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Petrology of the late lavas of the Eriksfjord Formation, Gardar province, South Greenland

by

Jørgen Gutzon Larsen

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Øster Voldgade 10, DK-1350 Copenhagen K

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Abstract

The uppermost 740–1300 m of the *c*. 3500 m thick Precambrian Eriksfjord Formation in South Greenland are composed of plagioclase- and olivine-porphyritic basalts and hawaiites of a transitional alkaline type, slightly nepheline-normative trachybasalts, trachyandesites and trachytes and a few flows of phonolite. One ultramafic lava also occurs. Evidence for acid volcanism is restricted to a single small occurrence. The rocks show varying degrees of contact metamorphism and hydrothermal alteration caused by the later Gardar intrusions. Major and trace elements show that fractional crystallization of plagioclase and olivine and minor amounts of clinopyroxene, hypersthene (?) and Fe-Ti oxides possibly governed the differentiation in the basic rocks at elevated pressures. The salic lavas belong to several lineages representing a large range in Na_2O/K_2O ratios. The covariance of the less mobile trace elements Zr, Nb, Y and Nd suggest that they are not derived from magmas represented by the basalts, but they may have been formed by differentiation of another type of basaltic magma.

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Fig. 1. Geological sketch map of the Narssaq peninsula and adjacent areas based on Poulsen (1964), Stewart (1964), Allaart (1967, 1970) and Larsen (1974).

INTRODUCTION

Regional setting and stratigraphy

A sequence of up to 3500 m of Precambrian supracrustal rocks, the Eriksfjord Formation, has been preserved in the Gardar province of South Greenland (fig. 1). Descriptions have been given by Ussing (1912), Wegmann (1938), Poulsen (1964) and Stewart (1964, 1970) and a review is given by Emeleus & Upton (1976). The rocks overlie the deeply eroded basement of the Ketilidian mobile belt which was formed 1800–1750 m.y. ago (van Breemen et al., 1971; Gulson & Krogh, 1971). At least the lower part of the Gardar supracrustal rocks are older than the early WNW–ESE trending dolerite dykes (Walton, 1965) and have ages of more than 1300 m.y. as indicated by the chronology and age determinations of the Igaliko nepheline syenites (Emeleus & Harry, 1970; Blaxland et al., in press). The youngest lavas on Narssaq peninsula are cut by dykes, which are possibly the continuation of the giant gabbro dykes on Tugtutôq (Larsen, 1974). These dykes were emplaced between 1175±9 – 1168±37 m.y. (van Breemen & Upton, 1972; Emeleus & Upton, 1976). There may not have been a great time span between the bottom and the top of the supracrustal rocks because no major unconformities exist which indicate substantial erosion of the lavas or changes in the tectonic pattern.

The lower 2300 m of the formation is composed of uniform continental sandstone, a few conglomerates, alkaline ultramafic and carbonatitic volcanics, basalt lavas and sills (Poulsen, 1964; Stewart, 1964, 1970). Recent descriptions of the basalts are given by Upton et al. (in press). They regard all the basaltic sills as lavas and have recorded a picritic hyaloclastite which belongs to the initial volcanic activity, an old sequence of plagioclase porphyritic olivine-poor basalts and a younger sequence of plagioclase-olivine porphyritic basalts.

The upper 740–1300 m of the formation, the Ilímaussaq Volcanic Member, is almost entirely built up of lavas. Its distribution is shown on fig. 1, and the stratigraphy is summarized in table 1. The lavas are composed of basalts grading into hawaiites, trachybasalts, trachyandesites, trachytes and phonolites. In addition one ultramafic lava flow occurs in a restricted area in the northern part of the peninsula, and a 10 cm thick alkali rhyolite tuff occurs in some sediments in the north-west.

A more detailed account of the stratigraphy is given by Larsen (1974). The frequency of the rock types in the volcanic pile is 56–35 per cent basaltic and hawaiitic lavas, 7–29 per cent of more differentiated basic (trachybasaltic?) lavas, 33–34 per cent trachytic and trachyandesitic lavas and 4–2 per cent sediments and tuffs. (The first figure refers to profiles north and east of the Ilímaussaq intrusion

and the second to profiles in the area south-west of this intrusion.) Within the whole Eriksfjord Formation on Narssaq peninsula it is estimated that basalts and hawaiites make up 70 per cent, more differentiated basic lavas 7 per cent, and trachytes 23 per cent of the lava pile. This frequency distribution is significantly different from the areal distribution of the intrusive rocks, where gabbros and dolerites only make up about 13 per cent (Watt, 1966).

The number of lava flows and the thickness of the different basaltic units generally increase towards the north and east indicating that the eruption sites should be sought in these directions i.e. in the fjord Sermilik and the eastern part of the fjord Tunugdliarfik. In the south-western part of the Narssaq peninsula the basalt sequences overlying the 'star' basalts are strongly reduced in thickness probably as a result of faulting, decreasing lava production or shifting of the eruptive sites or both. At least some of the eruptions of trachyte were located in the western part of the peninsula as indicated by the occurrence of agglomerates and distinct lavas, which do not occur to the east.

The Eriksfjord Formation is cut by E–W to WNW–ESE trending faults, several generations of NE trending dykes and smaller faults and the large intrusions, the Igaliko Complex, the Narssaq Complex and the Ilímaussaq intrusion. The later magmatic activity has probably produced substantial amounts of lava and

Table 1. Stratigraphy on the south-western part of the Narssaq peninsula

Narssaq Fjeld submember 400–210	100– 0 m	Basic lavas Trachytes
	330–160 m	Trachyandesites (rhomb-porphyries)
	30 m	Sediments and tuffs with at least one thin acid layer Phonolites
	150– 65 m	Trachytes and alkali trachytes, trachybasalts Porphyritic trachybasalt
Tunugdliarfik submember 340–155 m	40– 0 m	Alkali? trachytes
	100– 20 m	Basic lavas
	65– 20 m	Trachytes and alkali trachytes
Sermilik submember 680–230 m	50?– 0 m	Conglomerate
	210– 0 m	Basalts relatively low in TiO_2 and K_2O (in the less altered rocks).
	330– 90 m	Basalts and hawaiites enriched in K_2O and TiO_2
	3– 0 m	Ultramafic lava
	5– 0 m	Sediments and tuffs (basaltic)
	210–150 m	Basalts relatively low in K_2O and TiO_2 ('star' basalts)

heated the area so that the metamorphism of the lavas is a result of contact metamorphism, hydrothermal activity and perhaps burial metamorphism.

According to Berthelsen & Noe-Nygaard (1965) the supracrustal rocks were laid down into a graben controlled by the regional WNW–ESE to W–E trending faults and followed by the early Gardar dykes. A geochemical study on these dykes may show whether they could have been feeders to the lavas. A younger graben associated with the NE–SW trending dykes post-dating the lavas was proposed by Stewart (1964).

Classification

Upton (1974) classified the Gardar rocks on the basis of the alkali–silica diagram. This seems to give reasonable results for most of the lavas when compared to their bulk composition and mineralogy. Some of the strongest sericitized basalts, which were analysed to see how sericitization affected the chemical composition, have gained in alkalis and would be termed hawaiites in this diagram. However, in this case P_2O_5 <0.50 per cent, TiO_2 <2.50 per cent and Cr> 50 ppm indicate that the original rock was a basalt rather than a hawaiite. Instead of using names from the sodic rock series, trachybasalt is used for basic rocks with Na_2O/K_2O <2 (Macdonald & Katsura, 1964) when they are fresh or believed to be isochemically altered. The rocks corresponding to benmoreites in the alkali–silica diagram are termed trachyandesites. Actually they are tristanites but a more general term is preferred here (Streckeisen, 1967, p. 185). Alkali trachyte and alkali rhyolite are used for acmite normative trachytes and rhyolites respectively.

PETROGRAPHY

Metamorphic state of the lavas

With increasing distance to the east of the Ilímaussaq intrusion the following metamorphic zones can be distinguished: (1) an andesine-?actinolite-biotite zone 0.2–0.5 km from the intrusion, (2) an albite-oligoclase-epidote-chlorite zone 1–2 km away from the intrusion and (3) a sericite-chlorite zone more than about 2 km away from the intrusion. The zones correspond respectively to low grade hornblende-hornfels facies, albite-epidote-hornfels facies and low grade ?albite-epidote-hornfels facies according to the definitions of Winkler (1967) (see also Miyashiro (1973, p. 288) for the andesine-actinolite assemblage). The recrystallization is incomplete in all the zones, thus labradorite relics may occur in the andesine-?actinolite-biotite zone and both the original plagioclase and pyroxene may have survived in the other two metamorphic zones. More than 1–2 km away

from the intrusion the massive parts of the flows may be fresh except for altered olivine, while the porous lava tops and the thin flows usually have completely sericitized plagioclase probably due to hydrothermal activity. (In the analysed rocks the degree of sericitization ranges from a few per cent to 50 per cent.) This alteration pattern is different from the spilitization in the top zones of the Keweenawan lavas ascribed to burial metamorphism (Smith, 1974). A single occurrence of prehnite and pumpellyite on Ilímaussaq clearly indicates low pressure metamorphism. Therefore the mineral assemblages and their distribution indicate that contact metamorphism combined with hydrothermal activity (see later) dominated in the alteration of the lavas.

All the salic lavas to the west of the Ilímaussaq intrusion occur in the albite-oligoclase-epidote-chlorite zone of the basaltic rocks. The degree of recrystallization in the salic rocks is difficult to outline because the original minerals tend to be stable in the metamorphic aureole (e.g. alkali feldspar, biotite and amphibole). All the feldspars are low temperature modifications.

The original textures are usually well preserved except in rocks very close to the contacts of the intrusions. Fenitization is widespread on Kvanefjeld (Sørensen *et al.,* 1969) but has not been recorded outside this area.

Petrography of the rock types

The *basalts and hawaiites* have mostly less than 16 vol. per cent plagioclase phenocrysts (An$_{72-59}$) and up to 9 per cent of altered olivine phenocrysts. A few lavas contain up to 50 per cent of plagioclase phenocrysts up to 5 cm long. Glomerocrysts of plagioclase and plagioclase-olivine occur in the less evolved basalts and range from a few millimetres to 1 cm in length. Small scale oscillatory zoning is common, but some of the larger phenocrysts may have cores with An$_{59}$ surrounded by oscillatory zones with An$_{58-66}$ and an outer rim of An$_{69}$. Large, box-shaped phenocrysts up to 10 cm in length occur but are very scarce. The olivine phenocrysts are generally less than 1 mm in diameter.

The groundmass is mostly doleritic but there is a gradation into very fine grained varieties with a pilotaxitic texture. It is composed of plagioclase (An$_{69-48}$), altered olivine, clinopyroxene, partly altered titanomagnetite, apatite and interstitial chloritic material. The clinopyroxene is faint purple to colourless with a composition typical for alkali basalts (Ca$_{43.3}$Mg$_{36.4}$Fe$_{20.3}$) with 2.5 per cent TiO$_2$, 4.0 per cent Al$_2$O$_3$ and 0.6 per cent Na$_2$O.

The *trachybasalts* may contain phenocrysts of plagioclase up to 22 per cent, altered olivine and occasionally magnetite, ilmenite and apatite. The plagioclase is up to 3 cm long, but much larger megacrysts may occur. Only scattered plagioclase phenocrysts occur in the two analysed rocks. One of these (117211) is relatively fresh and looks like the basalts and hawaiites except that the groundmass labradorite has a thick rim of An$_{20}$. The other sample (117258) is metamorphosed

and has a groundmass composed of oligoclase, light green amphibole, biotite, chlorite, apatite, garnet, titanite, opaque minerals and alkali feldspar.

The *trachyandesites* are mostly rhomb-porphyries which grade into the trachytes. They contain up to 17 vol. per cent of rhomb-shaped oligoclase possibly originally anorthoclase (0.5–1.0 cm long) and in a few lavas tabular plagioclase phenocrysts. Also phenocrysts (3–0.2 mm in size) of altered olivine, Fe-Ti oxides, apatite, and perhaps pseudomorphed pyroxene occur. The plagioclase phenocrysts are recrystallized in equilibrium with epidote. The rhomb-shaped feldspar phenocrysts have an antiperthitic core with albite twinning and a potassic feldspar rim.

The groundmass is composed of densely twinned anhedral to subhedral oligoclase-albite, pseudomorphed olivine, opaque minerals and green biotite?, epidote and titanite.

The *trachytes* have very scattered phenocrysts of alkali feldspar (up to 1 cm long and platy) and few microphenocrysts of Fe-Ti oxides, apatite and altered olivine. The feldspar phenocrysts are antiperthites or mesoperthites. The groundmass is very fine grained to aphanitic and has trachytic or felty texture with densely twinned albite, potassium feldspar, green or brown micas, clinopyroxene, and amphibole.

The *alkali trachytes* are very similar to the trachytes but have groundmass aegirine-augite and less potassium feldspar.

The *phonolites* have less than 1 per cent of fresh nepheline phenocrysts up to 2 mm in diameter and up to 5 mm long, tabular antiperthitic feldspar, microphenocrysts of nepheline, aegirine-augite and apatite. The groundmass has a weakly developed trachytic texture and is composed of tabular alkali feldspar with thin albite twinning, interstitial aegirine-augite and opaque-pigmented areas after decomposed ?olivine. Secondary minerals are brownish micaceous aggregates, analcime and cancrinite after nepheline, and green mica, epidote, garnet and titanite after Mg-Fe silicates and Fe-Ti oxides.

The *alkali rhyolite* (117178) is composed of quartz feldspar intergrowth both in the felsitic groundmass and in spherulites. Dark minerals occur in central parts of the spherulites and in the patchy areas. They are composed of calciferous amphibole, alkali amphibole, epidote, yellov brown mica and zircon.

The *ultramafic lava* (114753) has platy olivine microphenocrysts up to 1 mm long, pseudomorphed by chlorite. The groundmass is composed of clinopyroxene, opaque minerals and chlorite. No fresh or altered feldspar was found. Less than 1 mm thick horizontal segregation(?) veins with carbonate, yellowish garnet and clinopyroxene occur.

Table 2. Representative chemical analyses of the late Gardar lavas

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
SiO2	46.7	46.7	43.7	46.6	46.7	47.1	45.5	46.6	47.9	58.0	56.2	55.4	56.2	58.5	77.38	35.0
TiO2	2.14	2.35	3.46	3.42	3.37	2.88	2.61	1.96	3.33	0.90	0.56	1.75	1.01	0.78	0.36	3.75
Al2O3	16.36	17.22	15.35	14.40	15.56	16.36	16.00	16.22	13.97	14.44	17.38	16.43	15.69	16.41	8.28	6.32
Fe2O3	11.39	8.21	14.20	9.98	10.10	12.47	12.43	10.63	8.93	8.09	4.70	6.20	6.64	5.81	2.09	12.43
FeO	2.13	5.13	2.08	5.57	2.73	2.32	2.09	2.33	5.06	2.53	2.03	1.87	2.44	2.89	3.63	5.36
MnO	0.14	0.26	0.14	0.19	0.19	0.20	0.18	0.14	0.25	0.22	0.17	0.14	0.16	0.20	0.09	0.28
MgO	5.55	5.39	5.08	3.67	4.41	3.84	4.65	5.91	2.88	0.74	0.43	1.72	0.55	0.64	0.05	13.78
CaO	7.96	7.94	6.13	7.01	8.18	7.85	8.37	8.01	5.97	2.18	2.39	3.44	2.61	1.79	0.28	17.54
Na2O	3.04	3.44	4.54	3.44	2.75	3.36	3.58	4.22	4.50	6.51	8.16	5.62	4.62	5.78	3.43	0.09
K2O	0.59	0.81	0.99	2.36	1.76	1.39	1.57	0.91	3.31	5.24	4.16	4.85	7.33	5.98	2.59	0.32
P2O5	0.33	0.40	0.63	0.92	0.81	0.56	0.48	0.29	1.48	0.20	0.23	0.62	0.21	0.15	0.06	0.88
l.o.i.	4.63	2.65	2.88	1.90	2.50	2.48	2.71	2.59	1.35	0.59	2.75	0.88	1.69	0.86	0.58	5.30*
	101.0	100.5	99.2	99.5	99.1	100.8	100.2	99.8	98.9	99.6	99.2	98.9	99.2	99.9	98.82	101.0

CIPW norms (with fixed Fe2O3/FeO = 0.15 and recalculated to 100%)

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	A	B
Q	–	–	–	–	–	–	–	–	–	–	–	–	–	–	46.1	–	–
or	3.7	4.9	6.2	14.4	10.8	8.5	9.6	5.6	20.1	31.2	25.4	29.4	44.8	36.0	15.6	–	1.0
ab	27.0	30.0	30.0	30.1	24.1	29.3	24.0	28.3	31.8	40.2	41.2	40.4	28.0	41.5	28.6	–	–
an	30.7	30.1	19.6	17.5	25.8	26.2	23.9	23.5	8.6	–	–	5.5	0.4	1.2	–	17.3	17.2
lc	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	1.6	0.8
ne	–	–	5.7	–	–	–	4.0	4.8	3.8	2.8	14.8	4.6	6.7	4.5	–	0.5	0.4
ac	–	–	–	–	–	–	–	–	–	3.8	2.5	–	–	–	0.7	–	–
di	7.0	6.5	6.8	10.4	9.0	8.5	13.4	13.1	10.0	8.4	9.4	6.7	10.1	6.0	1.2	28.9	43.2
hy	15.9	4.5	–	0.1	13.9	6.8	–	–	–	–	–	–	–	–	4.3	–	–
ol	8.2	15.9	20.4	15.7	5.4	11.1	16.1	8.5	12.7	8.2	3.8	7.2	5.8	7.4	–	31.9	11.9
mt	2.5	2.5	3.0	2.9	2.5	2.7	2.6	3.9	2.6	1.9	1.2	1.4	1.7	1.6	2.7	3.5	6.9
il	4.3	4.6	6.9	6.7	6.6	5.6	5.2	0.7	6.6	1.7	1.1	3.4	2.0	1.5	0.7	7.8	7.7
ap	0.8	1.0	1.6	2.3	2.0	1.4	1.2	–	3.6	0.5	0.6	1.5	0.5	0.4	0.1	2.3	2.2
cs	–	–	–	–	–	–	–	–	–	–	–	–	–	–	–	6.4	–
ns	–	–	–	–	–	–	–	–	–	1.3	0.0	–	–	–	–	–	he 8.6

Trace elements in ppm

Rb	20	12	33	44	36	27	29	17	82	134	200	106	168	174	81	—
Sr	410	—	413	483	394	404	384	456	332	65	116	623	90	106	29	—
Ba	385	360	585	1610	785	710	620	395	1975	268	263	2578	309	336	541	—
Y	20	—	35	30	31	26	23	18	—	96	46	26	53	63	125	—
Ce	n.d.	17	45	84	81	29	22	n.d.	88	200	220	102	255	307	425	—
Nd	16	12	34	58	52	24	20	n.d.	59	96	80	53	91	113	148	—
Zr	135	156	254	220	205	161	143	105	264	1160	941	285	888	664	1454	—
V	—,	210	220	240	220	170	240	230	80	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—
Nb	15	12	22	22	22	30	13	18	—	70	496	97	195	248	188	—
Cr	60	67	40	19	52	33	75	77	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	—
Ni	98	105	71	49	66	54	86	98	9	6	9	7	n.d.	n.d.	n.d.	—

Sermilik Submember
  Lower Unit
  1. 'Star' basalt, 117235, 'fresh'.
  2. 'Star' basalt, 117221, 'fresh'.
  Middle Unit
  3. Hawaiite, 116924, recrystallized.
  4. Trachybasalt, 117211, 'fresh'.
  5. Hawaiite, 117242, partly sericitized.

6. Hawaiite, 117243, strongly sericitized.
  Upper Unit
7. Basalt, 117282, strongly sericitized.
8. Basalt, 117287, partly sericitized.
Tunugdliarfik Submember
  9. Trachybasalt, 117258, recrystallized.
10. Alkali trachyte, 117121.
11. Phonolite, 117111.

Narssaq Fjeld Submember
  12. Trachyandesite, 117160, recrystallized.
  13. Trachyte, 117167.
  14. Trachyte, 117174.
  15. Alkali rhyolite, 117178, Narssaq Fjeld Submember.
  16. Ultramafic lava, 114753, Sermilik Submember.

All analysed samples are located on fig. 2.

n.d. = not detected.
*2.20% CO_2 included in this value.

All analyses were made by the author except no. 15 which was made by the chemical laboratory of GGU. Sodium was analysed by atomic absorption, the other elements by X-ray fluorescence spectrography. The major elements were analysed on glass discs after the method of Norrish & Hutton (1969) and calibrated after the U.S.G.S. standards. The trace elements were analysed on powder pellets and the results were corrected for mass absorption. All chemical analyses (41) and detailed analytical procedures are available from GGU or the author.

The CIPW norm was calculated by J. Thuesen after Kelsey (1965). No oxidation correction was applied to analysis no. 15. Two norms are given for no. 16: (A) with correction of the oxidation state and (B) without correction of the oxidation state. In both cases the normative calcite content was subtracted before recalculation to 100%.

CHEMISTRY

Chemical alteration

The altered nature of the lavas, and especially of the basalts, is seen from their high water (loss of ignition) and Fe_2O_3 contents. In order to correct for the effect of the strong oxidation in the CIPW norm (table 2) the Fe_2O_3/FeO ratio has been fixed at 0.15. This ratio is probably too low for the salic lavas and tends to increase the normative nepheline.

The extent to which the contact metamorphism and hydrothermal alteration have changed the original composition of the rocks has been tested within a lava flow traced towards the Ilímaussaq intrusion from the east (table 3; fig. 2). The main features are: (1) the K/Rb ratio decreases towards the Ilímaussaq intrusion possibly because of Rb metasomatism; (2) no systematic increase in the other alkalis occurs; (3) leaching of Ca was more prominent in the less metamorphosed rocks, which contain strongly sericitized plagioclase or oligoclase and epidote. This is probably due to the stability of amphibole and calcic plagioclase at the higher metamorphic grade closer to the intrusion. Elements like Ti, P, Zr, Nb, and Nd do not show significant variations along the length of the lava flow, and with one exception (117274) the same can be said about Y.

The effect of sericitization is seen in a vertical profile in a lava occurring c. 5 km to the east of the Ilímaussaq intrusion (table 4). The upper part of the lava is entirely sericitized and has lost Ca and gained Na, K, Rb, Ba, and Sr (table 4). Because of these features the lava top is nepheline normative and has low An content, while the bottom, which is 'fresh', is hypersthene normative. The rather high normative hypersthene content, however, is perhaps caused by a slight silicification of the olivines (table 4). Some of this quartz may have been formed by oxidation of the olivine, as it is partly replaced by haematite. The more porous top of the lava has not been silicified and this excludes any greater addition of silica from circulating groundwater which passed through the sandstone below. The alkali enrichment in the sericitized rock is believed to have been caused by hydrothermal alteration because weathering would tend to leach the alkalis (Goldich, 1938). It seems as if the strong sericitization has caused some leaching of Ce, Nd and Nb, but the degree is near that of the standard deviation of the analytical uncertainty. Zr and Y? are unaffected by such a process. From these two studies it can be concluded that Ti, P, Zr, Y, Nb and Nd are rather unaffected by the alteration. The good correlation between P_2O_5 and Ba (see later) suggests that Ba was not strongly affected by the metamorphism in most of the analysed rocks. The same is probably true for Ni, Cr and V, and variations in these elements may be due to settling of the mafic minerals in the lavas (e.g. the influence of olivine settling on the distribution of Ni in a lava can be seen from table 4).
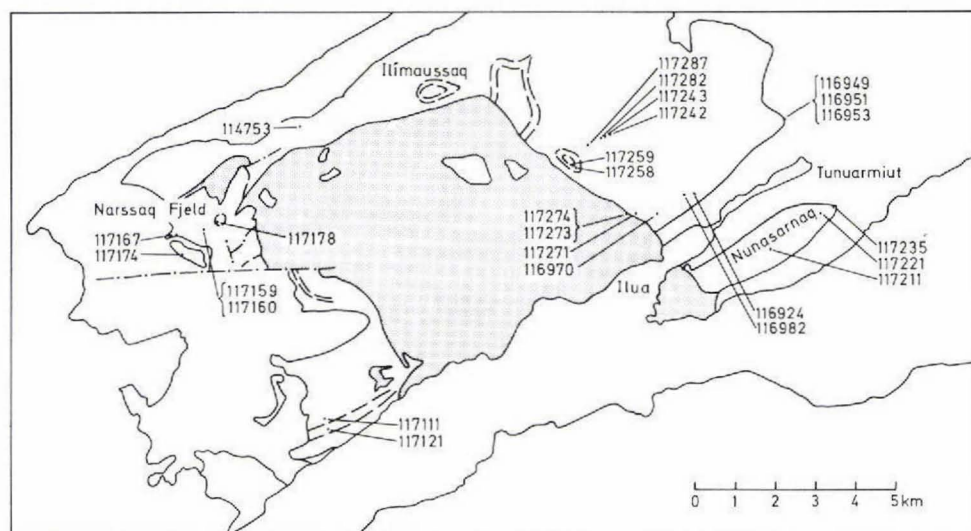
Fig. 2. Position of the analysed samples from the lavas of the Eriksfjord Formation presented in the tables.

Chemical characteristics of the rock types

The basalts and hawaiites. The less altered basic rocks are hypersthene normative, but they all plot in the alkaline field of the silica–alkali diagram (Macdonald & Katsura, 1964). For this reason and because the clinopyroxene is calcium rich like those of alkali basalts, the rocks may be termed transitional alkaline basalts.

The basalts have compositions similar to those of the hypersthene normative Gardar gabbros according to Watt (1966) (table 5). The hawaiites, however, have higher TiO_2 and lower Al_2O_3 contents than usually found in the more alkali enriched nepheline normative Gardar gabbros (Watt, 1966), which they otherwise resemble most (table 5). They show the closest similarity to one of the early WNW-trending dolerite dykes (table 5). The lavas are characterized by rather low MgO/FeO and CaO/Al_2O_3 ratios as are other basic Gardar rocks (Upton, 1971). Furthermore they have high Ni/Cr ratios of 1.0–2.5 compared to the 0.5 reported as normal for basalts (Prinz, 1967). The Ba and Sr concentrations are intermediate between those normally found in hypersthene and nepheline normative rocks according to data collected by Prinz (1967) and Fischer & Puchelt (1972) and this supports their transitional nature. They also seem to be enriched in light REE as indicated by a Nd/Y ratio close to 1.0 (compared to 0.3 in chondrites according to Haskin & Frey (1966), a feature they have in common with recent alkali basalts (Gast, 1968)).

Of the two analysed *trachybasalts* one (117211) has a chemistry similar to the hawaiites (except for the higher K_2O/Na_2O ratio). The other (117258) is comparable to the analysis of a trachydolerite presented by Ussing (1912) in being high in

Table 3. Mineralogical and chemical changes in a hawaiitic lava flow followed towards the Ilímaussaq intrusion

GGU sample no.	117273	117274	117271	116970	116982
Distance from contact (m)	2.5	18	200	500	1400

Mineralogy

Recrystallized minerals:

clinopyroxene		— — — —			
biotite					
actinolite					
hornblende		(—)	(—)		
apatite					
plagioclase	An 36-39			An 20	An 20
epidote					
titanite					
hydrogrossular?			— — — —		
chlorite?			— — — —		
quartz	— — — —				

Relics:

plagioclase			An 65 — * — — * — — * — — * —		
clinopyroxene				— — — —	

Chemistry

Major elements in wt. per cent on volatile-free basis

SiO_2	45.30	45.41	44.51	47.71	45.41
TiO_2	3.51	3.39	3.59	3.53	3.59
Al_2O_3	14.44	15.45	14.48	15.21	15.17
Fe_2O_3	10.72	12.04	12.25	11.10	15.18
FeO	4.91	3.83	5.17	5.13	1.55
MnO	0.22	0.18	0.23	0.25	0.21
MgO	6.75	5.54	6.35	4.56	5.73
CaO	8.95	7.75	8.36	7.01	6.64
Na_2O	3.03	4.06	3.01	3.35	3.00
K_2O	1.43	1.67	1.37	1.36	2.79
P_2O_5	0.75	0.73	0.73	0.79	0.78
l.o.i.	0.92	1.09	1.44	2.09	2.64

Trace elements in ppm on volatile-free basis

Rb	60	102	37	32	52±3
Sr	374	-	347	399	401±3
Ba	613	673	781	633	1664±9-15
Y	32	18	29	30	32±2
Ce	46	26	nd	37	50±10
Nd	30	24	37	31	32±5
Zr	234	222	219	224	224±6
Nb	19	26	23	22	24±3
V	182	192	203	194	154±15
Cr	67	37	74	-	43±3
Ni	82	58	85	55	67±2
K/Rb	239	163	364	422	537

The samples are located east of the Ilímaussaq intrusion (fig. 2).

— — —	small amounts.	l.o.i.	loss on ignition.
(—)	very few grains.	±3	standard deviation in
* — — *	more or less sericitized.		absolute values.

Table 4. Mineralogical and chemical changes in a vertical profile in a lava flow

GGU sample no.	116949	116951	116953
Metres above the base	4	9	20
Mineralogy	vol. per cent		
plagioclase phenocrysts	11±1.5	9±2	16±2
olivine phenocrysts	9±2	7±2	2±1
fresh plagioclase	+	−	−
mostly sericitized plagioclase	−	+	−
totally sericitized plagioclase	−	−	+
quartz in olivine pseudomorphs	+	−	−

Chemistry
Major elements in wt. per cent on volatile-free basis

SiO_2	48.6	47.4	49.3
TiO_2	2.31	2.38	2.17
Al_2O_3	17.07	16.01	18.87
Fe_2O_3	10.98	12.70	11.94
FeO	2.89	2.62	0.78
MnO	0.16	0.22	0.09
MgO	5.57	6.10	4.77
CaO	8.38	7.16	4.77
Na_2O	3.06	4.26	4.81
K_2O	0.61	0.81	2.40
P_2O_5	0.37	0.36	0.30
l.o.i.	2.83	2.96	3.09

Trace elements in ppm on volatile-free basis

Rb	9	15	38±3
Ba	405	371	872±9–15
Sr	398	325	616±3
Y	−	24	23±2
Ce	29	31	nd±9
Nd	19	22	13±5
Zr	150	158	145±6
Nb	18	13	11±3
V	144	216	103±10–20
Cr	75	73	69±3
Ni	113	130	72±2
Normative ne	−	2.5	4.6
" ab	26.2	31.8	32.7
" an	31.4	22.5	21.6

The samples are located 5 km east of the Ilímaussaq intrusion (fig.2)

Table 5. Comparison between basic Gardar lavas and intrusive rocks in wt.
per cent on a volatile-free basis

	1	2	3	4	5	6	7
No. of anal.	5	4	8	2	5	21	1
SiO_2	48.5	48.1	48.05	45.54	47.70	46.72	48.28
TiO_2	2.24	2.27	2.10	2.59	3.61	2.86	3.15
Al_2O_3	17.36*	16.36	16.45	16.87	15.64	16.78	14.52
FeO†	13.16	12.93	13.48	13.46	14.61	13.32	14.69
MnO	0.19	0.19	0.18	0.20	0.22	0.17	0.22
MgO	5.72	6.04	6.26	7.57	4.61	5.83	5.36
CaO	8.30	8.27	8.97	7.73	7.39	8.10	8.25
Na_2O	3.32	3.49	3.15	3.22	3.30	3.97	3.89
K_2O	0.87	1.36	0.99	1.05	2.10	1.37	1.02
P_2O_5	0.35	0.38	0.36	0.76	0.83	0.88	0.61

*Al_2O_3 = 16.3% on an aphyric basis.
†Total iron as FeO.

1. Average of the lowermost, most primitive basalts including one
   analysis presented by Stewart (1964).
2. Average of the uppermost basalts in the Sermilik Submember.
3. Hypersthene normative Gardar gabbros (Watt, 1966).
4. Chill zone of the giant gabbro dykes on Tugtutôq after Upton
   (1971).
5. Hawaiitic lavas including one trachybasalt (GGU 117211).
6. Nepheline normative Gardar gabbros (Watt, 1966).
7. Early WNW-ESE trending dolerite dyke (Watt, 1968, GGU 45501).

P_2O_5, Ba and TiO_2 and low in Al_2O_3 and also resembles some of the syenogabbros and trachydolerites in the province (e.g. Watt, 1966, No. 86; Macdonald, 1969).

The *trachyandesites* and *trachytes* are nepheline normative, and the most undersaturated of the latter can be termed phonolitic trachytes. As only slight chemical alteration is suggested from the study of thin sections, the original normative nepheline contents are probably intermediate between those obtained with the fixed oxidation ratio of 0.15 (2.8–7.4 per cent) and those obtained with the original Fe_2O_3 values (0.1 per cent normative quartz to 4.2 per cent normative nepheline. The rocks are characterized by large variations in the Na_2O/K_2O ratios, with the sodic rocks being oldest.

In general the trachytic lavas show chemical similarity to the syenitic rocks of the Gardar province, but the intrusive rocks within the region where the lavas occur generally show little resemblance to the lavas. As the intrusions appear to belong to the magmatic event around 1170 m.y., this may support the view that the lavas belong to the early magmatic phase around 1300 m.y. ago (Emeleus & Upton, 1976).

Table 6. Comparison of ultramafic rocks

	1	2	3	4
SiO_2	35.0	35.80	37.50	35.51
TiO_2	3.75	5.70	6.2	4.88
Al_2O_3	6.32	6.01	6.2	6.83
Fe_2O_3	12.43	11.51	5.9	9.68
FeO	5.36	7.92	12.0	2.70
MnO	0.28	0.22	0.2	0.22
MgO	13.8	16.34	13.1	11.67
CaO	17.5	11.76	7.2	16.0
Na_2O	0.09	0.80	0.2	1.56
K_2O	0.32	1.34	4.9	3.30
P_2O_5	0.88	0.54	1.0	1.18
H_2O	3.10	1.73*	1.6	4.42
CO_2	2.20	-	2.7	1.47
	101.0	99.67	99.5	99.12

*H_2O^+

1. Ultramafic lava from Ilímaussaq Volcanic Member (GGU 114753).
2. Average Narssaq-Tugtutôq ultramafic intrusive rocks (Upton & Thomas, 1973).
3. Mica-pyroxenite, Qagsiarssuk (Stewart, 1970).
4. Katungite, Katunga, Uganda (Holmes, 1950).

The *ultramafic lava* is characterized by a high content of Fe_2O_3+FeO, CaO and MgO, and a low content of SiO_2, Al_2O_3 and alkalis. Furthermore it has a low Na_2O/K_2O ratio. As seen from table 6 its composition is very similar to the biotite pyroxenites and biotite peridotites from Narssaq peninsula and Tugtutôq described by Ussing (1912) and Upton & Thomas (1973) and the ultramafic extrusives from Qagsiarssuk (Stewart, 1970) except for a much lower alkali content. These rocks have affinities to the katungites of the western part of the East African Rift (Upton & Thomas, 1973). However, katungites contain olivine and melilite phenocrysts, and neither melilite nor certain melilite pseudomorphs have been found in the ultramafic Gardar lava flow.

Chemical variation

Basalts and hawaiites

The basalts and hawaiites make up one lineage as seen from the P_2O_5 variation diagrams (figs 3 and 4). P_2O_5 has been used as a differentiation index because phosphorus is not seriously affected by the metamorphism (tables 3 and 4), and P_2O_5 should not be removed from basaltic liquids when apatite is not a phenocryst

phase (Anderson & Greenland, 1969). The nepheline normative basalts are lower in SiO_2 (fig. 2) and tend to be lower in CaO and higher in Na_2O. These features are possibly due to alteration as the rocks have a trace element pattern very similar to the hypersthene normative basalts.

Clear trends emerge from this diagram in spite of some scattering. With increasing P_2O_5 the K_2O, TiO_2 and Fe_2O_{3total} increase and Al_2O_3, CaO and MgO decrease. Na_2O shows no enrichment trend.

The modified P_2O_5 variation diagram (fig. 4) for the trace elements demonstrate a strong increase in Ba, Ce, and Nd with increasing P_2O_5 content, while Zr, Nb, and Y have moderate enrichment trends. Rb is scattered. Sr and V are rather constant except for some scattering. Ni and Cr tend to decrease.

It is surprising that only Rb and to a smaller degree Ce are scattered in fig. 4, while Ba, which is also a rather mobile element (see earlier), has a fairly high correlation with P_2O_5 ($r = 0.89$). The relatively good correlation between several incompatible elements in the basalts is demonstrated in fig. 7. Many of the trends can be extrapolated either through the zero point or very close to it as required in a model for fractional crystallization (Weaver *et al.,* 1972; Ferrara & Treuil, 1975).

The chemical variation can be explained by removal of plagioclase, olivine, clinopyroxene and small amounts of iron oxide. Only plagioclase and olivine occur as phenocrysts, but fractionation of clinopyroxene is needed to remove Y (Lambert & Holland, 1974), and iron oxide to remove V (Duncan & Taylor, 1968). Eclogite fractionation would give a strong Sr enrichment according to the distribution coefficients given by Gast (1968) and is therefore excluded.

Model calculations. A subtraction calculation between the average of the freshest, most primitive basalts and the average of the most evolved hawaiites with a composition close to the 'fresh' trachybasalt (117211) gives removal of the following normative constituents: 66 per cent plagioclase ($An_{53.5}$), 17 per cent olivine (Fo_{58}) and minor amounts of hypersthene, clinopyroxene and Fe-Ti oxides (table 7). The calculations were performed in a similar way as those by Bowen (1928, p. 75–78) and the subtraction lines are shown on fig. 3. The trace elements are in fair agreement with removal of the calculated fractionate as seen from table 8. In this table the calculated bulk distribution coefficients ($K_{cal.}$) for the subtracted mineral assemblage are compared with the distribution coefficients which can be calculated or estimated from fig. 4 ($K_{obs.}$). Rayleigh and equilibrium fractionation (see the equations in the appendix) give similar results for most elements except for Ni and Cr, which show the best agreement with the Rayleigh fractionation. A higher amount of clinopyroxene removal, 10–15 per cent, would give a better fit for Y.

The relatively low forsterite content of the normative olivine and the occurrence of normative hypersthene are not essential features as they are dependent on the accepted oxidation state and small changes in the silica/alkali ratio respec-
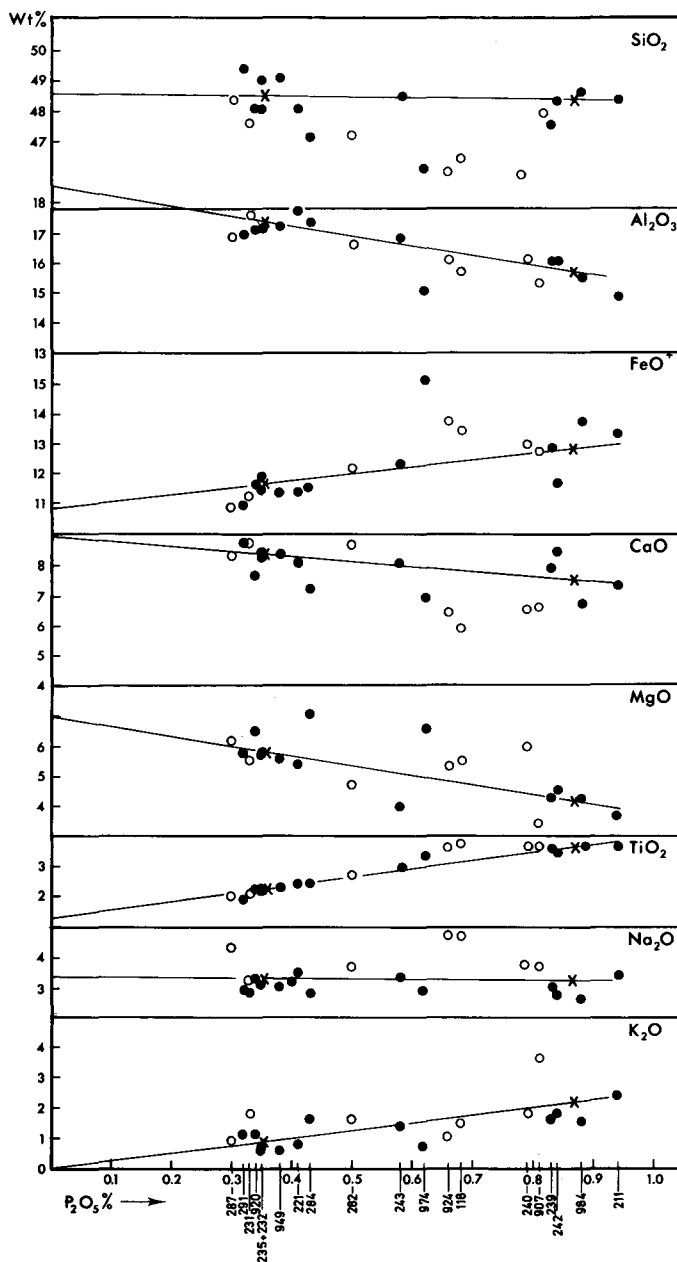
Wt%

SiO₂ ... uh

Wt%

50 49 48 47 — SiO₂

18 17 16 15 14 13 — Al₂O₃

15 14 13 12 11 — FeO⁺

8 7 6 5 4 — CaO

6 5 4 — MgO

3 2 — TiO₂

4 3 — Na₂O

4 3 2 1 0 — K₂O

0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0

P₂O₅%

287 291 231 920 235 232 949 221 284 282 243 974 924 118 240 907 242 239 984 211

Fig. 3. P₂O₅ variation diagram for major elements in the basaltic rocks. ● hy normative basalts and hawaiites. ○ ne normative basalts and hawaiites. × average composition of end members connected with a line extrapolated to P₂O₅ = 0. These two averages are those used in the model calculation in table 7. The last three figures of the sample numbers are given below the diagram. Some analyses are excluded, i.e. the pegmatoids and those rocks analysed to see what chemical changes the alteration has caused.
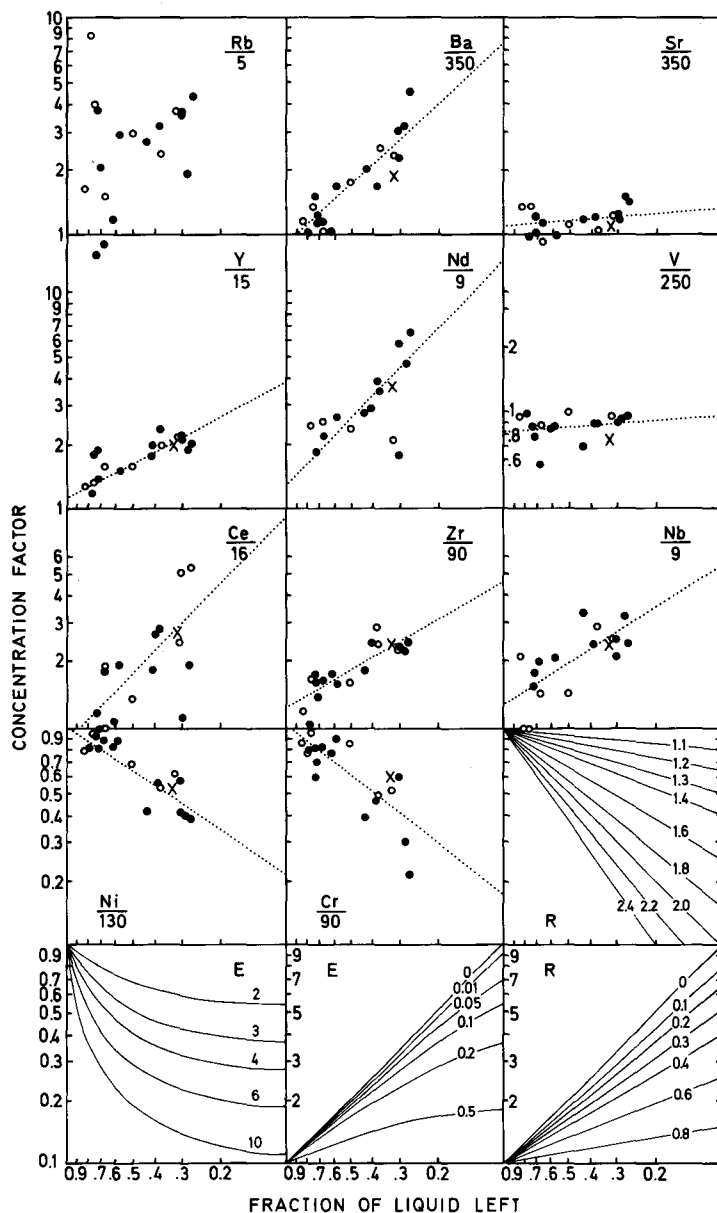
3*

Fig. 4. A modified P₂O₅ variation diagram for the trace elements in the basalts (same symbols as in fig. 3 with the exception that × is the average from the analyses in table 3). They are plotted as concentration factors relative to the most primitive value (given below the element symbol) against the fraction of liquid left as determined from the $P_2O_5^0/P_2O_5^{sample}$ ratio, where $P_2O_5^0$ is the most primitive value (0.25%) (it is assumed that phosphorus has not been removed from the magma by any phase). Trace element fractionation trends for different bulk distribution coefficients are shown in the lower part of the figure. R: Fractional crystallization by surface equilibration (Rayleigh fractionation). E: Equilibrium crystallization.

Table 7. Model calculations for the formation of the hawaiites

	1	2	3		4	5
SiO_2	48.5	48.2	48.6	ab	30.6	30.5
TiO_2	2.24	3.59	1.3	an	35.2	35.2
Al_2O_3	17.36	15.61	18.5	di	6.3	6.3
Fe_2O_3	-	-	1.6	hy	7.3	2.4
FeO	13.16	14.61	10.8	ol	17.1	24.5
MnO	0.19	0.21	0.1	fo	9.9	12.4
MgO	5.72	4.09	7.0	fa	7.2	12.1
CaO	8.30	7.41	8.7	il	1.8	-
Na_2O	3.32	3.19	3.4	mt	1.7	-
K_2O	0.87	2.21	0.0			
P_2O5	0.35	0.86	0.0			
	99.99	100.0	100.0		100.0	99.0

1. Average of the lower, more primitive basalts.
2. Average of the hawaiites (from table 5).
3. The chemical composition which has to be subtracted from the average basalt to get the composition of the average hawaiite. This composition has been obtained from fig. 3.
4. Molecular norm of the subtracted composition with the Fe_2O_3/FeO adjusted to 0.15.
5. Molecular norm of the subtracted composition when all Fe is recalculated as FeO and the TiO_2 content is ignored.

tively. The normative plagioclase has An53.5 in contrast to An73–58 in the plagioclase phenocrysts. Although this may be explained by alteration, there is no evidence to support this (see earlier), and it is assumed to be a primary feature which could be caused by removal of a more sodic plagioclase at elevated pressures in agreement with experimental data (Green, 1969; Thompson, 1972). High pressure fractionation of jadeiitic pyroxene and garnet has been excluded (see earlier). The proposed model agrees with that of Bridgwater & Harry (1968) where the granular anorthosites with An55–61 were formed by crystallization at depth from a rather primitive basaltic magma, which crystallized a more calcic plagioclase (An72–75) at low pressure. Furthermore the more sodic plagioclase cores found in some of the larger plagioclase phenocrysts in the lavas and in the most primitive Gardar gabbro (Pulvertaft, 1965) suggest an early crystallization of a more sodic plagioclase – a feature which has been explained by influx of new magma (Pulvertaft, 1965). Crystallization at elevated pressure would also favour separation of clinopyroxene together with plagioclase and olivine at 5–10 kb (Upton, 1971) and would agree with the formation of transitional basalts at about 8 kb of pressure according to Green & Ringwood (1967).

Table 8. Comparison between calculated and observed bulk distribution coefficients

		Normative constituents						Distribution coefficients		
		plag	ol	cpx	opx	il	mt	$K_{cal.}$	$K^r_{obs.}$	$K^e_{obs.}$
Wt. per cent		63.8	17.2	6.4	7.6	2.5	2.4			
K_{Sr}	accepted	1.6[2]	–	0.02[1]	–	–	–			
	weighted	1.06	–	0.01	–	–	–	1.1	0.9	1
K_{Ba}	accepted	0.18[2]	–	–	–	–	–			
	weighted	0.10	–	–	–	–	–	0.1	0.07	0.01
K_{Ce}		–	–	–	–	–	–	0	0.04	0.00
K_{Nd}		–	–	–	–	–	–	0	–0.04	–0.01
K_Y	accepted	–	–	4-2.5[8]	–	–	–	0.26	0.47	0.3
	weighted	–	–	0.26-0.15	–	–	–	0.15		
K_{Nb}	accepted	0.11[7]	0.15[7]	0.28[7]	–	8.3[7]				
	weighted	0.07	0.03	0.02		0.41		0.53	0.38	0.3
K_{Zr}	accepted	0.05	0.4[3]	1.0[3]	–	4.0[3]				
	weighted	0.03	0.06	0.06	–	0.2		0.35	0.43	0.3
K_V	accepted	–	–	2.1[4]	0.2	6.3[4]	33[5]			
	weighted	–	–	0.13	0.01	0.16	0.8	1.1	0.93	1
K_{Cr}	accepted	–	–	10[6]	5[6]	5.5[5]				
	weighted	–	–	0.64	0.38	0.13		1.15	1.79	2-6
K_{Ni}	accepted	–	10[6]	1.0[6]	1.0[6]	5.8[6]				
	weighted	–	1.7	0.06	0.08	0.13		2.0	1.65	2-4

K_{Sr} Distribution for Sr between the solid phase and the liquid taken from the literature.

K_{cal} Calculated bulk distribution coefficient from weighted normative compositions.

K^r_{obs} Calculated bulk distribution coefficients from the regression lines on fig. 4 assuming a Rayleigh fractionation model.

K^e_{obs} Measured approximate bulk distribution coefficients from fig. 4 assuming equilibrium fractionation.

Accepted and weighted distribution coefficients.

plag normative plagioclase, ol normative olivine, cpx normative clinopyroxene, opx normative orthopyroxene, il normative ilmenite, mt normative magnetite.

The distribution coefficients are based on:

1 Philpotts & Schnetzler (1970), 2 Larsen (1974, unpublished), 3 Degenhardt (1957, p. 292), 4 Wager & Mitchell (1951, Table 6), 5 Duncan & Taylor (1968, Table 1 and 2), 6 Gast (1968, Table 1), 7 Huckenholz (1965), 8 Haslam (1968, cited from Lambert & Holland, 1974).

Upton (1971, 1974) argued that clinopyroxene fractionation might have played an important rôle in the generation of the typical basic Gardar magma from a more primitive magma. This point of view is supported by the fact that the MgO richer Gardar gabbros (those with MgO > 7 per cent) are enriched in CaO relative to Al_2O_3. An early clinopyroxene fractionation in the most primitive basic magmas is in agreement with the low Cr content in the basic Gardar lavas.

Differentiated rocks

The chemical variation in the salic rocks is shown in figs 5 and 6 as a function of the fractionation index (F.I. normative content of ab+or+ne+qz+ac − Mac-

Fig. 5. Major element variation against the fractionation index (F.I.). ● hy normative basalts and hawaiites. ○ ne normative basalts and hawaiites. M moderate potassic differentiated lavas. K potassic differentiated lavas. A sodic differentiated lavas.
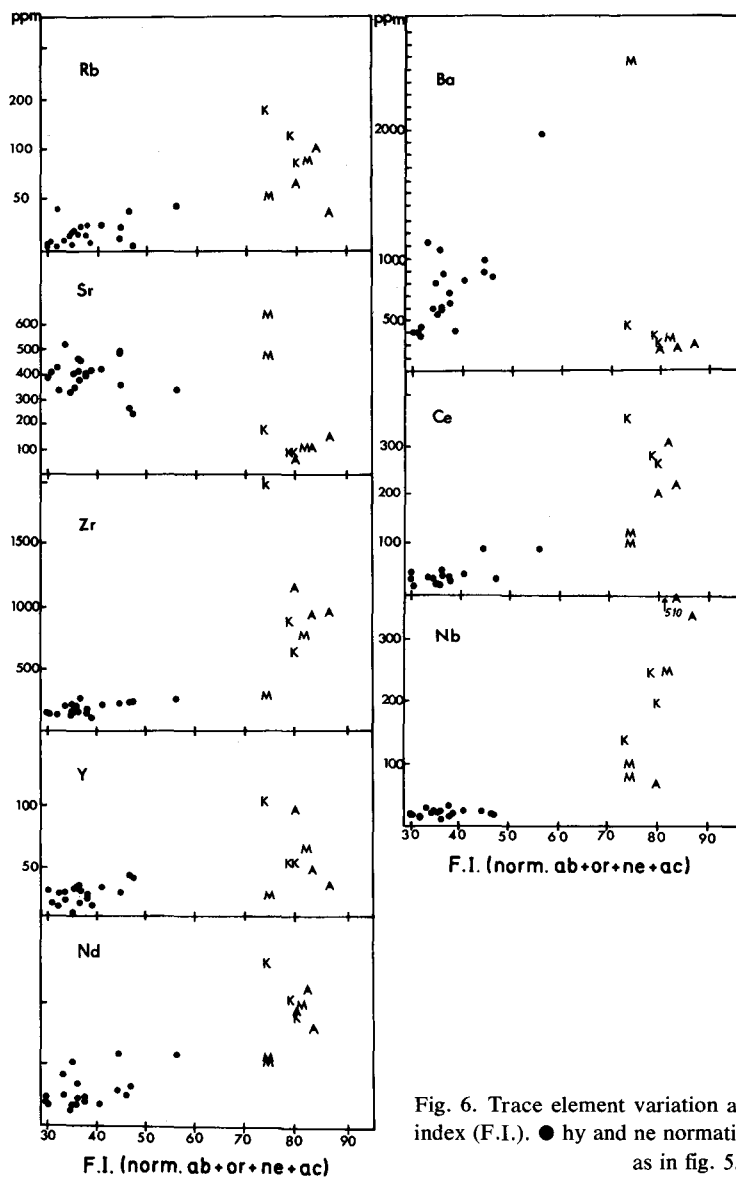
Fig. 6. Trace element variation against the fractionation index (F.I.). ● hy and ne normative basalts; K, M and A as in fig. 5.

donald, 1969) and compared with the basalts. Phosphorus cannot be used as an index in these rocks because apatite is fractionated. The strong bimodal distribution of basaltic and trachytic rocks corresponds to a compositional silica gap of 50–54 per cent as noted for the whole Gardar province by Upton (1974).

Some of the chemical variation can be explained by fractional crystallization, i.e. the CaO decrease may be due to plagioclase and clinopyroxene fractionation.
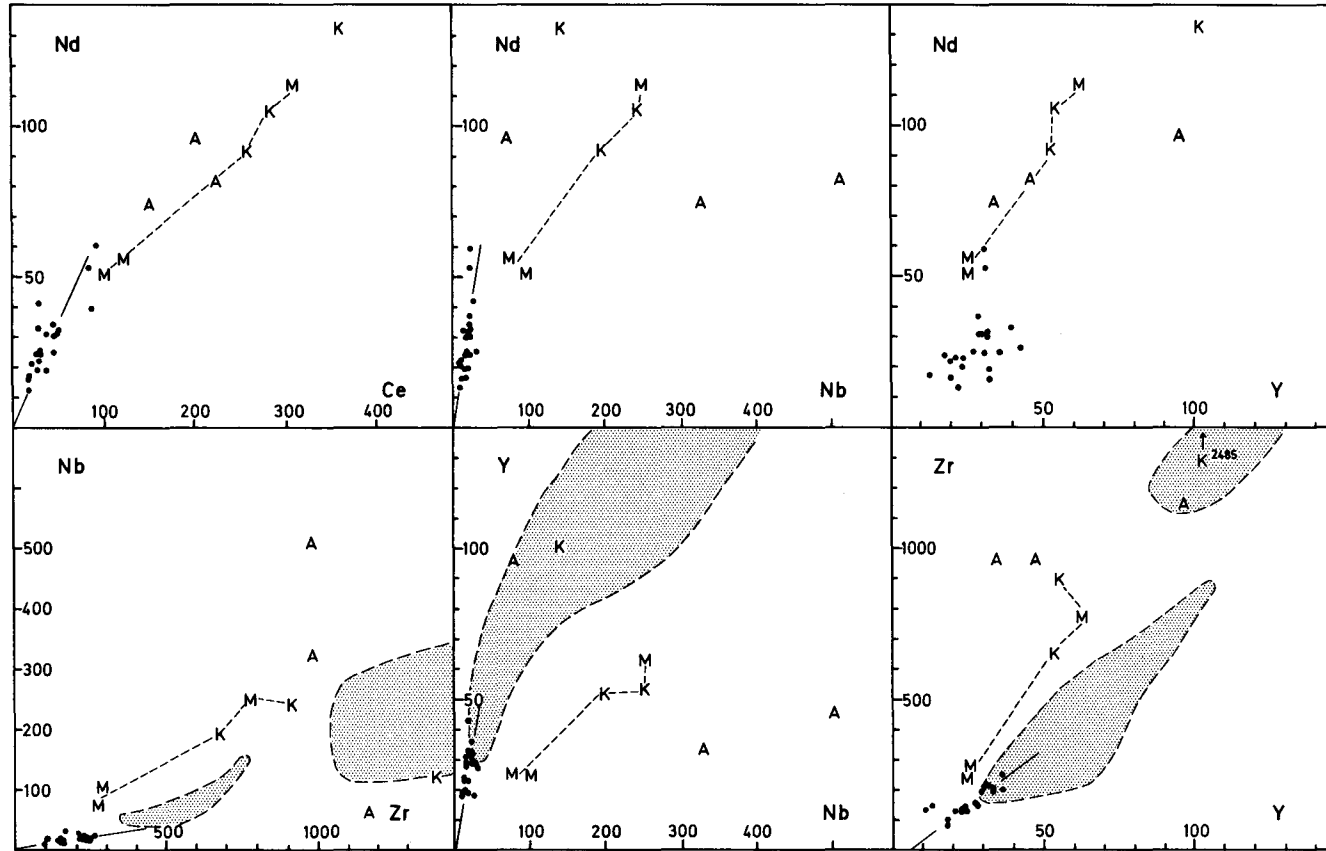
Fig. 7. Covariance of some immobile incompatible trace elements. ● basic lavas. M, K and A see fig. 5 ---- trend of the differentiated lavas from Narssaq Fjeld (the area north-west of the Ilímaussaq intrusion). Shaded areas dyke rocks from Tugtutôq, i.e. the composite Hviddal dyke (Upton, 1964) and the younger dykes (Macdonald & Edge, 1970; Macdonald & Parker, 1970; Macdonald, 1970).

Also an Ab rich plagioclase and alkali feldspar could be responsible for the removal of Sr and Ba in the salic rocks as seen from the distribution coefficients for these elements (Philpotts & Schnetzler, 1970; Macdonald & Edge, 1970). The decrease in Fe_2O_3 total and the low V contents (<6 ppm) in these rocks agrees with oxide fractionation. MgO, Cr and Ni could be removed in olivine and clinopyroxene. Apatite fractionation can explain the decreasing P_2O_5 content and the bend in the Ce–Nd variation (fig. 7), because Nd should be more effectively removed by apatite than Ce (Zielinski & Frey, 1970, table 4). Other chemical features such as the large scattering in Na_2O and K_2O in the covariance of the incompatible elements Nb and Zr (fig. 7) clearly exclude one line of descent.

Relation between the basalts and the salic rocks

According to most authors dealing with the Gardar province the syenites of the Gardar province were formed by differentiation from an alkali basaltic magma, in spite of the small amounts of gabbro in the province (Upton, 1971, 1974;

Table 9. Concentration factors and maximum possible production of various rock types

		Rb	Ba	Ce	Nd	Zr	Nb	cf.	A	B
Basalt[1]	I	17	419	21*	16*	152	15	1	100	
	II	1	1	1	1	1	1			
Hawaiite[2]	I	34	1160	53	43	212	23	2.5	40	
	II	2	2.7	2.5	2.7	1.4	1.5			
Trachybasalt[3]	I	83	2002	89	60	268	-	4.9	20	34
	II	4.9	4.8	4.2	3.8	1.8	-			
Trachyandesite[4]	I	106	2600	111	55	279	86	6.2	16	25
	II	6.2	6.2	5.3	3.4	1.8	5.7			
Trachyte II[5]	I	190	343	284	104	782	232	16	6.2	10.5
	II	11	-	14	6.5	5.1	16			
Phonolite[6]	I	206	270	223	82	967	496	33?	3?	5?
	II	12	-	11	5.1	6.3	33			

cf. Preferred concentration factor.

A   Maximum possible production of rock types from the basalts in per cent.

B   Maximum possible production of rock types from the total amount of basalts and hawaiites in per cent.

I   Concentration in ppm.

II   Concentration factor.

1   Average of the more primitive basalts.

2   Average of the most differentiated hawaiites.

3   GGU 117258.

4   GGU 117159 and 117160.

5   Without alkali trachytes and 117259.

6   GGU 117111.

*Not detected values are assumed to be 15 ppm Ce and 10 ppm Nd.

Sørensen, 1966; Bridgwater & Harry, 1968; Gill, 1973). An independent origin of the syenites, however, has not been excluded (Sørensen, 1966).

In the Eriksfjord Formation the volume is no problem as basalts and hawaiites make up 71 per cent, trachybasalts 5 per cent and trachytes and phonolites 24 per cent. In table 9 the concentration factors show that the amount of salic rocks fits the maximum possible production of the basalts and hawaiites together. Furthermore the salic lavas occur late in the volcanic cycle in agreement with a differentiation process.

Although fractional crystallization may have been an important process in the formation of the salic lavas, most evidence does not support their derivation from one parental basaltic magma similar in composition to that of the basalts. (1) The salic lavas comprise three groups according to their Na_2O/K_2O ratios compared to the basalts which form one rather homogeneous group. (2) Model calculations do not give reasonable results. The significance of these two points may, however, be weakened by the possibility that the metamorphism could have introduced chemical changes. (3) The covariance of the incompatible trace elements Zr, Nb, Nd and Y shows either scattered distribution or trends which cannot be extrapolated through the variation shown by the basalts (fig. 7). In rock series interrelated by fractional crystallization the covariance of ideal incompatible elements should have constant ratios and form trends which can be extrapolated to the zero point (Weaver et al., 1972; Ferrara & Treuil, 1975). It may be argued that the elements referred to above cannot be considered ideally incompatible, e.g. Nb may be removed by Fe-Ti oxides (Huckenholz, 1965) and Ce, Nd and Y by apatite (Zielinski & Frey, 1970; Haskin & Frey, 1966) and Y by clinopyroxene (Lambert & Holland, 1974). However, Weaver et al. (1972) showed that transitional lineages belonging to each volcano in the East African Rift have constant Zr–Nb ratios. Also Ce, Nd and Y increase during differentiation (Barberi et al., 1975).

It is interesting to note that the incompatible trace elements in the intrusive rocks from Tugtutôq (fig. 7) show a pattern, which might suggest that they have been derived from a magma similar to that represented by the basalts.

Therefore it is concluded that the trachytic lavas were neither derived from the basalts by fractional crystallization nor by any other process which would give a continuous variation in these trace elements. This conclusion is in agreement with the field relations suggesting that the eruption sites or at least some of them were located in different areas. Thus there were two volcanic events partly separated in space and time. The first event formed the basalts and hawaiites possibly by fractional crystallization from the same type of parental magma. The second event formed the differentiated lavas belonging to several suites and possibly erupted from several volcanic sites. The lack of basic parental magmas to these rocks could be explained according to the model of Gill (1973), where the ascending new basic magmas were trapped at the crust–mantle boundary and began to differentiate, and from where only the light salic magmas were able to reach the

4*

surface. However, formation of the salic magmas by partial melting of the lower crust or in the mantle (Barth, 1954; Sørensen, 1966; Bailey, 1974) could also account for the formation of these rocks.

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APPENDIX

Equations for removal of the trace elements.

For Rayleigh fractionation the equation

$$C_a^l/C_a^0 = F^{(Ka-1)} \tag{1}$$

is taken from Gast (1968) where
C_a^l is the concentration of the trace element a in the fraction of liquid left (F).
C_a^0 is the initial concentration of a in the original liquid.
K_a is the distribution coefficient between crystal and liquid.

In the present case F is measured by the P_2O_5 content by assuming that 0.25% P_2O_5 represents the initial phosphorus content and that this element has not been removed by any phase in the basalts and hawaiites. In fig. 5 C_a^l/C_a^0 is plotted against F (0.25/P_2O_5 content in the sample) on a logarithmic scale. In this figure the Rayleigh equation will give straight lines

$$\log (C_a^l/C_a^0) = (K_a-1) \log F$$

and the inclination of the line is given by K_a-1. Thus the inclination alone for the trace elements trends in fig. 5 can be used to calculate the bulk distribution coefficient.

For equilibrium crystallization the following equation holds

$$C_a^l/C_a^0 = 1/F(1-K_a)+K_a \tag{2}$$

(Noble & Hedge, 1970), where the symbols are the same as in equation 1. Curved trends in fig. 4 are the results of such fractionation.

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