. D., SCEAL, J. S. C. & GIBSON, I. L. 1972. Trace-element data relevant to the origin of trachytic and pantelleritic lavas in East African Rift System. *Contrib. Mineral and Petrol. 36*, 181–191.

YODER, H. S. & TILLEY, C. E. 1962. Origin of basalt magmas: An experimental study of natural and synthetic rock systems. *J. Petrol. 3*, 342–532.

ZIELINSKI, R. A. 1975. Trace element evaluation of a suite of rocks from Reunion Island, Indian Ocean. *Geochim. Cosmochim. Acta 39*, 713–734.

APPENDIX

Table 1A. *Sample list and petrographic data*

No.	Rock and lava type		Phenocrysts						Groundmass					
			vol. percent*							vol. percent*				
			Ol	Pl	Px	Fo	An	2Vz Px	An	Ol	Pl	Px	Mt	i.m.
	QEQERTALIK MEMBER													
72.	Transitional basalt,	–	+	10.9	+	al	63	50^{p} $55–50^{g}$	60	6.1	30.8	30.6	5.8	15.7
75.	Olivine tholeiite,	p	–	11.2	–	al	63–61	$56–50^{g}$	59–57	5.6	26.9	33.4	6.2	16.7
98.	Olivine tholeiite,	a	+	+	(+)	al								
101.	Tholeiite,	a	+	1.2	–	al	72–68	$50–49^{g}$	55–53	+	28.2	37.3	4.2	24.7
119.	Olivine tholeiite,	p	–	–	–	al	–	$54–52^{g}$	53–52	4.5	46.5	28.7	2.8	17.6
126.	Olivine tholeiite,	a	+	+	–	al								
131.	Olivine tholeiite,	p	6.3	–	–	al	80–78	$51–47^{g}$	–	7.3	35.4	24.8	1.6	24.4
141.	Olivine tholeiite,	a	–	10.2	–	al	71–67	–	–	1.2	26.4	46.3	9.4	6.6
161.	Olivine tholeiite,	p	–	3.8	–	al	73	$53–52^{g}$	62–59	2.5	36.7	30.7	4.8	21.6
473.	Olivine tholeiite,	p	16.1**	–	–	al	–	54^{g}	57–53	+	36.4	29.5	6.8	11.3
	NÛK TAKISÔQ MEMBER													
218.	Transitional basalt,	a	0.4	4.3	0.2	al	65–62	$49–48^{p}$						
221.	Transitional basalt,	a	0.5	5.5	0.7	al	66–63		54–53					
223.	Transitional basalt,	a	+	+	+	al								
225.	Olivine tholeiite,	p	+	+	–	al	82–79	$52–51^{g}$	69–57	4.4	47.4	21.8	5.5	20.5
237.	Transitional basalt,	a	–	+	+	63			63–59	4.3	39.5	46.7	6.4	3.1
333.	Hawaiite,	–	–	0.8	+	al	59–61	$60–52^{p}$ $58–40^{g}$	51–47					
344.	Hawaiite,	–	–	+	+	al		64^{p}	51–45					
351.	Transitional basalt,	–	–	0.4	+	al	65–61	$54–53^{g}$	58–47	+	40.6	30.6	9.3	19.1
354.	Transitional basalt,	–	–	0.8	+	al		$62–58^{p}$		+	28.8	38.5	10.1	20.6

Table 1A. *Continued*

		Ol	Pl	Px	Fo	An	2Vz Px	An	Ol	Pl	Px	Mt	i.m.
ERQUA FORMATION													
184. Alkali olivine basalt, ...	a	8.6	14.8	+	77–75	76–63							
188. Alkali olivine basalt, ...	a	0.2	4.1	2.2	al	81–77		58					
361. Basanite, ...	–	6.5	1.0	–	al	69–66		64–63	4.6	32.2	32.3	14.6	8.0
196. Basanite, ...	–	5.0	–	0.2	88–85	–	56–49^{p}						
201. Basanitoid, ...	–	8.3	+	+	86–85	–							
369. Alkali olivine basalt, ...	–	3.0	(+)	3.0			57–54^{p} 68^{pc}	57–53	6.0	23.0	27.4	8.3	29.3
380. Alkali olivine basalt, ...	–	1.4	–	2.6	82	–	55–52^{p} 68–76^{pc}						

All samples were collected in the lower massive parts of the lavas. The samples from the coastal cliffs. were taken several meters above high tide and they were free of joints with sea salt. Location on Fig. 2.

Symbols: a: aa lava; p: pahoehoe lava; Ol: olvine; Pl: plagioclase; Px: clinopyroxene, Mt: ores; i.m.: Interstitial material including altered pyroxene and probably also some olivine. Fo: Forsterite content in olivine based on 2V measurements in ordinary light (Trøger, 1959, p. 37). An: Anorthite content in plagioclase based on maximum extinction angle (Trøger, 1959, p. 111) or ⊥ on the a-axe (Burri *et al.*, 1967, Table XI). 2Vz: p: phenocrysts; p^c: greenish pyroxene cores; g: groundmass pyroxene; al: altered olivine. *) number of counts from 1000–3000. **) Including groundmass olivine.

Table 2A. *Chemical analyses*

Sample No.	72	75	98	101	119	126	131	141	161	473	218	221
SiO_2....	44.96	47.08	47.51	47.16	46.99	47.15	46.45	46.74	45.41	44.33	45.62	47.71
TiO_2....	3.45	2.58	2.07	1.82	1.63	1.59	1.33	2.15	2.28	1.42	2.97	3.34
Al_2O_3...	13.20	14.57	14.56	14.98	14.51	15.10	16.01	15.04	14.42	13.69	13.84	13.55
Fe_2O_3...	5.19	4.46	3.98	3.90	4.45	4.53	4.55	4.40	5.81	6.06	4.72	4.12
FeO	9.63	9.26	8.32	7.18	6.63	6.76	5.72	8.06	7.76	4.76	8.21	9.11
MnO ...	0.21	0.22	0.18	0.15	0.17	0.17	0.16	0.18	0.19	0.17	0.24	0.25
MgO ...	5.33	6.32	7.49	5.80	7.85	7.94	7.95	6.49	5.80	12.06	4.82	4.46
CaO	10.18	10.65	11.49	13.41	11.27	11.95	11.93	11.29	11.41	10.87	11.05	9.27
Na_2O ...	2.64	2.19	2.16	1.89	2.56	2.26	2.09	2.22	2.69	1.78	2.59	2.95
K_2O....	0.99	0.09	0.27	0.11	0.17	0.21	0.12	0.18	0.10	0.09	0.61	1.17
P_2O_5 ...	0.53	0.28	0.32	0.19	0.21	0.17	0.16	0.24	0.27	0.16	0.50	0.54
H_2O**..	2.96	2.93	2.03	2.15	3.43	2.80	4.05	3.76	3.46	4.75	5.00	3.60
CO_2	–	0.11	–	1.98	–	–	0.43	–	–	–	–	–
Totals ..	99.27	100.74	100.38	100.72	99.87	100.63	100.95	100.75	99.60	100.14	100.17	100.07
Molecular norms (with Fe_2O_3/FeO corrected to 0.15)												
Or	6.3	0.6	1.6	0.7	1.0	1.3	0.7	1.1	0.6	0.6	3.9	7.4
Ab.....	25.3	20.6	20.0	17.9	24.0	20.9	19.5	20.9	25.6	16.6	25.1	28.2
An.....	22.7	31.1	30.1	33.8	28.8	31.3	35.3	32.1	28.7	30.3	26.2	21.6
Ne	–	–	–	–	–	–	–	–	–	–	–	–
Di	22.1	17.9	21.2	28.1	22.5	22.9	20.2	20.1	23.7	19.8	23.5	18.9
Ol......	12.7	0.6	6.3	0.0	12.2	11.9	11.0	4.9	12.7	23.7	5.6	1.8
Hy.....	2.4	22.8	15.3	14.7	7.1	7.4	9.5	15.5	2.8	5.0	8.2	14.1
Mt.....	2.1	1.9	1.7	1.6	1.5	1.5	1.4	1.7	1.9	1.5	1.9	1.9
Il......	5.1	3.8	3.0	2.7	2.4	2.3	1.9	3.1	3.4	2.1	4.5	4.9
Ap.....	1.2	0.6	0.7	0.4	0.5	0.4	0.3	0.5	0.6	0.3	1.1	1.2
Totals ..	99.9	99.9	99.9	99.9	100.0	99.9	99.9	99.9	100.0	99.9	100.0	100.0
$Mg/Mg+Fe^{2+}$	0.52	0.56	0.62	0.59	0.66	0.65	0.67	0.59	0.54	0.75	0.53	0.51
Trace elements in ppm												
Co	41	43	42	36	40	41	39	40	41	43	33	40
Cu	288	175	195	256	193	173	135	282	230	187	191	260
Cr......	101	115	303	398	315	304	308	209	149	668	118	57
Ni	77	73	130	127	133	120	161	93	65	472	63	38
Zn	69	65	64	59	51	56	54	65	72	54	75	95
Pb	5	n.d.	n.d.	n.d.	2	n.d.	8	5	2	4	n.d.	9
Zr......	231	135	109	94	78	77	64	123	129	75	217	289
Nb.....	25	5	8	7	10	7	6	8	9	4	33	52
Y......	33	32	26	25	22	23	20	30	32	20	34	46
Sr......	379	243	211	207	262	211	220	203	250	179	355	305
Rb.....	14	n.d.	1	n.d.	1	3	n.d.	1	n.d.	2	6	15
Ba.....	249	113	52	75	107	101	33	98	54	44	521	568

* The chemical analyses of major- and trace elements were carried out on XRF by Dr. G. Hornung, major elements is described by Padfield & Gray (1971), and the trace elements were analysed on powder determined by the author after the method described by Hildebrand *et al.* (1953, p. 768) and the modified

** Determined by L.O.I. corrected for the oxidation of the FeO and for CO_2, when this element has been *of lavas from Ubehendt Ejland**

223	225	237	333	344	351	354	184	188	361	196	201	369	380
45.76	45.85	46.28	48.09	47.62	45.75	46.43	43.89	48.39	44.23	42.83	44.30	45.96	44.64
3.06	2.23	2.29	2.58	2.88	2.75	2.52	2.64	2.45	3.41	2.22	2.28	2.06	2.00
14.14	15.31	14.24	15.12	14.55	13.79	14.04	16.48	17.78	16.51	13.59	14.11	15.40	14.56
6.09	4.37	12.33°	3.39	4.95	3.37	3.33	3.70	4.65	5.51	4.13	4.02	3.94	2.62
6.48	5.97		8.01	7.84	9.55	9.15	8.96	5.72	7.42	6.97	7.10	6.54	7.48
0.23	0.15	0.19	0.19	0.24	0.18	0.21	0.19	0.14	0.15	0.20	0.19	0.15	0.19
4.30	6.58	6.13	4.28	3.31	4.67	5.26	7.34	4.25	5.58	10.20	10.14	7.20	6.78
10.62	11.80	11.91	8.75	7.74	8.86	10.48	9.35	8.35	9.14	11.16	11.18	10.40	10.85
2.69	2.44	2.44	3.64	4.03	3.26	2.83	3.04	3.43	3.43	2.50	2.87	2.45	2.58
0.67	0.56	0.46	1.52	1.74	1.00	0.73	0.78	2.07	1.47	0.63	0.43	1.38	1.08
0.40	0.29	0.35	0.51	0.70	0.57	0.41	0.47	0.71	0.59	0.52	0.65	0.73	0.74
4.86	3.87	–	2.85	1.54	2.97	2.71	2.55	2.90	3.41	4.20	3.44	4.45	3.49
–	–	2.60	1.86	3.29	2.16	2.50	–	–	–	–	–	0.15	2.25
99.30	99.44	99.22	100.79	100.43	99.24	100.60	99.39	100.84	100.85	99.15	100.71	100.84	99.26

4.3	3.5	2.9	9.5	11.0	6.4	4.6	4.8	12.6	9.0	3.9	2.6	8.5	6.9
26.3	23.1	23.2	34.1	36.4	31.7	27.1	22.0	31.7	20.8	13.8	17.7	23.0	23.0
26.7	30.8	28.1	21.5	17.5	21.7	25.0	30.1	27.8	26.3	25.1	24.9	28.1	26.8
–	–	–	0.2	1.3	–	–	3.8	0.0	6.7	5.8	5.2	–	1.1
22.3	23.2	25.7	16.6	14.8	17.6	22.1	11.9	8.1	13.5	23.5	22.0	16.7	20.7
3.2	12.0	8.4	11.6	11.3	11.9	8.8	20.9	13.3	15.7	22.0	21.5	16.7	15.4
9.8	1.9	5.8	–	–	3.3	5.8	–	–	–	–	–	0.9	–
1.8	1.4	1.6	1.6	1.8	1.9	1.8	1.8	1.4	1.8	1.5	1.5	1.5	1.5
4.6	3.3	3.4	3.8	4.3	4.1	3.7	3.8	3.5	4.9	3.2	3.2	3.0	3.0
0.9	0.6	0.8	1.1	1.6	1.3	0.9	1.0	1.5	1.3	1.1	1.4	1.6	1.7
99.9	99.9	99.9	100.0	100.0	99.9	99.8	100.1	99.9	100.0	99.8	100.0	100.0	100.1
0.51	0.65	0.60	0.53	0.43	0.50	0.54	0.63	0.56	0.58	0.72	0.72	0.66	0.65

39	37	38	31	27	38	34	41	27	41	40	41	33	35
235	180	43	25	26	39	77	47	24	44	113	114	73	83
104	118	206	75	42	76	113	49	42	98	504	565	327	337
54	103	28	18	13	25	29	58	11	94	238	273	113	134
70	59	62	69	76	71	69	66	62	55	56	56	69	76
4	45	n.d.	10	33	n.d.	7	5	31	2	57	2	4	4
216	150	105	252	278	201	155	202	242	242	212	211	232	216
33	25	23	53	59	37	28	52	79	58	82	80	94	86
35	24	24	36	40	38	28	29	29	30	27	26	27	24
361	350	397	427	473	379	388	639	678	725	645	633	1280	1252
10	8	7	36	44	18	14	18	51	31	17	7	28	33
477	319	455	1401	1659	973	799	779	1498	993	1207	1277	2745	2488

Department of Earth Sciences, Leeds University, England. The proceedure for the determination of the pellets and calibrated aginst U.S.G.S. standards and artificially prepared standards. CO_2 and FeO were Pratt method respectively.
determined. ° Total iron as Fe_2O_3. n.d. = not detected

Table 3A. *Distribution coefficient used in the model calculation*

	Pl	Ol	Cpx	Opx	Sp,Mt	Gt
Sr	2(2,4)	0.01(2)	0.1(2,5,6)	0.02(2)	–	–
Cr	–	1. (1,7a)	7 (3)	4 (7b)	77(7c)	7(8)
Ni	–	10 (3)	2 (3)	1 (1)	10(7d)	–

( ) References: 1) GAST, 1968; 2) PHILPOTTS & SCHNETZLER, 1970; 3) DALE & HENDERSON, 1972; 4) SUN *et al.*, 1974; 5) SCHIMIZU, 1974; 6) HART & BROOKS,1974;
7a) IRVING, 1974, inferred from Ol/Cpx ratios.
7b) – – – – Opx/Cpx – .
7c) – – – – Sp/Cpx – . Probably useless
7d) – – – – Sp/Ol – .
8) O'HARA *et al.*, (1975) inferred from Gt/Cpx ratios.

Table 4A. *Compositions of the assumed parental picritic magmas*

	1	2		1	2
SiO_2	45.3	45.9	Cr	1540	1880
TiO_2	1.20	0.77	Ni	1040	960
Al_2O_3	10.4	11.0	Cu	132	111
Fe_2O_3T	12.4	11.6	Zr	80	53
MnO	0.17	0.18	Y	17	18
MgO	19.0	20.0	Sr	190	189
CaO	9.9	9.4	Rb	2	2
Na_2O	1.4	1.1	Ba	50	56
K_2O	0.13	0.08			
P_2O_5	0.14	0.09			

1) Svartenhuk picrite type II and 2) Baffin Island picrite type II recalculated to 100 procent after CLARKE (1970). Trace elements in ppm.