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AZORES MANTLE BLOB: RARE-EARTH EVIDENCE

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Rare earths (RE) in basalts erupted within the rift of the Mid-Atlantic Ridge show a progressive change from light-RE enriched to depleted patterns from the Azores Platform (40°N) down to 33°30'N. South, the pattern remains light-RE depleted as along other "normal ridge" segments. A progressive increase in chemical variability of the basalts towards the Azores is also noted.

The latitudinal RE profile and corresponding ΣFeO/ΣFeO + MgO variations, together, indicate that the origin of these basalts cannot be accounted for simply by considering variable extents of partial melting of a single mantle source and subsequent fractional crystallization during the ascent of the magmas. These two processes produce only second-order effects on the RE patterns. The data requires the presence of a distinct, light-RE richer, mantle source beneath the Azores Platform relative to that of south of 33°30'N and an intermediate zone where both mantle types mix. The relative contribution of the Azores mantle source to the mix appears to decrease fairly regularly southward along the ridge and becomes negligible at 33°30'N. Increasing chemical variability of the basalts towards the Azores is probably caused by correspondingly larger extent of fractional crystallization at shallow depth, and/or greater variability in the extent of partial melting, apparently subsequent to, and superimposed on the mixing of the two mantle sources.

The combined morphological, geophysical and RE evidence along the profile are consistent with a model suggesting upwelling of a major blob (plume) under the Azores Plateau; and reveal the present extent of the blob's overflow and mixing with the asthenosphere depleted in large ionic lithophile trace elements. The influence of the Azores blob is geochemically detectable up to 1000 km southwestward beneath the ridge axis.

1. Introduction

The Azores region represents the junction of the European, African and North American plates [1], and thus plays an important role in the evolution of the North Central Atlantic. Yet the area has been neglected in most paleogeographic reconstructions of the Atlantic [1,2]. This is because of the tectonic complexity that the submerged platform and its islands represent, the lack of easily correlative magnetic anomalies and the lack of sufficiently detailed geophysical surveys of the platform and bordering tectonic elements: the Mid-Atlantic Ridge (M.A.R.), the East Azores Fracture Zone (E.A.F.Z.) and the Terceira Trough (Fig. 1). A first attempt describing in some detail the tectonic evolution of the area as a triple junction has been made by Krause and Watkins [3]. In this model, the two principal M.A.R. segments trending N–S and SW, act as major spreading centers, whereas the Terceira Trough plays the role of a secondary spreading center, initially as a leaky transform fault. Other interpretations have been suggested in the course of assessing the tectonic evolution of the Atlantic [1] and the Mediterranean Sea [4]. It has also been proposed that the Azores region is underlain by a rising mantle plume [5,6], but no supporting evidence has yet been presented.

Morphologically, the Azores Platform appears to represent a broadening of the M.A.R. best represented by the 1500-fm bathymetric contour in Fig. 1. The region is also characterized by a free-air positive gravity anomaly relative to the figure of hydrostatic equilibrium [7], which with the excess ridge elevation, suggests mantle upwelling beneath the Azores.

Here I present rare-earth (RE) abundance data for submarine basalts recently erupted along the M.A.R., across the platform from 40°N, and SW up to the Atlantis Fracture Zone, 30°N (Fig. 1). The M.A.R. is used as a geochemical window into the upper mantle to detect possible plume flow, in a fashion similar to previous studies of the Iceland–Reykjanes Ridge System [9] and around the Afar [10].

2. Sampling

Fig. 1 shows the location of basalts dredged with R/V "Trident" of the University of Rhode Island during cruises TR-86 and TR-89 in 1970, and TR-119, TR-122 and TR-123 in 1972. Detailed geophysical surveys of the Azores Platform and associated tectonic elements were also conducted during some of these cruises. These results have been presented by Krause and McGregor [11]. Bathymetric, magnetic and seismic reflection profiling was conducted across the crest of the ridge to locate the rift and recent volcanic features for dredging. Sampling of fracture zones (Fig. 1) was purposely avoided. This was made possible by using preliminary bathymetric and aeromagnetic maps [12,13], which were kindly made available prior to publication by Dr. J.D. Phillips, Woods Hole Oceanographic Institution, and Dr. D.C. Krause, United Nations Educational Scientific and Cultural Organization.

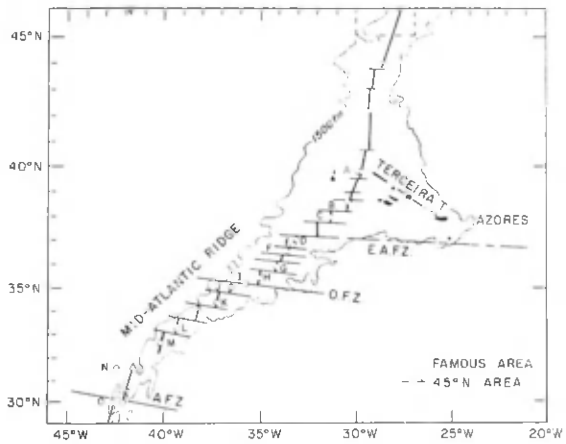

Fig. 1. Location of dredge hauls (see also Table 1). Position of rifts and fracture zones are based on refs. 12 and 13, D.C. Krause, UNESCO (personal communication), and unpublished R/V "Trident" profiles. Black areas represent the Azores Islands. E.A.F.Z., O.F.Z. and A.F.Z. stand for East Azores, Oceanographer and Atlantis Fracture Zones, respectively.

Fresh, glassy pillow basalts and pahoehoe crust, or glassy fragments with radial jointing, were found to be located along small central elongated hills of 100–200 m relief at the bottom of the rift valley, which appeared on our seismic records as fluffy irregular reflections. Such observations have now been confirmed in the area studied by the French–American Mid-Oceanic Undersea Survey (FAMOUS) [14] (Fig. 1). In a few profiles, the small median hills were lacking and dredge hauls had to be taken along one of the rift valley walls, near its bottom, and probably represents talus accumulations. There, the basalts have lost their glassy rim and often are more massive and columnar. They are probably at least a few hundred thousand years old, and often are covered with a thin coating of manganese oxide. Otherwise the basalts appear quite young judging from their glassy nature and position within the M.A.R. rift, and the general absence of glacial erratics in the dredge hauls [15].

Our R/V "Trident" sampling along the M.A.R. in FAMOUS quadrangle was kindly supplemented by Dr. W.B. Bryan, Woods Hole Oceanographic Institution (Fig. 1, stations E and F). Identification of the rift just south of the "Oceanographer Fracture Zone" was not possible, and only older altered pillows with 2–3 mm of manganese coating were obtained (station J). Subsequently, fresh glassy basalts dredged along the Oceanographer Fracture Zone offset were kindly provided by Dr. P.J. Fox, State University of New York, Albany, to complement our sampling (Fig. 1, station I); and also by Dr. B.C. Heezen, Lamont-Doherty Geological Observatory of Columbia University, for the region near 30°N (Fig. 1, stations N and O).

3. Petrology

In order to estimate possible local geochemical variability as well as geographical variations, at least three separate samples were selected for study from each of the R/V "Trident" dredge stations. Petrographically, most of the basalts are porphyritic and show typical variolitic and rapidly quenched textures as described by Bryan [16]. The most common phe-

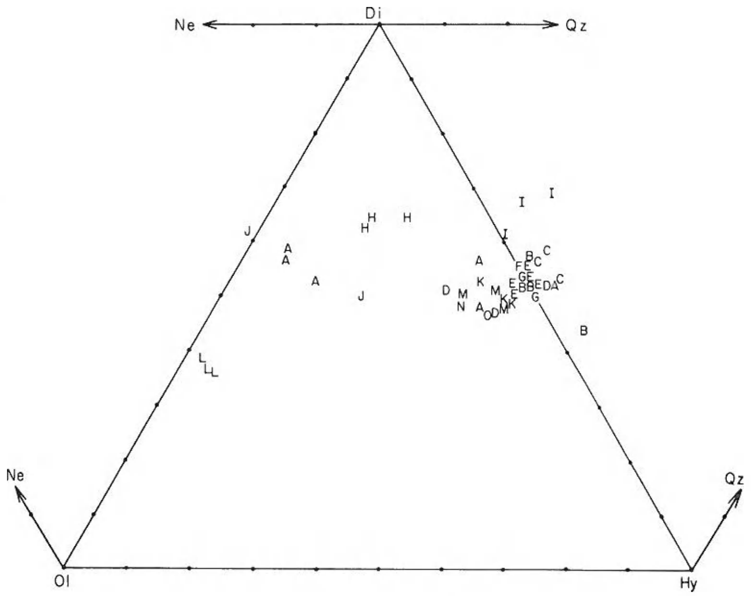

Fig. 2. Normative quartz–diopside–hypersthene–olivine diagram [18] of dredged basalts reported for rare earths in Table 1. For reference to letter symbols see Table 1 (complete analyses unpublished).

nocrysts are plagioclase (An_{73-89}), followed by olivine (Fo_{75-89}), then by clinopyroxene. Noteworthy is the increase towards the Azores of the abundance of pyroxene phenocrysts relative to plagioclase and olivine as similarly found along the Reykjanes Ridge [9] and in the Gulf of Aden near the Afar Triangle [10,17], and finally plagioclase relative to olivine as well. Detailed petrographic, mineralogic and petrologic discussion of our dredged rocks will be reported elsewhere. The CIPW norms of the basalts calculated from the major element chemistry are presented in Fig. 2 on a Ne–Ol–Di–Hy–Qz diagram [18]. All the rocks can be classified as basalts, and range mostly from mildly quartz to olivine-normative tholeiitic basalts with a tendency to cluster near the Di–Hy joint, similar to most results published for ocean-ridge basalts [19]. Their chemistry contrasts with those of the Azores Islands which are mostly alkalic [20]. The greatest chemical variability at a single latitude is found in the M.A.R. rift over the Azores Platform at station A (Fig. 1). At A, two dredge hauls were recovered and consist of basalts overlapping in composition, ranging from quartz-normative to olivine-normative tholeiitic basalts, and transitional basalts [21,22]. Thus, as apparent in Fig. 2, basalts from the M.A.R. over the Azores Platform cover the entire range found along the profile from 40°N to 30°N, including the FAMOUS area. The minimum chemical variability is found for stations L to O which are derived from what appears to be a "normal ridge" segment, as previously discussed in detail by Schilling [23]. Basalts from station L are Al_2O_3-rich picrites and are strongly light-RE depleted (Fig. 3). Station H just north, and station J just south of the Oceanographer Fracture Zone appear chemically and normatively distinct (Fig. 2). Both H and J basalts are unusually vesicular (~20% vesicles) for their depth of collection (~2350 m and ~1750 m respectively) [24]. Samples H were obtained near the bottom of the west wall of the rift, whereas J basalt was dredged off the rift and was covered with a thick layer of palagonite [24]. Sediment ooze infilling some of the vesicles was observed, and as the vesicles are very small and abundant, it was difficult to eliminate contamination during the analysis. This may be reflected in part by a somewhat higher CaO content (avg. 13.36 wt.%) for H basalt and consequently relatively high normative diopside. The small content of normative nepheline in one of the two samples analyzed from station J is probably due in part to the altered nature of this rock. However, J basalts are also distinct by having low SiO_2 content (47–48%). Ba-

TABLE I

Rare-earth abundances (ppm) of dredged basalts from the Mid-Atlantic Ridge, 40°N–30°N, determined by instrumental neutron activation analysis (Analyst - R. Kingsley). Precision and accuracy of the analytical technique can be estimated from rock standard BCR-1 also reported

Cruise	Station	Symbol	Latitude	Longitude	Depth (m)	La	Sm	Eu	Tb	Yb	Lu	$[La/Sm]_{E.F.}$	FeO (wt.%)	Fe_2O_3 (wt.%)	MgO (wt.%)
TR-89 [1]	30D-2-3	A	39°37.9'N	29°44.4'W	1950–2100	18.8	5.2	1.6	0.79	2.6	0.30	2.5	7.36	2.02	8.10
	30D-5	A	39°37.9'N	29°44.4'W	1950–2100	16.7	4.6	1.6	0.81	2.2	0.25	2.5	6.93	1.50	8.75
	30D-10B	A	39°37.9'N	29°44.4'W	1950–2100	6.3	2.4	0.85	0.37	2.1	0.29	1.8	7.68	1.13	9.24
	31D-1	A	39°37.6'N	29°42.3'W	1700–1800	25.1	5.7	1.8	0.91	1.5	0.25	3.1	6.45	2.89	7.98
	31D-3	A	39°37.6'N	29°42.3'W	1700–1800	30.7	7.5	2.4	1.2	2.3	0.40	2.9	8.21	3.23	5.30
	31D-5	A	39°37.6'N	29°42.3'W	1700–1800	7.1	2.7	0.93	0.63	2.3	0.30	1.9	8.32	1.39	7.54
	21D-1	B	38°26.0'N	30°21.4'W	2700–2850	18.4	5.5	1.7	1.1	2.0	0.46	2.4	8.10	2.39	5.67
	21D-2	B	38°26.0'N	30°21.4'W	2700–2850	18.0	5.4	1.6	0.81	1.5	0.30	2.4	8.94	1.57	5.71
	21D-3	B	38°26.0'N	30°21.4'W	2700–2850	20.0	6.0	1.8	0.86	3.3	0.33	2.3	8.71	1.89	5.72
	22D-1	B	38°25.3'N	30°27.0'W	1750–1850	15.1	4.2	1.6	0.60	1.6	0.33	2.5	7.62	2.15	7.92
	22D-4	B	38°25.3'N	30°27.0'W	1750–1850	11.2	4.1	1.2	0.79	3.1	0.38	1.9	9.18	1.88	6.90
	22D-5	B	38°25.3'N	30°27.0'W	1750–1850	11.7	4.5	1.4	0.91	2.1	0.41	1.8	8.59	2.37	6.88
TR-122	5D-2	C	37°43.6'N	31°28.2'W	1630–1670	13.4	4.8	1.5	1.0	3.1	0.58	2.0	9.03	2.34	6.25
	5D-4	C	37°43.6'N	31°28.2'W	1630–1670	9.9	3.3	1.1	0.67	2.5	0.35	2.1	9.28	1.96	6.34
	5D-5	C	37°43.6'N	31°28.2'W	1630–1670	10.7	3.7	1.4	0.71	2.2	0.40	2.0	9.38	1.85	6.39
TR-119	4D-1B	D	36°50.7'N	33°13.7'W	2275–2475	7.3	3.6	1.1	0.59	3.6	0.63	1.4	9.07	1.65	7.68
	4D-3A	D	36°50.7'N	33°13.7'W	2275–2475	9.8	3.4	1.1	0.78	2.7	0.38	2.0	7.68	1.28	10.13
	4D-4	D	36°50.7'N	33°13.7'W	2275–2475	8.5	3.3	1.1	0.79	2.9	0.44	1.8	9.43	1.23	8.53
AII-73 [2]	10-2-19	E	36°43' N	33°16' W	2300	5.7	2.6	0.87	0.51	1.9	0.30	1.5	7.93	1.52	8.05
	14-4-17	E	36°45.6'N	33°17.3'	2448	4.9	2.4	0.97	0.53	2.5	0.41	1.4	8.15	1.06	8.09
	16-5-2	E	36°43.2'N	33°17.5'W	2598	6.0	3.0	0.95	0.73	2.1	0.43	1.4	8.66	1.34	7.67
	16-5-5	E	36°43.2'N	33°17.5'W	2598	6.9	3.4	1.1	0.83	3.2	0.47	1.4	9.19	1.53	7.58
	18-6-1	E	36°46.3'N	33°18.1'W	2561	4.9	2.4	0.90	0.58	2.2	0.37	1.4	8.39	1.11	7.87
	50-13-6	F	36°29.0'N	33°38.7'W	2561	5.8	2.5	0.88	0.62	2.4	0.40	1.6	8.28	1.45	7.78
TR-119	6D-2B	G	35°50.2'N	34°10.8'W	2400–2500	5.4	2.8	1.0	0.73	2.5	0.41	1.4	8.39	1.51	7.34
	6D-3A	G	35°50.2'N	34°10.8'W	2400–2500	5.1	2.5	0.97	0.64	1.7	0.37	1.4	8.41	1.59	7.36
	6D-6	G	35°50.2'N	34°10.8'W	2400–2500	4.1	2.5	0.86	0.54	2.3	0.39	1.2	8.42	1.15	8.33
	7D-1	H	35°20' N	34°54' W	2100–2400	24.4	5.1	1.5	0.92	2.7	0.27	3.4	6.12	1.82	8.54
	7D-5	H	35°20' N	34°54' W	2100–2400	19.2	3.7	1.3	0.57	1.3	0.31	3.6	6.44	1.11	8.74
	7D-10	H	35°20' N	34°54' W	2100–2400	17.0	3.4	1.1	0.62	1.8	0.33	3.5	6.48	1.25	8.64
V-30	RD6-P1	I	35°09' N	35°43' W	2020	8.0	5.2	1.7	1.3	4.7	0.58	1.1	n.d.	n.d.	n.d.
	RD7-P3	I	35°08' N	35°44' W	2130	8.4	5.1	1.6	1.1	4.9	0.57	1.2	6.49	3.38	6.00
	RD7-P10	I	35°08' N	35°44' W	2130	8.5	5.1	1.6	1.2	4.2	0.61	1.2	n.d.	n.d.	n.d.
	RD8-P1	I	35°09' N	35°44' W	2135	7.9	3.2	1.1	0.61	2.7	0.35	1.7	5.83	3.47	7.63
	RD8-P2	I	35°09' N	35°44' W	2135	8.7	5.8	1.8	1.3	5.1	0.69	1.1	7.18	5.08	5.58
TR-119	8D-1	J	34°56.3'N	36°36.7'W	1720–1780	17.4	5.2	1.7	1.0	2.3	0.57	2.3	8.79	1.70	8.94
	8D-5	J	34°56.3'N	36°36.7'W	1720–1780	16.1	4.8	1.6	0.89	2.2	0.43	2.4	8.22	2.84	8.71

TABLE 1 (continued)

Cruise	Station	Sym-bol	Latitude	Longitude	Depth (m)	La	Sm	Eu	Tb	Yb	Lu	$[La/Sm]_{E.F.}$	FeO (wt.%)	Fe_2O_3 (wt.%)	MgO (wt.%)
TR-123	1D-5A	K	34°13.9'N	37°07.6'W	3100	3.7	2.7	1.0	0.79	3.5	0.52	0.95	9.03	1.59	8.35
	1D-6	K	34°13.9'N	37°07.6'W	3100	4.5	3.6	1.3	0.98	4.5	0.68	0.88	8.94	1.28	7.94
	1D-7	K	34°13.9'N	37°07.6'W	3100	3.1	3.0	1.6	0.87	2.9	0.46	0.71	9.10	1.10	8.06
	1D-8F	K	34°13.9'N	37°07.6'W	3100	2.6	2.8	0.93	0.67	2.1	0.54	0.66	n.d.	n.d.	n.d.
	4D-5	L	33°22.2'N	39°04.8'W	1950	0.92	1.8	0.73	0.54	2.8	0.39	0.35	8.87	1.78	12.05
	4D-7	L	33°22.2'N	39°04.8'W	1950	0.53	1.6	0.67	0.38	3.0	0.34	0.24	9.09	0.62	11.60
	4D-9	L	33°22.2'N	39°04.8'W	1950	0.73	1.6	0.74	0.40	2.2	0.38	0.32	8.76	1.04	11.59
	5D-1	M	32°37.4'N	39°52.1'W	2700	2.8	4.4	1.5	1.1	4.8	0.59	0.45	10.31	1.28	7.60
	5D-2	M	32°37.4'N	39°52.1'W	2700	2.6	3.4	1.2	0.97	3.2	0.56	0.55	9.71	2.06	7.68
	5D-3	M	32°37.4'N	39°52.1'W	2700	3.0	4.0	1.3	0.84	4.7	0.48	0.53	10.04	1.36	7.55
A150	RD-8	N	31°49' N	42°25' W	3700	3.5	4.2	1.4	1.1	4.2	0.51	0.59	8.78	1.64	8.57
	RD-7	O	30°01' N	42°04' W	4280	2.8	3.3	1.2	0.87	3.2	0.50	0.58	8.42	1.73	8.63
	RD-20	O	30°04' N	42°16' W	4144	2.7	4.2	1.5	1.0	4.1	0.66	0.45	9.17	1.86	7.33
BCR-1 [4]			rock standard			26.5	7.4	2.2	1.3	3.6	0.52	—			
						±6.5%	±7.2%	±7.8%	±15%	±13.3%	±5.6%				

[1] TR - refers to collection with R/V "Trident", URI.
[2] A - refers to collection with R/V "Atlantis", WHOI.
[3] V - refers to collection with R/V "Vema", LDGO. See ref. [52] for a detailed petrological account on these rocks.
[4] Average of 12 replicate analyses and percent standard deviation from the mean (1 S.D.).

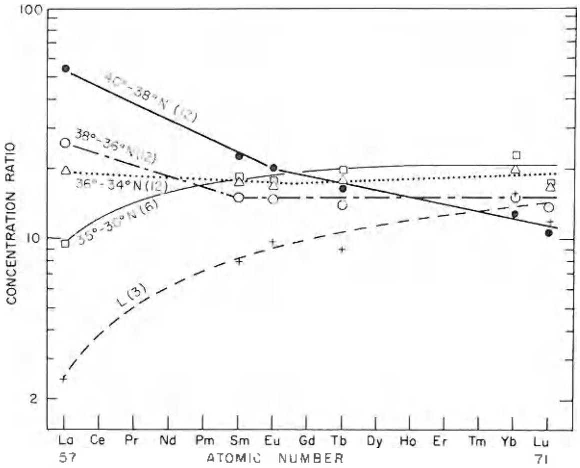

Fig. 3. Chondrite normalized rare-earth patterns of M.A.R. dredged basalts, averaged over every 2° of latitude between 40° and 34°N, except stations M, N and O between 33–30°N which are all grouped together. Stations H and J have been omitted and picritic basalts from station L averaged separately. The number of samples used for the average is given in parentheses. Data is taken from Table 1.

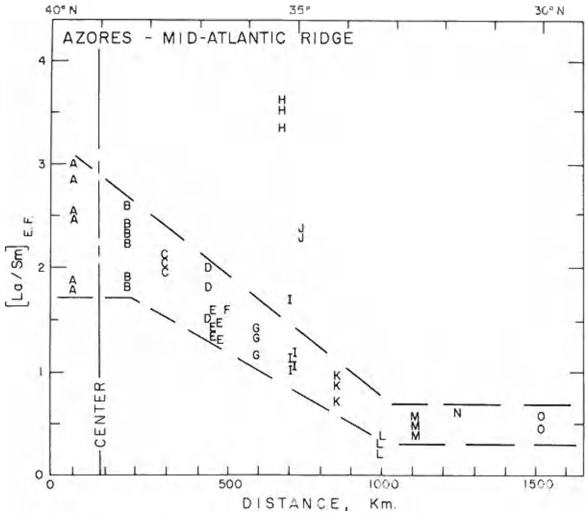

Fig. 4. Variation of chondrite normalized La/Sm ratio against latitude or radial distance from the Azores Platform. Data is taken from Table 1.

salts from stations J and particularly H have anomalous RE content relative to neighboring stations.

4. Rare-earth variations

Table 1 lists the RE abundances measured by instrumental neutron activation. Fig. 3 shows the RE pattern variation along the M.A.R. averaged over segments of two degrees of latitude from 40°N to 34°N, and between 33° to 30°N as a single group. A progressive decrease from light-RE enriched to light-RE depleted patterns relative to chondrites is clearly apparent from the Azores Platform southwestward along the M.A.R. (Fig. 3). On the other hand, the heavy RE increase slightly towards the Azores (disregarding the picrites of station L). As a result, a cross-over of the RE fractionation patterns occurs near the middle of the RE series. Thus, it appears by excluding the picrites L, that the latitude averaged RE pattern variation of Fig. 3 could, to a first order, be accounted for by mixing in varying proportions the two most end-member RE patterns. The two end-member RE patterns correspond also to basalts located at both extremities of the M.A.R. profile.

The change of the $[La/Sm]_{E.F.}$ ratio along the profile further illustrates the light-RE variation and reveals three distinct segments of the Mid-Atlantic Ridge (Fig. 4). First, the M.A.R. segment, south of 34°N, is marked by a relatively constant low $[La/Sm]_{E.F.}$, much less than unity, which is characteristic of "normal ridge" segments [23]. Second, the transitional segment, between 34°N and the Azores Platform, is marked by a smooth and progressive northeast increase of the $[La/Sm]_{E.F.}$ (excluding anomalous stations H and J). Finally, basalts derived from the M.A.R. rift transecting the Azores Platform show a maximum $[La/Sm]_{E.F.}$ value and maximum dispersion as well. Similar trends have been obtained southwest of Iceland along the Reykjanes Ridge [9], or about the Afar along the Gulf of Aden and the Red Sea [10]. Invariably, whether about Iceland, the Afar and now the Azores, the $[La/Sm]_{E.F.}$ anomaly trends all converge outward to a relatively constant low level of light-RE depleted basalt patterns characteristic of "normal ridge" segments [23]. I have attributed such geochemical trends as reflecting mantle plume upwelling, and subhorizontal flow at shallow depth under the ridge, as well as extent of mixing of plume-derived material with the asthenosphere relatively uniformly depleted in light RE and other large ionic lithophile elements (LIL) [9,10]. A similar phenomenon appears warranted for the Azores and the Mid-Atlantic Ridge, southwest. I have shown that the $[La/Sm]_{E.F.}$ of tholeiitic basalts can be considered as to be representative of that of the mantle source from which such basalts are derived, regardless of whether the mantle souce is composed of a spinel lherzolite, a plagioclase lherzolite, or a garnet lherzolite mineral assemblage [23]. This is because the $[La/Sm]_{E.F.}$ of basaltic melts become increasingly similar to that of its mantle source as the degree of partial melting increases, at least for the three mineral lherzolite assemblages considered and usually assumed for the upper mantle. Above some 25–30% of partial melting required for generating the tholeiitic basalts [25], the $[La/Sm]_{E.F.}$ is practically identical to that of its mantle source to within 25% or better; and the ratio can be reliably used as a mantle source indicator as also commonly done with $^{87}Sr/^{86}Sr$ and Pb isotopic ratio of young volcanic rocks (see e.g. [26]). The relation has been convincingly demonstrated along the Iceland–Reykjanes profile, where both the $[La/Sm]_{E.F.}$ and $^{87}Sr/^{86}Sr$ clearly reveal the presence of two distinct mantle sources and their mixing along a transitional zone [9,26].

5. Mantle blob mixing model

Using arguments similar to those previously developed for the Iceland–Reykjanes Ridge System [9,10,27], the high $[La/Sm]_{E.F.}$ over the Azores Platform is interpreted as to reflect a mantle source different from that south of 34°N which represents a normal section of the Mid-Atlantic Ridge. The transitional zone between 34°N and the Azores Platform is also interpreted as a zone of mixing. Since no $^{87}Sr/^{86}Sr$ or lead-isotopic data is yet available, and in view of the larger chemical variability and tendency for some of the submarine rift basalts over the Azores Platform to be transitional (suggesting some fractionation), the mixing model is now further substantiated by considering the relationship of the $[La/Sm]_{E.F.}$ with indices of differentiation based on the major element chemistry of these basalts. For instance, Figs. 5 and 6a show the variations of total iron relative to magnesium along the M.A.R. south of the Azores, as well as with $[La/Sm]_{E.F.}$ values, respectively. No systematic increase of the $\Sigma FeO/\Sigma FeO + MgO$ towards the Azores is apparent, even if occasionally low values representing picritic melts are excluded. This is in contrast to the Reykjanes Ridge where the $\Sigma FeO/\Sigma FeO + MgO$ ratio tends to increase progressively towards Iceland; trends which led O'Hara [28] to propose a mechanism of increasing fractional crystallization towards Iceland for explaining the general $[La/Sm]_{E.F.}$ increase (see [27] for reply). Fig. 6a shows considerable overlap of the $\Sigma FeO/\Sigma FeO + MgO$ ratio along the latitudinal profile, whereas this is not so for the $[La/Sm]_{E.F.}$ which at a fixed $\Sigma FeO/\Sigma FeO + MgO$ keeps increasing with latitude. A similar diagram has been obtained for the Iceland Plume–Reykjanes Ridge System (in preparation). Local variation of the $\Sigma FeO/\Sigma FeO + MgO$ at any latitude is likely to reflect either variations in extent of fractional crystallization during magma ascent, and/or extent of mantle partial melting prior magma ascent, but the two processes cannot alone produce the light-RE fractionation pattern increase towards the Azores [23,27]. Even a fortuitous combination of these two processes operating together appears unable to work. This could also readily be seen by using a $[Yb]_{E.F.}$ versus $[La/Sm]_{E.F.}$ diagram as previously done for Iceland [23,27,29]. The difficulties encountered with a model of increasing fractional crystallization towards the Iceland plume

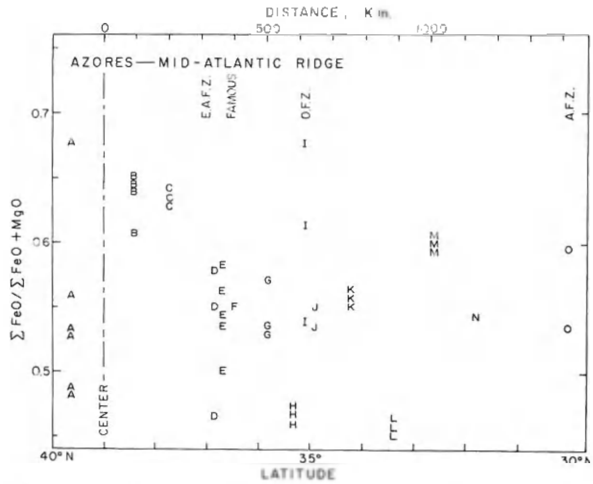

Fig. 5. Variation of wt.% ratio $\Sigma FeO/\Sigma FeO + MgO$ in M.A.R. dredged basalts against latitude or distance from the center of the Azores Platform. ΣFeO refers to total iron expressed as FeO.

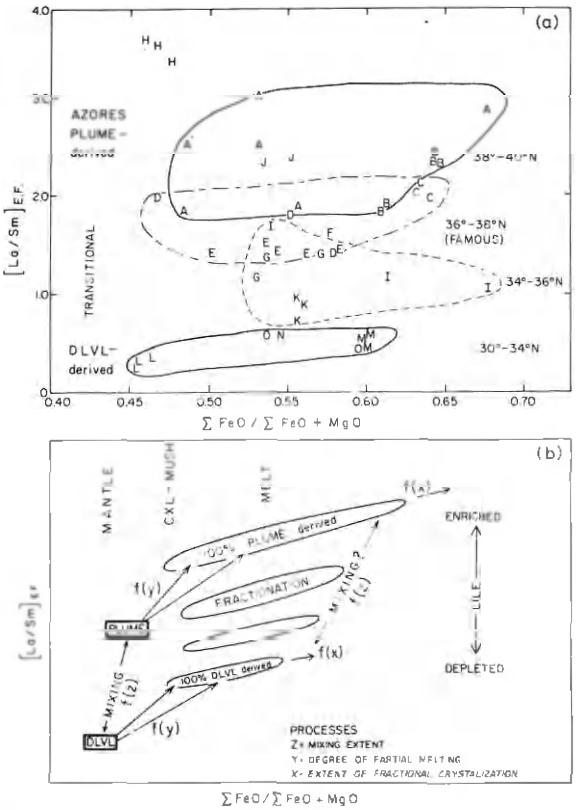

Fig. 6. (a) Variation of wt.% ratio ΣFeO/ΣFeO + MgO in M.A.R. dredged basalts against chondrite normalized La/Sm ratio, $[La/Sm]_{E.F.}$. Fractionation trends have been contoured for every 2° of latitude from 40°N to 34°N and as a single group along the normal ridge segment between 34–30°N. Note that values of the ΣFeO/ΣFeO + MgO ratio for a given region commonly cover most of the range observed along the entire length of the ridge surveyed; whereas this is not the case for $[La/Sm]_{E.F.}$ which keeps increasing with latitude. DLVL stands for depleted low-velocity layer.

(b) Idealized sketch showing the various processes and controlling parameters involved in the proposed mixing model, and their relative effects on the $[La/Sm]_{E.F.}$ and ΣFeO/ΣFeO + MgO ratio. The length of the vector (Y) is inversely related to the degree of partial melting which it represents. The origin of the vector (Y) represents $[La/Sm]_{E.F.}$ and ΣFeO/ΣFeO + MgO ratio of the mantle source whereas the apex, that of the melt produced. Vector (X) shows the direction that $[La/Sm]_{E.F.}$ and ΣFeO/ΣFeO + MgO will take during increasing fractional crystallization at shallow depth. Mixing of the two end member mantles, or mushes (and less likely, melts), superimposed by variable degrees of partial melting and of fractional crystallization will produce the fractionation trends at each latitude; with (Z) the fraction of plume derived material to the mix decreasing with decreasing latitude, away from the Azores plume center.

[27,28], or any other single mantle source model [9], would be further magnified for the Azores region because of the higer $[La/Sm]_{E.F.}$ of the Azores basalts relative to those of Iceland; whereas the low $[La/Sm]_{E.F.}$ level along the "normal segments" of the M.A.R. south of 34°N for the Azores, and south of 61°N for Iceland, are practically the same. Only the existence of two distinct mantle sources beneath the Azores and south of 34°N, and an intermediate zone of mixing, appears compatible with the RE data and detailed model developments for rare earth partitioning during magmatic processes [23,27,29].

Fig. 6b schematically depicts various components of the mixing model proposed to explain the $[La/Sm]_{E.F.}$ and ΣFeO/ΣFeO + MgO variations of Fig. 6a. At any latitude, variation in the ΣFeO/ΣFeO + MgO is explained by small variation in the extent of partial melting (Y) and subsequent fractional crystallization during magma ascent (X). Combination of these two processes at any latitude produces the dispersion of the $[La/Sm]_{E.F.}$ about the general trend of increase towards the Azores, but not the trend itself (Fig. 4). Unfortunately, the data in hand does not permit an estimation of the relative extent of these two processes. Along the transition zone, mixing of the two mantles occurs in proportion varying regularly along the ridge, with the relative contribution of the Azores mantle blob (Z) to the mix decreasing southwestward; and this is the process responsible for the general decrease of $[La/Sm]_{E.F.}$ and heavy RE increase southward along the M.A.R. The problem remaining is to decide at what stage the mixing is in reality occurring and to speculate on the physical form involved. Are the two mantle sources mixing prior partial melting within the asthenosphere? Or alternatively, are only the melts derived from both mantle sources mixing at shallower depth? Or, perhaps more likely, most of the mixing occurs at some intermediate stage and depth by mixing of crystalline mushes rising as diapirs [9,10]. These are difficult questions which are not entirely resolvable from the geochemical evidence alone and whose solutions reside in deciphering the dynamics of the process, in particular the flow pattern is the asthenosphere of the two mantle sources revealed geochemically.

A possible clue to partially resolve the ambiguities is that the concentration variation of major and minor elements along the M.A.R. southwestward of the Azores (unpublished) are more subtle and irregular than the $[La/Sm]_{E.F.}$ variation, and major element co-variations do not readily satisfy simple linear mixing equations anticipated. This is probably because the major element chemistry reflects the last equilibrium with mantle minerals during the rise of diapirs and partial melting, or subsequent equilibration with phenocrysts crystallizing and separating during magma ascent, after the melts segregated from residual mantle phases. Such magmatic conditions and operating rates are in turn controlled by local tectonic and spreading conditions, and thermal regimes, which may be quite variable along the ridge. The lack of more regular major element trends may suggest that mixing must have occurred prior to such last partial melting or fractional crystallization equilibrations, thus modifying any regular major element trends previously established by mixing of the two mantle sources both in a crystalline mush state of aggregation. In contrast, the main stage of partial melting while the diapirs are rising, tends to restore the $[La/Sm]_{E.F.}$ of the melts to a value practically identical to that of its mantle source, which is now already represented by a mix of crystalline mushes, according to this scheme. Furthermore, I have shown [27,29] that $[La/Sm]_{E.F.}$ is relatively insensitive to fractional crystallization of basaltic melts unless extensive and improbable amounts of pyroxene or garnet were to be removed during magma ascent. The presence of phenocrysts and more irregular major and minor element trends along the ridge do indeed suggest some fractional crystallization prior to eruption, but not to the extent of explaining the general RE trend towards the Azores. The increase of chemical diversity and dispersion towards the Azores as for example shown in Fig. 5, and also observed for other major, minor elements such as K_2O, P_2O_5, TiO_2, as well as individual trace elements such as La, suggest that the M.A.R. basalts might have also suffered an increasing extent of fractional crystallization towards the Azores prior to eruption, in addition to some small variations in the degree of melting and the major mixing process. Increasing chemical dispersion towards the Azores probably reflect a progressively thicker crust approaching the Azores as well as under the Azores Platform. A similar effect is apparent along the Reykjanes Ridge through Iceland, and is accompanied by increasing crustal thickness [9,30,31].

6. Morphological and geophysical constraints

Although the RE data presented suggest two distinct mantle sources beneath the Azores and the Mid-Atlantic Ridge south of 34°N, and an intermediate zone of mixing, it does not directly reveal any dynamical aspect of the process involved. So far, it is only by drawing analogy to the Iceland–Reykjanes Ridge System [9] that the presence of a blob (or plume) rising beneath the Azores has been inferred. Therefore, it is now important to relate the RE anomaly to the morphology, tectonics, and other geophysical evidence available around the Azores, in an attempt to unravel further some of the dynamics. I have already mentioned the anomalous elevation of the Azores Platform accompanied by a free-air positive gravity anomaly, suggesting swelling and upwelling of the mantle beneath [7,8]. Perhaps more striking is the funnel-shaped, time transgressive, morphology of the Mid-Atlantic Ridge decreasing in width southwestward from the triangular-shaped Azores Platform. This is best seen from the 1500-fm contour line in Fig. 1. The funnel-shaped ridge tapers and begins to maintain a narrow ridge topography at about the same place where the geochemical anomaly ends, around 34°N. Such morphology is compatible with the RE evidence and probably reflects forceful subhorizontal mantle flow beneath the ridge from the Azores blob (or plume), similar to south of Iceland along the Reykjanes Ridge where also a similar funnel-shaped, time transgressive topography is apparent [9,32]. The Azores blob flow appears not to be forceful enough to feed the entire length of the spreading Mid-Atlantic Ridge, and thus light-RE depleted material from the low-velocity layer complements in increasing proportion soutwestward. South of 34°N, the ridge becomes "normal" and only depleted asthenospheric material passively feeds the rift in response to spreading [23,33].

I have also shown that higher discharge rates of volcanism and formation of a thicker crust about the Iceland plume would be expected if blobs (or plumes) are rising from deeper than are asthenospheric diapirs commonly feeding the spreading axis along "normal ridge segments" [9]. A possible increase of the crustal thickness towards and over the Azores Platform was earlier suggested on the basis of increasing geochemical dispersion. Independent seismic evidence demonstrating a thicker crust beneath the Azores Platform, and a southwest decrease, would be one possible additional test of the plume flow proposed. Nafe and Drake [34] suggest a general increase of the depth to the mantle northeast towards the Azores, varying from 6 km around 30°N to 11 km below sea level over the Azores Platform (39°N). After subtracting water depth, this would give roughly a change in crustal thickness from 4 km to 7 km northeastward, thus consistent with the geochemical evidence presented and the thermodynamical inferences previously discussed [9]. However, refraction data is scarce in the area and such variations should be considered with caution [35–37]. More refraction lines have recently been reported in the FAMOUS area (36°30'N–37°N) [38–40]. Based on the RE profile, FAMOUS lies well within the intermediate zone of mixing (stations D, E and F in Fig. 4). Intermediate crustal thickness is expected, as well as tectonic processes and seismicity reflecting both normal spreading and the subhorizontal axial flow from the postulated Azores mantle blob upwelling. Unfortunately, the refraction lines taken in FAMOUS area are within the rift of the Mid-Atlantic Ridge or very close to it, and are either incomplete or inconclusive in terms of the present problem. Whitmarsh [38] indicates mantle velocities at a depth of 5.78 km beneath the sea floor which includes layer 3, thus compatible with the prediction. On the other hand, at the same location, Fowler and Matthews [39] report an absence of layer 3 and an anomalous upper mantle velocity at 2.63 km below the rift floor.

Additional dynamical evidence might be gained by considering variations of seismicity along the ridge. Francis [41] has shown that the seismicity of the Reykjanes Ridge is significantly less active north of 59.5°N along the transitional zone revealed by the RE, than south along the "normal ridge" segment. Francis, independently of the RE evidence, attributed the seismicity contrast either to reflect the Iceland mantle plume extending beyond the confines of Iceland itself, or alternatively, to reflect the ridge morphology characterized by an elevated central block north of 60°N, whereas to the south the morphology is more like "normal ridge" segments. Francis also acknowledged the possibility that both effects might be the consequence of Icelandic volcanism. Because of the remarkable coincidental change of the seismicity and the RE geochemical nature of the Reykjanes Ridge, I prefer to believe that it reflects the Iceland plume and its flow along the ridge axis, as discussed above. Again, similar results south of the Azores would further strengthen the blob model proposed for the region. A microearthquake study of the Mid-Atlantic Ridge in the transitional area FAMOUS (36°30'–37°N) reveals low microseismicity and incidence of swarms relative to both, the faster spreading Gulf of California and Galapagos spreading center [42]. However, a more recent microearthquake monitoring of the same area, but with a better and more sensitive sonobuoy array coverage of the rift, revealed higher activity confined along the decoupling boundary of the valley floor and eastern wall of the rift; thus probably reflecting ongoing development of the rift wall by uplift of faulted blocks [43]. Thus, the seismic evidence along this transitional segment of the M.A.R. remains so far inconclusive, as studies using the same recording system are not available for direct comparison with seismic activity south of 34°N along the "normal ridge" segment.

Finally, I now consider possible geothermal variations towards the Azores, which according to the plume model would be expected to increase [6,9]. So far, conventional heat flow measurements in the area are insufficient for drawing any conclusions. It is also questionable whether the heat flow variations would in any case be sufficiently large and unambiguous to reveal the effect, thus less direct approaches need to be explored. Increasing major element dispersion towards the Azores was noted earlier. Although the effect was attributed to possible increase in crustal thickness, an increase of the geothermal gradient towards the Azores is also compatible and both effects might prevail. An increase of the geothermal gradient towards the Azores could enhance chemical diversity in two possible ways:

(1) Magmas ascending independently and in excess of the lithosphere spreading input rate above, would tend to stagnate at shallow depth beneath the litho-

sphere in a zone which is also hotter. Such magmas would cool more slowly, thus enhancing fractional crystallization.

(2) A hotter zone under the Azores should also reduce viscosity and facilitate interstitial melts to segregate earlier from residual solids during the rise of mantle diapirs, decompression and partial melting [44].

The latter mechanism should enhance the probability of melt fractions produced by smaller degrees of melting and derived from greater depth, to reach occasionally and more easily the overlying rift over the Azores, relative to the Mid-Atlantic Ridge southwestward. Although such considerations are compatible with increasing temperatures towards the Azores, these cannot be taken as proof. A more fruitful approach is to determine magma temperatures using various petrological geothermometers, which are currently being determined in this laboratory.

It appears that the variation of the morphology and geophysical features of the Azores Platform and the Mid-Atlantic Ridge southwest show many similarities to those of the Iceland–Reykjanes Ridge System [9], but geophysical data is too scarce for the Azores region to reach definite conclusions on this basis alone. The presence of a rift and small, closely spaced, fracture offsets along the transitional zone southwest of the Azores (60–64°N) is in contrast to the transitional zone of the Reykjanes Ridge. The difference may also be of seismic significance, but apparently not geochemically.

7. Conclusions

The following conclusions are emphasized:

(1) The progressive change from light-RE enriched to light-RE depleted patterns and respective variation of the $\Sigma FeO/\Sigma FeO + MgO$ of basalts erupted along the Mid-Atlantic Ridge from the Azores (40°N) to 30°N cannot be accounted for simply by variable extents of partial melting of a single mantle source and subsequent fractional crystallization during magma ascent. These two processes have only a second order effect on the RE patterns. The data suggest two distinct mantle sources, and an intermediate zone of mixing. The relative contribution of the Azores mantle source to the mix appears to decrease fairly regularly southward along the ridge and becomes negligible at 33°30'N. Increasing chemical variability of the basalts towards the Azores is probably caused by correspondingly larger extent of fractional crystallization at shallow depth, and/or greater variability in the extent of partial melting, apparently subsequent to and superimposed on the mixing of the two mantle sources.

(2) Combination of the above geochemical evidence with (a) the general funnel-shaped morphology of the Azores Platform and southwest Mid-Atlantic Ridge; (b) free-air positive gravity anomaly over the Azores Platform; and (c) the inference of a thicker crust underlying the Azores Platform is consistent with a model suggesting the presence of a major blob (or plume) upwelling under the Azores Platform in an analogous way as for Iceland [9] and the Afar [10].

Within the framework of this model, the RE profile delineates the extent of subhorizontal flow of blob material and extent of mixing with asthenospheric material characteristically depleted in large lithophile elements. It appears that the Azores blob (or plume) is forcefully injecting geochemically distinct, probably hotter and lighter, mantle material and derivative melts at a volume rate exceeding the amount required to fill the gap left by the overlying separating plates of lithosphere, thus allowing the development of the Azores Platform and an underlying thicker crust.

(3) The Azores blob (or plume) activity is inferred for the present or recent past only, as the geochemical anomaly profile reported here is for basalts located within the rift of the Mid-Atlantic Ridge of approximately zero age. The time of the first appearance of a blob beneath the Azores remains unknown and has not yet been investigated.

(4) Any alternative models such as those considering the presence of a triple junction, secondary spreading centers, change of direction and distinct spreading rate history north and south of the Azores, for triggering the excess topography of the Azores Platform [3,20] require revision. Such models need to take into account the RE variations in basalts along the Mid-Atlantic Ridge presented here, as well as arguments suggesting two distinct mantle sources for these basalts.

(5) The coincidence of a blob (or plume) upwelling beneath the Azores Platform with that of a major

triple junction in the same area remains to be elucidated. As a working model, I propose that the appearance of a blob beneath the Azores Region and its doming effect on the lithosphere may indeed have generated the triple junction; perhaps in a similar fashion as discussed recently by Burke and Dewey [45] for other plume-generated triple junctions. Correlaries of this model should be tested by considering in detail the kinematic evolution of the American, African and European Plates around the Azores as well as the Western Mediterranean Sea, prior to and after the appearance of the first blob beneath the Azores Region.

(6) Finally, an important question remaining unresolved is whether such blobs (or plumes) come from deeper than the depleted low-velocity layer [9] or alternatively from a vertically inhomogenous and stratified asthenosphere as suggested by Green [46]. I have shown with simple thermodynamical considerations for Iceland [9] that if one assumes that blobs (or plumes) do indeed penetrate the depleted low-velocity layer from below, the model not only explains the excess rate of basalt discharge by greater extent of partial melting, but also explains the mixing along the transitional zone, as well as thicker anomalous mantle extending deeper under the plume region than beneath ridge axes [47–50]. Whether such blobs (geochemically distinct) come from the base of a stratified asthenosphere, or deeper in the mantle as suggested by Morgan [5], remain unresolved. Geochemical comparison of the Azores and Iceland seems insofar to suggest distinct blob compositions for the two regions, or alternatively, different stages of blob activity [51]. This is in marked contrast to the depleted low-velocity layer source, which to a first-order approximation appears widely uniform in time and space [23,29].

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