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Mid-Atlantic Ridge: zero-age geochemical variations between Azores and 22°N

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The MAPCO cruise of the RV J. Charcot sampled zero-age basalts along the Mid-Atlantic Ridge from the Azores Triple Junction to 24 N. Preliminary shipboard geochemical analyses together with earlier data show that some trace elements are not randomly distributed along the ridge. The latitude of the Hayes transform delineate two regions of rare earth element distribution: north from Hayes, is flat to light rare earth (or equivalent) enriched; south from Hayes, is light rare earth (or equivalent) depleted. These findings indicate large scale heterogeneity of the upper mantle.

THE IPOD program (International Phase for Ocean Drilling) has obtained many samples of igneous rocks from the ocean floor during the past five years. The studies related to this sampling and to samples collected by the more classical dredging method have provided many data which have been interpreted and discussed in terms of the fundamental processes of basalt genesis and the composition of the upper mantle. Some of these compositions are impossible to relate to one another by conventional magmatic processes of fractional crystallization, accumulation of crystalline phases and partial melting. In addition to these conventional processes, two main hypotheses have been proposed to account for the chemical heterogeneities in oceanic basalts that are observed at different scales. One of these hypotheses invokes magma mixing in one form or another; the second hypothesis assumes primitive heterogeneity of different source regions in the upper mantle. One interpretation does not preclude the other. Mixing, either of more or less fractionated liquids derived from the same source[1-3] or of liquids derived from different sources[4,5], is necessarily restricted to local areas. The mantle heterogeneity concept can also be considered as a large-scale (regional) property[6-9]. The research reported here is an attempt to examine regional heterogeneities along a portion of the Mid-Atlantic Ridge.

Area and techniques of analysis

The RV J. Charcot is equipped with a multi narrow-beam echo-sounding system (SEABEAM)[10] which produces a real-time bathymetric map of the sea floor. The system scans an area whose width, normal to the ship's track, is two-thirds of the depth. Because it allows the immediate observation of large scale structures and of fine scale features (20-m contour interval), the SEABEAM system permits relatively easy recognition of the rift valley and fracture zones (large-scale structures) and choice of a dredge site based on observation of fine scale features (such as, central high, volcano, steep slope). The objective of our analysis was to locate the inner floor of the central valley to dredge 'zero age' basalts. The rift valley area chosen for dredging was first surveyed by a track, approximately perpendicular to the ridge axis, roughly 30 miles long (15 miles to either side of the axis). This track was enhanced by a return profile located ~1.5-3 miles to the north or south of the initial crossing. In addition to providing information for dredging, each of these tracks constitutes data for structural interpretation. Dredge surveys and intermediate transits allowed us to obtain 54 transects of the ridge between 35 N and 24 N. Five profiles were made over each of three major transforms, Oceanographer, Hayes and Atlantis.

During this cruise, a new deredging system, 'active weight', was tried and used successfully. It is a percussion system: when the tension of the cable at the level of active weight, which is situated in front of the dredge, is approximately 3 tons, an impulse of 25 tons is communicated to the dredge. The system can act repeatedly at the bottom as it is reset by a return spring when no tension exists between the active weight and the dredge. Ten dredges along the ridge axis, with tracks of 0.5-1.5 miles, were attempted with this system and each dredge was half full to full of rocks. With this dredging method and with simultaneous use of SEABEAM, well positioned dredges can apparently be achieved with a minimum length of the dredge track, probably less than 0.5 miles.

Table 1 Different characteristics between the FAMOUS area (36 N) and sites 395, 396 (22 N). /Ch for Ta/La and Hf/La means normalized ratios*

	Ta/La /ch	Hf/La /ch	$^{206}Pb/^{204}Pb$	$^{87}Sr/^{86}Sr$	ΔNd
22 N (leg 45, 46)	0.56	2. – 2.6	18.0	0.7025	+13
FAMOUS	1.09	0.77 – 1.4	18.8	0.7028	+10

*Refs 20, 21.

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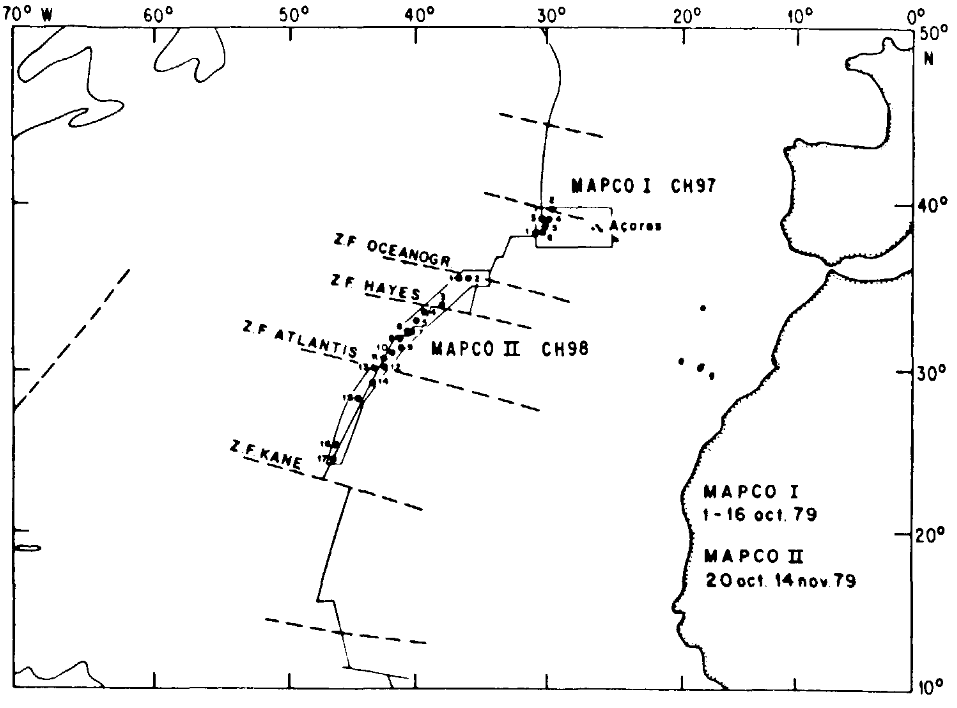

Fig. 1 Map of the studied area. Dots represent dredge sites.

Thin sections were made on board and an X-ray fluorescence unit, similar to the unit used on board the Glomar Challenger[11,12], allowed us to obtain selected trace element and major element data. The precision of the data is comparable to that of an onland laboratory: ±1% (relative) for major elements and ±2 p.p.m. (absolute) for trace elements.

The primary objective of the first part of MAPCO (CH 97) was the structural analysis of the Azores Triple Junction between 39 N and 37 N (reported elsewhere); the primary objective of the second part of MAPCO (CH 98) and the secondary objective of MAPCO (CH 97) was to sample zero age basalts from the axis of the Mid-Atlantic Ridge. The secondary objective of MAPCO (CH 98) was to collect bottom topographic profiles, with emphasis on examining the progressive increase in average depth of the rift valley floor from North to South along the ridge.

Results and discussion

Six dredges were attempted proximal to the Azores Triple Junction during MAPCO (CH 97) and four of these were successful; 17 dredges were conducted as close as possible to zero age during MAPCO (CH 98) and 16 were successful (Fig. 1). The morphologic nature of basalt samples recovered during both parts of the cruise is varied. Two-thirds of the total recovered material is comprised of pillow basalt; one-quarter is comprised of segments of glassy crust varying from 1 to 10 cm in thickness and up to 40 cm in length. The remainder of the material is comprised of small broken fragments. Most of the samples are remarkably fresh and have clean vitreous surfaces. The pillow basalts exhibit characteristic radial fracturing, glassy margins, and have very well preserved extrusive forms of lava fingers or tubes up to 15 cm long. The basalt crusts or sheets are glassy on both sides; the presumed upper portion of these crusts has a ropy appearance and the glass is occasionally oxidized and veneered by sediment, while the lower surface contains portions of thin vertical walls of large cavities (up to 20 cm diameter) and/or frozen droplets of basalt. In dredges CH 98 11 and 12 we recovered massive glass blocks up to 15 cm diameter, glass shards, and thin flat sheets (1 cm thick) of glass. The crusts or sheets are interpreted to be either fragments of large pillows or tubes that were rapidly emptied, or fragments of surfaces of lava lakes[13]. In addition to these basalt samples, scoriaceous basalts of probable subaerial origin were dredged at 900 m depth in the Azores Triple Junction area (CH 97 DR 05). One fragment of granitic metamorphic rock (garnet, cordierite) and a large number of blocks of sediment were recovered in dredge CH 98 DR 06 situated roughly 10 miles west of the rift valley axis.

Most of the basalt samples (two-thirds) are aphyric to subaphyric (phenocrysts < 5%). Nearly all of these basalt fragments contain a few rounded plagioclase phenocrysts, possibly better referred to as xenocrysts, and one or two samples also contain rounded olivine phenocrysts. Microphenocrysts of euhedral olivine, quench olivine and plagioclase are all common. The remainder of the samples are porphyritic basalts (5-30% megacrysts, phenocrysts and/or microphenocrysts). Plagioclase is by far the dominant phenocryst phase; crystals are as large as 1 cm in length and are often rounded and partially reversely zoned. Some are better characterized as glomerocrysts. Most contain inclusions of glass or microcrystalline material. Olivine is a common, though usually minor, phenocryst phase. It is occasionally seen as rounded crystals up to 0.5 mm across but is generally subhedral to anhedral and fresh. Olivine contains rare small red-brown spinel. Clinopyroxene is observed infrequently as a phenocryst phase in these basalts, but is spectacularly present in dredge CH 97 DR 05 (in the Azores Triple Junction area) where it forms 15% of the rock.

Extensive geochemical data from the northern region (Azores Triple Junction and FAMOUS area) and the southern

Table 2 Duplicate analyses of three samples of CH 97 DR 02 Sr, measured from the same pellet preparations as for Nb, Zr and Y determinations, has been used to improve the classification of rock types within one dredge, because of its relative higher precision. Ti was measured from a glass disk preparation

	Sr	Nb	Zr	Ti	Y
101 a	138.0	14.1	75	7,020	26
101 b	136.4	13.6	78		
202 B a	141.6	13.1	76	6,900	26
202 B b	141.1	13.7	74		26
304 a	150.0	15.1	71	6,720	24
304 b	149.3	13.1	74		24

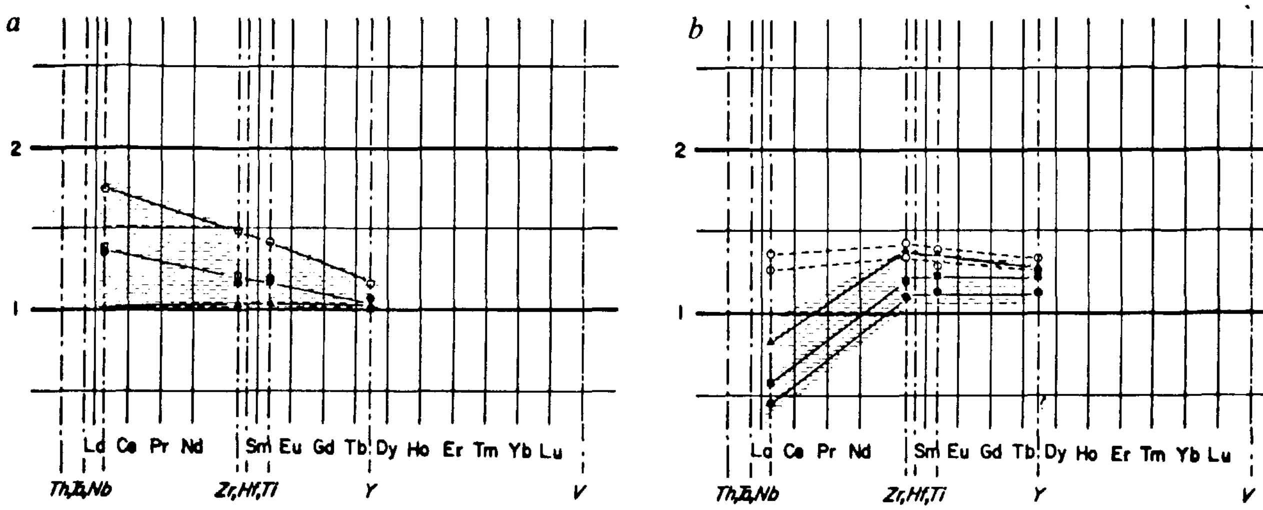

Fig. 2 Examples of extended rare earth diagrams including non rare earth hygromagmaphile elements. *a*, The spectrum observed in the Azores Triple Junction–FAMOUS area (data from refs 14, 16, 17, 23, 25); *b*, 22 N (data from refs 18, 19, 23). The preferred normalizing abundances corresponding to non rare earth elements are, in p.p.m.: Th, 0.028; Nb, 0.53; Ta, 0.031; Zr, 5.13; Hf, 0.128; Ti, 460; Y, 2.16; V, 22. In *a*, flat to light rare earth patterns, Nb, Ta and La plot at the same ordinate position (normalized Ta/La or Nb/La ratios are ≃ 1.09); *b*, light rare earth depleted patterns, Nb and Ta plot at a lower ordinate position than La (normalized Ta/La ratio is ≃ 0.5) see text.

region (22° N) have been interpreted as suggesting that there are significant differences in the isotopic compositions and trace element chemistry of the upper mantle sources between these two areas[14–20]. Table 1 summarizes these data for the FAMOUS area and 22 N (ref. 21). Clearly from our present knowledge only isotopic data obtained from basalts can be interpreted unambiguously in terms of mantle sources. Hygromagmaphile element ratios such as Hf/La (similar to Zr/La or Sm/La) in basalts depend on both mantle source and partial melting. The two different ranges of Hf/La in the FAMOUS area and at 22 N are interpretable in terms of different mantle sources (one for each region) in agreement with the isotopic data. The range of this ratio in each area is probably due to different extents or ways of melting[22,23]. As the main target of the MAPCO cruise is the examination of regional heterogeneities along a portion of the Mid-Atlantic Ridge, namely the transition between the Azores Triple Junction FAMOUS area and 22 N, selected hygromagmaphile elements or their ratios can help, at least in part, to describe these heterogeneities or this transition.

It has been shown for some samples that elements whose ions present a rare gas electronic structure can be included in the rare earth Coryell Masuda plot[24,25]; a comparative geochemical study of more than 300 oceanic basalts showing different rare earth patterns gave precise normalization values and relative behaviour of non rare earth hygromagmaphile elements compared with rare earth elements[26]. Figure 2 presents such a diagram for samples from the Azores Triple Junction FAMOUS region and from 22 N (refs 14–19, 23, 25).

In the northern region the extended rare earth patterns are from flat to light rare earth enriched (Azores Triple Junction, FAMOUS, Sites 411, 412, 413 and 332, 334, 335 of DSDP);

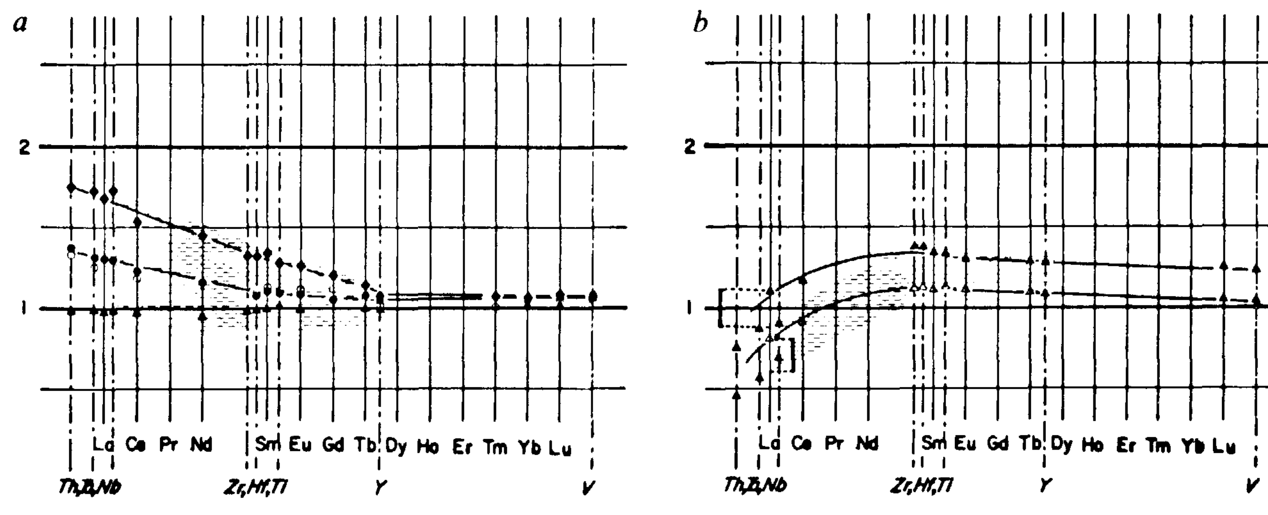

Fig. 3 *a*, Spectrum of non rare earth normalized patterns observed north from the Hayes transform. The end members of this spectrum are CH 97 DR 03 101, 39 N in the Triple Junction (○) and CH 98 DR 03 201, 33 N immediately north from Hayes fracture zone (FZ) (▲). The □, CH 97 DR 05 3.. at 38 N, ● CH 98 DR 02 1.. at 35 N (immediately south from Oceanographer FZ) have been chosen as examples showing similar distributions at different latitudes in this area. *b*, Spectrum of non rare earth normalized patterns observed south from Hayes transform. The plotted samples selected for examples are CH 98 DR 04, 33 N immediately south from Hayes FZ (●), CH 98 DR 07, 32 N (■) and CH 98 DR 17 301, 24 N (▲). The two exceptions (○) correspond to two groups in dredge CH 98 DR 08 at 31 N.

Table 3 Sr, Nb, Zr, Ti and Y data obtained on board; the figure in parentheses corresponds to the number of analysed samples

	Sr	Nb	Zr	Ti	Y
CH 97					
DR 02 — See Table 1					
DR 03 39 06'N 29 54'W					
101 (1)	365	29	160	12,060	32
DR 05 38 42'N 29 57'W					
1.. (3)	397	28	155	11,460	27
2.. (4)	241	16	104	8,100	26
3.. (6)	192	13	86	6,840	21
DR 06 38 31'N 30 18'W					
1.. (6)	260	31	135	11,100	32
CH 98					
DR 02 35 11'N 36 14'W					
1.. (2)	155	12	75	7,400	26
201 (1)	110	8.5	74	8,220	33
DR 03 33 44'N 37 40'W					
1.. (2)	95	6	46	4,770	23
201 (1)	102	5	57	5,220	24
4.. (2)	92	6	61	5,850	25
DR 04 33 30'N 39 05'W					
1.., 2.. (4)	99	1.5	63	6,240	28
DR 05 33 02'N 39 20'W					
101 (1)	93	2	86	8,100	35
DR 06 32 17'N 40 21'W					
101 (1)	87	2	91	8,880	37
DR 07 32 17'N 40 11'W					
1.. (4)	93	2	80	8,000	34
DR 08 31 54'N 40 58'W					
1.., 501 (3)	133	12	134	10,260	45
102 (1)	111	9.5	111	8,580	38
2.. (2)	81	2	90	8,340	38
DR 09 31 28'N 40 57'W					
101 301 (2)	91	2	87	8,460	36
201 (1)	89	1	69	6,780	30
DR 10 31 04'N 41 25'W					
101 (1)	110	3.5	113	10,080	42
2.. (2)	101	1.5	77	7,620	32
3.. (2)	75	1.5	71	6,960	31
DR 11 30 41'N 41 49'W					
1..., 3..., 4.. (7)	92	1.5	92	8,650	36
DR 12 30 10'N 41 55'W					
103, 204 (2)	92	2.5	103	9,600	41
DR 13 29 56'N 42 46'W					
204 et 301 (2)	122	3	105	8,940	36
DR 14 29 17'N 43 05'W					
101, 304 (2)	105	1.5	85	7,750	32
103, 201, 301 (3)	110	2.5	93	8,750	35
DR 15 27 46'N 44 05'W					
102, 301 (2)	113	1.5	95	8,190	32
2.. (2)	113	2.5	52	5,220	23
DR 16 25 16'N 45 20'W					
1.. (2)	128	3.0	100	8,300	33
201 (2)	119	3.5	112	9,360	39
202 (1)	124	5	92	7,320	30
DR 17 24 28'N 46 15'W					
101 (1)	148	3.8	121	9,300	35
201 (1)	167	2.6	99	7,260	31
301 (1)	136	3.5	125	10,260	38
401 (1)	138	3.0	110	9,000	34
Preferred chondrite abundance		0.53	5.13	460	2.16

the normalized Ta/La or Nb/La ratio (≥ 1) is independant of the light rare earth enrichment (as well as for 45 N, site 410, and Reykjanes sites 407, 408 and 409). In the southern region (22 N) the extended rare earth patterns are systematically light rare earth depleted; the normalized Ta/La or Nb/La ratio is 0.5. Knowing this behaviour of hygromagmaphile elements, rare earths and non rare earths, it is possible to use Nb, Zr, Ti and Y concentrations measured through X-ray fluorescence on board to obtain chondrite normalized diagrams equivalent to a rare earth diagram. The data may be interpreted in terms of mantle heterogeneity if these diagrams show sufficiently large differences as we know that a range of Sm/La or Zr/Nb ratios can be observed within a restricted area (FAMOUS and site 411, 412, 413 of DSDP).

Table 2 shows duplicate analyses of samples CH 97 DR 02 used to test the accuracy of measurements on board. Table 3 shows from north to south the results obtained during the cruise. Examination of these data indicates that the distribution of these elements is not random along the axis of the Mid-Atlantic Ridge as mentioned for rare earths by White and Schilling[27]. Nb concentrations, the most hygromagmaphile element investigated, clearly show lower values in the southern region than in the northern region. The range of variation of (Nb, Zr, Ti, Y) chondrite normalized patterns are shown in Fig. 3. North from the Hayes transform these patterns are flat to Nb enriched (equivalent to light rare earth enriched); south from the Hayes transform they are Nb depleted (equivalent to light rare earth depleted); one exception in the southern region is observed in CH 98 DR 08 where two groups of samples show flat or only slightly Nb depleted patterns.

The large difference of the chondrite normalized plots of Nb, Zr, Ti and Y (equivalent to rare earth plots) between north and south from Hayes transform allow us to interpret these preliminary results in terms of regional mantle heterogeneity. The suggested limit (latitude of the Hayes transform) will have to be confirmed by isotopic data. It will be also interesting to study the Ta/La ratio between the Hayes transform and 22 N to confirm whether or not the single normalized Ta/La ratio found so far ($\simeq 0.5$) for light rare earth depleted material comparatively to the single value ($\simeq 1$) observed for flat to light rare earth enriched materials.

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