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FAEROE–ICELAND PLUME: RARE-EARTH EVIDENCE

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Rare-earth abundances through the 3000-m thick Faeroes Plateau basalt monitor the Faeroe-Iceland plume activity with time. An abrupt change from light Re-enriched to depleted patterns is observed naer the boundary of the middle and upper series of the Faeroes Plateau basalt. The discontinuity seems to reflect a change of volcanic regime from plume-derived to more akin to oceanic type. The change also coincides with field evidence for beginning of subsidence of the plateau. Using existing spreading rate history for the North Atlantic during the 50–60-m.y. B.P. period, which is one of deceleration, the change of volcanic regime suggests a decline of intensity of the Faeroe–Iceland plume during the late part of the period. Rising blobs, rather than a continuous plume, appears preferable for modeling the temporal plume activity.

1. Introduction

Wilson [1] originally suggested that branching aseismic ridges are the topo-volcanic expression of hotspot activity and movement of the lithospheric plates over the mantle with time. Dietz and Holden [2] suggested that plateau basalts on the border of continents reflect initial plume activities at the onset of continental breakups and drifts. Vogt [3] using excess topography and derived volcanic production rates has estimated plume activity with time for Iceland and Hawaii. Recently, Schilling [4] has inferred the present Iceland plume intensity and extent of overspill along the Reykjanes Ridge from the geochemistry of dredged basalts along the ridge.

Because of the geochemical imprinting, the possibility exists subject to a number of conditions, to monitor mantle plume activity with time, and/or overlying ridge-spreading history.

This can be done by following geochemical variations through piles of tholeiitic plateau basalt flow accumulation, to aseismic ridges and tholeiitic basalt presently erupting over related plumes; similarly as Vogt used excess topography [3].

Here we report RE data on the Faeroe basalts and for comparison some East Greenland Plateau basalts, a few basalts across Iceland and the Reykjanes Ridge at 60°N (Fig. 1). These results are interpreted in terms of the early Iceland–Faeroe plume activity with time.

2. Model

We consider the Mid-Atlantic Ridge–Iceland plume system from the time of the onset of continental drift to its present configuration. We combine Gass's [5] lithothermal model for doming at the onset of continental breakup and drift, and Schilling's [4] Iceland plume model, which stresses two distinct mantle rock types as the source of basaltic lavas. The plume is considered not only as a hotter portion of the mantle, but also made of slightly lighter and more primordial material (primary hot mantle plume,

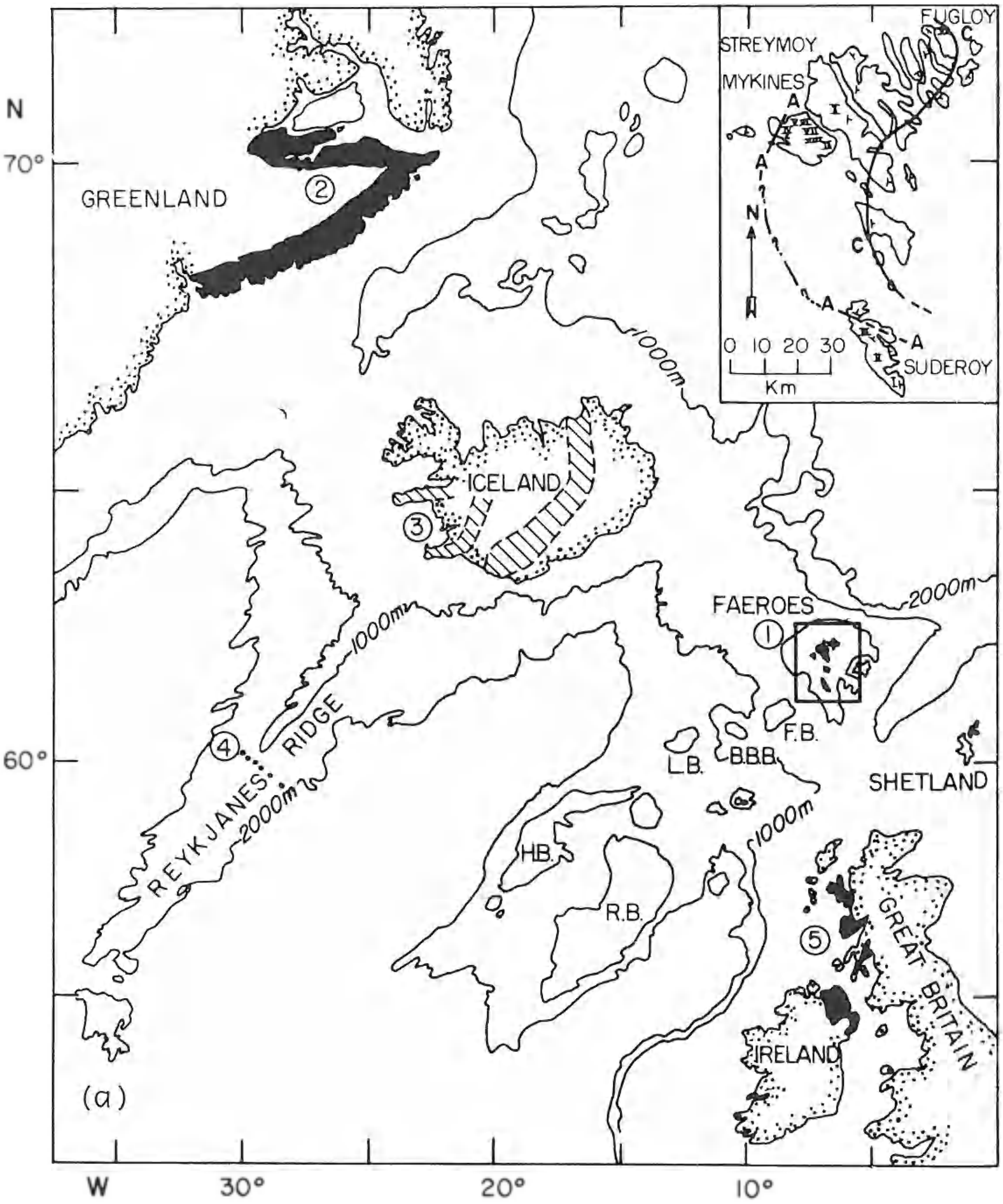


Fig. 1 (for legend see next page).

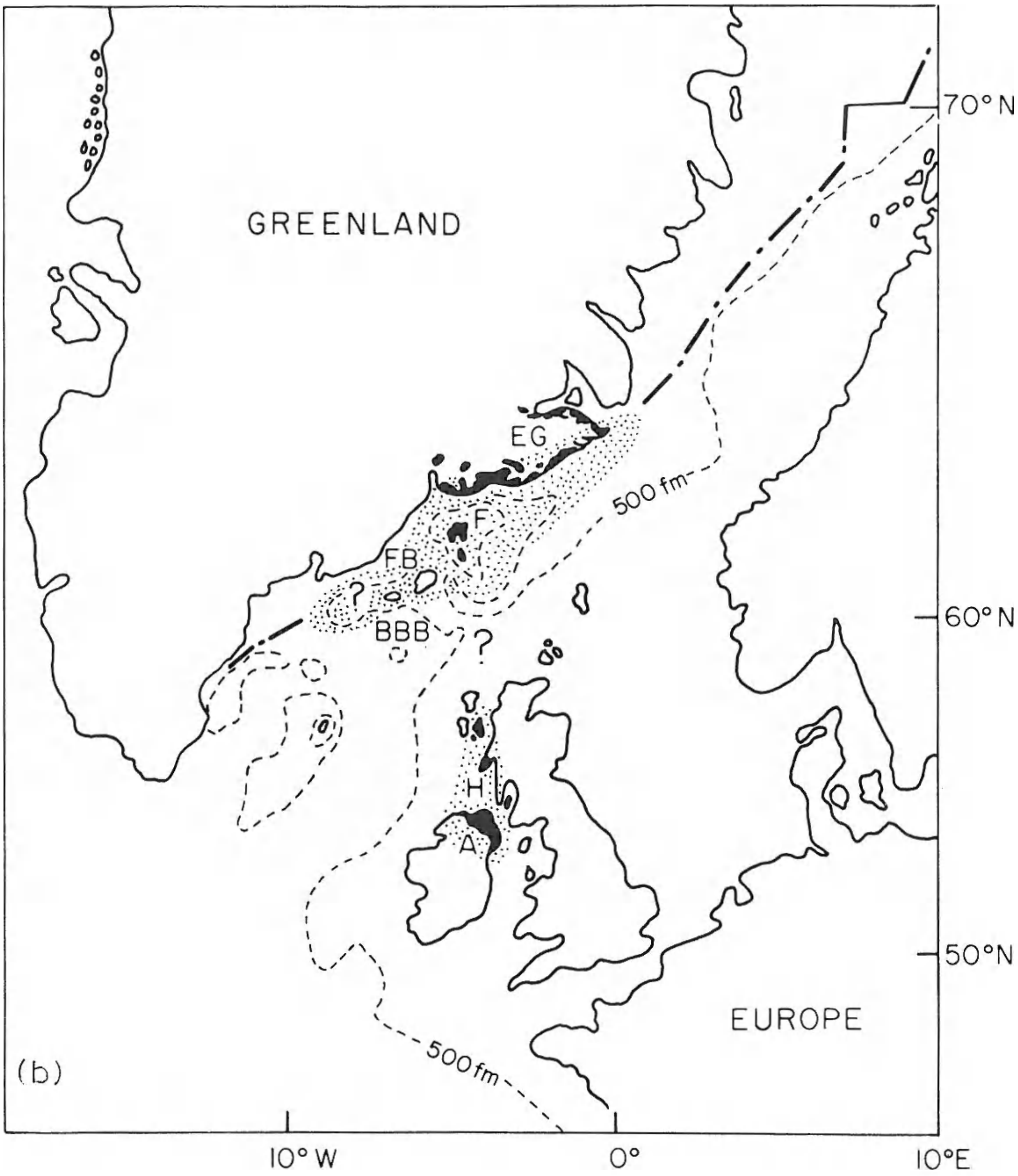
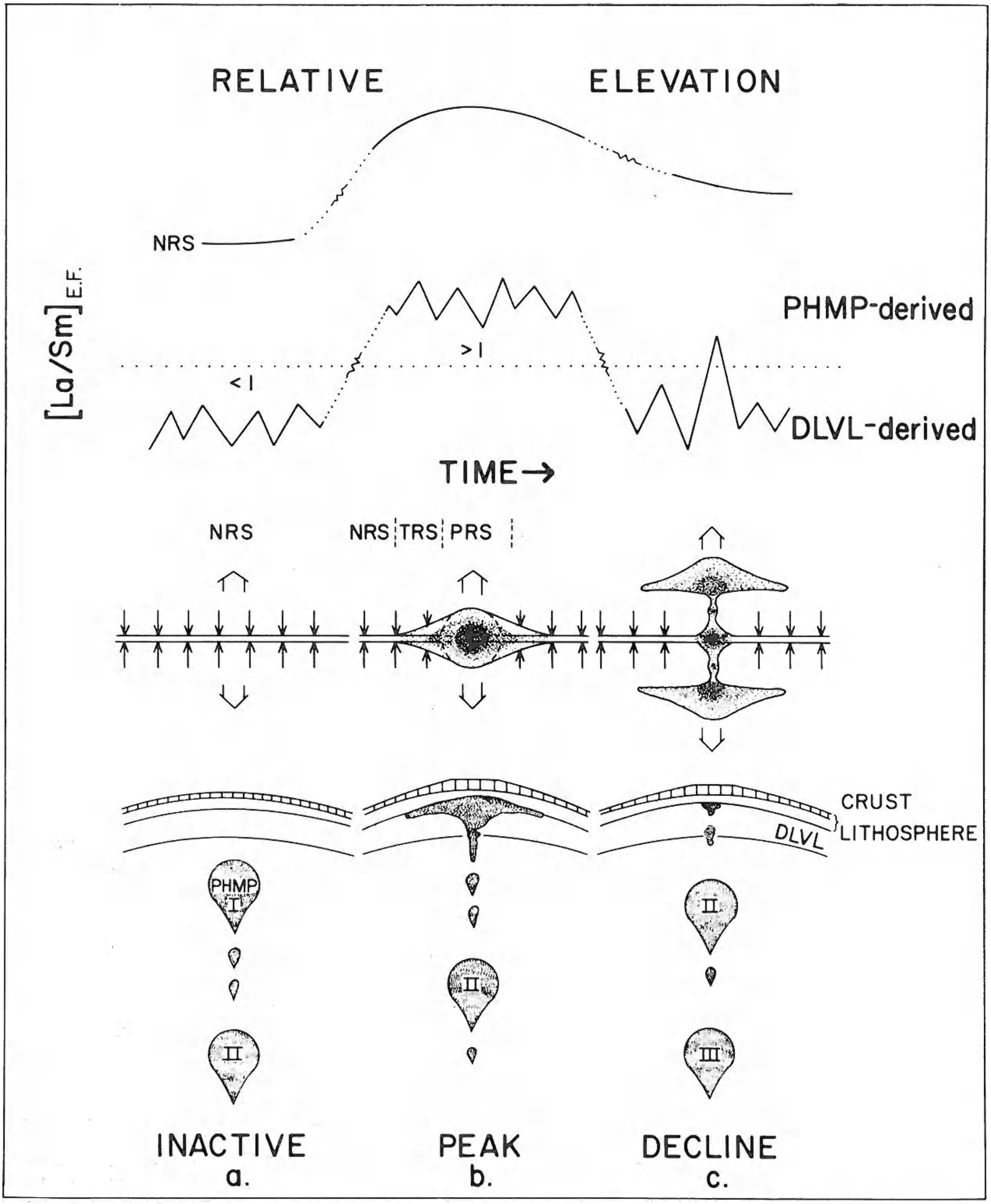


Fig. 1. (a) Present bathymetric map of the North Atlantic. Areas: 1 = Tertiary plateau basalts of the Faeroe Islands, 2 = East Greenland Tertiary basalts (Scoresby Sund), 3 = Iceland, hatched areas are neovolcanic zones, 4 = Dredged basalts across the Reykjanes Ridge up to 4 m.y. B.P. [55], 5 = Hebrideans Tertiary basalts, including Antrim Plateau basalt, blackened. Upper right insert shows location of the Faeroes lava flow horizons studied.

(b) A 60-m.y. paleogeographic reconstruction of the North Atlantic [34], showing the position of Tertiary plateau basalt volcanism, and possible general trends of blob flattening and spill, which remains to be established (dotted areas). F = Faeroes, EG = East Greenland, H = Hebrides, A = Antrim, FB = Faeroe Bank, and BBB = Bill Bailey Bank. Dot-dash line marks probable position of rift at the time.


RELATIVE ELEVATION
NRS
[La/Sm]E.F.
PHMP-derived
>1
<1
DLVL-derived
TIME→
NRS
NRS TRS PRS
CRUST
DLVL
LITHOSPHERE
PHMP I
II
II
II
III
INACTIVE
a.
PEAK
b.
DECLINE
c.

PHMP), chemically [4] and isotopically [6] distinct from the surrounding depleted low-velocity layer (DLVL) which the plume penetrates from below. The plume evolution over a ridge spreading at a *constant* rate is sketched in Fig. 2.

Three critical segments of spreading ridges and derived sea floor need to be considered: (1) normal spreading-ridge segments sufficiently remote from the plume to be free of its influence, (2) directly over the plume, and (3) the transitional ridge segment.

2.1. "Normal ridge segments (NRS)"

Along NRS, diapirs made of crystal mush rise passively from the low-velocity layer in *response* to spreading, and so does the tholeiitic melt produced by further partial melting and segregation during the rise and decompression of the diapirs. NRS are characterized by normal ridge elevation, well-developed and symmetrical magnetic anomalies, typical oceanic crustal thickness and structure [7], similar and uniform characteristics of subsidence of the newly formed lithosphere, apparently independent of spreading rates [8], and finally greater seismicity than TRS, judging from the Reykjanes Ridge [9]. Sea-floor basalts from NRS are tholeiitic, depleted in large ionic lithophile elements, low in radiogenic isotopes [6] and are DLVL-derived. The $[La/Sm]_{E.F.}$ of DLVL basalts source is less than unity and remains mostly independent of time, and sea-floor spreading rates except perhaps for very slow spreading ridges [10–12]. The DLVL mantle source is a zone of incipient melting, worldwide spread and appears comparatively remarkably uniform in time and space relative to mantle plume sources. Evidence for such a postulate is now well documented [10–12]. The survey includes the NRS of the Reykjanes Ridge, south of 61°N where the Iceland plume influence fades out.

2.2 "Plume ridge segments (PRS)"

Ridge segments lying presumably over rising plumes, such as beneath Iceland and the Azores, are characterized by unusual ridge elevation marked often by a satellite gravity high [13], branching aseismic ridges or island chains, crustal structure and thickness intermediate between typically oceanic and continental, and higher geothermal gradients at least for the upper 100 km depth [14,15]. Plume material along PRS is *forcefully* injected at a rate often exceeding in volume the amount required to fill the gap left by the overlying spreading plates of lithosphere, thus allowing accumulation of thick plateau basalt and formation of anomalously thick oceanic crust. The geochemistry of *rift tholeiitic* basalts over PRS is more complex than along NRS, even excluding central volcano-complexes such as on Iceland. Their trace element and radiogenic isotope ratios may vary with time in a way which primarily depends on the upward mantle plume flux and its accompanying volcanic discharge relative to the horizontal sea-floor spreading rate [4, and Schilling, in preparation]. For the moment, these two rates are assumed independent. Two critical conditions are geochemically detectable over PRS:

(1) The plume input flux is in excess of usual amount of rocky material needed to heal the gap created by the overlying spreading axis. Thus new lithosphere over the plume segment is entirely derived from PHMP material and the lava has a $[La/Sm]_{E.F.} > 1$ and radiogenic isotopes characteristic of the particular plume. Plateau basalts can accumulate as the plume is forcefully feeding the spreading axis.

Fig. 2. Plume-ridge model system showing possible plume flux variation with time and cycle consistent with geochemical variations observed in basaltic discharges (blob model). Phases: (a) plume is rising over an existing spreading ridge, (b) plume flux is in excess of the overlying lithospheric production rate, thus creating blob flattening and spill along spreading directions. This will allow plateau basalt accumulation over the plume segment and possibly an elevated crestal block along the transitional ridge segment; (c) tailing phase of the blob and thus decline of plume activity. The plume flux is insufficient to feed the overlying spreading ridge and DLVL material complements. Phase (a) can be modified to consider blob rising beneath a continent, and creating doming [5], continental breakup, blob flattening and spill along direction of weakness possibly as shown in Fig. 1b. Phase (b) and (c) would remain essentially the same except for spreading rift breaking configuration. Small arrows indicate lateral asthenospheric flow lines of DLVL material toward the ridge axis. Large arrows indicate spreading directions of the overlying plates of lithosphere.

Excess material will spill on either side of the plume in the asthenosphere just beneath the ridge axis, because the axis is already hotter, softer, and tends to be mass deficient because of the spreading. This is the case observed today along the Reykjanes Ridge and over Iceland [4].

Such conditions over PRS can be altered, either by decreasing the upward plume flux, or by tapering of the plume diameter as shown in Fig. 2 for a "blob" model, or alternatively by acceleration of the spreading velocity.

(2) The other critical condition is when the plume flux becomes less than the amount required by the overlying spreading axis. Then, DLVL material passively will complement laterally, mix with PHMP material and produce hybrid lavas with a $[La/Sm]_{E.F.}$ ratio and radiogenic isotopic imprinting intermediate between values for pure PHMP and DLVL sources, and dependent on the mixing proportions [4, and Schilling, in preparation].

2.3. *"Transitional ridge segments (TRS)"*

Over this transition zone, the $[La/Sm]_{E.F.}$ of tholeiitic lava varies along its length at a rate depending on the condition of plume flux overflow with time, and spreading rate of the overlying ridge. Values ranging from PHMP to DLVL imprinting will be obtained reflecting the mixing condition in space and time; and the presence or absence of an elevated crestal ridge block rather than a rift [7,15] may be related to such plume spill. Because of its complexity, little knowledge can be gained from this zone, unless extremely detailed sampling in space and time can be obtained.

On the other hand, monitoring of plateau basalt lava piles over plume regions PRS, and across NRS should corroborate this model, and indicate the plume intensity with time, or alternatively the spreading rate history. The two alternatives can be resolved by obtaining independent information on spreading rate with time from magnetic lineament correlation studies [16–19]. If the spreading rate is found relatively constant, then any significant variation in $[La/Sm]_{E.F.}$ above fluctuation caused by fractional crystallization during magma ascent or variation in extent of partial melting, should then reflect the plume activity and intensity with time.

On the basis of this above promise we now inspect the preliminary results obtained for the Thulean Province emphasing data from the Faeroe Islands.

3. Faeroe Islands

The Faeroe Islands expose a 3000-m thick lava sequence composed nearly exclusively of tholeiitic basalts [20]. The plateau basalt pile is divided into three series separated by two marker horizons, A and C. Horizon A is a 10-m thick series of sediments containing a coal seam, and Horizon C, an easily recognizable sequence of lava flows. The lower series is composed of mainly aphyric quartz tholeiites, the middle series of porphyritic quartz tholeiites, and the upper series of olivine tholeiites. The petrology and geology of the Faeroe lava pile has already been discussed extensively [20–22]. The lavas were erupted between 50 and 60 m.y. B.P. [23].

Table 1 gives the rare-earth concentration variations of these lavas. Fig. 3 shows a stratigraphic profile for the $[La/Sm]_{E.F.}$ through the lava pile. SiO_2, TiO_2, $TiO_2/\Sigma FeO$ and $\Sigma FeO/\Sigma FeO + MgO$ contents are also reproduced here for comparison. In general, the La and $[La/Sm]_{E.F.}$ ratio closely correlates with Ti content. On the basis of chondrite normalized RE patterns, or equivalent ratios in Fig. 3, two distinct groups are clearly apparent. All flows of the lower series, and nearly all of the middle series except one (X-4), are light RE-enriched ($[La/Sm]_{E.F.} > 1$); whereas the lava flows from the upper series rapidly fluctuate between light RE-depleted ($[La/Sm]_{E.F.} < 1$) to light RE-enriched patterns and ending with light RE-depleted patterns. TiO_2 and $TiO_2/\Sigma FeO$ general level closely correlates with these two groupings, just as other petrochemical characteristics [20]. The lower and middle series quartz tholeiites are distinctly Fe and Ti richer and Al poorer than most of the olivine tholeiites of the upper series [21]. Flows III-7 and III-8, which have an unusually low Ti content for the lower series, however, have RE patterns indistinguishable from the main sequence of the lower and middle series.

The two main RE pattern groupings discussed above cannot be explained by different extent of fractional crystallization or partial melting as evident, for example, from the lack of correlation between $[La/Sm]_{E.F.}$ with $\Sigma FeO/\Sigma FeO + MgO$ or akin in-

TABLE 1
Rare-earths concentrations (ppm) in Faeroes lava flows*

Flow horizon	Location	La	Sm	Eu	Tb	Dy	Yb	Lu	$[La/Sm]_{E.F.}$
II-A-10	Havnnafelli	17.4	7.6	2.5	–	6.6	2.5	0.41	1.6
III-1	Skarvgjogv	11.1	5.5	1.9	–	5.5	–	0.33	1.4
III-3	Skarvgjogv	19.5	8.0	2.7	1.13	7.2	2.6	0.39	1.7
III-4	Skarvgjogv	17.1	7.3	2.4	0.94	5.9	2.6	0.42	1.6
III-6	Skarvgjogv	9.0	4.9	1.7	–	4.5	1.6	0.31	1.3
III-7	Skarvgjogv	5.8	2.9	1.1	0.62	–	2.5	0.37	1.4
III-8	Skarvgjogv	7.1	3.5	1.2	0.76	–	2.6	0.46	1.4
III-9	Skarvgjogv	18.2	9.1	2.9	–	9.1	3.5	0.51	1.4
IV-1	Vikar	7.9	4.9	1.7	–	5.4	1.7	0.28	1.1
IV-10	Vikar	6.8	4.5	1.5	–	4.4	1.6	0.19	1.0
VII-2	Hovdagjogv	16.3	8.8	2.8	–	7.7	3.1	0.47	1.3
VIII-4	Krossafelli	11.8	6.1	2.1	–	6.6	2.4	0.36	1.3
X-2	Sneis	14.6	7.2	2.4	–	6.2	2.1	0.33	1.4
X-4	Sneis	1.4	2.5	1.0	0.60	–	2.1	0.29	0.40
X-5	Sneis	14.1	7.3	2.4	–	7.1	2.5	0.35	1.3
X-6	Sneis	14.5	7.8	2.6	–	8.6	2.9	0.41	1.3
X-10	Sneis	10.0	5.9	1.9	0.94	6.0	2.0	0.25	1.2
X-14	Sneis	13.5	3.9	1.2	0.68	4.4	–	–	2.4
X-16	Sneis	2.2	2.5	0.96	0.51	4.6	2.0	–	0.60
XI-3	Villimgadalsfjall	2.0	2.4	0.99	0.51	3.9	1.7	0.30	0.59
XI-5	Villimgadalsfjall	2.0	2.7	1.0	–	–	2.4	–	0.54
XI-7	Villimgadalsfjall	10.1	6.3	2.1	1.18	5.3	2.3	0.31	1.1
XI-8	Villimgadalsfjall	12.2	6.3	2.0	1.04	6.4	2.8	–	1.3
XI-10	Villimgadalsfjall	7.0	4.8	1.6	1.05	6.7	3.6	–	1.0
XI-13	Villimgadalsfjall	2.8	2.5	0.95	–	3.7	1.9	0.35	0.79
XI-16	Villimgadalsfjall	1.9	2.2	0.89	–	3.4	1.8	0.29	0.62
XI-19	Villimgadalsfjall	2.9	2.4	0.90	0.59	3.8	–	0.29	0.85
XI-23	Villimgadalsfjall	3.1	3.2	1.2	0.78	4.6	2.8	–	0.68

* Location of the flow horizons is given in refs. 20 and 21. RE measurements were obtained by instrumental neutron activation analysis. Calculated precision for rock standard BCR-1 (1σ, 10 replicate analyses) is: La 6.5%, Sm 7%, Eu 7.7%, Tb 15%, Dy 7.5%, Yb 13.3% and Lu 5.6%. Accuracy of the method, repeatedly tested against rock standards BCR-1 or JB-1, compares well with other laboratories [12].

dexes of differentiations (Fig. 3). The difficulty of bridging melts with light RE-depleted pattern to melts with light RE-enriched pattern, by either fractional crystallization or by different degrees of melting from a single mantle source has been previously argued against with the use of chondrite normalized Yb vs. La/Sm plot [10,24]. The two Faeroe geochemical groupings also plot separately on such a diagram. The difference must then be attributed to two distinct mantle sources according to our model. All flows of the lower series and nearly all of the middle series are PHMP-derived. The first occurrence of DLVL-derived basalt is horizon X-4, an isolated flow in the upper part of the middle series. In the upper series, rapid fluctuation occurs between flows mostly DLVL-derived to flows PHMP-derived; and the last volcanic activity on the Faeroe Islands is predominantly DLVL-derived. This arrest in the Faeroe volcanic activity appears then to have been followed by subsidence and rifting [20].

4. Age relations

We now need to relate these variations to time and the early tectonic history of the North Atlantic and Arctic. Tarling and Gale [23] have K/Ar dated the Faeroe basalts to range between 50–60 m.y. B.P. as

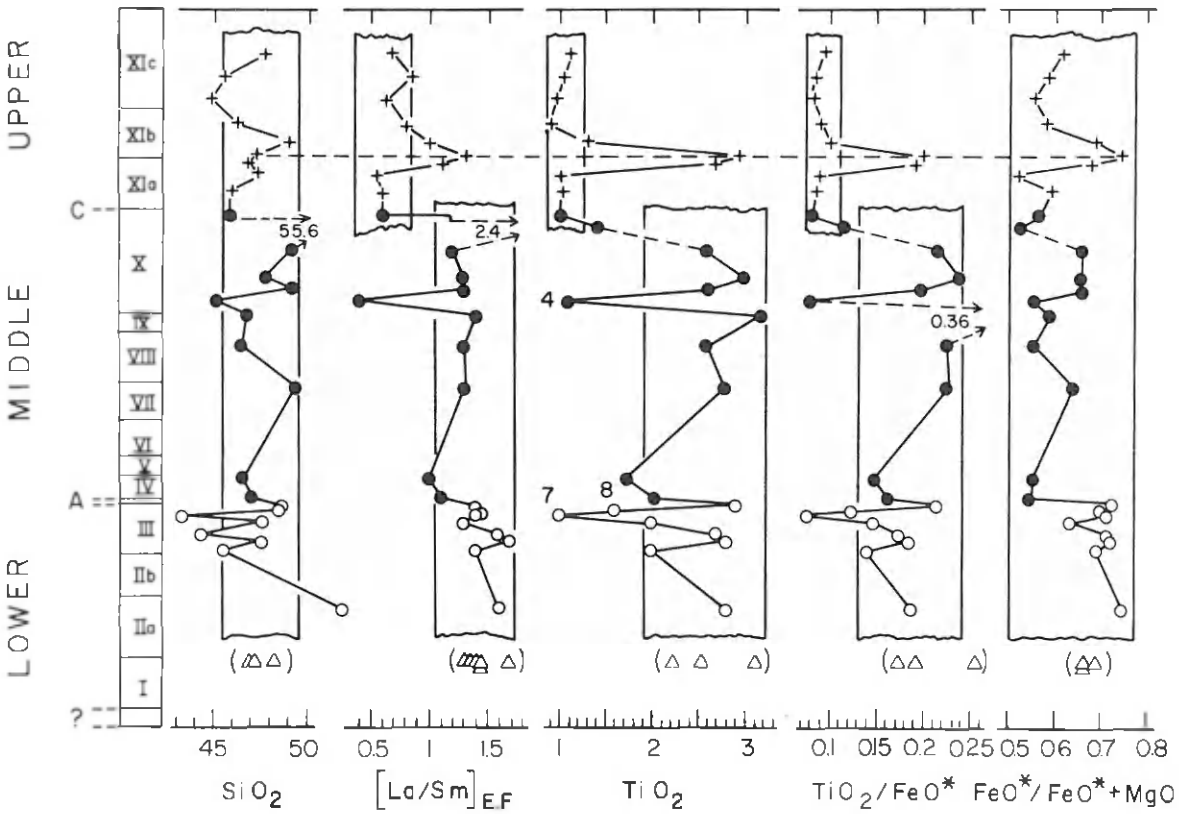


Fig. 3. Geochemical profiles through the 3000-m thick Faeroe Plateau basalt. Rare-earth data is given in Table 1, whereas other data is taken from Noe-Nygaard and Rasmussen [20] and Rasmussen and Noe-Nygaard [22]. Open triangles are for the East Greenland Tertiary basalts of the Scoresby Sund area [25]. Open circle, closed circle and cross are for basalts of the lower, middle and upper series of the Faeroes, respectively. Note the lack of correlation of SiO_2 and $\Sigma FeO/\Sigma FeO + MgO$ with respect to the two groupings based on $[La/Sm]_{E.F.}$, TiO_2 and TiO_2/Σ FeO (lower and middle series, and upper series). The East Greenland basalts are indistinguishable from the Faeroes lower and middle basalt series. Also note horizon X-14 in Sneis, a differentiated hyperstene bearing tholeiitic lava with almost 56% silica, and a high La/Sm ratio. Most noticeable diversification of composition of the Faeroes lavas occurs in the uppermost 100–200 m of the middle series which includes X-14 flow. This time period starting with light RE-depleted flow X-4, marks the end of the plume activity proper, with some differentiation in isolated pockets of magma, trapped, and late eruptions of residual liquids as horizon X-14. Star is for summation sign indicating total Fe, calculated as FeO, i.e. FeO + 0.9 Fe_2O_3. Numbering along TiO_2 profile indicates particular flow horizons 7 (III-7), 8 (III-8) and 4 (X-4).

minimum age. No systematic age sequence through the lava pile is observed apparently because of argon release and hydrothermal alteration. Therefore, for lack of better, we have in Fig. 4 spread the RE data for the Faeroes over the 50–60 m.y. B.P. interval, with age decreasing upward through the pile, starting with the lower series.

For comparison we also report on RE from the East Greenland plateau basalts of the Scoresby Sund area [25]. These predominantly quartz tholeiitic basalts appear to have been erupted at the same time as the Faeroe Islands [26]. The RE patterns of East Greenland basalts are indistinguishable from those of the lowest series of the Faeroe Islands (Figs. 3 and 4) and, therefore, are apparently also PHMP-derived. However, predrift geographical reconstruction of the North Atlantic shows the Scoresby Sund area to be significantly north of the Faeroe plume center, thus apparently it would seem geographically not directly related [16] (Fig. 1b).

Fig. 4 illustrates the temporal and spatial RE distribution of tholeiitic basalts of the Thulean Province

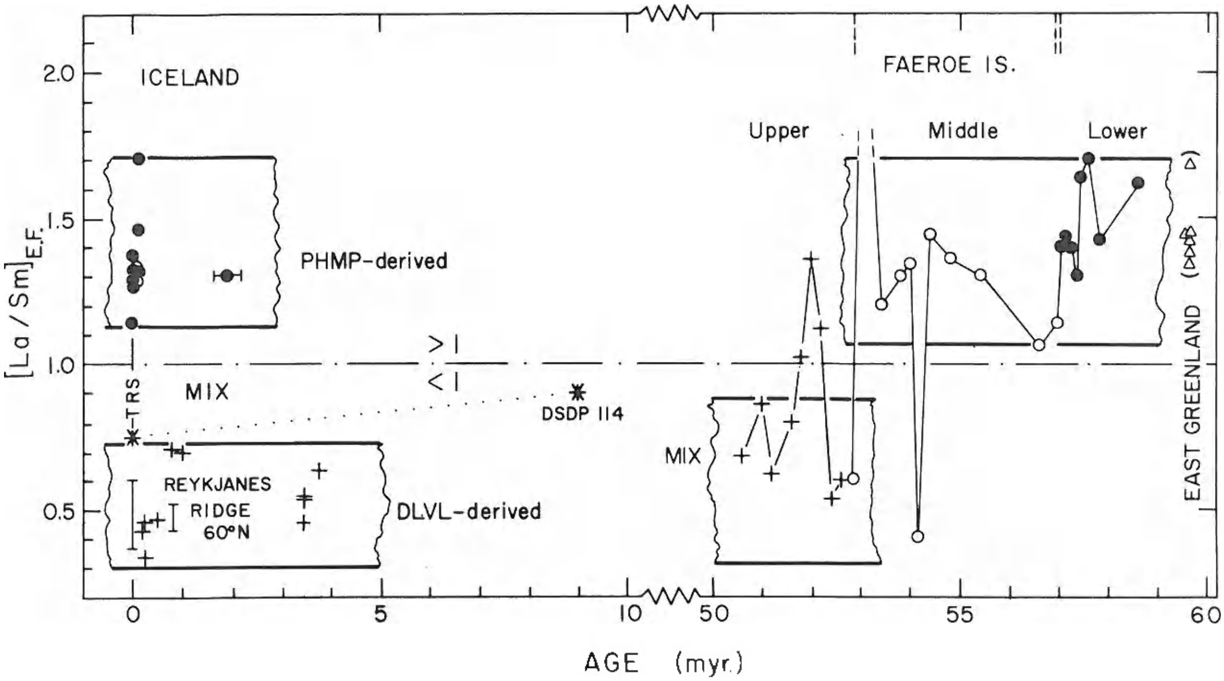


Fig. 4. Temporal and spatial [La/Sm]$_{E.F.}$ variation in tholeiitic basalts of the Thulean Province known currently for: (1) the Faeroes (50–60 m.y. B.P.), Iceland (0–3 m.y. B.P.) for regions over the plume; (2) Reykjanes Ridge 60°N (0–4 m.y. B.P.) for "normal" ridge segments [11,12]; and (3) transitional ridge segments (TRS) along the Reykjanes Ridge (61°N to Iceland). Only one data point (star, 0 m.y., 61°30′N) and its conjugate DSDP 114 (9–10 m.y. B.P.) is shown along TRS for simplicity, although a complete transition has been observed at time ~ 0 by Schilling [4]. The Tertiary Scoresby Sund basalts of East Greenland are also shown for comparison.

known currently. It shows that over PRS, the early part of the Faeroe volcanic activity (60–54 m.y.) is PHMP-derived and similar to that over the middle neovolcanic zone of Iceland since post-glacial time, as well as for at least the last few million years. This suggests a similar plume intensity (or plume-ridge spreading condition) during both the 60–54 m.y. B.P. and 0–2.5 m.y. B.P. periods. The RE in the Faeroe upper series suggests a decline in the plume intensity for the period 54–50 m.y. B.P. or alternatively rifting and acceleration in spreading. It also suggests rapid fluctuation of the plume-spreading rifting conditions for the same interval of time. So far, no record over the plume region is yet available for the period 50–2.5 m.y. B.P. Over TRS, both DSDP 114 basalt and its present conjugate have a [La/Sm]$_{E.F.}$ indeed intermediate between DLVL and PHMP-derived basalts; as would be anticipated along transitional ridge segments in a steady-state condition. Schilling's mixing model predicts [La/Sm]$_{E.F.}$ of basalt along TRS to be a function of the plume flux and the spreading rate [4, and Schilling, in preparation]. Although meager, the two conjugate data points are consistent with the suggestion of a similar plume-spreading ridge and spilling condition 9–10 m.y. B.P. and since post-glacial time (if not during the entire last 9–10 m.y.).

We now have to turn to independent evidence on the spreading history of the North Atlantic Thulean Province to attribute the RE evidence to either by plume intensity variation or spreading rate variation, as our model alone cannot distinguish between the two alternatives.

5. Spreading history and plume intensity variation

Most paleogeographic reconstruction based on magnetic lineament studies place the early separation of Europe from North America and Greenland at at

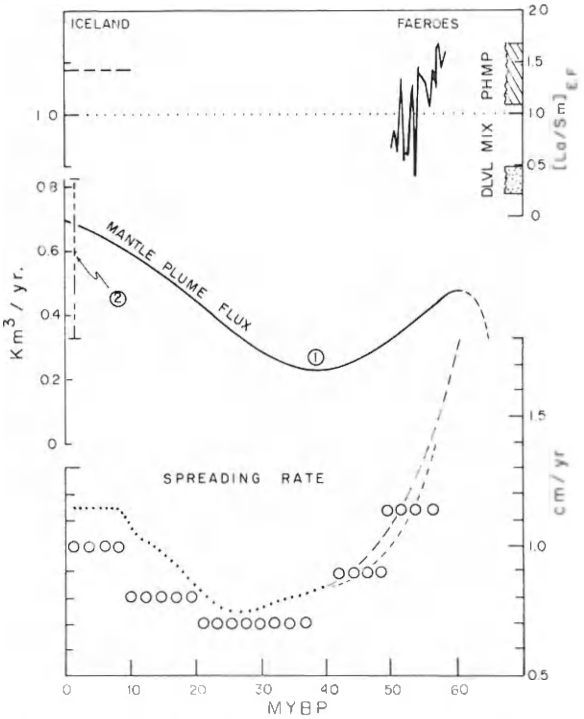


Fig. 5. Reykjanes Ridge spreading rates, Faeroes–Iceland mantle plume flux and $[La/Sm]_{E.F.}$ variations with time. Lower curves are: spreading rates by Vogt and Avery [16] dotted-dashed curves; and by Herron and Talwani [17] open circles. Middle curve: (1) mantle plume flux estimated from Vogt and Avery [16] basaltic plume discharge, assuming 25% degree of melting, i.e. mantle plume flux = 4 times basaltic plume discharge; (2) post-glacial, minimum Iceland mantle plume flux estimated by Schilling [4, and in preparation] from geochemical gradients along the Reykjanes Ridge and mixing model. Note the good order of magnitude agreement between this estimate and Vogt and Avery [16] independent estimate based on topographic mass excess. Upper diagram shows $[La/Sm]_{E.F.}$ variation of the Iceland–Faeroe plume (Fig. 4) for the 60–50 and 10–0 m.y. periods. Note that the $[La/Sm]_{E.F.}$ decrease between 60–50 m.y. parallels Vogt and Avery's mantle plume flux decrease, and cannot be explained by a spreading acceleration, as the evidence is for spreading deceleration (lower diagram). Therefore, the $[La/Sm]_{E.F.}$ decrease confirms the decrease in plume activity independently predicted by Vogt [3] and further discussed by Vogt and Avery [16].

least 60 m.y. ago (anomaly 24) and perhaps slightly before, depending on the latitude [16–19] (Fig. 1b).

Vogt and Avery [16] have reviewed and extended evidence on the spreading rate history of the North Atlantic, and Fig. 5 shows data so far available for the Iceland–Faeroes and Reykjanes Ridge region. There is a rapid decrease in spreading rate between 60–50 m.y. with a minimum near 30 m.y., and constant spreading rate for the last 10 m.y. comparable in magnitude to the operative rate for the 50–60 m.y. period.

Taking into account this spreading rate history the following suggestions can be made:

(1) The possibility in our model of attributing the decline of $[La/Sm]_{E.F.}$ of the Faeroes basalt in the late 60–50 m.y. period to spreading acceleration must be eliminated, as the independent spreading rate evidence is for a deceleration during this period. The $[La/Sm]_{E.F.}$ decrease must therefore be attributed to a rapid decline of the plume flux over the Faeroe Islands, proportional to the $[La/Sm]_{E.F.}$ level observed. $[La/Sm]_{E.F.}$ over PRS directly reflects the contribution of DLVL-derived and PHMP-derived material of the mix. The assumptions of the model are discussed in detail elsewhere [4, and Schilling, in preparation].

(2) The similarity of spreading rate for the period 50–60 m.y. B.P. and the last 10 m.y., as well as the similarity of $[La/Sm]_{E.F.}$ of the lower and middle series on the Faeroes and over Iceland for the corresponding two periods, suggests the Faeroe–Iceland plume-spreading condition must have been similar for these two periods of time. Thus the Faeroe plume intensity must have been similar to that of Iceland today.

(3) The uniform spreading rate over the last 10 m.y. and the similarity of the two RE conjugate data points along the TRS of the Reykjanes Ridge suggests a plume intensity and spill along the ridge similar in intensity as at present.*

Fig. 5 sketches, on a relative basis only, the Faeroe–Iceland plume intensity with time for periods where RE data is available, and is compared with Vogt and Avery's [16] similar estimate made on the basis of completely independent evidence. Our curve is based on points 1 to 3 above. The absolute plume flux cannot be estimated directly by our model for PRS alone. As indicated, once the plume flux is sufficient to feed entirely the overlying spreading rift, all the lavas erupting are PHMP-derived; and the total flux with time remains unknown unless the extent of spill into the asthenosphere around and particularly along the ridge (as measured by the length of TRS) is known at any time.

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* See footnote next page.

Both our data with its limitation and Vogt and Avery's curve based on excess topography are in agreement as to reveal a peak activity of the plume of the same magnitude for the periods 60–54 m.y. B.P. and 0–3 m.y. B.P., as well as a decline around 50 m.y. B.P. The spreading rate minimum between 50 and 10 m.y. B.P. suggests that only a small plume flux needs to have been maintained in order to create the Faeroes–Iceland Ridge with its anomalous crustal thickness. The total flux of basalt discharged by the Iceland plume is estimated to be 0.17 km^3/yr by Vogt and Avery [16]. A minimum mantle plume flux ranging between 0.30 and 0.95 km^3/yr has been estimated for the Iceland plume since post-glacial time by Schilling [in preparation] for an extent of partial melting ranging between 0.2 and 0.3. The minimum plume flux estimate assumes a bidirectional pipelike flow for the spill north and south of Iceland as suggested by Vogt [27], in contrast to a radial plume flow into the asthenosphere as suggested by Morgan [28]. For direct comparison Vogt's estimate of basaltic flux needs to be multiplied by a factor of 3 to 5 to take into account partial melting and obtain the mantle plume flux, that is 0.51–0.85 km^3/yr since post-glacial time. Both estimates are remarkably close, yet they were obtained by quite independent methods. Further geochemical tests of the Faeroe–Iceland plume intensity with time requires extending the RE monitoring to older plateau basalts of eastern Iceland, which one of us [J.G.S.] is in the process of doing*, and by drilling of the Faeroes-Iceland Ridge by JOIDES.

6. Mantle plume or mantle blobs?

Morgan [28,29] suggested that mantle plumes may be responsible for the movement of lithospheric plates. The mechanism has been reemphasized by Vogt and Avery [16] who noted the near coincidence of the Iceland plume flux variation with time and North Atlantic spreading rate variations over the same period. It is, therefore, important to focus attention on how the flux of a convecting mantle plume may vary with time. Two extreme cases can be considered: (1) mantle plumes represent continuous jets as visualized by Morgan [28], or (2) mantle plumes rise as separate blobs or mantle diapirs as experimented and theoretically studied by Ramberg [30] and Berner et al. [31]. Flux variation with time is easy to visualize in the case of a string of blobs rising and tapered as inverted droplets (Fig. 2), whereas case 1 requires a detailed theoretical analysis of the phenomenon. However, it is intuitively easy to realize that in view of the momentum involved and thermal nature of the phenomenon, time-flux variation for a continuous plume will occur over longer periods than geochemically monitored during deposition of the Upper Faeroe basalt series; whereas for the blob model the frequency of alternance of the two mantle types (or mix) can be much smaller and irregular. The sudden change from PHMP-derived to DLVL-derived RE patterns of the Faeroe lavas from the middle to the upper series, and subsequent rapid fluctuation, appears to be best explained by the blob model. Furthermore, since the Faeroe–Iceland plume is presumably rising beneath a spreading ridge, whose rate probably varies intermittently and sporadically, the probability of rapid fluctuation in space and time of tapping PHMP-derived, DLVL-derived, or mixed lavas is greatly enhanced, especially near the tapering phase of a mantle blob spill (Fig. 2).

Only sudden rift jumping and tapping of DLVL asthenospheric material at the plume margin could possibly explain the rapid fluctuations observed if case 1 of a continuous plume is considered. However, no field evidence is apparent in support of such a possibility.

Another advantage of the blob model is that each rising blob need not be of identical composition to the previous one, and the model is amenable to tests. For example, assuming that plumes come from a single layer in the mantle, one might expect a relation between their time of appearance at the earth's surface, the size of blobs, trace element content, particularly heat-

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* Since the writing of this paper, new RE data obtained through the eastern Iceland Plateau Basalt indicates a tendency for a secular decrease of the $[La/Sm]_{E.F.}$ similar to that observed for the Faeroe Plateau between 60 and 50 m.y. B.P.; thus suggesting a decline of the Iceland plume activity from approximately 13 m.y. B.P. to the present, rather than remaining constant. This recent decline is also consistent with secular variations in $^{87}Sr/^{86}Sr$ reported by O'Nions and Pankhurst for Icelandic lavas of the same period, but from different localities [56]. These additional results do not alter our main conclusions.

ing elements such as U, Th and K, as well as radiogenic isotopic ratios. If, on the other hand, plumes or blobs are derived from inhomogeneous pockets at the mantle/core boundary, as suggested by Anderson [32], such relations are not necessarily to be expected.

7. Blob flattening and flow pattern in the asthenosphere?

The tendency in recent interpretations of geophysical surveys on and around the Faeroe Platform [33–40] has been to consider the Faeroe–Iceland crust as continental, and place its extensive volcanic activity at the onset of further continental breakup and drift around 60 m.y. B.P. [34]. Results from a recent crustal seismic refraction experiment in the North Atlantic further emphasize that the Faeroe Islands are probably underlain by continental type of crust [40].

Most 60-m.y. B.P. reconstructions (see e.g. Fig. 15 in ref. 16) of the North Atlantic show widespread volcanic centers northeast, southwest and south of the Faeroe Islands positions, such as the Scoresby Sund Plateau basalts of East Greenland, Bill Bailey–Faeroe Banks, and the Hebridean volcanic province–Antrim Plateau basalts, respectively. These volcanic centers are practically all contemporaneous [23,26, 41], yet quite distant from each other. Rather than reflecting plume traces, from polar wandering, mantle rolling or relative movements of the kind [42–45], could these volcanic centers be related to large mantle spills along directions of lithosphere weakness or of very slow spreading, by a large blob (or plume) rising and flattening against the base of the lithosphere during doming at the onset of continental breakup and drift? Perhaps the center of such a lithothermal system [5] could have been beneath the Faeroe Platform? If so, the area would have been heated most and supplied with light mantle material, light RE-enriched, and thus would have subsided less rapidly than the surrounding, and managed to remain paramarine during the last 60 m.y. of spreading [46]. Similar situations have been described for the Afar [5,47] and similarly explained by Brooks [48]. Blob flattening and spill during the doming period could perhaps have occurred along preferential directions within the asthenosphere, just beneath the lithosphere.

The remarkable similarity of the lower and middle series Faeroe basalts and East Greenland plateau basalts, if related to a single blob flattening 60 m.y. B.P., would require a spill along a northeast direction. Intense plume activity with very slow northeast spreading would be required to allow the spill to occur over a 500-km distance along this direction. For preventing any dilution with DLVL material the spill configuration would have been similar to the present Iceland plume spill along the Reykjanes Ridge [4], but northward at the time. The plume intensity could have been similar to that of Iceland at present, or perhaps of lower intensity if only minor spreading occurred just at the breakup and onset of drift.

The possibility of blob flattening during the doming period along a southern preferential direction, needs also to be explored. Roberts [49] has noted the possible relation of northwest-trending Tertiary dike swarms and the location of Tertiary intrusive centers in Scotland along northwest directions, roughly leading to the Faeroe Platform. Extensive submerged basalt flows have recently been reported in the Sea of Hebrides by McQuillin and Binns [50]. Also, preliminary results for Ireland indicate that the Causeway sequence of the middle lavas of the Antrim Plateau [51,52] have light RE-enriched patterns, whereas the last flow is again light RE-depleted; suggesting a similar sequence through time for the Faeroes and the Antrim Plateau basalts [Schilling and Preston, in preparation]. However, $[\mathrm{La/Sm}]_{\mathrm{E.F.}}$ of the Causeway lava sequence is sufficiently higher than those of the lower and middle Faeroe series to preliminary suggest a distinct mantle source origin (distinct blobs) for the derivation of the two plateau basalts. Thus, the extent of the Faeroe plume spill or flattening along this southern direction remains to be investigated, and so is the Faeroes–Bill Bailey's–Lousy Banks general trend of topographic heights [35,53,54], which might have been related as a series of short en echelon ridge fracture segments, some 60 m.y. B.P.

To establish the extent and the rate that the Faeroe swell may have had on the opening and evolution of the North Atlantic, and its exact timing, as well as test its relation to the Tertiary volcanism of the Hebrides Region, there is a need for: (1) detailed paleogeographic reconstruction of the area around 80–40 m.y. B.P. based on more detailed geophysical and structural surveys, (2) more extensive drilling by DSDP, northwest, southwest and south of the Faeroes, to sample and date basement, followed by (3) detailed geochemical studies of the kind presented here.

8. Conclusions

We wish to emphasize the significance of the abrupt change from light RE-enriched to depleted closely monitored near the boundary of the middle and upper series of the Faeroes basalt. The transition represents our first witnessing of a change from tholeiitic volcanism derived from a typical plume regime to one more akin to normal mid-ocean ridges, according to our model. The change can indeed be rapid and reflect either: (1) a sudden and extensive rifting and spreading. This solution appears so far ruled out because of the decrease in spreading rates as indicated by Herron and Talwani [17] and Vogt and Avery [16], and providing of course that the 60–50 m.y. age for the Faeroes Plateau basalt is correct; or, and more likely, (2) near exhaustion of the geochemically distinct mantle blob source postulated, at least momentarily, as it is possible with the blob model introduced in this paper.

Finally, it needs to be pointed out that the spreading rate history for the North Atlantic determined by Vogt and Avery [16], and Herron and Talwani [17] for the 50–60 m.y. B.P. period was taken at face value. Should this spreading rate history or the extrapolated marine magnetic time scale used by these authors be changed, our conclusions for a decline in the Faeroe–Iceland plume intensity during the late 50–60 m.y. B.P. period, rather than an acceleration in rifting, would have to be revised accordingly.

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