Trace element variations in Faeroese basalts and their possible relationships to ocean floor spreading history

HALDIS BOLLINGBERG, C. KENT BROOKS and ARNE NOE-NYGAARD

Bollingberg, H., Brooks, C. K. & Noe-Nygaard, A.: Trace element variations in Faeroese basalts and their possible relationships to ocean floor spreading history. *Bull. geol. Soc. Denmark*, vol. 24, pp. 55–60. Copenhagen, November 19th., 1975.

Average values are presented for spectrographic determinations of 8 trace elements in 71 samples of Faeroese basalts. An upper series of olivine tholeiites are poorer in Sr, Ba, Zr, Cu and V and richer in Ni and Cr than the aphyric quartz tholeiites of a lower series. The plagioclase-phyric quartz tholeiites of a middle series are intermediate between the two. It is suggested that the lower series were erupted during an early period of more active plume discharge while the upper basalts, which resemble typical ocean ridge tholeiites, were erupted during a subsequent period of low plume influence, for which there is independent evidence.

H. Bollingberg and C. K. Brooks, Institut for Petrologi, Øster Voldgade 5–7, DK-1350 København K, Denmark. A. Noe-Nygaard, Mineralogisk Museum, Øster Voldgade 5–7, DK-1350 København K, Denmark. February 2nd, 1975.

The Faeroe Islands (Rasmussen & Noe-Nygaard, 1970) are important for studies of sea-floor spreading history in the North Atlantic as the 3 km thick sequence of basalts exposed here was erupted during the early stages of rifting, about 60 m.y. ago (Tarling & Gale, 1968).

Detailed studies of stratigraphy, petrology and major element chemistry by Noe-Nygaard & Rasmussen (1968) and Rasmussen & Noe-Nygaard (1970) have shown that systematic changes occur throughout the volcanic succession, which stratigraphically is divided into three series. Thus there is a lower series of predominantly aphyric quartz tholeiites a middle series of mainly plagioclase-phyric quartz tholeiites (but also include lavas which are forerunners for the upper series) and an upper series, which consists largely of olivine tholeiites. Two minor unconformities separate the three series.

Noe-Nygaard (1967) found that a high TiO_2 content, average 2.8 %, was characteristic of the iron-rich quartz tholeiites of the first stages of volcanic activity, whereas the lavas of the upper series, olivine tholeiites, only had 1 % TiO_2 on an average. The middle series with 2.3 % lay in between these two but closer to the values in the lower series.

In plots of alkalis versus SiO_2 and iron enrichment versus SiO_2 presented by Noe-Nygaard & Rasmussen (1968) it was clearly demonstrated that the aphyric quartz tholeiites of the lower series follow one trend line, the olivine tholeiites of the upper series another, while the middle series take up an intermediate position.

Recently, Schilling & Noe-Nygaard (1974) have shown that there is an abrupt change in rare earth patterns near the boundary between the middle and upper series. Below this level the basalts are relatively enriched in the light rare earths relative to the heavy rare earths, while higher up, the light rare earths are relatively depleted. Schilling & Noe-Nygaard explained this by analogy with other areas, thought to represent the sites of convective plumes upwelling from deep levels in the mantle (Schilling, 1973 a & b) by postulating that the lower part of the succession is plume-derived, whereas the olivine basalts of the upper series which resemble basalts dredged from the mid-ocean rifts are derived from the low velocity zone of the upper mantle. It is interesting that Pálmason (1965) found a seismic discontinuity at about the same level in the Faeroes succession.

Brooks & Jakobsson (1974) have drawn attention to the fact that the quartz tholeiites

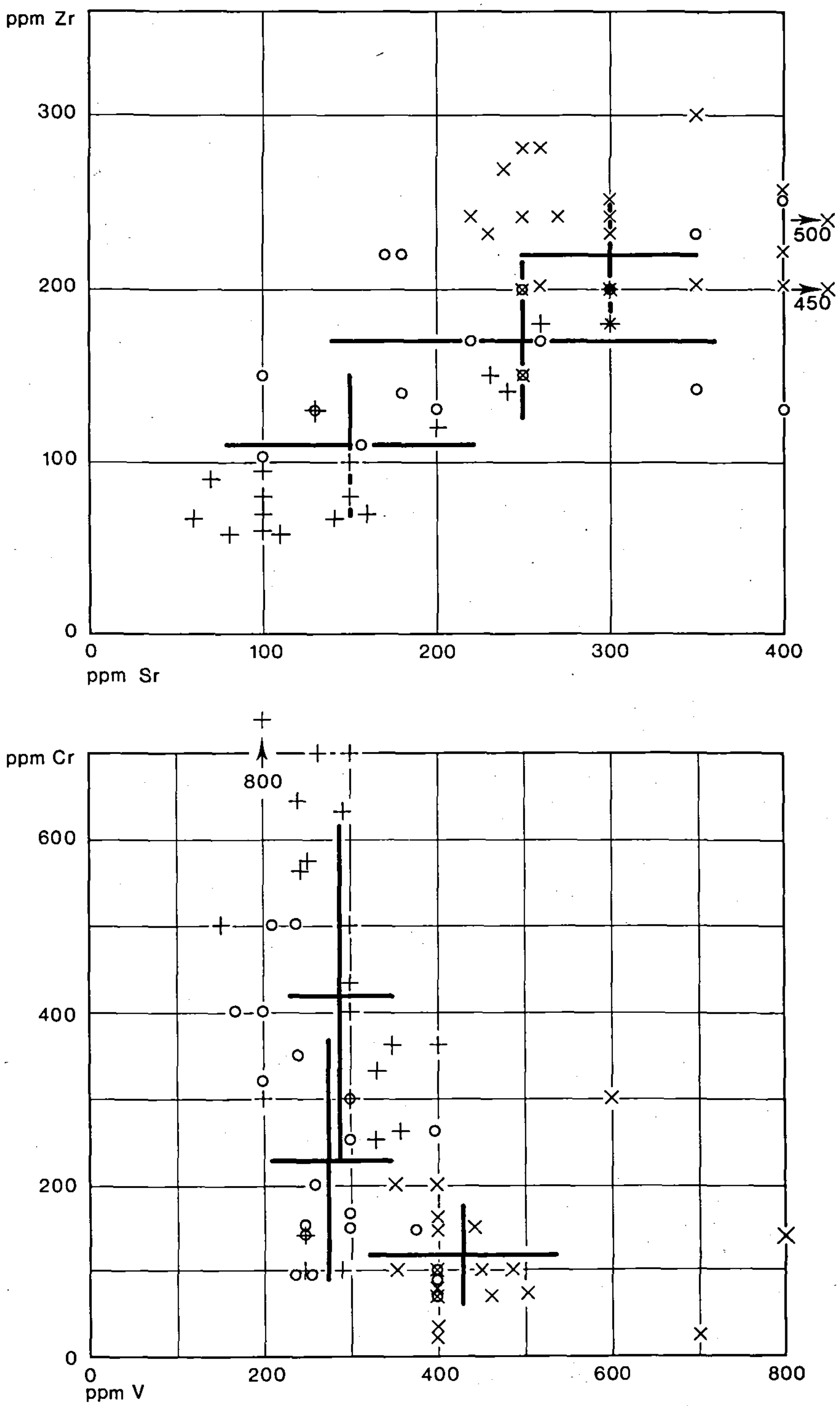

Fig. 1. The correlation between Zr and Sr (above) and Cr and V (below) in Faeroese basalts showing the observed spread of the data. Symbols are: x, lower series; o, middle series; +, upper series. Each series is defined as in table 2. Heavy crosses show the averages and standard deviations for the three groups of data.

closely resemble the group of Fe-Ti-rich basalts which are characteristic of hot spots and believed by many to be derived from rising plumes of hot mantle material. Their composition is indistinguishable from many of the Recent Icelandic basalt analyses compiled by Jakobsson (1972).

In this note we present the results of determinations of 8 trace elements in 71 samples of Faeroese basalts in an attempt to define the trace element characteristics of the three lava series and to see to what extent the differences observed in petrology and major elements are reflected in the trace elements.

Results

The analytical work was carried out by H.B. using emission spectrographic techniques for which the uncertainty is regarded as being a maximum of 10 relative per cent for most of the results reported. Calibration was carried out using well-established synthetic standards. Mean values and observed standard deviations for the three basaltic series are reported in table 1. Individual results are not presented here but may be obtained from the authors on request. Fig. 1 is included to give an impression of the spread of the data and the

Table 1. Average major element compositions. C.I.P.W. norms and trace elements in the three Faeroese lava series.

	1 'lower series'	2 'middle series'	3 'upper series'	4 ocean ridge basalt	5 plume basalt
SiO_2	48.8 ± 2.1	49.5 ± 2.3	47.4 ± 1.3	50.44	50.42
Al_2O_3	12.9 ± 0.9	14.5 ± 1.1	14.8 ± 1.0	15.75	13.56
Fe_2O_3	7.6 ± 2.7	4.3 ± 1.2	4.1 ± 1.5	1.19	3.53
FeO	8.3 ± 2.3	8.4 ± 1.6	8.6 ± 1.4	8.65	11.91
MgO	5.9 ± 1.0	7.2 ± 1.4	9.6 ± 1.9	8.31	5.60
CaO	10.4 ± 0.9	10.9 ± 1.0	11.8 ± 1.1	10.72	9.21
Na_2O	2.4 ± 0.3	2.3 ± 0.3	1.8 ± 0.1	2.93	2.49
K_2O	0.4 ± 0.2	0.4 ± 0.2	0.3 ± 0.1	0.13	0.56
MnO	0.2 ± 0.0	0.2 ± 0.0	0.2 ± 0.0	0.16	0.24
TiO_2	2.9 ± 0.5	2.3 ± 0.7	1.4 ± 0.5	1.70	2.48
C.I.P.W. weight norm (after Fe_2O_3/FeO adjusted to 0.15)					
Q	–	–	–	–	1.30
or	2.4	2.4	1.8	0.78	3.34
ab	20.5	19.1	15.7	24.89	21.15
an	23.2	28.4	31.2	29.49	24.29
di	24.1	21.5	22.5	18.46	16.80
hy	20.7	20.4	8.0	14.17	24.79
ol	0.5	1.5	15.8	7.11	–
mt	2.9	2.4	2.4	1.87	2.90
il	5.6	4.3	2.6	3.24	4.73
Trace elements no. of samples	27	21	23		
Ba	90 ± 30	70 ± 30	20 ± 30	10	130
Sr	300 ± 50	250 ± 110	150 ± 70	135	182
Zr	220 ± 30	170 ± 45	110 ± 40	89	180
Cu	300 ± 120	200 ± 80	190 ± 60	62	91
Co	70 ± 20	50 ± 10	60 ± 10	41	47
Ni	120 ± 50	120 ± 50	260 ± 100	135	30
V	430 ± 110	280 ± 70	290 ± 60	313	460
Cr	120 ± 60	230 ± 140	430 ± 200	303	25

Cols. 1–3: Major element data in percent from Rasmussen & Noe-Nygaard (1969)
Trace element data in p.p.m. rounded to two significant figures with observed standard deviations.
Sample grouping: see Table 2.
Col. 4: Typical ocean ridge basalt. (Brooks & Jakobsson, 1974).
Col. 5: Typical basalt from plume area (Brooks & Jakobsson, 1974).
All major element analyses recalculated to 100 % H_2O–P_2O_5-free.

Table 2 Sample groupings of Faeroese basalts

'upper series' (olivine tholeiites)	Flows of profiles XI–1 to 6 and XI–13 to 23, together with flows IV–2, –10, –11; V–I and –3; VI–2 and 3 and X–4.
'middle series' (plagioclase-phyric quartz tholeiites)	Flows of profiles IV–X and XIb except those noted above.
'lower series' (aphyric quartz tholeiites)	All flows of profiles I, IIa & IIb.

For profile location see Rasmussen & Noe-Nygaard (1969), p. 18, English edition. NB: profile III from the lower series has been omitted entirely as certain flows are strongly weathered and several are porphyritic.

degree of overlap between the different groups. The major element compositions in table 1 are computed from the compilations in Rasmussen & Noe-Nygaard (1969) and the C.I.P.W. norms have been calculated after adjustment of the Fe_2O_3/FeO ratio to 0.15, a value close to that commonly observed in fresh glass from dredged oceanic basalts. This latter procedure is designed to eliminate the effects of secondary oxidation on the normative mineralogy and allow a more objective comparison. However, if this is done, the normative quartz disappears from the lower and middle series basalts, and they become very weakly olivine normative whereas the upper series becomes strongly olivine normative. The original nomenclature which is retained here, is based on normative compositions derived from the analytical Fe_2O_3/FeO values.

It should be noted that the grouping of samples in table 1 is not entirely after stratigraphic position as petrology and stratigraphy do not fully coincide. Thus certain flows in the upper part of the lower series are plagioclase-phyric and are best grouped with the middle series, while similar anomalies occur in the middle series and the lower part of the upper series (Rasmussen & Noe-Nygaard, 1969). For this reason a grouping into "lower", "middle" and "upper series" which is based on petrological features is preferable to one using rigorous stratigraphic criteria. The rare earth data of Schilling & Noe-Nygaard (1974) confirm that certain flows occupy an anomalous position (eg. flow X-4 in the upper part of the middle series). Details of this grouping are explained in table 2. This slightly different grouping accounts for minor variations from the earlier averages of Noe-Nygaard (1967).

The new results corroborate the three-fold division of the Faeroese basalts based on other factors. Thus, the lower basalts are distinctly richer in Sr, Ba, Zr, Cu and V (as well as total Fe and TiO_2) than the upper series, which, in turn, are richer in Ni and Cr (as well as Mg). Again, the middle series tend to be intermediate in character.

Discussion

If the averages reported in table 1 are compared with typical values for basaltic rocks from oceanic areas tabulated by Brooks & Jakobsson (1974) it is found that the lower series are typical plume or hot-spot type tholeiites, rich in Fe, Ti and incompatible elements such as Sr, Ba and Zr. The upper basalts, on the other hand, are depleted in these elements and are typical of basalts dredged from abyssal portions of the mid-ocean ridge system. The trace element data are therefore in harmony with the major element and rare earth data as noted above. Although the data presented here are somewhat equivocal on this point, we do not believe that these variations can be interpreted on a fractional crystallisation model, because the trace element contents do not lie on differentiation curves defined by ocean tholeiites. However, more accurate determinations of some of the more critical elements will be necessary before a definite conclusion can be reached.

It has been suggested (Schilling, 1973a & b) that the Icelandic, or Fe-Ti rich-type basalts are derived from a hot rising mantle plume of relatively primitive material which may possibly be the driving force of plate tectonics. The basalts from abyssal parts of the mid-ocean ridge originate by a passive melting process in the low velocity zone and owe their low level of large radius lithophile elements to the fact that these have been removed from the low velocity zone during previous episodes of partial melting. Whatever the mechanism of these observed differences is, the chemistry of the Faeroese basalts indicates clearly that a change took place here during the eruption of the 3 km sequence of flows during the lowermost Tertiary from one of these environments to the other. It is extremely tempting to correlate this change with the decrease in plume activity about this time which was deduced by Vogt (1972) from entirely different considerations. Such a correlation has previously been drawn by Schilling & Noe-Nygaard (1974). On this basis, it seems that the lower series were erupted during a period of vigorous plume activity approximately 50–60 m.y. ago (Tarling & Gale, 1968), which may well correspond to the time of initiation of ocean floor spreading in this part of the North Atlantic. Basalts of this age and petrochemical type are abundant in East Greenland (Fawcett, Brooks & Rucklidge, 1973; Noe-Nygaard & Pedersen, 1974) and Brooks (1973) has suggested that these basalts were continuous with the Faeroe plateau at this time. The middle series of the Faeroe basalts were erupted during the waning phase of plume activity, possibly when the discharge rate had become low enough to allow the formation of plagioclase phenocrysts during ascent to the surface. By the time the upper series were erupted, the plume influence was virtually non-existent and the magmas were typically of ocean tholeiite-type, derived passively from a layer of the asthenosphere, which has been depleted in large ionic radius lithophile elements.

Rasmussen & Noe-Nygaard (1969) give the following volumes for the various series: lower series 30 %, middle series 40 % and upper series 30 %. However, the base of the series is not exposed and it is likely that the lower series is by far the most voluminous and the upper series least voluminous as it does not appear that there has been drastic loss of the upper part of the plateau by erosion. These relationships would be expected from the model postulated by Schilling & Noe-Nygaard (1974) and in this paper.

These ideas, although speculative, are capable of further investigation. We should, for example, expect that basalts similar to the Faeroese upper series are present in the East Greenland succession although they have not yet been recognized. Vogt (1972) suggested that mantle plume discharge might be synchronous on a global scale. If this is the case, similar variations in chemistry should be seen at other plume sites and along plume traces.

Acknowledgement. We thank Tom Svane Petersen for help with data processing.

Dansk sammendrag

Der er blevet foretaget spektografisk bestemmelse af en række sporelementer i basalterne i den 3 km tykke færøske lagsøjle. De opnåede resultater viser, at den nedre series kvarts-tholeiiter præges af en aktiv »plume« virksomhed, hvorimod den øvres olivin-tholeiiter er nært beslægtet med normale oceanryg-basalter; den mellemste serie danner en overgang mellem de to. Sporelementernes vidnesbyrd bekræfter dermed fuldt ud de ad anden vej opnåede indikationer.

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