14. RARE-EARTH, Sc, Cr, Fe, Co, AND Na ABUNDANCES IN DSDP LEG 38 BASEMENT BASALTS: SOME ADDITIONAL EVIDENCE ON THE EVOLUTION OF THE THULEAN VOLCANIC PROVINCE

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INTRODUCTION

Earlier views on the origin of the Thulean or Brito-Arctic Volcanic Province in the North Atlantic have been drastically changed with the enunciation of the sea-floor spreading and mantle plume theories (Vine, 1966; Morgan, 1971; Vogt, 1971; Schilling, 1973). The gross compositional tholeiitic similarity and fissural mode of eruption of Tertiary plateau basalts from East Greenland, Iceland, the Hebrides, and Antrim in Northern Ireland led earlier students to believe that a great flood of basalt had poured over this entire area of the North Atlantic during the Tertiary. It was also hypothesized that subsequent fragmentation and subsidence of parts of this great Thulean flood basalt land led to the formation of the North Atlantic (Tyrell, 1937).

Subsequent age dating of these basalt masses and Paleocene predrift reconstructions based on magnetic anomaly lineaments at sea and the theory of sea-floor spreading have reduced considerably the area of extent of the Thulean Flood Basalt Province for the Tertiary (see, e.g., Brooks, 1973a; Vogt and Avery, 1974; Talwani and Eldholm, in press). However, the sea-floor spreading theory by itself has been unable to explain the anomalous volume, elevation, and trace element chemistry of the Thulean tholeiitic lava piles, as well as the presence of the Iceland-Faeroe aseismic ridge and other complexities in the Norwegian Basin. Recourse to the concept of mantle plume upwelling was required to explain the onset of drifting and the anomalous massive outpouring of lava of the Thulean Province (see Schilling, 1973; Brooks, 1973b; Schilling and Noe-Nygaard, 1974). Geochemical monitoring of such mantle upwelling activity during the opening history of the North Atlantic has been attempted, using rare-earth (RE) abundance patterns of tholeiitic basalts as a mantle source indicator (Schilling, 1973; Schilling and Noe-Nygaard, 1974). However, due to sampling availability, such efforts have been limited to the early period of opening of the North Atlantic (Faeroes and East Greenland plateau basalts) and the last 15 m.y. of the Iceland-Mid-Atlantic Ridge mantle plume and drifting activity (Schilling, 1973; Schilling et al., 1974).

The DSDP Leg 38 basement sampling of the Iceland-Faeroe Ridge, Vøring Plateau, and Norwegian Basin should provide us with a better understanding of the volcanic evolution of the Thulean Province during the opening of the Atlantic. The sampling should also offer a new opportunity to extend over a greater time span the geochemical monitoring of mantle plume upwelling activity in the region and should permit further tests of such a concept against other alternative models (Schilling, 1973).

For such purposes, we report RE abundance patterns and Sc, Cr, Fe, Co, and Na in 21 basement basalts or diabases obtained at Sites 336, 337, 338, 342, 343, 344, 345, 348, and 350 (Figure 1). Implication of the results are briefly discussed in terms of the binary asthenosphere-mantle plume mixing model proposed by Schilling (1973) and Schilling and Noe-Nygaard (1974), as well as alternative models.

RESULTS

Sampling of various core levels was made on the basis of megascopic appearance of the rocks, using criteria such as texture and freshness, and to insure coverage of the entire core length and apparent lithologic flow units. Samples were prepared for analysis by carefully breaking the core section into small fragments to avoid altered patches, small calcite veinlets, and zeolites or chalcedony amygdules, whenever present. Selected fragments were then washed in distilled water prior to grinding.

Major element chemistry on splits of the same powder batch used for RE and petrographic descriptions of these rocks are reported separately by Ridley (this volume). The classification used subsequently in this note is based on the CIPW normative constituents of these rocks and Yoder and Tilley's (1962) Qtz-Di-Hy-Ol-Ne tetrahedron. The CIPW normative mineral content of the rocks was estimated from Ridley's major element analyses expressed: (1) on a water-free basis, (2) as an arbitrarily fixed 1.5% Fe_2O_3 content, and (3) on estimated P_2O_5 contents based on K_2O content of these rocks and two K_2O-P_2O_5 correlation diagrams prepared from published analyses of subaerial and submarine basalts of the Thulean Province (Schilling, 1973 and unpublished).

On this basis, all the basalts analyzed, including those from the Vøring Plateau and the Knipovich Ridge, are slightly quartz or olivine normative tholeiites, and plots close to the diopside-hypersthene join in the Qtz-Di-Hy-Ol-Ne tetrahedron. Nepheline normative, or transtitional alkali basalts were not encountered in this sampling. Sample 344-34-2, 27-30 cm (2), containing specks of pyrite and 345-33-2, 56-59 cm (6) and 345-35, 145-148 cm (8), both containing calcite, are anomalously CaO poor and normatively diopside deficient. It is uncertain whether these compositional anomalies are due to analytical errors or are real. However, it is clear that the compositions of these samples were postdepositionally altered.

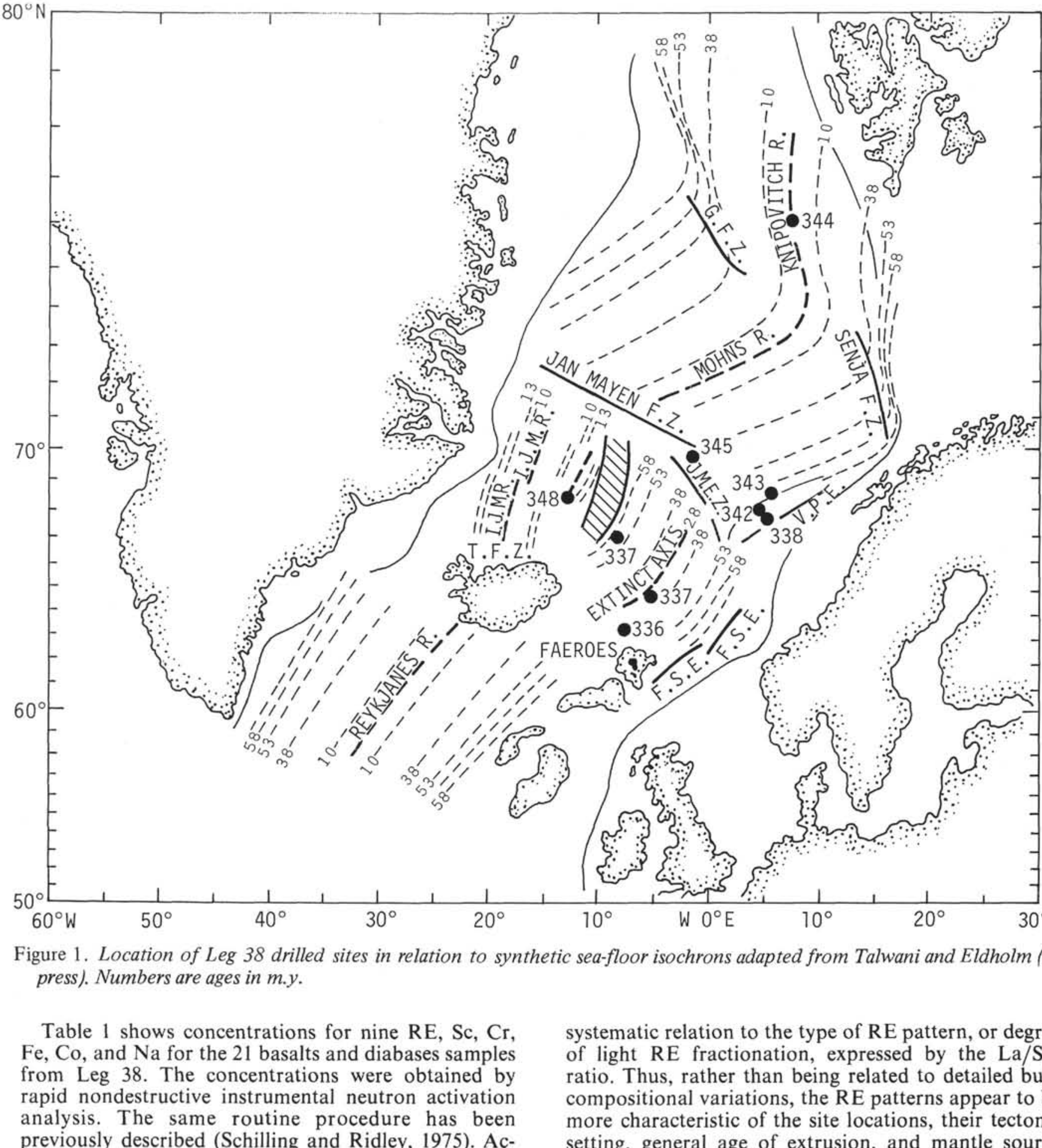

Figure 1. *Location of Leg 38 drilled sites in relation to synthetic sea-floor isochrons adapted from Talwani and Eldholm (in press). Numbers are ages in m.y.*

Table 1 shows concentrations for nine RE, Sc, Cr, Fe, Co, and Na for the 21 basalts and diabases samples from Leg 38. The concentrations were obtained by rapid nondestructive instrumental neutron activation analysis. The same routine procedure has been previously described (Schilling and Ridley, 1975). Accuracy and precision of the analyses can be estimated from the JB-1 rock standard average listed in Table 1, and one single JB-1 analysis obtained with one of the neutron irradiations of Leg 38 samples.

Figures 2-4 show separately the RE fractionation patterns obtained for each site. With the exception of Sites 336 and 345, these figures show uniform RE patterns within each hole, irrespective of the level of sampling, grain size, and textures of the rocks. The FeO*/FeO*+MgO index of fractionation shows no systematic relation to the type of RE pattern, or degree of light RE fractionation, expressed by the La/Sm ratio. Thus, rather than being related to detailed bulk compositional variations, the RE patterns appear to be more characteristic of the site locations, their tectonic setting, general age of extrusion, and mantle source derivation. These relationships are now further scrutinized, considering each site separately.

Site 336: Faeroe-Iceland Ridge (40-50 m.y.?)

Both, Sample 41-1(1B) and Sample 42-1, 144-146 cm (13B) have slightly light RE-depleted patterns and closely resemble the type of RE patterns dominating the upper series of the Faeroe Plateau basalt (Figure 2). However, their Cr content is surprisingly low (50-60 ppm) and their TiO_2 content slightly higher than basalts

TABLE 1
Concentrations of Rare Earths, Co, Cr, Sc, Fe, and Na, in Leg 38 Basalts by Instrumental Neutron Activation Analysis (Analyst R. Kingsley)[a]

Sample (Interval in cm)	La	Ce	Nd	Sm	Eu	Tb	Tm	Yb	Lu	$[La/Sm]_{E.F.}$	Co	Cr	Sc	Na_2O	FeO
336-41-1 (1B)	4.2	12.7	9.1	3.7	1.4	0.91	0.65	3.0	0.42	0.80	50	54	48	2.57	12.27
336-42-1, 144-146 (13B)	4.0	12.6		3.9	1.4	0.91	0.68	3.5	0.57	0.72	46	53	46	2.46	11.29
336-44-2, 71-74	8.5	23.3	12.7	4.1	1.5	0.89	0.66	2.9	0.34	1.5	39	60	47	2.97	11.72
337-13-2, 140-143	2.4		7.4	2.6	0.95	0.75		3.1	0.43	0.65	49	420	45	2.63	9.95
337-14-2, 91-94 (14)	3.1		6.7	2.7	1.0	0.82	0.62	3.4	0.45	0.80	50	389	45	2.49	9.95
337-15-2, 137-140 (12)	2.4	8.2	7.8	2.8	1.1	0.86	0.65	3.9	0.54	0.60	53	391	45	2.50	9.34
338-43-2, 115-118 (16)	3.8	11.6		2.6	1.0	0.61	0.43	2.0	0.31	1.0	43	301	41	2.46	9.17
338-43-4, 54-57 (7)	3.8	10.8	7.9	2.5	1.0	0.61	0.47	2.3	0.31	1.1	43	324	42	2.33	9.30
338-45-2, 56-59 (8)	4.3	11.1	9.4	2.9	1.1	0.74	0.53	3.0	0.45	1.0	46	173	46	2.33	10.56
342-7-2, 137-140 (16)	15.5	43.1	29.6	7.9	2.4	1.4		3.3	0.40	1.4	52	186	49	3.19	11.56
342-7-5, 126-129 (20)	16.2	43.1	26.8	7.4	2.3	1.5		3.7	0.49	1.5	73	160	44	3.23	11.29
342-8-2, 65-68 (12)	15.4	39.6	26.3	7.0	2.2	1.5	0.88	3.6	0.52	1.5	48	168	43	2.94	12.64
343-13-2, 20-23 (2)	14.2	39.7	23.9	6.8	2.1	1.3	0.97	4.4	0.49	1.5	39		44	3.77	16.8
344-34-2, 27-30 (2)	8.9	19.8		3.6	1.2	0.72		2.2	0.29	1.7	37	357	35	3.09	7.37
344-35-4, 87-90 (7)	8.1	17.4	9.5	3.2	1.2	0.73		2.3	0.33	1.8	33	328	32	3.06	7.16
344-37-2, 135-137 (8)	8.2	17.1	9.1	4.0	1.3	0.74		2.8	0.32	1.4	32	335	38	3.43	7.45
345-33-2, 56-59 (6)	11.1	24.3	18.4	4.1	1.5	0.88	0.63	3.2	0.43	1.9	40	551	36	2.66	8.52
345-35-1, 145-148 (7)	14.3	40.3	20.4	5.0	1.6	0.81		1.8	0.21	2.0	36	229	34	2.52	8.05
348-32-4, 93-96 (9)	3.3	10.6		3.5	1.4	1.1	0.86	4.1	0.58	0.66	53	159	50	2.40	13.26
348-34-2, 107-110 (14)	2.8			3.0	1.2			4.5	0.55	0.65	54	166	51	2.47	13.54
350-16-2, 30-33 (5)	15.6	44.8	26.1	6.7	2.2	1.3		3.8	0.50	1.6	44	89	40	2.89	13.27
JB-1 Split 8[b]	39.3	75.5	29.6	5.1	1.6	1.2		2.5	0.26	5.4	36	442	27		
JB-1 Average of (4)[c]	41.2	75.9	30.3	5.6	1.6	1.2		2.1	0.29	5.2	37	458	28		
	±2.1	±4.5	±2.1	±0.3	±0.1	±0.1		±0.3	±0.02	±0.1	±1	±25	±1		
JB-1 (Recommended)[d]	36	67	25	4.8	1.5	0.5		2.1	.31	5.3	39	417	26		

[a]Concentrations in ppm except for Na_2O and FeO (total iron as FeO), both in wt%. All analyses are based on prepared standard solutions except for FeO and Na_2O based on recommended values for JB-1 (Flanagan, 1974), namely: 9.04%, 2.79 wt%, respectively. For precision and accuracy of the method used, see Schilling and Ridley, 1975.

[b]Analyzed with Leg 38 irradiated samples.

[c]Analyzed with Leg 37 irradiated samples (Schilling et al., 1976 Initial Reports of the Deep Sea Drilling Project, Volume 37.)

[d]Flanagan, F.J., 1974.

from the upper Faeroe basalt series. The $[La/Sm]_{EF}$ values of these two basalts (0.8 and 0.72, respectively) fall in the upper range of normal mid-ocean ridge basalts.

Based on the binary asthenosphere-mantle plume mixing model proposed by Schilling (1973) and Schilling and Noe-Nygaard (1974), such La/Sm values suggest a mantle source derivation dominantly from the light RE-depleted asthenosphere, during a period of low mantle plume upwelling activity. In this model, the RE pattern of a basalt reflects primarily the mixing proportions between: a light RE-enriched mantle plume source ($[La/Sm]_{EF} > 1$) and the asthenosphere characteristically depleted in light RE ($[La/Sm]_{EF} \leq 0.6$). The mixing proportions, in turn, are the result of the interplay of the rate of mantle plume upwelling and rate of lithospheric plate divergence above, both varying independently through time. The above inference is also in agreement with that of Vogt and Avery (1974) who, on the basis of the topographic relief of the Iceland-Faeroe Ridge alone, predicted a decreasing basalt discharge rate caused by both a decrease of the Mid-Atlantic Ridge spreading rate at this latitude and a flux decrease of the Faeroe Iceland mantle plume for this period of time (lower to middle Eocene).

In contrast, Sample 44-2, 71-74 cm, representing stratigraphically an older basalt than the 41-1(1B) and 42-1, 144-146 cm levels, is light RE enriched (Figure 2); and apparently would not support the above interpretation. Nevertheless, judging from the upper Faeroe basalt series, rapid alternance between light RE-enriched to more dominantly light RE-depleted basaltic flows may well be characteristic of the tailing phase of a mantle blob activity (Schilling and Noe-Nygaard, 1974). It is conceivable that the declining phase of activity of a blob may be characterized by inefficient mixing with the light RE-depleted asthenosphere, which the blob must penetrate from below, thus leaving occasional schlierens of light RE-enriched mantle blob material as a minor source of basalts with such RE patterns upon melting. If this were the case, Sample 44-2, 71-74 cm would not invalidate the above inference.

Finally, it needs to be noted that Sample 44-2, 71-74 cm was altered and contained amygdules and altered zones, which were purposely avoided in preparing the sample for RE analysis, but the procedure reduced the amount of powder to such a small size that the major element could not be determined. Thus, the significance of this sample remains uncertain, and Site 336 warrants further detailed studies.

Site 337: Mid-Atlantic Ridge Extinct Axis (~28-38 m.y.)

Three stratigraphic levels of basalt were studied. Both Samples 13-2, 140-143 cm near the top and 15-2, 137-140 cm (12) near the bottom of the hole are parts of variolitic zones of pillow lavas and petrographically show typical quenced crystal morphologies (Ridley, this volume). Both samples have light RE-depleted patterns typical of normal mid-ocean ridge segments (Figure 2). Chemically, they are both typical low K_2O

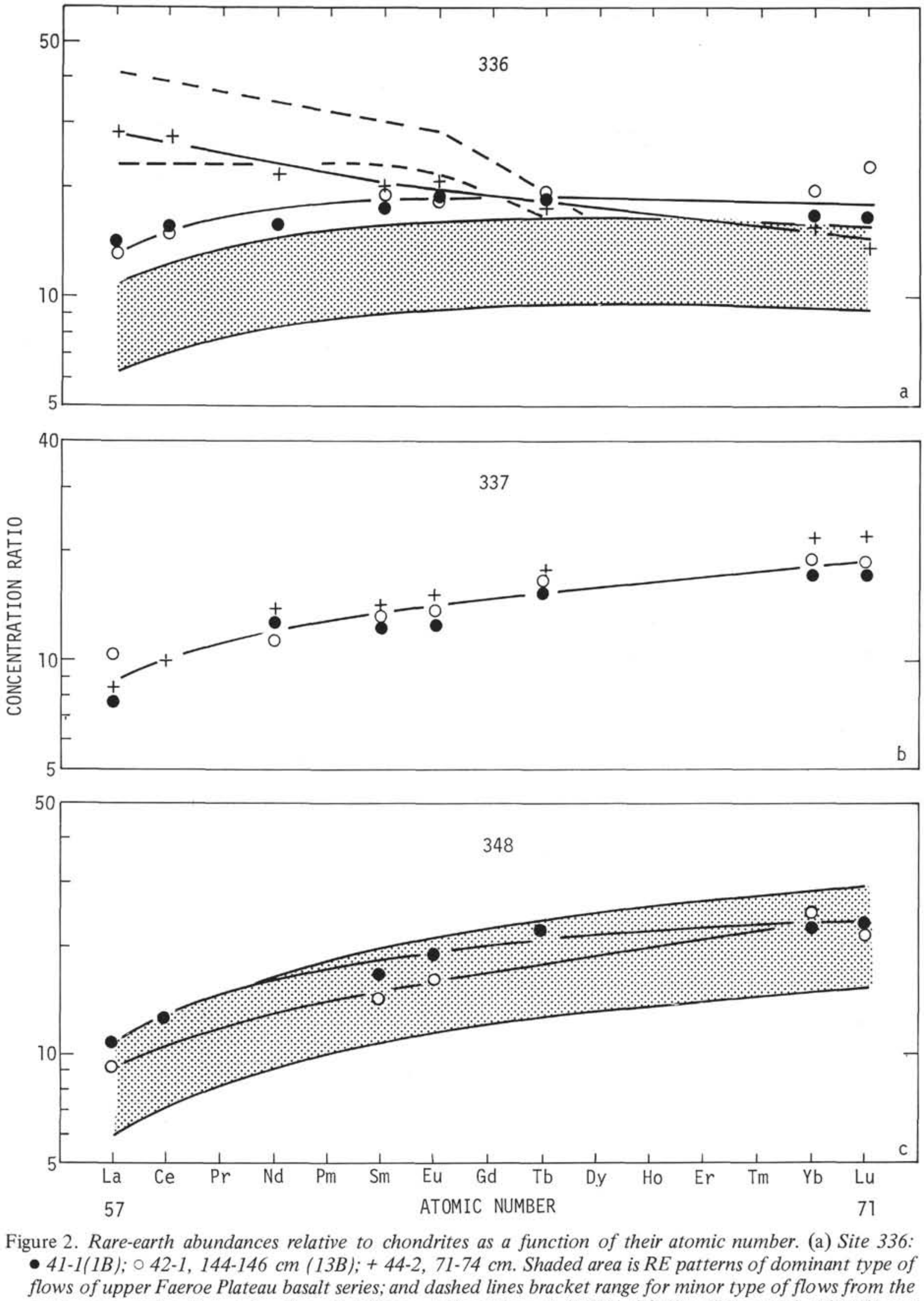

Figure 2. *Rare-earth abundances relative to chondrites as a function of their atomic number.* (a) *Site 336: ● 41-1(1B); ○ 42-1, 144-146 cm (13B); + 44-2, 71-74 cm. Shaded area is RE patterns of dominant type of flows of upper Faeroe Plateau basalt series; and dashed lines bracket range for minor type of flows from the same upper series. Data taken from Schilling and Noe Nygaard (1974).* (b) *Site 337: ● 13-2, 140-143 cm; ○ 14-2, 91-94 cm (14); + 15-2, 137-140 cm (12).* (c) *Site 348: ● 32-4, 93-96 cm (9); ○ 34-2, 107-110 cm (14). Shaded area, RE patterns of dredged tholeiites between 68°35'N-69°10'N on present axis of the Kolbeinsey Ridge, just north and south of the Spar Fracture Zone, and corresponding approximately to the same flow line as Site 348. Data taken from Schilling et al. (1974 and unpublished).*

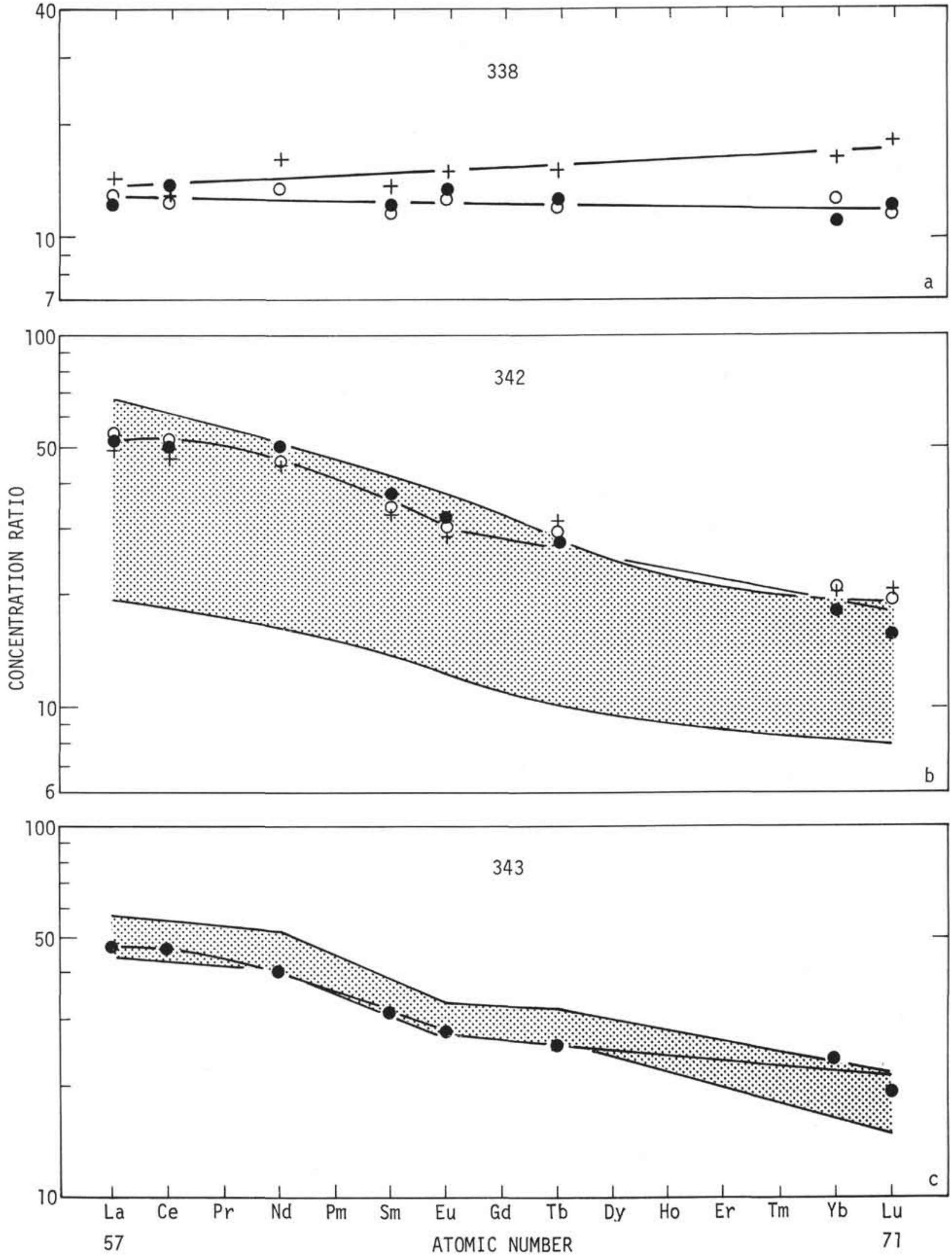

Figure 3. *Rare-earth abundances relative to chondrites as a function of their atomic number. (a) Site 338: ● 43-2, 115-118 cm (16); ○ 43-4, 54-57 cm (7); + 45-2, 56-59 cm (8). (b) Site 342: ● 7-2, 137-140 cm (16); ○ 7-5, 126-129 cm (20); + 8-2, 65-68 cm (12). Shaded area is for range of RE patterns dominating the middle and lower Faeroe Plateau basalt series. (c) Site 343: ● 13-2, 20-23 cm (2). Shaded area is range of RE patterns obtained at Site 342, also shown above.*

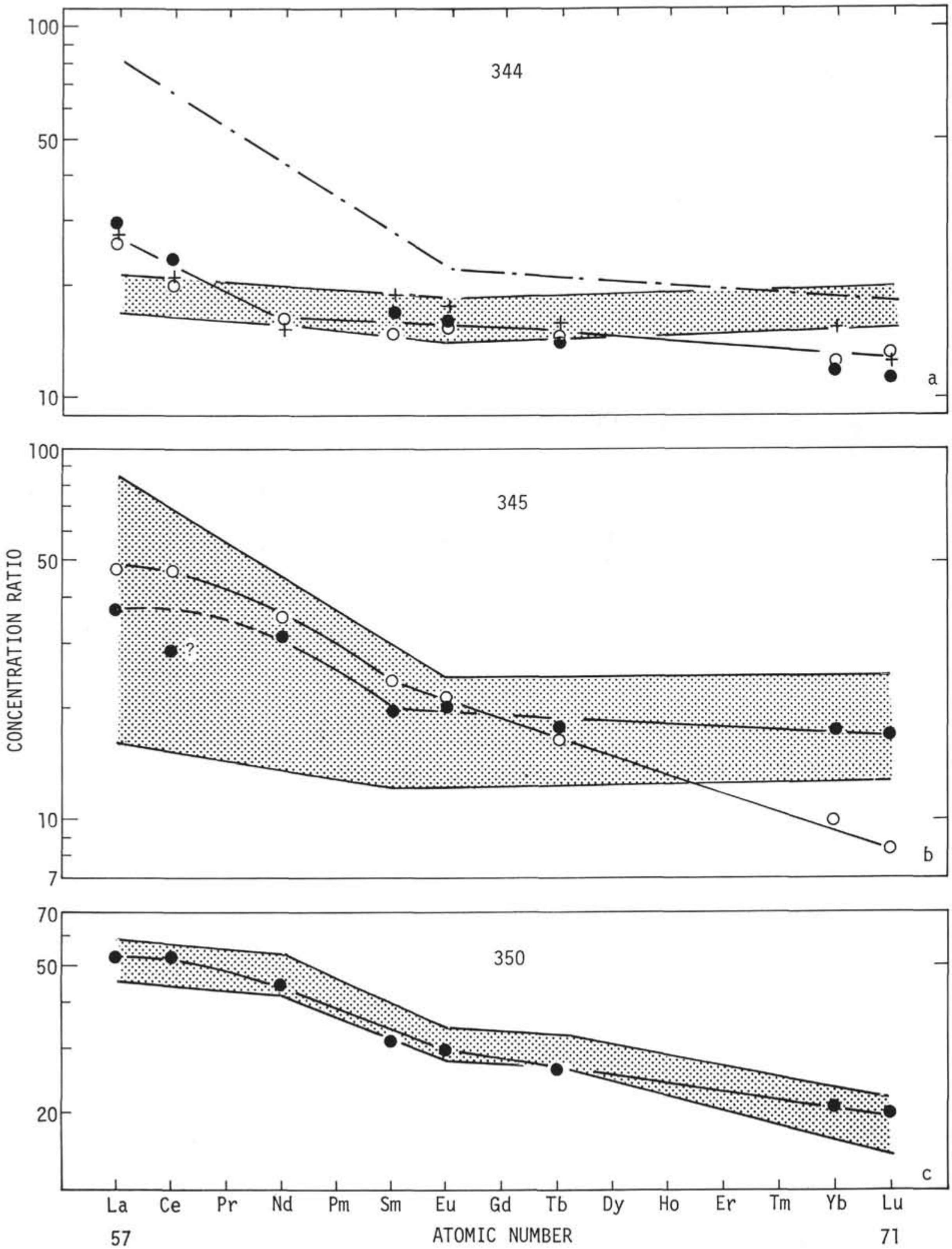

Figure 4. *Rare-earth abundances relative to chondrites as a function of their atomic number. (a) Site 344: ● 34-2, 27-30 cm (2); ○ 35-4, 87-90 cm (7); + 37-2, 135-137 cm (8). Shaded area is RE pattern range of tholeiites dredged on the bottom of rift of the Mohns Ridge between 72°10'N and 73°N (3 stations); and dash-dotted line for station TR139, 30D at latitude 71°49'N also on the present Mohns Ridge Axis. Data taken from Schilling et al. (1974 and unpublished). (b) Site 345: ● 33-2, 56-59 cm (6); ○ 35-1, 145-148 cm (7); Shaded area is for range of RE patterns of tholeiites dredged on the present axis of the Kolbeinsey Ridge north 71°N up to the Jan Mayen Fracture Zone, and of the Mohns Ridge northeast of Jan Mayen up to 73°N. Data taken from Schilling et al. (1974 and unpublished). (c) Site 350: ● 16-2, 30-33 cm (5). Shaded area is for range of RE patterns from Sites 342 and 343, combined.*

mid-ocean ridge tholeiites. The sample from an intermediate level, 14-2, 91-94 cm (14), is slightly coarser grained, contains some olivine phenocrysts, and is probably from the interior of a pillow lava or flow. It also has a light RE-depleted pattern, but its [La/Sm]EF is slightly enhanced (0.80) relative to the other two (0.65 and 0.60, respectively); on this basis, this lava could have suffered more extensive shallow depth crystal fractionation. However, the bulk chemistry of these three quartz tholeiites are practically identical (Ridley, this volume). This includes also Cr (Table 1) and their fractionation index FeO*/FeO*+MgO, thus suggesting that these three lavas are part of the same eruptive sequence.

The above evidence fully supports the mid-ocean ridge nature of these three basalts. The RE pattern suggests that they were derived from the uniform light RE-depleted asthenosphere source (Schilling, 1975); and that the Faeroe-Iceland mantle plume source did not extend north to Site 337, approximately 28-38 m.y. ago.

Site 338: Vøring Plateau (>50 m.y.)

Three cores with diabasic textures, representing interiors of flows, were studied from this site. Both Samples 43-2, 115-118 cm (16) and 43-4, 54-57 cm (7) are slightly olivine normative-bearing tholeiites, whereas 45-2, 56-59 cm (8) is a slightly quartz normative-bearing tholeiite. The three samples have very uniform flat RE patterns, unfractionated relative to chondrites (Figure 3). Their relative patterns would appear intermediate between mantle plume and asthenosphere source derived basalts, in terms of the binary mixing model proposed by Schilling (1973) and Schilling and Noe-Nygaard (1974). However, the somewhat overall low level of RE enrichment of these basalts (12-15× chondrites) may not support directly such a derivation. The RE patterns of the Site 338 diabase appear less fractionated than basalt from the entire Faeroe Plateau basalt series (Schilling and Noe-Nygaard, 1974), or relative to the Mesozoic basaltic dike from the eastern coast of North America (Weigand and Ragland, 1970). Further discussion of these Vøring Plateau basalt is postponed until evidence from other drilled site on the plateau are considered.

Site 342: Vøring Plateau (>50 m.y.)

The three samples studied from this site are again diabasic, but somewhat finer grained than those from Site 338. Sample 7-2, 137-140 cm (16) is an olivine-bearing tholeiite containing 1.48% TiO_2 and 0.15% K_2O (Ridley, this volume). Samples 7-5, 126-129 cm (20) and 8-2, 65-68 cm (12) are slightly quartz normative-bearing tholeiites, containing 3.18% TiO_2 and 0.31%-0.38% K_2O. The difference in TiO_2 and K_2O are not reflected in the RE patterns. All three basalts have practically identical light RE-enriched patterns, characteristically mantle plume-like derived (Figure 3). These RE patterns are also very similar to those found in flows of the lower Faeroes Plateau basalt series, or of the East Greenland Plateau basalt of the Scoresby Sund Area (Schilling and Noe-Nygaard, 1974). These three plateau basalts appear to be of very similar Paleocene age (Tarling and Gale, 1968; Beckinsale et al., 1970; Talwani, this volume) and are related to the extensive Thulean volcanic activity at the onset of drifting of the Eurasia and Greenland continental masses.

Site 343: Foot of Vøring Plateau, in Lofoten Basin (>50 m.y.)

Only one sample—13-2, 20-23 cm (2)—was studied from this site. It is an aphyric, slightly quartz normative-bearing basalt, very similar to the two high TiO_2 basalts from Site 342. It also has a light RE-enriched pattern which is indistinguishable from those found at Site 342 (Figure 3). A similar mantle plume source origin for basalts from Sites 343 and 342 is suggested, despite the fact that Site 342 is on the Vøring Plateau and Site 343 is on the foot of the plateau, and both are probably of a somewhat different age.

Site 344: Knipovich Ridge (0-10 m.y.)

Three doleritic flows were studied from this site. Sample 34-2, 27-30 cm (2) is TiO_2 and FeO* rich (3.52% and 17%, respectively) and anomalously poor in CaO (4.5%), judging from the analysis presented by Ridley (this volume). However, the high FeO* content is not corroborated by neutron activation analysis on the same powder (FeO*-7.37%, in Table 1). An analytical error is suspected. The other two dolerites—35-4, 87-90 cm (7), and 37-2, 135-137 cm (8)—are only slightly quartz-normative tholeiites, with normal TiO_2 content (~1.4%) and FeO* content (6.5-7%). Despite these apparent major element discrepancies, the three dolerites have uniform light RE-enriched patterns (Figure 4). The patterns fall within the range of those observed along the Mohns Ridge (Schilling et al., 1974) and also resemble those observed on the middle Neovolcanic Zone of Iceland (Schilling, 1973). So far, no light RE-depleted patterns typical of the normal mid-ocean ridge have been observed on the Mid-Atlantic Ridge north of Jan Mayen, and evidence from Site 344 on the Knipovich Ridge further reinforces this observation.

Schilling et al. (1974) indicated that this segment of the ridge appears to be transitional, reflecting mantle plume upwelling beneath the Jan Mayen platform and mixing with asthenospheric material beneath Mohns Ridge. Outward mantle plume flow and mixing over an extended zone is expected for a ridge spreading at low rate relative to the plume flux, as is the case for Mohns Ridge (0.8-0.9 cm/yr, half rate). However, Figure 4 shows that fractionation of the light RE along the Mid-Atlantic Ridge decreases rapidly from the Jan Mayen region to about 72°N reflecting a decreasing contribution from the Jan Mayen plume, but then appears to increase slightly to 76°N by including Site 344. Speculatively, this reversal of trend may reflect the presence of another unsuspected mantle plume upwelling northward, toward Svalbard.

Site 345: Jan Mayen Fracture Zone Extension (32-38 m.y.?)

Two relatively altered basalts from this site were studied. Sample 33-2, 56-59 cm (6) is an aphyric basalt peppered with calcite veinlets and is located just above a zone of basaltic breccia. Sample 35-1, 145-148 cm (7) is an aphyric basalt, also containing some calcite alteration. The basalts are rich in MgO (~10%) and Al_2O_3 (~18%). Despite the calcite alteration, these basalts are anomalously poor in CaO, particularly Sample 35-1, 145-148 cm (6) which contains only 4% CaO, and as a result are diopside normative defficient (Ridley, this volume). Both basalts are light RE enriched, Sample 35-1, 145-148 cm (7) is more so (Figure 4). A crossover of patterns occurs, with Sample 33-2, 56-59 cm (6) being more enriched in the heavy RE end. This could mean involvement of garnet during the generation of these melts in the mantle, or during subsequent fractional crystallization as the magma ascents; thus reflecting deeper depth of origin. The RE patterns tend to fall also in the range of those observed on the Vøring Plateau (compare Figure 3 with Figure 4), or recently erupted lava on the Kolbeinsey Ridge north of 71°N, approaching the West Jan Mayen Fracture Zone (Figure 4).

Site 345 light RE-enriched patterns can be interpreted to suggest that these basalts were derived from the activity of a mantle plume located beneath the Jan Mayen platform. The Jan Mayen mantle plume would have, at the onset of continental drifting, produced the Vøring Plateau basalts and possibly the East Greenland tholeiite plateau basalt located just north of Franz Joseph Fjord, 73°N (Noe-Nygaard, 1974). In this case, the structurally and magnetically ill-defined wide band bordering the East and West Jan Mayen Fracture Zone, branching from the Vøring Plateau to Jan Mayen and the Greenland plateau basalt north of 73°N (Figure 1), would be a topographic reflection of the Jan Mayen plume activity with time. Alternatively, it may be that the volcanic activity at Site 345 and the associated light RE enrichments reflect an association with the Jan Mayen Fracture Zone and its particular thermal or volcanic regime. The cause of light RE enrichment from such an association remains unknown. Further work on this site is particularly warranted.

Site 348: Extinct Iceland-Jan Mayen Ridge (15-28 m.y.)

Two basalts were studied from this site. Sample 32-4, 93-96 cm (9) is a fresh, fine-grained diabase or relatively coarse basalt. Sample 34-2, 107-110 cm (14) is a fresh aphyric basalt. Both are low K_2O, very slightly olivine-normative tholeiites, typical of mid-ocean ridges. The light RE-depleted patterns confirm the typical normal mid-ocean ridge basalt nature of this site (Figure 2). The relative patterns of the Site 348 basalts are also very similar to basalts recently erupted on the Kolbeinsey Ridge along the same flow line (Figure 2). These data further suggest that no light RE-enriched mantle component from the Iceland or Jan Mayen mantle plume reached this region of the Iceland-Jan Mayen Ridge at the time of deposition of the Site 348 basalts. The apparent lack of northward Iceland mantle plume flow beneath the ridge has been interpreted to reflect: (1) repeated jumping of the ridge axis, which would tend to prevent the establishment of a relatively steady-state shallow mantle plume flow pattern for the region; and/or (2) damming of shallow mantle plume flow by a ridge offset, such is the present case with the Tjörnes Fracture Zone (Schilling, 1973; Schilling et al., 1974; Vogt and Johnson, 1975).

Site 350: Outward East Flank of Jan Mayen Ridge

Only one sample, 16-2, 30-33 cm (5), was studied from this site. It is a fresh aphyric, slightly quartz-normative basalt (Ridley, this volume). It is light RE enriched (Figure 4), and the pattern is remarkably similar to that of Sites 342 and 343 on the Vøring Plateau, or of the lower and middle Faeroe basalt series (Figure 3). The similarlity extends to the bulk chemistry of these basalts, including relatively high Fe and TiO_2 contents. Predrift reconstruction maps for the Norwegian Basin (Talwani and Eldholm, in press) would bring Site 340 in between the Vøring and Faeroe plateaus, closer somewhat to this later location. However, these basalts would not necessarily be contemporaneous in age. They would, however, be closely related to the volcanic activity at the early stage of the opening of the Atlantic in this region. The light RE-enriched pattern may suggest mantle plume derivation, which was apparently at its peak during this period and may have been responsible for the extensive doming, flexuring, and breakup of the continental plate and its subsequent early drifting (Brooks, 1973a; Schilling and Noe-Nygaard, 1974; Vogt and Avery, 1974). Alternatively, and as earlier believed by Schilling (1971), it may be that light RE-enriched tholeiitic magma characteristic of continental margins of the North Atlantic may have been related to particular conditions of magma generation and/or thermal regime at the onset of continental breakup and drifting. The exact cause of light RE enrichment in this later model remains undefined. However, it needs to be emphasized that the existence of Iceland, also built up dominantly of light RE-enriched tholeiitic basalts, does not appear consistent with this latter alternative. Continental crust assimilation has also been suggested, but does not appear a viable model for such large volumes of tholeiites of such uniform composition.

TENTATIVE CONCLUSIONS

The following points are emphasized:

1) The RE patterns of basalts from Sites 337 and 348 suggest that lavas erupted along the Mid-Atlantic Ridge in the Norwegian Basin at these particular locations and time of deposition (~28-38 m.y. and ~15-28 m.y., respectively) were apparently derived from the characteristically light RE-depleted asthenosphere, apparently of near worldwide occurrence (Schilling, 1975).

2) Mixed types of RE patterns at Site 336 on the Faeroe-Iceland Ridge suggest a primarily low Iceland mantle blob activity for this period (40-50 m.y.), thus being consistent with independent inferences made by Vogt and Avery (1974) and Schilling and Noe-Nygaard (1974).

3) So far, there is no evidence that the Iceland mantle plume flowed northward beneath the Mid-Atlantic Ridge within the last 40 m.y., as it has apparently done southward beneath the Reykjanes Ridge (Vogt, 1971; Schilling, 1973). This may reflect the frequent jumping of the Mid-Atlantic Ridge Axis in the Norwegian Basin (Talwani, this volume), whereas during all this time the Reykjanes Ridge has spread fairly symmetrically and its axis remained relatively fixed in space. It is believed that frequent rift jumpings and possibly associated formation of ridge offsets, as is the present case with the Tjornes Fracture Zone just north of Iceland, would tend to prevent the establishment of a relatively steady-state flow configuration involving the interaction of both independent directions and rates of flow of the plume and the asthenosphere.

4) Light enriched RE patterns of basalts erupted: (a) on the Vøring Plateau some 50-60 m.y. ago (Sites 338, 342, and 343), (b) on the structurally and magnetically ill-defined zone bordering the Jan Mayen Fracture Zone (Site 345), (c) on the present spreading axis of the Mid-Atlantic Ridge just north or south of the Jan Mayen Platform (Mohns Ridge and Kolbeinsey Ridge, respectively) are consistent with the presence of a mantle plume (or blob) upwelling beneath the Jan Mayen Platform. In this model, the Vøring Plateau would reflect the Jan Mayen plume activity at the onset of continental drifting some 50-60 m.y. ago; just as the Faeroes Plateau basalt reflects the early activity of the Iceland plume. The complex zone bordering the East and West Jan Mayen Fracture Zone would then be a topographic reflection of the Jan Mayen plume activity, as this is also apparently the case for the Faeroe-Iceland Ridge with respect to the Iceland mantle plume.

5) The similarity of basalt RE patterns at Site 337 (>50 m.y.) with the lower and middle Faeroe Plateau basalt series (50-60 m.y.), East Greenland Plateau basalts near Scoresby Sund (50-60 m.y.), and the Vøring Plateau (>50 m.y.), is consistent with an intense and broad mantle upwelling activity at the onset, or early phase, of continental drifting in this region. Such extensive plume activity may have been responsible for the doming of continental lithosphere, and breakup of Eurasia from Greenland (Brooks, 1973a; Vogt and Avery, 1974; Schilling and Noe-Nygaard, 1974). It remains to investigate in this model whether the Iceland-Faeroe or Jan-Mayen-Vøring plumes represent independent blobs, or are part of a much broader and deeper upwelling; in which case, and by analogy, the Iceland and Jan Mayen plumes would represent only the humps of a camelback.

6) Commonly referred alternative model(s) have been to associate the light RE-enriched tholeiitic volcanism at the onset of continental drifting, to some peculiar conditions of magma generation, thermal regime, or progressive light RE depletion of the upper mantle with time (Philpotts and Schnetzler, 1970), and/or contamination by continental crust.

Although pro and con arguments cannot be discused in detail here, it needs to be emphasized that the dominance of light RE-enriched tholeiitic basalts erupting along the present Mid-Atlantic Ridge Axis near shallow oceanic volcanic platforms, such as south and on Iceland or just northeast or southwest of Jan Mayen, illustrates the limitation of these later models and prevents a unified theory to be developed. However, we believe that for the limited area studied here, the combined model of mantle plume spreading theory explains best the chemical, morphological, and geological observations made in time and space.

7) RE data on basaltic basement from Leg 38 rule out the earlier idea of a vast *uniform* Thulean Flood Basalt Province and its subsequent fragmentation and local foundering to form the present Atlantic (Tyrell, 1973). The geochemical data presented and predrift reconstructions (Talwani, this volume) reduce considerably the extent of the iron, titanium, light RE-rich Thulean Tholeiitic Volcanic Province, but certainly do not diminish its importance in terms of the development and evolution of the North Atlantic.

8) RE data from Site 344 may suggest the presence of an unsuspected mantle plume upwelling somewhere further north; or perhaps and as an alternative, the data may reflect, somehow, the rather slow spreading rate of the Knipovich Ridge. Whatever the explanation may be, it opens up a new era of investigation in the Arctic.

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