Mineralogical and geochemical variations across three basaltic lava flows from the Faeroe Islands

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Three basaltic lava flows from the Faeroe Islands, one from the lower, one from the middle and one from the upper lava series, have been sampled with a maximum vertical separation between samples of 2 m, and with two parallel sample profiles for each flow.

The investigations based on this close sampling have shown that significant mineralogical and chemical variations are to be found within single extrusive bodies.

On the basis of 97 chemical analyses, microscopic investigations comprising modal analyses and determination of the oxidation stages of the Fe-Ti-oxides, and electron microprobe analyses of plagioclase, pyroxenes and Fe-Ti-oxides, the mineralogical and geochemical variations across the flows are described.

Only averages of the chemical analyses for each flow are presented, but the results of all the 97 analyses can be seen in the figures, which give the variations across the flows for the main oxides, except P_2O_5 which hardly varies.

In a TiO_2–K_2O–P_2O_5 diagram the samples from the flows from the lower and upper series fall in the oceanic field, whereas the samples from the flow from the middle series cross the border between the oceanic and non-oceanic fields.

In a F_1–F_2 diagram the samples from the lower and upper series fall in the within-plate basalts field, whereas the samples from the middle series fall in the field common to calc-alkali basalts and low-potassium tholeiites. In a F_2–F_3 diagram the samples from the middle series fall mainly in the field of low-potassium tholeiites; the contact samples fall in the middle of this field, while most of the other samples trend towards the field of ocean-floor basalts, and two samples from the middle of the flow actually reach the field of ocean-floor basalts.

Plotted in a total alkalies versus silica diagram the samples all fall in the tholeiitic field well below the dividing line of Macdonald & Katsura (1964).

The variations in the flows from the lower and middle series are interpreted as being due mainly to pre-eruptional processes whereas the variations in the flow from the upper series are believed to be due entirely to post-eruptional processes.

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Introduction

The petrology of the 3000 m thick sequence of early Tertiary flood-basalt lavas that make up the Faeroe Islands has been described by Noe-Nygaard & Rasmussen (1968), and a geological map of the Faeroe Islands was issued in 1969 (Rasmussen & Noe-Nygaard 1969). The 3000 m pile of basaltic lavas is divided into three series: the lower series, the middle series and the upper series (Noe-Nygaard 1962). The lower series comprises 900 m of mainly aphyric quartz tholeiitic basalts and is separated from the middle series by a 15 m thick sedimentary coal-bearing sequence. The average thickness of single lava flows in the lower series is about 20 m, whereas the single flows of the middle series, which com-prises 1350 m of mainly porphyritic quartz tholeiitic basalts, are considerably thinner, having thicknesses down to 10 cm. The upper series comprises 675 m of mainly olivine tholeiitic basalts, the single flows being about 10 m in thickness.

One flow from each of these three lava series has been investigated on the basis of samples taken across the flows with a maximum distance of 2 m between samples. Two separate profiles were sampled from each flow with an average distance between profiles of 5 m.

The purpose of this close sampling was to find out to what extent mineralogical and chemical composition is dependent on position in a flow, and the amount of variation that can occur within a single flow, compared to the variations between

a limited number of samples from different flows to which much significance is often attached in petrological discussions. The result is a rather comprehensive study of mineralogical and geochemical variations across three basaltic lava flows from the Faeroe Islands.

Sampling

The lower basalt series was sampled on the Kvalbø side of the road tunnel between Tverå and Kvalbø, Suderø (fig. 1), where the second uppermost flow of the series is exposed. Here a thickness of 13,5 m of the flow was sampled, but the bottom of the flow is not exposed, and the actual top has been eroded away. It is estimated that the lowermost samples were taken about 2 m above the lower contact, and that the uppermost 1,5 m of the flow is missing. Thus the profiles sampled presumably represent 13,5 m of a 17 m thick flow.

In order to try to cover the missing few metres supplementary samples were taken from the low-ermost 2 m of the third uppermost flow and from the uppermost 1,5 m of the fourth uppermost flow. These supplementary samples were taken somewhat farther east, where a layer of red tuff clearly marks the contact between the third and fourth uppermost flow of the lower basalt series.

The middle basalt series was sampled in the quarry at Klaksvig, Bordø, where an 11 m thick flow is exposed, which is unusually thick for a flow from the middle series. The profiles cover the flow completely from lower to upper contact.

From the upper basalt series the flow occurring along the quay in Torshavn was sampled. In the quarry on the quay two 11,5 m thick profiles through the flow were established. However, neither the upper nor the lower contact are ex-posed at the locality, but whereas probably only very little of the flow is missing at the top, it is estimated that 7 m of the lowermost part of the flow is missing. The lower part of the same flow is exposed at Højvig, and here profiles were estab-lished through the lowermost 7 m, including the lower contact. Together the Højvig and Torshavn samples thus constitute profiles through an ap-proximately 18,5 m thick flow, but without re-presentation of the actual border at the top.
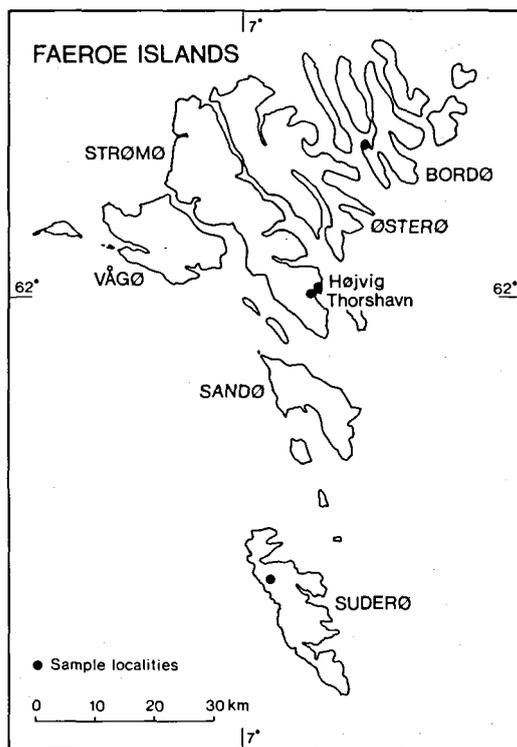

Fig. 1. Sketch map of the Faeroe Islands showing the sample localities.

Sample description

All the samples of the main profiles of the lower series have a grey colour and are fine-grained. From the lowermost sample up to 3 m above there is a slight increase in grain size, and from 12 m above the lowermost sample there is a slight upwards decrease in grain size.

The texture is intersertal to intergranular. The larger grains of plagioclase and augite are occasionally clustered into glomeroporphyritic aggregates, the diameter of which can exceed 1 mm.

Occasionally the samples contain a few vesicles filled with seladonite. The vesicles are frequently somewhat elongated and the largest dimension can reach 5 mm, but usually the vesicles are con-siderably smaller.

All the samples of the supplementary profiles of the lower series have a grey colour. The samples are plagioclase-porphyritic and the phenocrysts are frequently clustered into glomeroporphyritic

aggregated up to 3 mm in diameter. The groundmass is fine-grained and shows an intersertal to intergranular texture. There is a slight increase in grain size from the contacts inwards in the flows. The sample from the lower contact in the B-profile contains numerous about 1 mm large vesicles filled with seladonite. The other samples contain occasional vesicles filled with seladonite. The vesicles can reach 7 mm in diameter, but are generally considerably smaller.

The two samples from the upper contact of the flow from the middle series are red-brown. In the A-profile the two samples just below the contact sample are grey with a reddish tint, the remaining samples all have a grey colour.

The samples carry phenocrysts of orthopyroxene up to 2 mm; these may be clustered in glomeroporphyritic aggregates up to 4 mm. The groundmass is fine-grained and shows intergranular to intersertal texture. The grain size increases from the contacts inwards in the flow. The increase continues to 1 m below the upper contact and to 5 m above the lower contact.

Occasionally the samples contain a few vesicles about 1 mm large which are more or less filled with seladonite. In the B-profile the sample from the upper contact and the sample just below the upper contact contain some vesicles about 1 mm large and filled with zeolites.

In the upper series the two lowermost samples in both profiles are red-brown and vesicular; the uppermost sample of the A-profile also has a red-brown colour, but is not vesicular. The vesicles are partly filled with seladonite and zeolites. The remaining samples are all grey, most of them however with a distinct reddish tint.

The samples are all plagioclase-porphyritic and the phenocrysts are generally clustered into glomeroporphyritic aggregates up to 5 mm in diameter. The groundmass is fine-grained and shows intergranular to intersertal texture.

There is no noticeable difference in grain size between the samples from the lower contact and the samples taken 1 m above the contact, but these samples have a grain size larger than all the other samples. The smallest grain size is found in the sample taken 2 m above the lower contact and from here and until 7 m above the contact the grain size increases gradually. From 7 m to 14–16

m above the contact the grain size remains constant. From here upwards the grain size decreases gradually so that the uppermost samples have a grain size corresponding to that found 2 m above the lower contact.

Mineralogical composition

The mineralogical compositions have been determined by point counting of at least 1500 points in each sample. The main mineral groups are plagioclases, pyroxenes and opaque minerals. Glass is not seen, but anisotropic green and brown alteration products, mainly occurring interstitially, may in some samples constitute as much as 14% and are never less than 2% of the rock. Zeolites are not conspicuous; amounts exceeding 1% are found in only three samples, and the average amount of zeolites in the profiles is below 0.1%.

The average composition of the main profile of the flow from the lower series is: 38.9 plagioclase, 40.1 clinopyroxene, 10.4 opaque minerals and 10.6 alteration products, expressed in volume percentages. From the supplementary profiles it can be seen that the amounts of opaque minerals and alteration products increase towards the contacts, whereas the amounts of plagioclase and clinopyroxene decrease.

The average composition of the flow from the middle series is: 31.2 plagioclase, 52.3 clinopyroxene, 2.0 orthopyroxene, 6.8 opaque minerals and 7.7 alteration products. The amount of plagioclase decreases towards both contacts, most markedly towards the upper contact. Clinopyroxene also decreases towards the upper contact but towards the lower contact clinopyroxene shows an increase. The amount of opaque minerals increases towards both contacts, most strongly towards the upper contact and less prominently towards the lower contact. The amount of alteration products increases strongly towards the upper contact, but does not show much change towards the lower contact.

The average composition of the flow from the upper series is: 27.5 plagioclase groundmass, 10.8 plagioclase phenocrysts, 44.3 clinopyroxene, 10.1 opaque minerals and 7.3 alteration products. The values are somewhat fluctuating across the flow, and changes towards the contact are not

more prominent than the fluctuations inside the flow.

Plagioclases

The composition of the plagioclases has been determined by partial electron microprobe analyses, determining K, Na and Ca. The plagioclases were analysed with a Hitachi XMA-5B electron microprobe using 15.0 kV accelerating voltage and a sample current on a Faraday cage of 20.0 nA. Stoichiometric silicates were used as standards. The correction programme used, EMSKOR, is based on the programme made by Springer (1967), but modified by J. Rønsbo, Institute of Mineralogy, University of Copenhagen, in accordance with the suggestions of Sweatman & Long (1969). The totals of the analyses when recalculated to weight percent feldspar molecules lie between 99.3% and 100.3%.

The results of the analyses are shown in fig. 2. In the flow from the lower series (A) most of the grains lie within the labradorite range, but some of the smaller grains are andesines. An-values exceeding 63% were obtained only from the central part of large grains.

With one exception the measured feldspars from the flow from the middle series (B) are all labradorites. The exception outside the labradorite range is an andesine with the composition $Or_{3.9}Ab_{58.0}An_{38.1}$.

In the flows from the lower and middle series no significant differences were found between the contact samples and samples from the interior of the flows. In the flow from the upper series, however, the groundmass plagioclase in the middle of the flow (D) is clearly lower in An than the groundmass plagioclase in the other samples (C). Thus andesine is found only in the middle of the flow, whereas in the outer parts groundmass plagioclase is all labradorite. For the phenocryst plagioclases no variation with position in flow is found (E). The whole range obtained can be found as zoning within single grains. The phenocrysts thus are zoned from bytownite to labradorite.
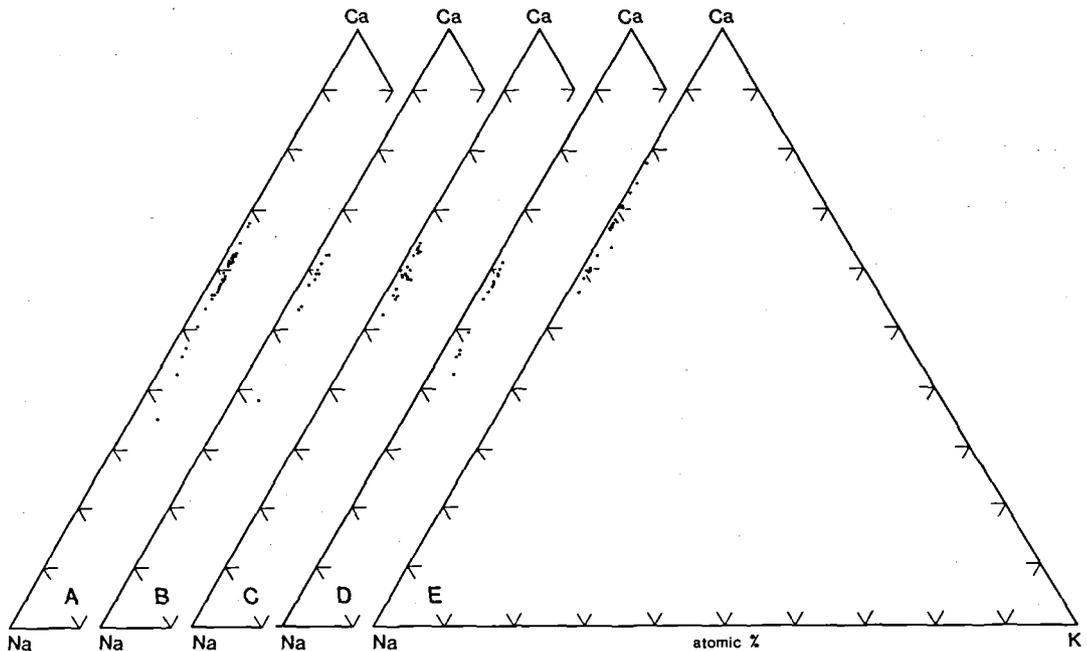

Fig. 2. Plot of partial plagioclase microprobe analyses. Atomic proportions. A: lower series. B: middle series. C: groundmass plagioclase from outer parts of the flow from the upper series. D: groundmass plagioclase from the middle of the flow from the upper series. E: phenocrysts from the upper series.

Pyroxenes

Electron microprobe analyses of pyroxenes were carried out on the same samples as were used for partial electron microprobe analyses of plagioclases. These pyroxene analyses, however, have already been dealt with in detail (Jensen, 1978) and therefore only a brief summary of the composition of the pyroxenes as regards the major elements Ca, Mg and Fe will be given here.

Augite is the only pyroxene present in the flow from the lower series. The composition ranges from $Ca_{32.2} Mg_{48.3} Fe_{19.5}$ ($Ca_{42.5} Mg_{42.4} Fe_{15.1}$) to $Ca_{36.2} Mg_{35.5} Fe_{28.3}$.

The flow from the middle series carries phenocrysts of orthopyroxene, and the groundmass pyroxene comprise pigeonite as well as augite. The orthopyroxene phenocrysts are bronzites with a composition varying from $Ca_{4.5} Mg_{78.4} Fe_{17.1}$ to $Ca_{4.6} Mg_{66.6} Fe_{28.8}$, and this whole range can be found as zoning within single grains.

The augites cover a range from $Ca_{34.6} Mg_{49.5} Fe_{15.9}$ ($Ca_{36.9} Mg_{49.0} Fe_{14.1}$) to $Ca_{35.2} Mg_{40.0} Fe_{24.8}$ and the pigeonites vary from $Ca_{10.1} Mg_{58.3} Fe_{31.6}$ to $Ca_{10.1} Mg_{53.5} Fe_{36.4}$.

Augite is the dominant pyroxene in the flow from the upper series, the composition ranging from $Ca_{39.0} Mg_{47.2} Fe_{13.8}$ to $Ca_{33.9} Mg_{34.9} Fe_{31.2}$. In the sample from the contact augite is the only pyroxene present, 4 m above the contact pigeonite occurs in sparse amounts, and in the middle of the flow (9 m above the contact) pigeonite is much more frequent and occurs often as rather large grains. The pigeonites vary in composition from $Ca_{10.1} Mg_{57.0} Fe_{32.9}$ to $Ca_{10.4} Mg_{40.1} Fe_{49.5}$. The compositions of the augites are approximately the same in samples from the contacts as in samples from the centres of the flows.

Opaque minerals

The opaque minerals are strongly dominated by different phases of Fe-Ti-oxides, but besides there occur very small amounts of native copper and sulphides. The sulphides comprise both copper-bearing sulphides such as digenite, covelline (blaubleibenden) and chalcopyrite, and the non copper-bearing sulphides pyrrhotite and pyrite; the sulphides are present in even smaller amounts than native copper.

The difficulties with determination of the amounts of native copper in polished sections have been dealt with in a previous paper (Jensen, 1975), and the occurrence of native copper and sulphides will be further dealt with in a paper in preparation concerning the distribution of Cu across the lava flows. Accordingly the description of opaque minerals here will be restricted to the Fe-Ti-oxides.

Oxidation stages

Before describing the Fe-Ti-oxides in the Faeroe Islands basalts it is appropriate to discuss the different approaches to the description of oxidation stages of Fe-Ti-oxides.

Ade-Hall & Wilson (1963), Ade-Hall (1964) and Wilson (1964) found that there was a good correlation between normal and reversed polarity on the one hand and the absence or presence of ilmenite lamellae after {111} of the magnetite on the other.

Ade-Hall, Wilson & Smith (1965) correlated the distribution of Curie points with three different groups of titanomagnetite representing increasing degree of oxidation: a) homogeneous titanomagnetite; b) mixed titanomagnetite, with either a few of the titanomagnetite grains containing a lot of ilmenite lamellae, or many grains with a small content of ilmenite lamellae; c) titanomagnetite with all grains containing abundant ilmenite lamellae.

Wilson (1965) showed that lavas with reversed polarity contain more ilmenite (both as lamellae after {111} in magnetite and as discrete ilmenite grains) than lavas with normal polarity.

Watkins & Haggerty (1965) showed the intensity of magnetisation to be proportional to the degree of oxidation of the Fe-Ti-oxides, which they split up into three zones: I) Maghemite zone with minimum oxidation characterised by unaltered ilmenite and magnetite with local alteration to maghemite. II) Intermediate zone where between 10 and 20% of the Fe-Ti-oxide grains show some alteration. Magnetite is martitised along {111} planes and at grain boundaries and has exsolutions of spinel along {100} planes. {111} lamellae of ilmenite in magnetite are al-

tered to a fine-grained intergrowth of hematite and rutile. Discrete grains of ilmenite have spindle-like exsolutions of hematite along {0001} planes. III) Hematite-pseudobrookite zone representing the maximum degree of oxidation where discrete grains of ilmenite as well as titanomagnetite grains are altered to intergrowths of pseudobrookite, hematite and rutile.

Wilson & Haggerty (1966) published colour photographs of progressive oxidation stages for titanomagnetite and for discrete ilmenite grains separately.

Wilson & Watkins (1967) made a five-fold classification of the different oxidation stages based on the development of the titanomagnetite: Class I: Homogeneous titanomagnetite. Class II: Titanomagnetite containing a few ilmenite lamellae in some or all of the grains. Class III: Titanomagnetite completely filled with ilmenite lamellae, usually on a very fine scale. Class IV: The ilmenite lamellae of Class III have been altered to a silver brightly reflecting form. Class V: The original titanomagnetite is changed in one or both of two ways: to an irregular intergrowth of pseudobrookite and hematite, or to a brown host containing short rods of spinel and surrounded by wide laths or lamellae of an intergrowth of rutile and hematite.

Watkins & Haggerty (1967) extended the five-fold classification of Wilson & Watkins (1967) to a six-fold classification and changed the nomenclature from Classes I-V to Oxidation Indices I-VI: Oxidation Indices I-IV correspond to the Classes I-IV of Wilson & Watkins (1967) Oxidation Index V is characterized by the presence of rutile which occurs as oriented intergrowths in a host of titanohematite. Relic areas of titanomagnetite can still persist, and contain rods of spinel. Oxidation Index VI represents the maximum degree of oxidation and is characterised by the presence of pseudobrookite. The oxidation development described can be accompanied by the oxidation of titanomagnetite to titanomaghemite, this oxidation, however, being restricted to Oxidation Indices I-III.

Watkins, Gunn & Coy-yll (1970) used the Oxidation Indices of Watkins & Haggerty (1967) but extended the classification to include the development of ilmenite in discrete grains. They state that the oxidation development of discrete ilmenite grains corresponds to the development

of ilmenite lamellae in titanomagnetite, starting at Oxidation Index IV, discrete ilmenite grains thus being unaltered through Oxidation Indices I-III.

Haggerty (1976) established a seven-fold classification for the oxidation development of titanomagnetite, stages C1–C7, as well as of ilmenite in discrete grains, R1–R7. C1–C5 correspond to Oxidation Indices I-V of Watkins & Haggerty (1967). C6 is characterised by incipient formation of pseudobrookite, while C7 is characterised by the abundance of pseudobrookite. R1 is unaltered ilmenite and coexists with C1–C3, whereas C4 is accompanied by the appearance of a few thin lenses of ferrian rutile in the ilmenite, R2, and more abundant and thicker lenses of ferrian rutile, R3. R4 is characterised by the four-phase metastable assemblage: ferrian ilmenite, titanohematite, ferrian rutile and rutile. R5, R6 and R7 correspond to C5, C6 and C7 respectively.

The Fe-Ti-oxides in the basalts of the Faeroe Islands show some deviations from the descriptions of Haggerty (1976).

Ilmenite in descrete grains is frequently seen to develop some lenses of ferrian rutile in samples where none of the titanomagnetite grains is oxidised beyond stage C2. Composite grains consisting partly of stage C3 titanomagnetite and partly of ilmenite masses in areas equal to the areas of titanomagnetite are as often found with the ilmenite masses containing a network of sigmoidal lenses of ferrian rutile as with ilmenite masses unaltered. Furthermore there are several samples where the titanomagnetite has reached stage C6 while ilmenite has reached only stage R4 or R5.

The opposite trend, with ilmenite attaining a higher oxidation stage than titanomagnetite, is found in only one sample (apart from the case of direct oxidation of ilmenite to rutile described later) which has R7 together with C6.

These deviations have not prevented the use of the stages C1–C7 and R1–R7 of Haggerty (1976) to characterise the oxidation stages of the Fe-Ti-oxides in the Faeroe Islands basalts. However, neither the suggestion of Haggerty (1976) that one should calculate a mean oxidation number, nor the idea of the previous authors of establishing a so-called overall oxidation state has been
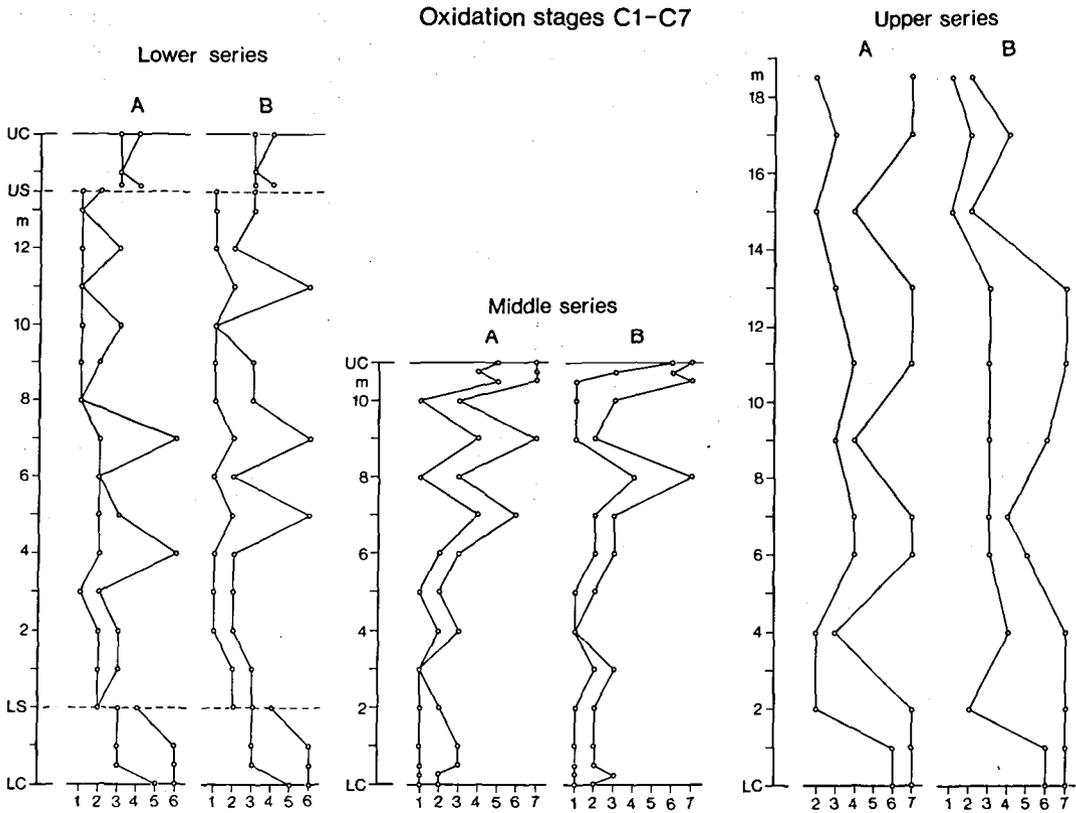
Fig. 3. The distribution of oxidation stages C1–C7 across the three lava flows.

followed. Instead the present study describes which oxidation stages are actually present in each sample. This procedure gives a clearer impression of the degree of equilibrium with regard to P_{O_2} that has been attained in the different samples.

The variations in oxidation stages C1–C7 across the three flows of Faeroe Islands basalts are shown in fig. 3. Maghemitisation and martitisation, generally weak, are frequently found in titanomagnetite grains in stages C1–C4.

In the main profiles of the flow from the lower series oxidation maxima are found at 4 and 7 m above lowermost sample in the A-profile, and at 5, 7 and 11 m above lowermost sample in the B-profile. From the supplementary profiles it is seen that the lower contact (third uppermost flow) is considerably more oxidised than the upper contact (fourth uppermost flow).

The flow from the middle series can clearly be divided into a lower half with low oxidation and an upper half with high oxidation. Maxima occur

at 7 and 9 m above lower contact and at the upper contact in the A-profile, and at 8 m above lower contact and at the upper contact in the B-profile.

In the flow from the upper series the lower contact is strongly oxidised in both profiles. Across the flow the A-profile shows minima at 4, 9 and 15 m above lower contact, whereas corresponding minima in the B-profile are found at 7 and 15 m above lower contact.

Variations in oxidation stages R1–R7 are not shown. They give the same general picture as C1–C7 but are less detailed for the lower stages.

Concerning the oxidation of ilmenite in discrete grains it is interesting to note that the alternative oxidation trend described by Haggerty (1976), where pseudobrookite develops directly from ilmenite, is found in the sample taken 2 m below upper contact in the A-profile of the flow from the middle series. According to Haggerty (1976) this alternative oxidation trend is caused by rapid oxidation at temperatures above 800°C and is found in a small percentage of basalts.

In the sample from the middle series with direct oxidation from ilmenite to pseudobrookite the titanomagnetite shows oxidation stages C4–C7. In the sample taken 1 m below upper contact in the B-profile of the flow from the middle series, titanomagnetite shows stages C1–C3, while the ilmenite in discrete grains follows a direct oxidation trend similar to that described by Haggerty (1976) but with rutile, and not pseudobrookite, as the final oxidation product.

Composition

The composition of some of the Fe-Ti-oxides has been determined by electron microprobe analyses. The analyses were carried out at Vrije Universiteit, Amsterdam, by Dr. C. Kieft with the Cambridge Geoscan electron microprobe of the Instituut voor Aardwetenschappen. The accelerating voltage was 20 kV, and as standards were used stoichiometric oxides, silicates and metals. The correction programme used is based on Springer (1967), but modified by P. Maaskant and C. Kieft.

In the sample taken 9 m above lower contact in the B-profile of the flow from the upper series the compositions of the pseudobrookite, rutile and hematite phases in composite grains and the composition of ilmenite in separate grains have been determined. The results are given in table 1.

The corresponding Fe-Ti-oxides in the sample

TABLE 1

Electron microprobe analyses of Fe-Ti-oxides

Weight %	Pseudobrookite	Rutile	Hematite	Ilmenite
FeO	1.0_5	1.4[x]	10.1_5	42.5_5
Fe_2O_3	55.2		69.1_5	3.7_5
TiO_2	40.8_5	99.0	17.1	51.5_5
MgO	2.4_5		2.5_5	1.9
MnO	0.5_5		0.7	0.4_5
Total	100.1	100.4	99.6_5	100.2

Molecular composition	Pseudobrookite		Hematite		Ilmenite
	$FeTi_2O_5$	3.5	$FeTiO_3$	21.8	$FeTiO_3$	88.5
	$MgTi_2O_5$	14.0	$MgTiO_3$	9.8	$MgTiO_3$	7.0
	$MnTi_2O_5$	1.8	$MnTiO_3$	1.5	$MnTiO_3$	1.0
	Fe_2TiO_5	80.7	Fe_2O_3	66.9	Fe_2O_3	3.5

x) Oxidation state not determined, the 1.4% FeO corresponds to 1.55% Fe_2O_3.

taken 13 m above lower contact in the A-profile of the flow from the upper series have been analysed for Fe and Ti, with results similar to those obtained from the first sample, except that in two cases a much purer hematite phase was encountered, giving as much as 95% Fe_2O_3.

Whole rock analyses

All the 97 rock samples have been analysed in the laboratory of the Geological Survey of Greenland by Ib Sørensen. H_2O^+ was determined by the Penfield method and Fe^{++} by wet chemistry. Mg was determined by complexometric titration, Na by flame photometry, and the remaining elements were analysed by XRF on glass discs.

Table 2 shows the average values for the three different flows together with the calculated C.I.P.W. weight norms. The norms are calculated with the ratio Fe_2O_3/FeO as found by analyses (first column) as well as with this ratio adjusted to 0.15 (second column).

Using the ratio Fe_2O_3/FeO found by analysis all three flows are quartz tholeiites (Yoder & Tilley, 1962). This remains true for the lower and middle series flows when the adjusted ratio is used, but using this ratio the flow from the upper series becomes an olivine tholeiite.

Compared to the average quartz basalt and the average olivine tholeiite of Manson (1967), the flow from the lower series is low in Al and K, and high in Ti, Fe, Mn and P. Si and Ca correspond to the average olivine tholeiite, and Mg and Na correspond to the average quartz basalt. The ratio Fe_2O_3/FeO is somewhat higher than that of the average quartz basalt.

The flow from the middle series has an unusual composition as MgO is higher than CaO. Compared to the average quartz basalt and the average olivine tholeiite the flow is low in Ti, Al, Fe, Mn, Ca and P, high in Si and Mg, while Na corresponds to the average olivine tholeiite and K is intermediate between the two basalts. The ratio Fe_2O_3/FeO is similar to that of the average olivine tholeiite.

The flow from the upper series is slightly too high in Fe_2O_3 to pass Manson's (1967) screen for rocks of basaltic composition, and the ratio Fe_2O_3/FeO is twice as high as that of Manson's average quartz basalt. In relation to the average

quartz basalt as well as to the average olivine tholeiite the flow is low in Al and K, and high in Ti, Fe, Ca and Na, whereas the values of Si and Mg lie between the values of the two average basalts. P corresponds to the average value of the olivine tholeiite and Mn to the common average value of the two basalts.

Schilling & Noe-Nygaard (1974) suggested that the Fe-Ti-rich basalts of the lower and middle series of the Faeroe Islands basalts were plume-derived, whereas the upper series is more akin to normal mid-ocean ridge basalts. This idea was further elaborated by Bollingberg, Brooks & Noe-Nygaard (1975) who suggested that the lower series was erupted under vigorous plume activity characterised by Fe-Ti-rich magmas, the middle series erupted during the waning phase of plume activity, and the upper series erupted by typical ocean tholeiite magmatism without influence from plume activity.

The flow from the lower series investigated here corresponds well with the average of the lower series (Rasmussen & Noe-Nygaard, 1969; Bollingberg, Brooks & Noe-Nygaard, 1975) and could be classified as a Fe-Ti-rich basalt characteristic of plume activity.

The flows from the middle and upper series, however, cannot be taken as representative for their respective series, and some of the elements deviate beyond the standard deviation given by Bollingberg, Brooks & Noe-Nygaard (1975). Nevertheless, they may reflect a development away from the plume-derived Fe-Ti-rich basalts of the lower series towards more normal mid-ocean ridge basalts.

Thus in the flow from the middle series only the four elements: Al, Ca, Na and K show values closer to plume-derived basalts than to ocean ridge basalts, whereas the remaining elements have values closer to ocean ridge basalts than to plume-derived basalts.

The flow from the upper series has a TiO_2 value characteristic of plume-derived basalt and a MnO value corresponding to ocean ridge basalts, while the remaining elements have values lying between the values of plume derived and ocean ridge basalts.

The 97 rock analyses are not listed here in table form, but figures 4–11 show some plots based on the results of the analyses, and figures 12–18

TABLE 2

Averages of chemical analyses of rock samples

	Lower series Main profiles only Average of 30 analyses		Middle series Average of 32 analyses		Upper series Average of 24 analyses	
		Standard deviation		Standard deviation		Standard deviation
SiO_2	48.65	0.38	53.62	0.41	48.89	0.42
TiO_2	3.30	0.07	1.49	0.03	2.70	0.11
Al_2O_3	13.14	0.16	12.76	0.16	14.23	0.37
Fe_2O_3	4.93	0.87	2.36	1.61	6.17	2.15
FeO	9.26	0.72	7.61	1.40	6.88	2.10
MnO	0.22	0.02	0.04	0.06	0.17	0.06
MgO	5.67	0.27	8.95	0.22	6.03	0.16
CaO	10.44	0.20	8.69	0.09	10.58	0.18
Na_2O	2.55	0.05	2.35	0.10	2.76	0.11
K_2O	0.37	0.05	0.71	0.11	0.39	0.08
H_2O	0.99	0.18	1.02	0.22	1.18	0.44
P_2O_5	0.39	0.01	0.13	0.01	0.24	0.03
Sum	99.91		99.73		100.22	
Total Fe as FeO	13.69	0.17	9.72	0.16	12.43	0.38

C.I.P.W. weight norms

Q	4.68	1.16	5.59	4.38	4.35	
or	2.19	2.19	4.20	4.20	2.30	2.30
ab	21.58	21.58	19.89	19.89	23.36	23.36
an	23.32	23.32	22.17	22.17	25.29	25.29
wo ⎫	10.83	10.83	8.39	8.39	10.70	10.70
en ⎬ di	6.56	5.08	5.45	5.10	7.89	5.32
fs ⎭	3.67	5.62	2.36	2.82	1.79	5.17
en ⎫	7.56	9.04	16.83	17.18	7.12	8.25
fs ⎬ hy	4.22	10.00	7.28	9.48	1.61	8.02
fo ⎫						1.02
fa ⎬ ol						1.10
mt	7.15	2.62	3.42	1.87	8.95	2.38
il	6.27	6.27	2.83	2.83	5.13	5.13
ap	0.90	0.90	0.30	0.30	0.56	0.56

show the variation with position in flow for all the elements, except P which hardly varies across the flows.

Using the ratio Fe_2O_3/FeO found by analysis

the 97 samples are all quartz tholeiites. But whereas the middle series and the main profile of the lower series remain quartz tholeiites also with the adjusted ratio, the use of this ratio turns most
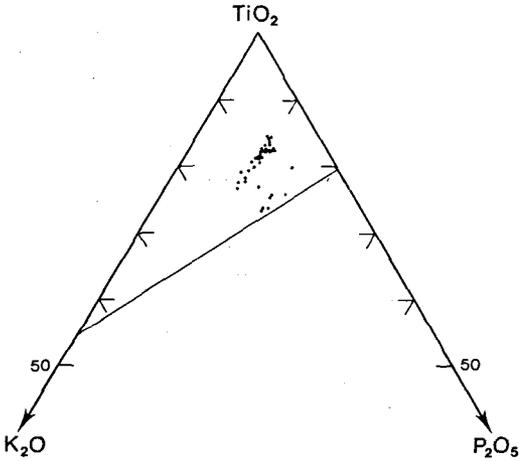
Fig. 4. TiO$_2$–K$_2$O–P$_2$O$_5$ diagram (Pearce, Gorman & Birkett, 1975) for the samples from the lower series. Oceanic field above and non-oceanic field below dividing line.
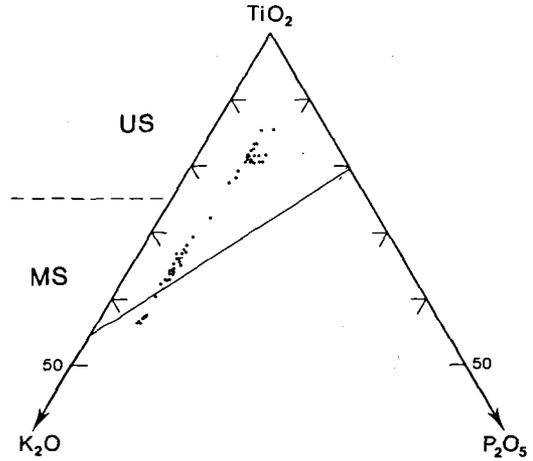

Fig. 5. TiO$_2$–K$_2$O–P$_2$O$_5$ diagram for the samples of the middle and upper series. MS: middle series. US: upper series.

of the samples from the upper series and half of the samples of the supplementary profiles from the lower series into olivine tholeiites.

Plotted in the TiO$_2$–K$_2$O–P$_2$O$_5$ diagram of Pearce, Gorman & Birkett (1975) the samples of the main profile of the lower series, and the samples of the supplementary profiles representing the uppermost part of a flow (i.e. the samples from the second and the fourth uppermost flows) fall in the middle of the oceanic field, whereas the samples from the third uppermost flow (supplementary profiles representing lowermost part of flow) are relatively richer in P$_2$O$_5$ and fall closer to the border against the non-oceanic field (fig. 4).

The samples from the upper series also fall in the middle of the oceanic field, whereas the samples from the middle series cross the border between the oceanic and non-oceanic fields. The samples in the non-oceanic field are five of the lowermost samples and the two samples 1 m below upper contact, whereas the samples closer to the upper contact (including the contact samples) fall well within the oceanic field, fig. 5.

In a F$_1$–F$_2$ diagram (Pearce, 1976) the samples from the main profiles of the flow from the lower series fall well inside the within-plate basalt field (WPB). In the supplementary profiles the sample from the upper contact falls on the border between the WPB field and the common field of calc-alkali basalts and low-potassium tholeiites (CAB + LKT), and the two samples below the

upper contact fall within the WPB field, whereas one of the samples from the lower contact falls well within the CAB + LKT field and the remaining samples from lowermost part of flow fall near the triple point between CAB + LKT, WPB and OFB (ocean-floor basalts) (fig. 6).

Plotted in a F$_2$–F$_3$ diagram (fig. 7) the sample from the upper contact and one of the two samples from the lower contact (the one that falls well inside the CAB + LKT field in the F$_1$–F$_2$
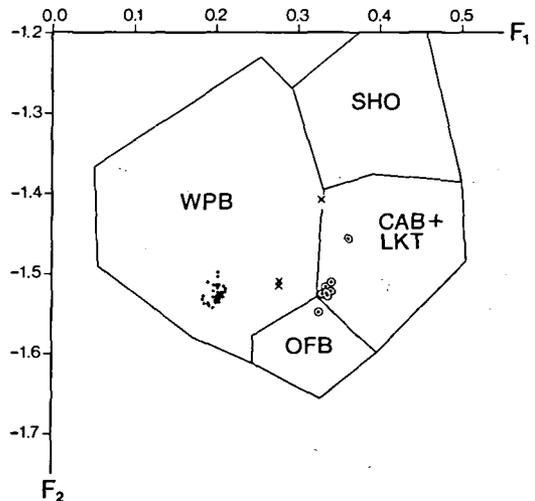

Fig. 6. Plot of discriminant functions. F$_2$ against F$_1$ (Pearce, 1976), for the samples from the lower series. Main profiles = second uppermost flow: · Third uppermost flow: ○ Fourth uppermost flow: x.
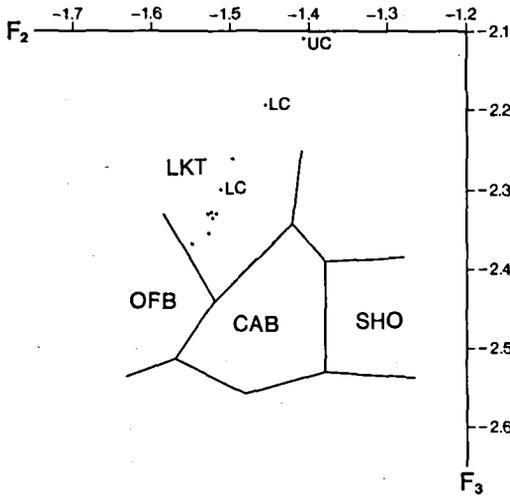
Fig. 7. Plot of discriminant functions, F_3 against F_2 (Pearce, 1976), for samples from the lower series falling outside the WPB field of the F_1–F_2 diagram. UC: upper contact sample. LC: lower contact samples.

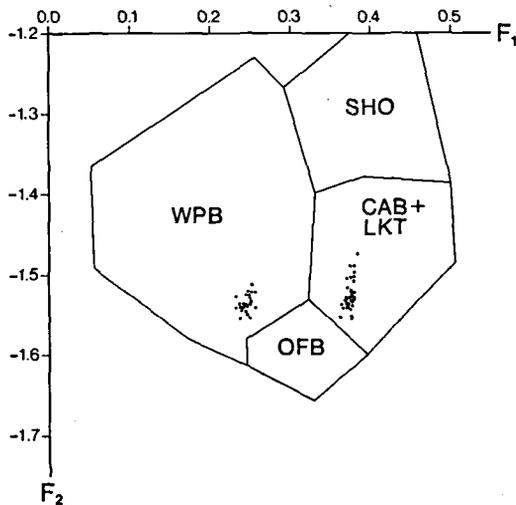Fig. 9. Plot of descriminant functions, F_3 against F_2 for the samples from the middle series.

Fig. 8. Plot of discriminant functions, F_2 against F_1, for the samples from the middle series (CAB + LKT field) and from the upper series (WPB field).
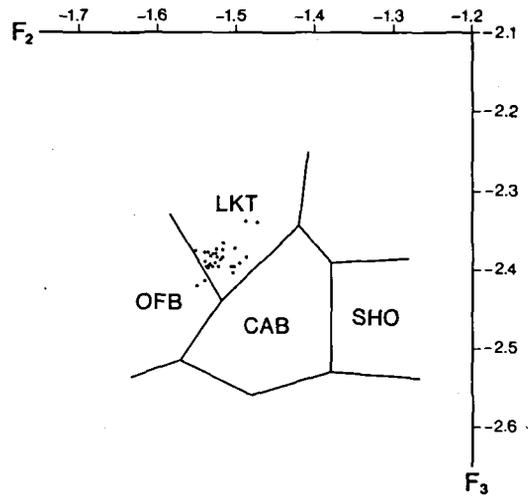
diagram) fall in the extension of the LKT field, whereas the remaining samples fall in the LKT field proper.

The samples from the middle series all plot in the CAB + LKT field in a F_1–F_2 diagram (fig. 8). The distribution of the samples from the middle series in a F_2–F_3 diagram is shown in fig. 9: two samples from the middle of the flow fall in the OFB field, whereas all the other samples fall in the LKT field. The contact samples fall in the middle of the LKT field while the remaining samples trend towards the OFB field.

The samples from the upper series all plot in the WPB field of a F_1–F_2 diagram (fig. 8), but closer to the OFB border than the samples from the main profile of the lower series (fig. 6).

In the main profile of the flow from the lower series the indicator ratio (Coombs, 1963) varies between 0.31 and 0.36. The indicator ratio thus lies in the range where hypersthene appears to be unknown and pigeonite rare or absent, and none of these minerals are seen in the samples. The indicator ratio for the samples of the supplementary series lies in the same range, except for the contact samples, the indicator ratio of which is high: 0.66 for the lower contact and 0.83 for the upper contact; that is to say the contacts lie in the range where hypersthene characteristically appears early, but neither hypersthene nor pigeonite has been found in any of the samples from the supplementary profiles.

The samples from the middle series have indicator ratios between 0.49 and 0.56, with the exception of the sample from the upper contact in the B-profile, the ratio of which is 0.65. 0.50 is considered a limiting value below which hypersthene is characteristically absent and pigeonite rare. The sample from the middle series carry bronzite as phenocrysts and have pigeonite as well as augite in the groundmass.
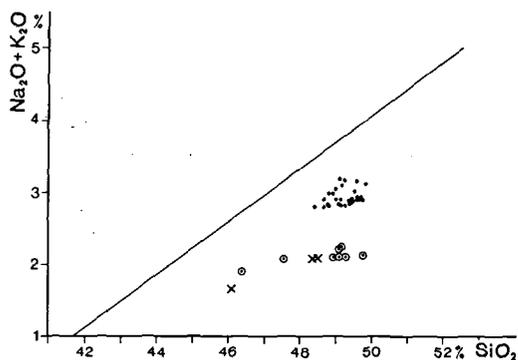
Fig. 10. Plot of total alkalies against silica (water-free compositions recalculated to 100%) for samples from the lower series. Main profiles = second uppermost flow: · Third uppermost flow: ○. Fourth uppermost flow: x. The line is the Hawaii dividing line between tholeiitic and alkaline compositions (Macdonald & Katsura, 1964).

The samples from the upper series have indicator ratios between 0.25 and 0.33. This is in the range where hypersthene appears to be unknown and pigeonite rare or absent. Hypersthene is not found in the samples, but although pigeonite is absent in the contact samples it is found in the interior of the flow.

In plots of total alkalies against silica the 97 samples all fall well below the dividing line between Hawaiian tholeiitic and alkaline compositions (Macdonald & Katsura, 1964), (figs 10 and 11).

Chemical variations

The variations in chemical composititon across the flows are shown in figs 12–18. The values used are the oxide values as found by chemical analyses, but the recalculation of the oxide values to 100% based on water-free composition does not give any changes in trends with the following exceptions:

The use of water-free values reverses the slight decrease in SiO_2 towards the upper contact in the A-profile of the flow from the upper series, and changes the slight increase in SiO_2 at the upper contact of the B-profile to a slight decrease.

The use of water-free values gives a slight increase in total Fe at the upper contact in the A-profile of the flow from the upper series.

The more or less pronounced maxima in SiO_2, TiO_2, Al_2O_3, CaO, MgO and Na_2O at seven

metres above lower contact in the B-profile of the flow from the middle series are removed or strongly reduced by the use of water-free values.

In studying the variations in the lower series it must be remembered that the profiles here are put together from three different though successive flows. The main profiles are from the second uppermost flow of the series, whereas the supplementary profiles showing the variations at the contacts are from the third uppermost flow (lower contact), and from the fourth uppermost flow (upper contact). These three successive flows clearly differ in chemical composition.

The third uppermost flow is lower in total Fe, TiO_2, Na_2O and P_2O_5 (P_2O_5 is not shown in the figures), and higher in Al_2O_3, CaO and MgO than the second uppermost flow.

The fourth uppermost flow is lower in SiO_2, TiO_2, Na_2O and P_2O_5, and higher in Al_2O_3, CaO and MgO than the second uppermost flow. Most probably the fourth uppermost flow is also lower in total Fe than the second uppermost flow.

The average value of TiO_2 is 2.22% in the fourth uppermost flow, 1.36% in the third uppermost flow, and 3.30% in the second uppermost flow. Thus the TiO_2 values in three successive flows can change from 2.22 to 1.36 to 3.30%. Noe-Nygaard (1967) has shown that the average value of TiO_2 decreases from 2.8% in the lower series through 2.3% for the middle series to 1.0% for the upper series, and used this as evidence for a development from 'intraoceanic' (more than
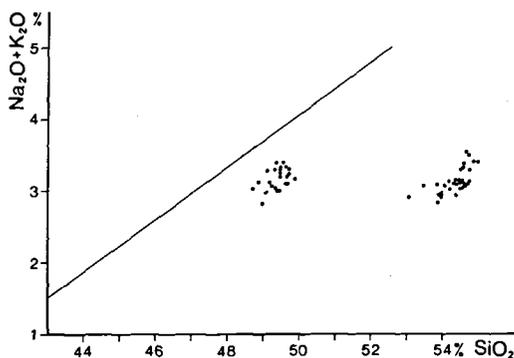

Fig. 11. Plot of total alkalies against silica (water-free compositions recalculated to 100%) for samples from the middle series (above 53% SiO_2) and upper series (below 50% SiO_2). The line is the Hawaii dividing line between tholeiitic and alkaline compositions (Macdonald & Katsura, 1964).
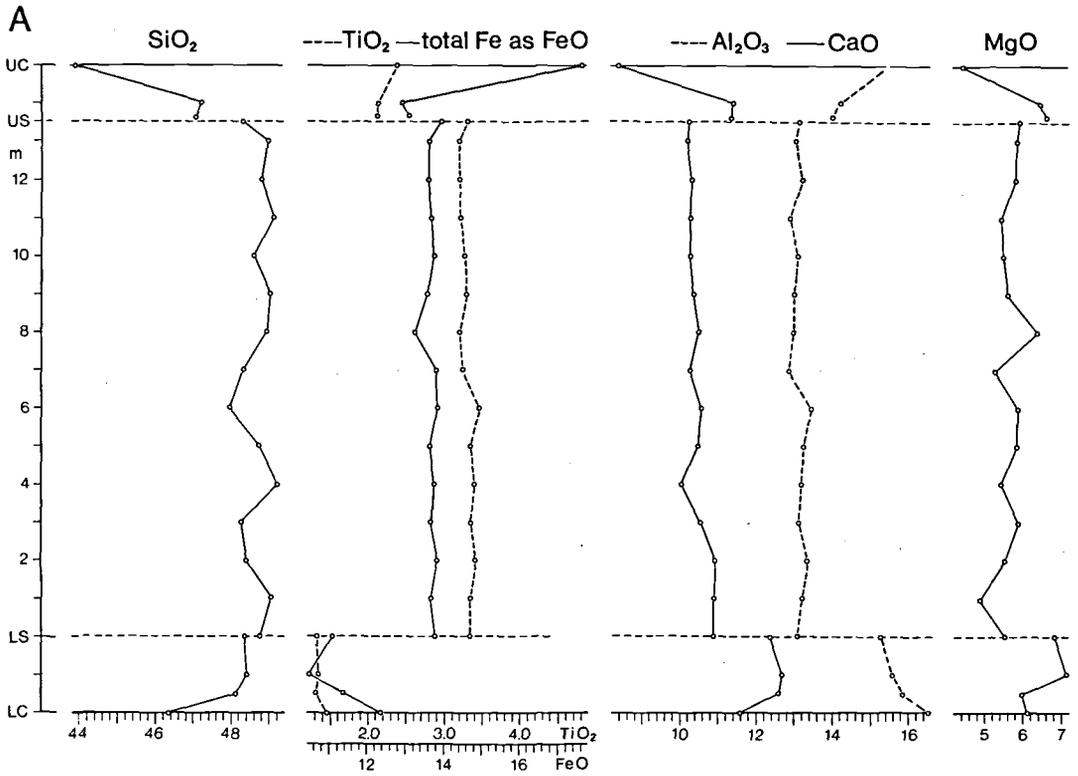
A

Fig. 12. Variations in SiO_2, total Fe as FeO, TiO_2, Al_2O_3, CaO and MgO across the flow from the lower series. A-profile. LC: lower contact. UC: upper contact. LS: lowermost sample of main profile. US: uppermost sample of main profile. Figures on ordinate are metres above lowermost sample of the main profile. Figures on abscissa are weight percentages.
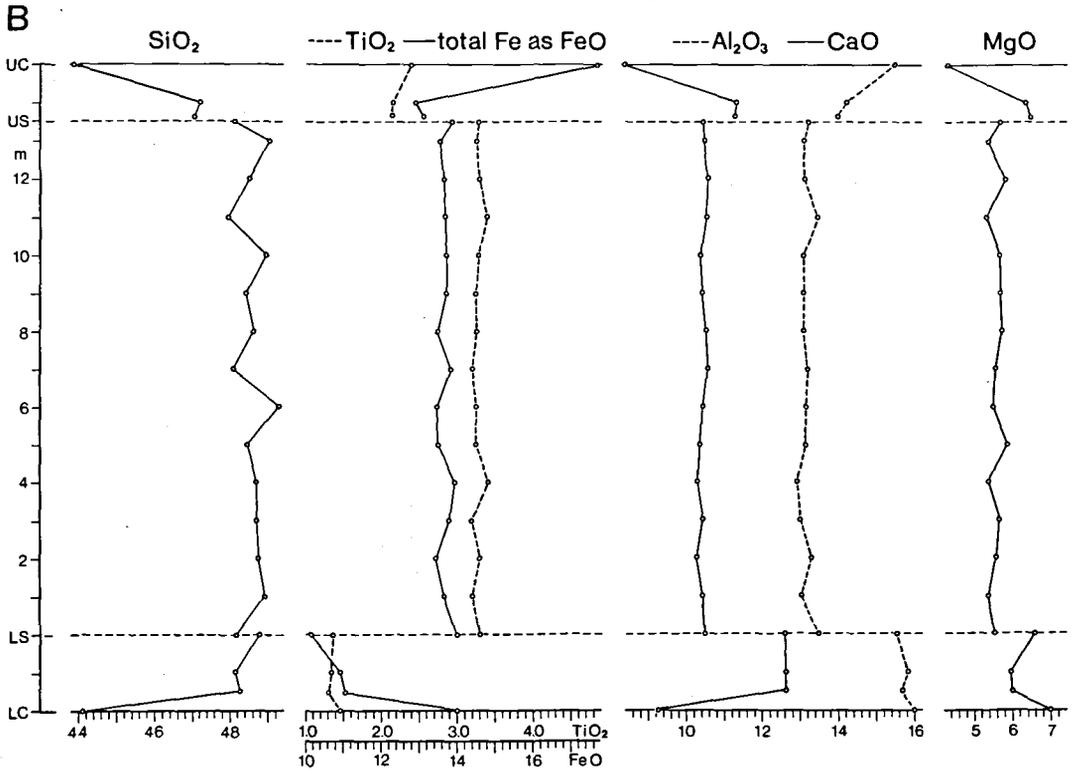
B

Fig. 13. Variations in SiO_2, total Fe as FeO, TiO_2, Al_2O_3, CaO and MgO across the flow from the lower series. B-profile. Notations as in Fig. 12.
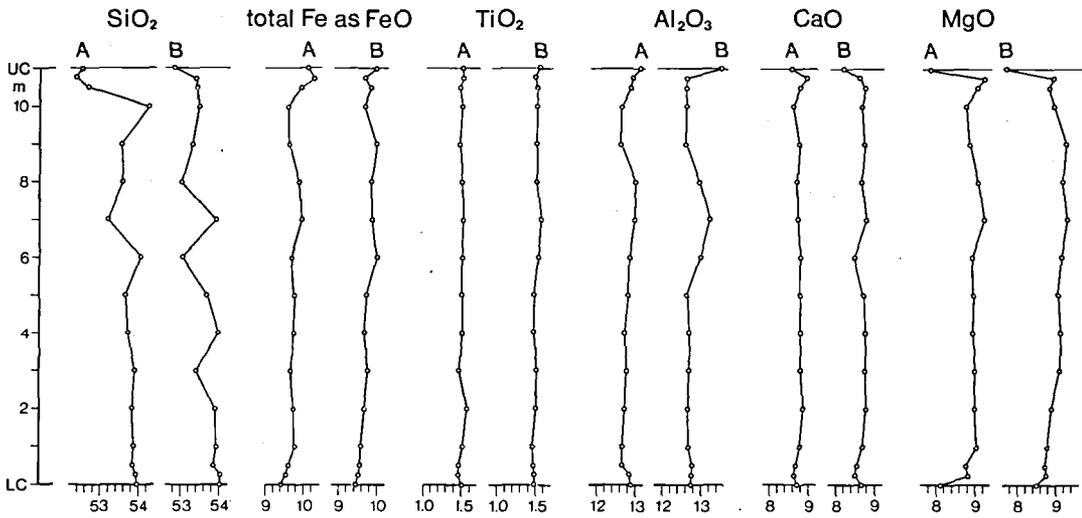
Fig. 14. Variations in SiO₂, total Fe as FeO, TiO₂, Al₂O₃, CaO and MgO across the flow from the middle series. Figures on ordinate are metres above lower contact. Figures on abscissa are weight percentages. A: A-profile. B: B-profile.
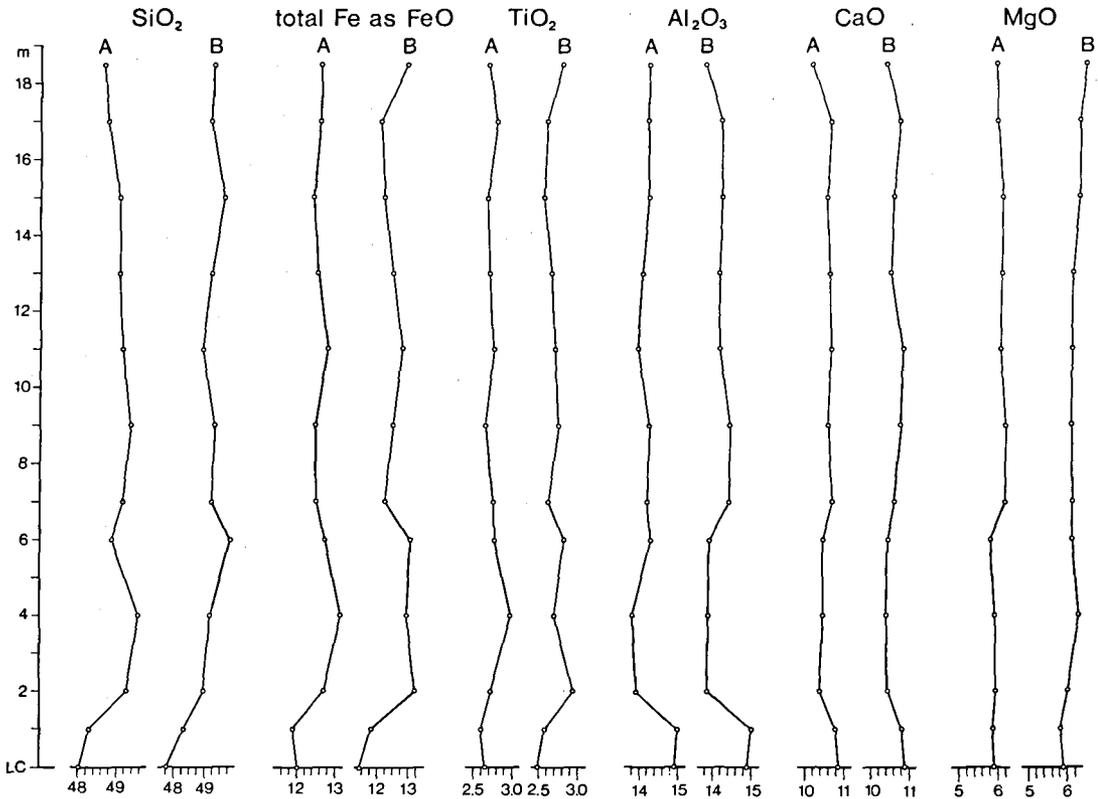

Fig. 15. Variations in SiO₂, total Fe as FeO, TiO₂, Al₂O₃, CaO and MgO across the flow from the upper series. Notations as in Fig. 14.
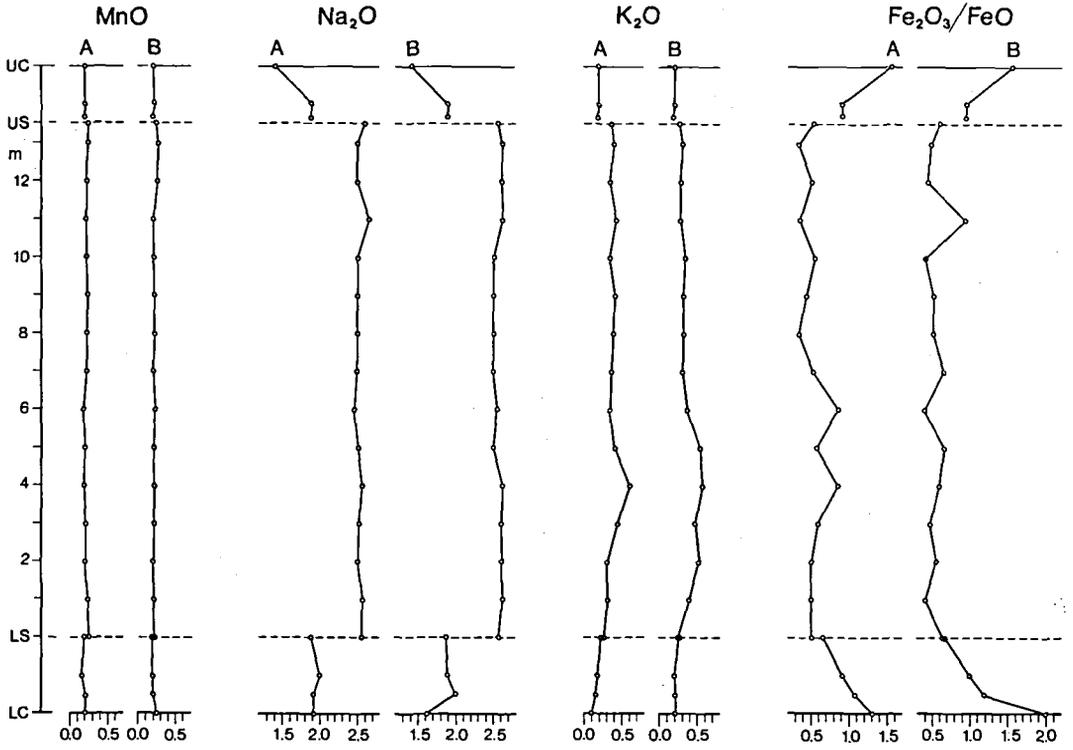
Fig. 16. Variations in MnO, Na$_2$O, K$_2$O and the ratio Fe$_2$O$_3$/FeO across the flow from the lower series.
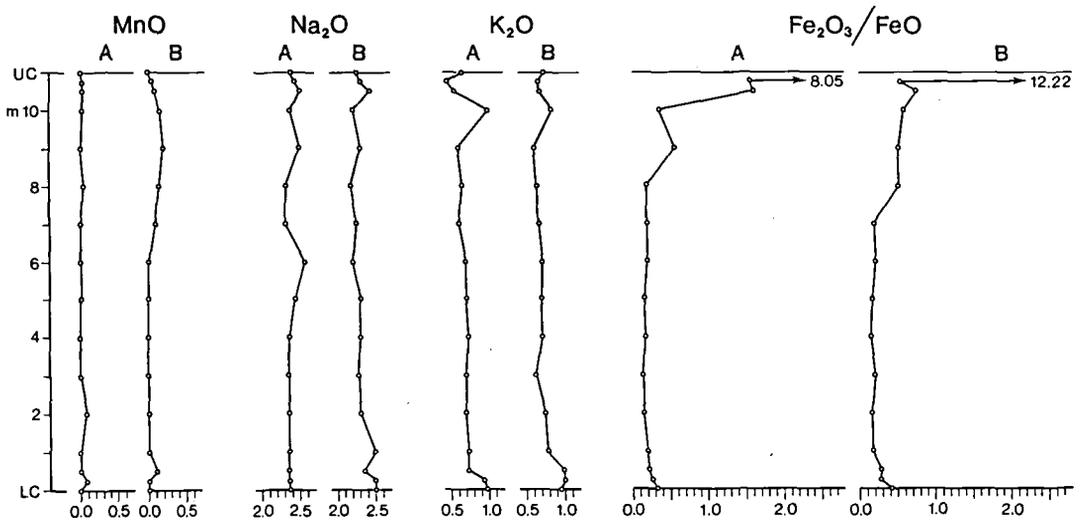
Fig. 17. Variations in MnO, Na$_2$O, K$_2$O and the ratio Fe$_2$O$_3$/FeO across the flow from the middle series.

2.0% TiO_2) to 'circumoceanic' (less than 1.5% TiO_2) basalts (Chayes, 1964; 1965) through the 3 km pile of lavas on the Faeroe Islands. The present investigation shows that the development from intraoceanic to circumoceanic and back to intraoceanic can occur in three successive flows in the lower series.

In the flow from the lower series SiO_2 is negatively correlated with total Fe, TiO_2 and Al_2O_3. In the supplementary profiles SiO_2, CaO and Na_2O all decrease at the contacts, however for Na_2O the decrease is most pronounced at the upper contact.

In the flow from the middle series SiO_2 is negatively correlated with total Fe, and possibly also with TiO_2, but here the variations in TiO_2 are too small to allow any conclusion. Na_2O seems to be negatively correlated with K_2O, and in the A-profile K_2O seems to be positively correlated with SiO_2.

In the flow from the upper series SiO_2 is positively correlated with total Fe and TiO_2, and negatively correlated with Al_2O_3 and CaO.

The values of P_2O_5 are rather constant through all the flows, but the values differ between the flows. P_2O_5 is present in amounts proportional to the amount of TiO_2 in the flow.

Variations in the ratio Fe_2O_3/FeO across the flows are shown in figs 16–18. As could be expected the curves agree well with the curves of oxidation stages shown in fig. 3. It is to be noted that as low a value for the Fe_2O_3/FeO ratio as 0.15, which some petrologists use as a correction factor in calculation of C.I.P.W. norms, has not been obtained in the flows from the lower and upper series, and only a few samples in the flow from the middle series have such low values.
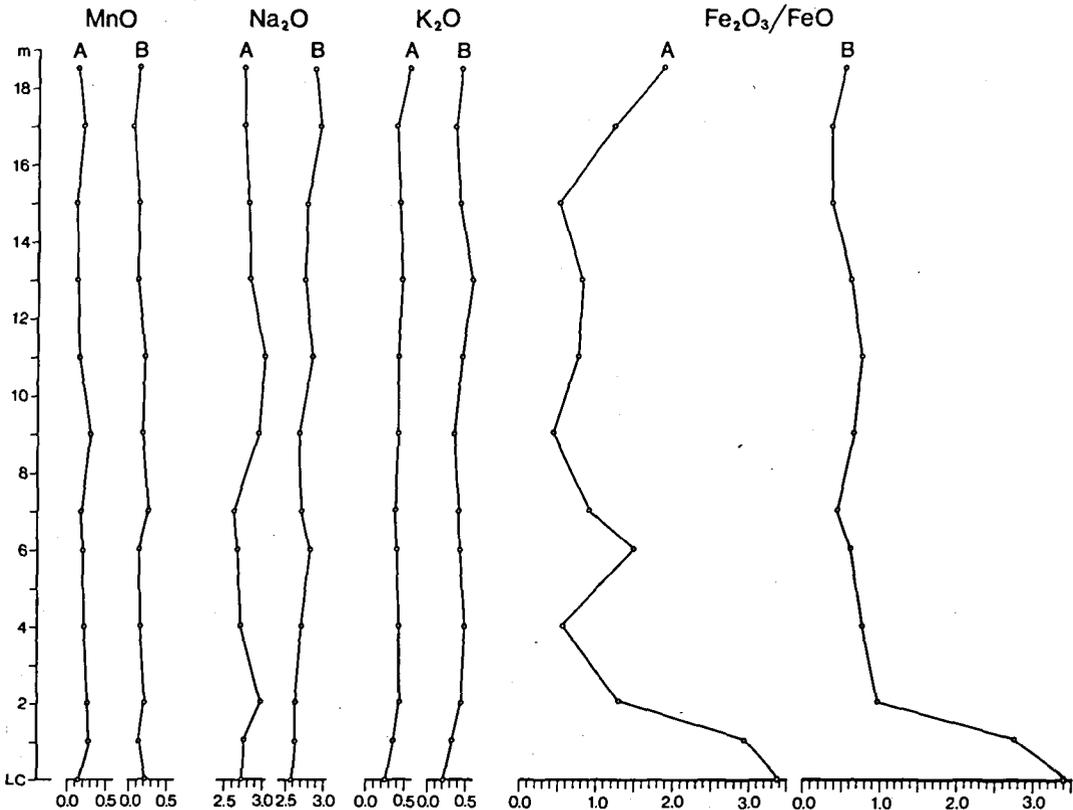

Fig. 18. Variations in MnO, Na_2O, K_2O and the ratio Fe_2O_3/FeO across the flow from the upper series.

Conclusions

Variations in mineralogy and chemistry related to position within flow are found across all three lava flows. In two of the flows (lower and middle series) variations are most pronounced within the metre closest to the contact. In the 18,5 m thick flow from the upper series the pronounced variations in chemical composition with distance from contacts persist until two metres from the lower contact, whereas changes in the amounts of the main mineral groups: plagioclase, pyroxenes and opaque minerals, towards the contacts are no more pronounced than the variations in the inner part of the flow. However, it is found that pigeonite is not present at all at the contact, but occurs in increasing amounts away from the contact.

It is difficult to draw any immediate conclusions as to whether the variations are caused by pre-eruptional or post-eruptional processes, or by combinations hereof. Amongst previous studies of variations within single extrusive bodies, post-eruptional processes have been inferred mainly in studies on lava lakes (Peck, Wright & Moore, 1966; Richter & Moore, 1966; Moore & Evans, 1967; Evans & Moore, 1968), while variations within lava flows have been ascribed to pre-eruptional differentiation – the most differentiated magma being first extruded, and later fractions becoming more basic – by Murata & Richter (1966), Richter & Murata (1966) and MacDonald (1967). Watkins, Gunn & Coy-yll (1970) ascribe the variations within an Icelandic lava as being partly due to the effects of initial-cooling oxygen fugacity gradients, but find it necessary also to invoke the possibility that the magma may have changed composition during eruption.

The relations at the contacts of the flow from the lower series and at the upper contact of the flow from the middle series are characterised by decrease towards the contacts in SiO_2, CaO and MgO, and increase in total Fe, TiO_2 and Al_2O_3. The sympathetic behaviour of SiO_2 and MgO is conspicuous as an antipathetic variation between these two oxides is generally expected and found, due to variations in the compositions of the silicates.

The modal changes towards the contacts are a decrease in pyroxenes as well as plagioclase and

an increase in Fe-Ti-oxides. The increase in Fe-Ti-oxides might be able to explain the observed chemical variations. An increase in total Fe and TiO_2 must involve a reduction in the percentages of the remaining oxides, and the effect will be greatest with SiO_2, the most abundant oxide.

If the chemical compositions are recalculated on a Fe–, Ti– and H_2O–free basis, then the decrease in SiO_2 towards the contacts becomes an increase, without the trend of the other oxides being changed.

It is therefore believed that the decrease of SiO_2 towards the contacts is caused entirely by the increase in Fe-Ti-oxides, and that if only silicate phases are considered SiO_2 will increase towards the contacts. If this is so the changes from the upper contact inwards are decrease in SiO_2 and Al_2O_3 combined with increase in CaO and MgO, and this is interpreted as the result of pre-eruptional differentiation.

The variations farther in the flows are too erratic to offer any possibilities for interpretation, but this does not exclude the possibility of post-eruptional differentiation, but any such differentiation must have been counterbalanced by the pre-eruptional differentiation.

In the flow from the upper series the variations are most pronounced towards the lower contact (the actual upper contact is not represented). SiO_2, total Fe and TiO_2 increase from the lower contact inwards, CaO and Al_2O_3 decrease, while the behaviour of MgO is not clear. These variations do not point to pre-eruptional differentiation, but are more akin to be the result of post-eruptional differentiation.

The author agrees with Watkins, Gunn & Coy-yll (1970) in their view that changes in Fe-Ti-oxides due to differences in initial-cooling oxygen fugacities play a very important role in the development of basic extrusives during solidification. Unfortunately the behaviour of the Fe-Ti-oxides is frequently ignored in petrological work, and the way in which some petrologists have chosen to get around this problem, namely the freezing of the Fe_2O_3/FeO ratio at some arbitrary value when comparing different rocks, is not in the opinion of the author an acceptable solution.

If corrections are needed it seems to be better not to use ilmenite and magnetite as normative

minerals when the oxidation of the Fe-Ti-oxides has reached stage 5, but simply to transfer TiO_2 and Fe_2O_3 as rutile and hematite, and leave all FeO for silicates. For lower oxidation stages an appropriate amount of TiO_2 and Fe_2O_3 could be used to previously form rutile and hematite, but in such cases ilmenite and magnetite should not be completely omitted. Such a procedure will give a better correspondance between the norm of ore minerals and the ore minerals actually present, and generally it would also prevent quartz tholeiites being turned into olivine tholeiites.

The samples from the same flows show a considerable spread in the different diagrams. Thus for instance the samples from the middle series change from the lower contact upwards from non-oceanic, to oceanic, to non-oceanic, to oceanic.

With the Fe_2O_3/FeO ratio adjusted to 0.15 it is found that the composition in the flows from the lower and upper series, from the lower contact upwards, can vary from olivine tholeiitic to quartz tholeiitic and back to olivine tholeiitic.

It is therefore concluded that unless a considerable number of samples is taken across each extrusive body, comparisons between different extrusive bodies cannot safely be made.

Dansk sammendrag

Variationer i mineralogi og kemi på tværs af lavabænke er blevet undersøgt ved hjælp af prøver taget på tværs med maksimalt 2 meters afstand gennem en bænk fra hver af de tre lavaserier på Færøerne. Der er taget prøver i to parallelle profiler gennem hver af de tre bænke.

De mineralogiske variationer er beskrevet på grundlag af mikroskopiske undersøgelser omfattende punkttællinger og bestemmelse af oxidationsindex for Fe-Ti-oxiderne og mikrosondeundersøgelser af de tre hovedgrupper af mineraler: Plagioklaser, pyroxener og Fe-Ti-oxider.

De kemiske variationer er baseret på 97 analyser. Der er dog i tabelform (tabel 2) kun gengivet gennemsnit af analyserne for hver af de tre bænke, men resultaterne af alle 97 analyser fremgår af figurerne 12–18, der viser variationen på tværs af bænkene for de almindeligste oxider, undtagen P_2O_5 der er praktisk taget konstant.

I et TiO_2–K_2O–P_2O_5 diagram (Pearce, Gorman & Birkett 1975) falder prøverne fra bænkene i nedre og øvre serie i oceanfeltet, medens prøverne fra bænkene i mellemste serie krydser grænsen mellem oceanfeltet og non-oceanfeltet.

I et F_1–F_2 diagram (Pearce 1976) falder prøverne fra nedre og øvre serie i feltet for pladetholeiter, medens prøverne fra mellemste serie falder i det felt der er fælles for kalk-alkali basalter og lav-kalium tholeiter.

I et alkali-silica diagram falder alle prøverne i det tholeitiske felt klart under grænselinien givet af Macdonald og Katsura (1964) for Hawaii-basalter.

Variationerne i bænkene fra nedre og mellemste serie antages hovedsagelig at skyldes præeruptional differentiering medens variationerne i bænken fra øvre serie formodes udelukkende at skyldes posteruptionale processer.

Sammensætningen af Fe-Ti-oxiderne varierer stærkt på tværs af bænkene, og hvis man ved normberegningen anvender korrektion af det fra analysen givne forhold mellem Fe_2O_3 og FeO til en arbitrær værdi, som det ofte er tilfældet i petrologiske arbejder, kan bjergartssammensætningen fra nedre kontakt og opefter variere fra olivintholeitisk til kvartstholeitisk og tilbage til olivintholeitisk.

En sådan korrektion kan derfor ikke betragtes som acceptabel. Hvis ændring i normberegningen ønskes foreslås det i stedet, at man i den udstrækning malmmineralerne faktisk er til stede som TiO_2, Fe_2O_3 og Fe_2TiO_5, slet ikke anvender ilmenit og magnetit som normative mineraler, men direkte overfører analysens TiO_2 og Fe_2O_3 som rutil og hæmatit, og reserverer al FeO til silikater. Denne fremgangsmåde vil give bedre overensstemmelse mellem norm og modus og desuden gennemgående forhindre at kvartstholeiter bliver beregnet som olivintholeiter.

Undersøgelsen har vist at variationerne i mineralogi og kemi inden for samme lavabænk er så store at sammenligninger mellem forskellige lavabænke ikke kan foretages på et sikkert grundlag, medmindre de er baseret på et betydeligt antal prøver fra hver enkelt bænk.

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