

22. TRACE ELEMENT GEOCHEMISTRY AND PETROGENESIS OF BASALTS FROM DEEP SEA DRILLING PROJECT SITES 556-559 AND 561-564¹

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ABSTRACT

Forty-three samples from DSDP Holes 556-559 and 561-564 were analyzed for rare earth elements (REE), Sc, Cr, Co, Hf, Ta, and Th by instrumental neutron activation analysis.

The recovered basalts range from those depleted in light REE (LREE) to those enriched in LREE. The two types of basalts occur together in Holes 558 and 561. The depleted basalts have remarkably constant La/Yb, La/Sm, and La/Ti ratios and apparently derive from a large, homogeneous, mantle source underneath a segment (1200 km long) of the Mid-Atlantic Ridge. The almost twofold variation in the concentrations of incompatible trace elements in the depleted basalts is primarily due to different degrees of batch partial melting.

The variation of highly to moderately incompatible elements in the Leg 82 enriched basalts can be successfully explained in terms of source mixing between depleted mantle sources and alkaline or nephelinitic magmas similar to Azores Islands magmas. However, the correlation of LREE enrichment with distance from the Azores Triple Junction is tenuous at best, and the enriched alkaline component is probably not directly related to the Azores volcanism.

INTRODUCTION

The geochemical studies of mid-ocean ridge basalts (MORB) from different regions in the northern Atlantic Ocean have revealed regionally marked differences in isotopic and trace element composition that are thought to be related to heterogeneities in the mantle source regions. One of these geochemically anomalous regions in the northern Atlantic is the Azores Triple Junction. Various hypotheses about the nature and origin of such anomalies have been developed based on one of two assumptions: either a mantle plume, enriched with large ion lithophile (LIL) elements rising beneath the Azores (White and Schilling, 1978), or the presence of separate magma reservoirs with different chemistries resulting from a complex melting history in the upper mantle (Wood, 1979).

One objective of Leg 82 was to relate regional variations of basalt geochemistry to geodynamic processes in an anomalous segment of the Mid-Atlantic Ridge, the Azores Triple Junction. *Glomar Challenger* drilled at nine sites southwest of the Azores (Fig. 1) during Leg 82. The recovered basalts span a wide range in age and trace element composition, varying from 14 to 37 Ma and from samples enriched in LREE to samples depleted in LREE. In this paper we present rare earth element (REE) and other trace element (Sc, Cr, Co, Hf, Ta, Th) data from 43 selected samples. The trace elements have

been determined by instrumental neutron activation analysis (INAA). Two companion papers (Sachtleben et al. and Jenner et al., this volume) deal with the petrology, chemistry (major elements and Cr, Ni, Rb, Sr, Y, Zr, Nb, Ba), and Nd and Sr isotopic composition of the same samples.

ANALYTICAL TECHNIQUES

Samples for this study were selected (1) to be representative of the chemical units (magma groups) as defined by the shipboard party and by onshore analyses (Sachtleben et al., this volume), and (2) to be as fresh as possible. These criteria were checked by major element analyses taking into account only samples with low H₂O and/or CO₂ whenever possible. In addition, thin sections were examined for alteration.

Samples were coarsely crushed in an iron mortar and ground in an agate mill to 60 μ m. Aliquots containing 800 mg of sample were irradiated for 7 hours in a thermal neutron flux of about 2×10^{12} neutrons cm⁻² sec⁻¹ in the Thetis reactor at Gent University, Belgium. The gamma-ray intensities were measured at Leuven University with a large volume Ge(Li)-detector and a hyperpure Ge "Low Energy Photon Detector" at intervals of 7 and 20-30 days after irradiation. Concentrations were determined relative to a secondary "in-house" alkali basalt standard, which has been repeatedly calibrated against USGS BCR-1 reference rock. For details of the analytical technique, see Hertogen and Gijbels (1971). Analytical precision for the different elements can be judged from the errors ($2 \times$ standard error of the mean) reported for Sample 564-9-1, 1-4 cm (Table 1). The errors were calculated from counting statistics and the observed dispersion of results from different countings and/or different gamma rays. The precision is generally better than 2% for Sc, Cr, Co, Sm, and Eu; 6% for La, Tb, and Yb; and 12% for Ce and Lu. The errors for Nd, Ta, and Th rapidly increase with decreasing concentration and may be as high as 15-20% for the most LIL-depleted samples.

RESULTS

The trace element data obtained by INAA are presented in Table 1. Chemical unit assignments listed in Table 1 are taken from Sachtleben et al. (this volume).

¹ Bougault, H., Cande, S. C., et al., *Init. Repts. DSDP*, 82: Washington (U.S. Govt. Printing Office).

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Table 1. Trace element concentrations (ppm) in Leg 82 basalts.

Hole-Core-Section (interval in cm)	Chemical unit	Sc	Cr	Co	La	Ce	Nd	Sm	Eu	Gd	Tb	Yb	Lu	Hf	Ta	Th
556-2-1, 83-85	I	38.8	306	51.3	1.8	6.1	5.9	2.28	0.89	3.2	0.61	2.68	0.45	1.56	0.09	0.15
556-2-5, 5-7	II	36.0	243	40.3	2.6	9.2	8.8	3.23	1.18		0.85	3.53	0.63	2.35	0.13	≤0.15
556-3-2, 19-21	II	38.8	261	44.8	2.8	9.6	9.4	3.44	1.28	4.7	0.94	3.74	0.69	2.55	0.14	0.20
556-6-5, 68-70	II	37.6	275	47.1	2.4	8.3	8.1	3.02	1.12	4.0	0.80	3.25	0.57	2.14	0.11	0.22
556-7-1, 85-87	III	38.7	364	44.6	1.5	5.0	5.2	2.09	0.88	3.1	0.57	2.44	0.42	1.42	0.07	≤0.2
556-8-2, 27-29	III	40.8	281	43.6	1.45	4.8	5.0	1.88	0.79	2.7	0.51	2.20	0.39	1.29	0.07	≤0.15
556-12-3, 78-80	III	38.4	394	42.8	1.7	5.9	5.8	2.11	0.87		0.57	2.35	0.42	1.45	0.07	≤0.15
556-16-2, 131-133	V	40.6	47	42.9	2.3	7.9	6.9	3.01	1.18		0.80	3.22	0.59	2.13	0.13	≤0.4
557-1-1, 105-108		33.9	33	48.9	19.4	47.1	28.6	7.13	2.42	7.8	1.29	3.5	0.62	4.96	1.95	1.81
558-27-3, 69-72	I	32.3	478	48.1	5.7	14.4	9.3	2.72	1.02	3.5	0.63	2.34	0.42	1.84	0.53	0.63
558-27-3, 116-118	I	32.3	488	50.1	5.9	14.2	9.0	2.69	1.01	3.4	0.61	2.25	0.41	1.83	0.53	0.65
558-28-3, 118-120	II	38.5	402	40.2	2.7	8.4	7.3	2.49	0.94	3.7	0.65	2.63	0.47	1.70	0.15	0.31
558-29-1, 63-65	III	35.2	342	44.2	9.8	22.6	13.4	3.37	1.19		0.72	2.45	0.42	2.19	0.96	1.12
558-29-4, 83-85	III	33.9	321	40.3	9.4	21.3	13.2	3.28	1.15	3.7	0.64	2.35	0.41	2.10	0.90	1.00
558-31-1, 79-82	III	34.8	335	43.5	9.7	23.0	13.2	3.36	1.21		0.69	2.50	0.47	2.17	0.97	1.08
558-32-1, 123-125	III	35.6	337	47.7	10.0	22.9	13.8	3.42	1.22	3.6	0.68	2.45	0.43	2.24	0.98	1.11
558-33-2, 71-73	IVA	35.7	370	37.9	8.9	20.2	11.6	3.07	1.12	3.7	0.64	2.15	0.43	1.97	0.86	0.97
558-34-1, 30-32	IVA	35.5	366	44.1	8.7	20.5	12.2	3.03	1.09	3.3	0.60	2.18	0.38	1.94	0.86	0.94
558-35-3, 110-113	IVB	37.3	368	50.2	6.8	16.6	10.8	2.89	1.05	3.4	0.65	2.48	0.47	1.89	0.62	0.65
558-35-4, 106-108	IVB	36.3	362	42.8	6.6	15.8	9.9	2.79	1.01		0.60	2.35	0.41	1.77	0.59	0.69
558-38-1, 34-36	V	35.2	446	49.7	4.8	11.8	7.1	2.13	0.81	2.6	0.51	2.02	0.36	1.32	0.46	0.52
558-38-2, 61-63	IVA	37.1	342	44.0	7.8	18.5	11.5	3.05	1.10	3.6	0.65	2.53	0.45	2.07	0.71	0.83
558-40-1, 92-94	VI	36.5	462	50.2	5.0	11.8	6.7	2.18	0.83	2.8	0.50	2.06	0.39	1.40	0.47	0.55
558-40-2, 7-9	VI	36.0	500	41.5	13.5	27.6	17.8	3.69	1.33		0.62	1.85	0.31	2.18	1.32	1.45
559-1-1, 25-29	I	39.0	271	45.4	9.2	20.5	10.8	3.45	1.26		0.77	3.00	0.50	2.42	0.96	1.09
559-1-2, 52-56	I	37.9	260	42.5	8.5	19.7	11.8	3.36	1.20		0.76	2.93	0.58	2.37	0.91	0.94
559-8-1, 127-129	I	39.0	265	47.4	9.4	21.5	12.3	3.56	1.28	4.5	0.81	3.06	0.59	2.52	0.99	1.07
561-1-1, 33-38	I	34.8	391	50.5	12.3	25.9	13.5	3.4	1.2	3.7	0.69	2.51	0.46	2.16	1.29	1.52
561-2-1, 143-146	II	43.6	239	47.8	2.7	9.0	8.9	3.12	1.22	4.3	0.88	3.72	0.69	2.11	0.17	0.34
561-2-2, 138-141	II	41.4	232	66.5	2.6	8.3	8.3	2.95	1.13	4.0	0.79	3.48	0.62	2.00	0.16	0.26
561-3-2, 47-53	II	39.1	232	42.9	2.4	7.8	7.3	2.77	1.06	3.9	0.76	3.29	0.58	1.85	0.14	0.19
562-1-1, 110-112	I	39.6	228	44.3	2.6	9.0	9.3	3.28	1.25	4.8	0.89	3.61	0.64	2.30	0.14	≤0.15
562-4-1, 91-93	I	39.1	228	44.4	2.7	9.3	8.1	3.29	1.23	4.5	0.87	3.58	0.66	2.33	0.17	0.20
562-6-3, 120-123	I	41.0	244	48.5	3.1	10.0	9.5	3.41	1.31	5.0	0.93	3.69	0.70	2.47	0.21	0.25
562-6-4, 1-5	II	36.4	247	42.4	2.5	6.8	6.7	2.55	0.98	3.7	0.70	2.79	0.50	1.72	0.16	≤0.2
562-8-2, 6-9	II	38.5	254	43.5	2.4	7.8	7.7	2.70	1.03		0.73	3.10	0.56	1.82	0.16	0.19
563-23-1, 30-34	I	44.7	334	44.6	2.0	6.4	5.9	2.20	0.91		0.65	2.78	0.54	1.51	0.12	0.17
563-25-1, 19-22	I	41.1	321	45.2	1.85	5.7	5.3	2.06	0.83	3.0	0.57	2.51	0.43	1.41	0.11	0.24
563-25-2, 21-24	II	43.9	257	52.0	3.6	11.0	9.5	3.30	1.26		0.88	3.74	0.70	2.34	0.25	0.29
564-1-2, 21-25	I	43.7	333	46.3	1.9	5.6	5.6	2.14	0.89	3.1	0.61	2.64	0.48	1.47	0.11	0.21
564-1-2, 38-40	II	42.4	259		3.3	10.3	9.9	3.13	1.20		0.84	3.40	0.61	2.25		≤0.6
564-6-4, 71-74	II	39.9	227	50.7	3.8	10.6	8.7	3.13	1.17	4.2	0.81	3.40	0.59	2.25	0.28	0.35
564-9-1, 1-4	II	40.0	219	42.5	4.3	11.2	9.5	3.28	1.20	4.3	0.84	3.53	0.64	2.25	0.32	0.38
		±0.5 ^a	±5	±0.8	±0.2	±0.7	±0.8	±0.06	±0.03	±0.4	±0.03	±0.15	±0.07	±0.08	±0.02	±0.07

^a 2 times standard error of the mean.

Compatible Trace Elements (Sc, Cr, Co)

Sc, Cr, and Co concentrations are within the ranges typical of MORB from the North Atlantic (Bougault et al., 1979; Wood et al., 1979).

Sc and (to a lesser extent) Co contents are rather constant, which is in keeping with the scarcity of highly fractionated basalts in the Leg 82 holes. Neither systematic hole-to-hole differences nor clear-cut correlations with magma groups have been observed for Sc and Co.

Cr contents correlate with MgO values; for more details, see Sachtleben et al. (this volume), who report Cr data for a larger number of samples.

Incompatible Trace Elements (REE, Hf, Ta, Th)

Ta and Th strongly correlate with La, whereas Hf correlates with Sm. The following discussion is, therefore, largely restricted to the REE data.

Hole 556. The eight analyzed samples represent four magma groups and are all "normal" LREE-depleted basalts (N-MORBs) (Fig. 1). Absolute REE abundances span a rather large range, but the relative patterns are markedly similar (i.e., virtually constant La/Yb ratios; see Fig. 8 for details). Magma Groups II and V have

consistently higher TiO₂ contents (Fig. 9) and lower Mg-numbers (58 ± 2 versus approximately 67 ± 2; Sachtleben et al., this volume) than Groups I and III. The same dichotomy shows up in the absolute REE abundances (Fig. 1).

Hole 557. Basalts from this site are unique among Leg 82 samples; they are highly fractionated (Mg-value of 44) and rich in Fe and Ti (15% FeO_{tot}, 3.6% TiO₂) (Sachtleben et al., this volume). The single sample analyzed for trace elements (557-1-1, 105-108 cm) is strongly enriched in LREE (Fig. 1), Hf, Ta, and Th.

Basalts of similar major and trace element compositions are known from Hole 407 in the Reykjanes Ridge at 63°N (Wood et al., 1979). However, the strongly LREE-enriched basalts from Holes 410 and 410A (Mid-Atlantic Ridge, 45°N) have a distinctly different major element chemistry; most are much less fractionated (Mg-values up to 66), and all have lower TiO₂ (1.4-1.5%) and FeO_{tot} (7-9%) contents (Wood et al., 1979). The Hole 557 basalts also differ from the Fe-rich and Ti-rich basalts from the Galapagos spreading center, which are typically depleted in LREE (Clague et al., 1981).

Hole 558. The 15 analyzed samples represent 6 magma groups, and all but one (558-28-3, 118-120 cm; Group

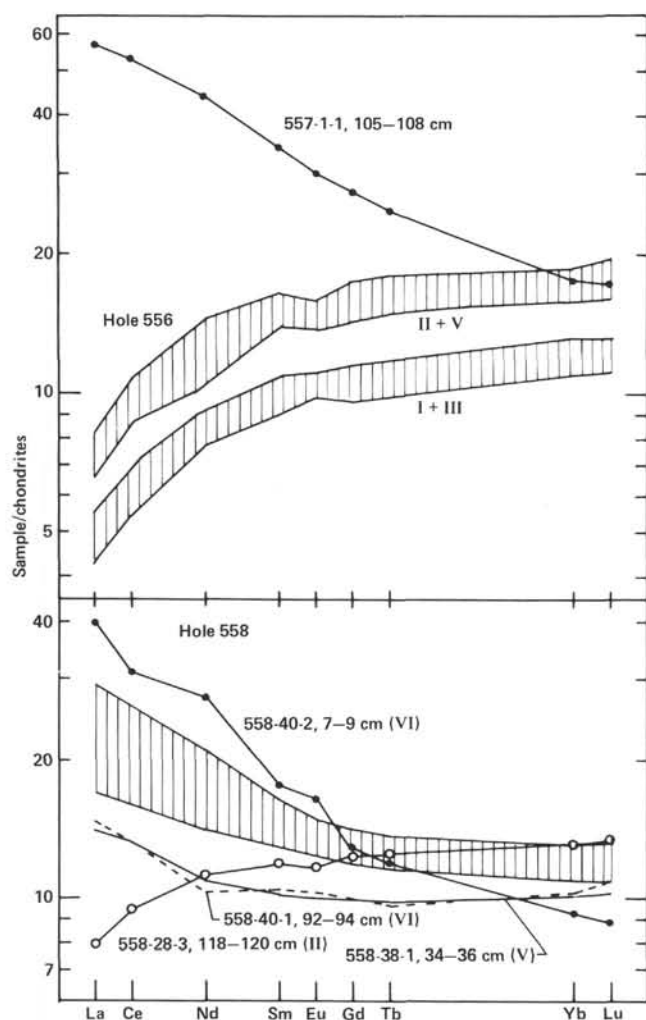


Figure 1. Rare earth element (REE) patterns of basalts normalized to chondrites from Holes 556 (8 samples), 557 (1 sample), and 558 (15 samples). Samples from different magma groups (chemical units in Roman numerals) generally have different REE contents. The samples from Hole 558 show the greatest diversity of REE patterns, ranging from LREE-enriched to LREE-depleted. The hatched field for Hole 558 covers the closely spaced patterns of 11 E-MORB samples from Groups I, III, and IV. The irregular REE distribution of Sample 558-40-2, 7-9 cm could be due to alteration.

II) are LREE-enriched basalts (Fig. 1). For the LREE-enriched basalts, a correlation between magma group and LREE enrichment is observed: $V < I < IVA < IVB < III$. Group VI is apparently a special case, because the two samples show grossly different REE patterns (558-40-1, 92-94 cm and 558-40-2, 7-9 cm). The Group VI samples belong lithologically to a breccia unit, but do not seem to form a single chemical unit (Sachtleben et al., this volume). The irregular REE pattern of 558-40-2, 7-9 cm could be due to alteration; the CO_2 content (0.94%) of this sample is among the highest measured in our sample suite.

The LREE-depleted basalt (558-28-3, 118-120 cm) also has the high La/Ta and Hf/Ta ratios typical of N-MORB (Fig. 5). However, this sample is unusual among the Leg 82 N-MORBs, because its $^{143}Nd/^{144}Nd$ isotopic ratio is virtually indistinguishable from that of

the E-MORBs (enriched MORB) from Hole 558 (Jenner et al., this volume).

Hole 559. The basalts from this hole form a single magma group. The three analyzed samples are LREE enriched (Fig. 2) and show only limited variations of trace element abundances.

Hole 561. The two magma groups have distinctly different trace element (Fig. 2) and Nd isotopic (Jenner et al., this volume) characteristics. The occurrence of both E-MORBs and N-MORBs in a single hole underscores the small scale of mantle heterogeneities or the localized nature of mixing processes.

Hole 562. The five analyzed samples are all LREE depleted (Fig. 3). Basalts from magma Group I have consistently higher REE abundances than those from magma Group II.

Hole 563. The two magma groups are LREE depleted but are clearly separated by absolute REE abundances, which are much lower in Group I than in Group II (Fig. 3). Note the similarities between Groups I and II from Holes 563 and 564.

Hole 564. The sample from magma Group I (564-1-2, 21-25 cm) is a typical, depleted N-MORB (Fig. 3). The Group II basalts from Holes 563 and 564, though LREE depleted, have a more transitional character; the La/Yb ratios are higher (Fig. 8) and the Hf/Ta and La/Ta ratios (Fig. 5) are lower than in depleted basalts from the other Leg 82 holes. They are also clearly separated from the

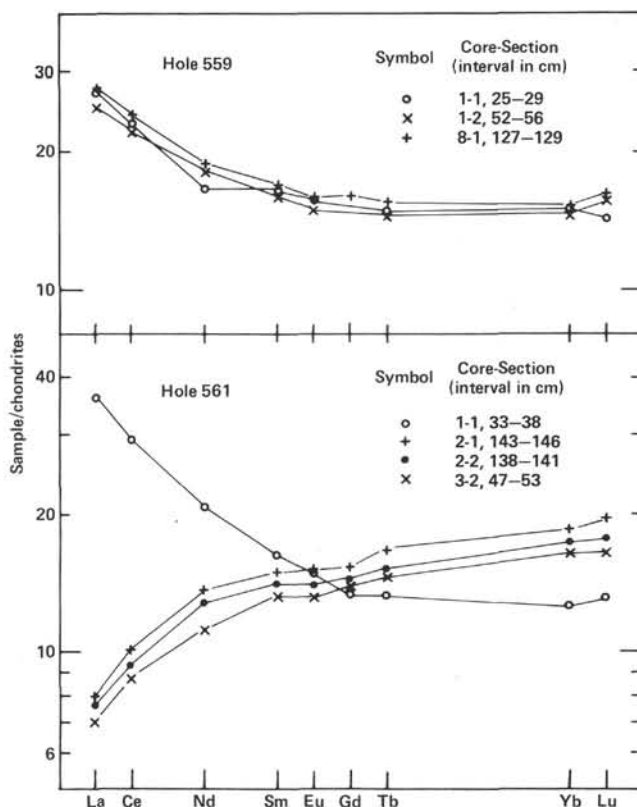


Figure 2. Rare earth element patterns of basalts normalized to chondrites from Holes 559 and 561. The Hole 559 basalts form a single, very homogeneous, magma group. Enriched (Group I) and depleted (Group II) basalts occur together in Hole 561.

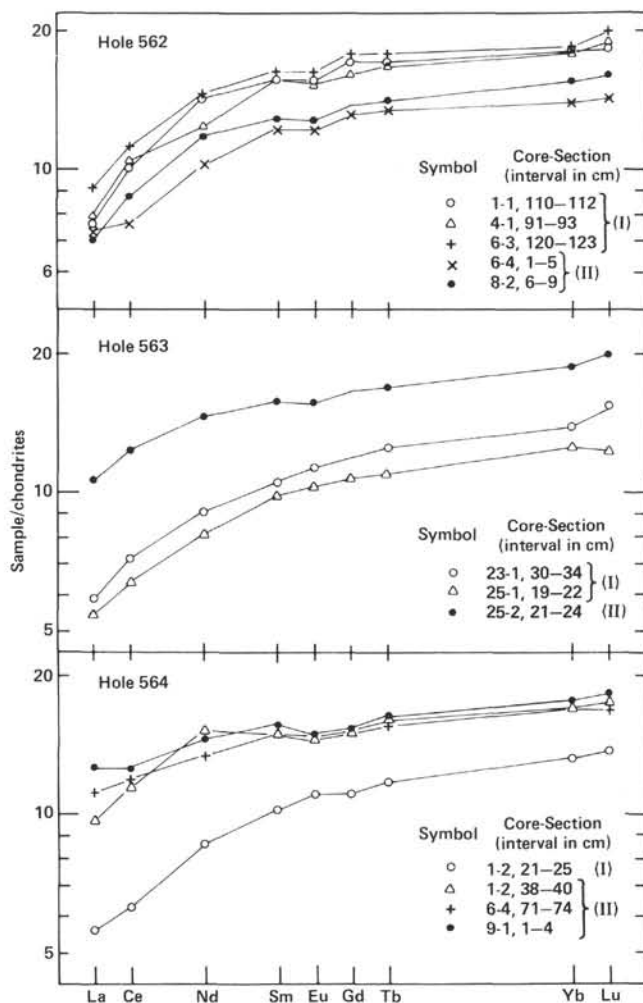


Figure 3. Rare earth element (REE) patterns of basalts normalized to chondrites from Holes 562, 563, and 564. Note the similarity of REE patterns of Group I and II samples from Holes 563 and 564. The Group II basalts from these two holes have somewhat higher La/Sm and La/Yb (see also Figs. 6 and 8) ratios than the LREE-depleted MORBs from the other Leg 82 holes.

common depleted basalts in the TiO_2 versus La variation diagram (Fig. 9).

DISCUSSION

Trace Element Variations in the Leg 82 N-MORBs

For the present discussion N-MORBs are defined as those samples that have a La/Yb ratio (normalized to chondrites) less than 0.5 and a La/Ta ratio greater than 15 (Figs. 5 and 8). The transitional Group II basalts from Holes 563 and 564 (Fig. 3) will be discussed together with the E-MORBs.

The Leg 82 N-MORBs have remarkably constant La/Yb, La/Sm, and La/Ti ratios, in spite of the almost twofold variation of absolute REE abundances (Figs. 6, 8, 9). This large variation of REE and other incompatible elements may be due to either substantial (40–50%) crystal fractionation or different degrees of partial melting. To determine which of these two processes is the most important or the most plausible, we will consider

the variation of some critical major and trace elements in the Hole 556 N-MORBs that encompass the whole range of chemical variation in the Leg 82 N-MORBs (see also Sachtleben et al., this volume). Data for some key elements have been summarized in Table 2 to facilitate the discussion.

The chemical variation within the Hole 556 sequence cannot be explained by high-pressure clinopyroxene fractionation (above 10 kbar; Bender et al., 1978; Fujii and Bougault, 1983). This would lead to a noticeable increase in the La/Yb and La/Ti ratios and a significant decrease of Sc content with increasing La content. These trends are not observed (Figs. 8 and 9; Table 2). Low-pressure fractionation of olivine alone can also be dismissed because it would rapidly deplete the magmas in MgO (Fig. 4) and Ni. The depletion in MgO and Ni could be largely offset by simultaneous plagioclase crystallization. However, extensive plagioclase fractionation is definitely ruled out by the absence of large negative Eu-anomalies and by the increase of the $\text{Al}_2\text{O}_3/\text{CaO}$ ratio in the Hole 556 N-MORBs (Table 2). Fractionation of plagioclase with $\text{Al}_2\text{O}_3/\text{CaO}$ around 1.8—as observed in the cores of phenocrysts—would produce an opposite $\text{Al}_2\text{O}_3/\text{CaO}$ variation trend. The Ca/Al fractionation by plagioclase could in turn be offset by cocrystallization of clinopyroxene. Least-squares mass balance calculations, using high-pressure (7–10 kbar) olivine, clinopyroxene, and plagioclase compositions from Fujii and Bougault (1983), suggest that Sample 556-3-2, 19–21 cm could be related to Sample 556-8-2, 27–29 cm by 21% clinopyroxene plus 12% plagioclase fractionation. This result conflicts with the constancy of Sc concentrations and La/Yb and La/Ti ratios. Moreover, clinopyroxene plus plagioclase without olivine does not appear to be a liquidus phase assemblage within the 1 atm to 15 kbar pressure range (Bender et al., 1978; Fujii and Bougault, 1983). Therefore, if the major and trace element variation in the Leg 82 N-MORBs are to be explained by crystal fractionation, complex mechanisms have to be invoked, such as the fractionation of a continuously replenished magma chamber (O'Hara, 1977). It is, however, beyond the scope of this paper to test the plausibility of this class of models.

Different degrees of batch partial melting of a lherzolite mantle source readily account for the twofold variation of incompatible elements and for the constant La/Yb and La/Ti ratios of the Leg 82 N-MORBs. A calculated partial melting path has been superimposed on Figure 8 to illustrate this point. The melting model assumed a depleted source consisting of 65% olivine (OL), 25% orthopyroxene (OPX), 10% clinopyroxene (CPX) with 0.26 ppm La ($0.76 \times$ chondrites), and 0.4 ppm Yb ($2 \times$ chondrites). The melting proportions were $\text{OL}_{0.2}\text{OPX}_{0.2}\text{CPX}_{0.8}$ from 0 to 12.5% melting and $\text{OL}_{0.2}\text{OPX}_{0.8}$ above 12.5% melting. Crystal/liquid partition coefficients for OL, OPX, and CPX were 0.001, 0.001, and 0.03 for La and 0.001, 0.05, and 0.3 for Yb. The outcome of calculations for a garnet-bearing mantle source is virtually identical provided that the garnet is exhausted from the source at 8 to 10% melting. The systematic decrease of the La/Sr ratio with decreasing

Table 2. Selected data for Hole 556 samples.

Measured value	Core-Section (interval in cm)							
	8-2 27-29	7-1 85-87	12-3 78-80	2-1 83-85	16-2 131-133	6-5 68-70	2-5 5-7	3-2 19-21
MgO (%)	8.09	6.74	7.99	7.80	6.57	6.94	6.18	6.10
Mg-number	68.8	64.6	67.2	67.2	56.4	61.6	56.4	57.6
Al ₂ O ₃ /CaO	1.11	1.03	1.23	1.23	1.37	1.34	1.34	1.37
Ni (ppm)	136	128	112	121	55	109	79	72
Sc (ppm)	40.8	38.7	38.4	38.8	40.6	37.6	36.0	38.8
La (ppm)	1.45	1.5	1.7	1.8	2.3	2.4	2.6	2.8
Sr (ppm)	98	106	95	114	120	103	108	108
(La/Sr) × 10 ⁴	148	142	179	158	192	233	241	260

Note: From this work and Sachtleben et al. (unpublished data).

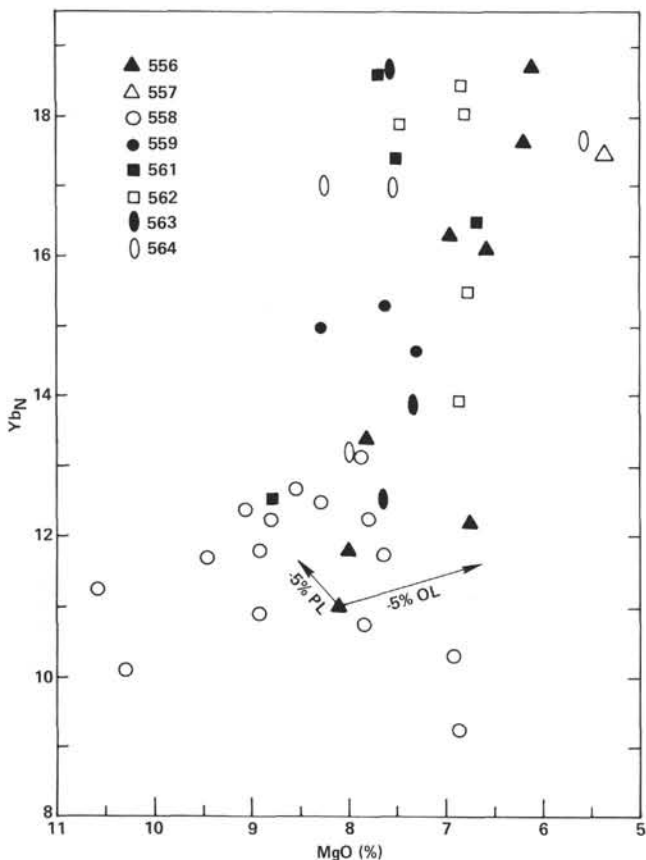


Figure 4. Ytterbium (Yb_N) content normalized to chondrites versus MgO content for Leg 82 basalts. In order to produce the twofold increase of heavy rare earth element (REE) abundances in the N-MORBs (e.g., from Hole 556), low-pressure olivine (OL) + plagioclase (PL) fractionation should be dominated by plagioclase, as shown by the two fractionation vectors. Because extensive plagioclase fractionation is ruled out by the lack of large negative Eu-anomalies and the variation of the Al/Ca ratios, the large variation of REE abundances appears to be the result of different degrees of partial melting (see also Fig. 8).

La content (Table 2) and the small negative Eu-anomalies in some N-MORBs (Figs. 1-3) could imply that plagioclase was a residual source mineral throughout most of the melting range. This would be consistent with the model proposed by Fujii and Bougault (1983).

However, all Leg 82 N-MORBs have MgO contents and Mg-numbers that are too low to qualify the N-MORBs as primary or near-primary mantle melts (Rhodes and Dungan, 1979; Frey et al., 1980). So, even if the twofold variation of incompatible trace elements was primarily established by partial melting, the parental magmas of all N-MORBs most likely went through a stage of olivine fractionation before eruption (Stolper and Walker, 1980). Figure 4 suggests that the N-MORBs could have evolved from a parallel sequence of high-Mg magmas ($\geq 10\%$ MgO) by 5 to 15% olivine fractionation.

Although the constant La/Yb and La/Ti ratios of the Leg 82 N-MORBs require a very homogeneous mantle source, the substantial variation of the La/Ta, Hf/Ta, and La/Hf ratios (Fig. 5) nevertheless suggests some source heterogeneity or mixing. Indeed, it is generally assumed that basalts inherit the Hf/Ta and La/Ta ratios of their source region, because these incompatible elements are not substantially fractionated from each other by partial melting and fractional crystallization (Bougault et al., 1979; Wood et al., 1979; Langmuir et al., 1978).

The linear array of the Leg 82 N-MORBs in the Hf/Ta versus La/Ta diagram (Fig. 5) could be interpreted as a mixing line between N-MORB magmas (or sources) and E-MORB magmas or alkaline magmas similar to Azores alkali basalts. Mixing relations are further explored in Figure 7. The mixing curve was calculated for mixing between Sample 556-8-2, 27-29 cm and the alkali basalt F33 from Faial Island, Azores Island (White et al., 1979). This particular Faial sample (42.2 ppm La, 4.2 ppm Ta) has been chosen as being representative of relatively primitive (Mg-number > 65), enriched mantle magmas. The La/Ta ratios of the N-MORBs ($La/Ta > 15$) are very poorly correlated with La content, which is consistent with the tenet that La/Ta and La/Hf ratios are not systematically fractionated by moderate degrees of melting or crystallization. Figure 7 offers one explanation for the La/Ta variations in the Leg 82 N-MORBs, i.e., mixing of N-MORB magmas with less than 2% of an enriched alkaline component. This small amount of mixing will have a minor effect on absolute LREE contents but will not significantly alter La/Yb, La/Ti, and La/Sm ratios (Figs. 6, 8, 9). Actually, the E-MORB magmas also qualify as enriched end-members, but the re-

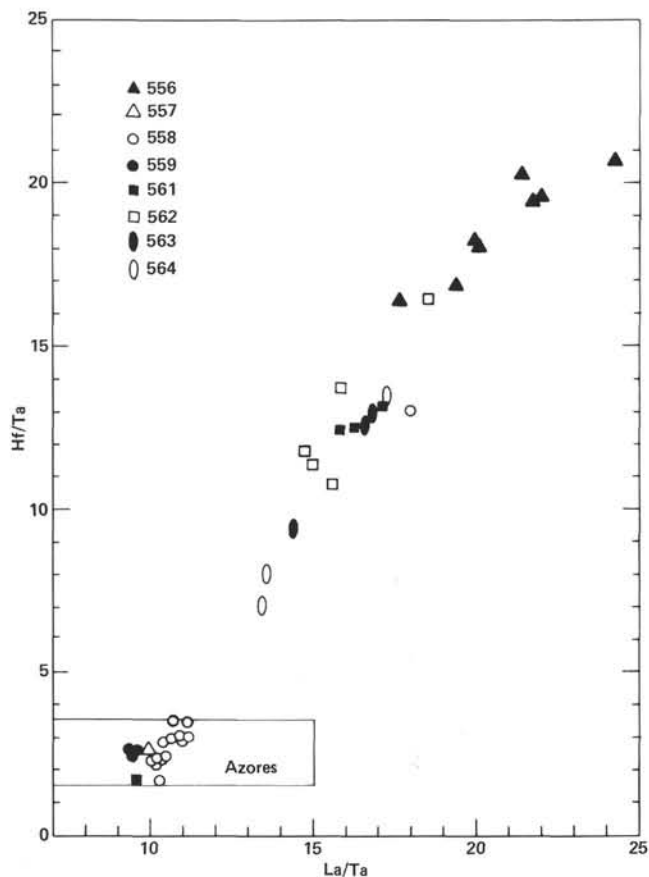


Figure 5. Hf/Ta versus La/Ta for Leg 82 basalts. The linear data array suggests that the variation is due to mixing involving an enriched alkaline end-member similar to Azores alkali basalt magmas (White et al., 1979). See Figure 7 for details of the mixing model.

quired amount of enriched component would then be five to ten times larger. The discussion in the next section will show that interpretation of the La/Ta variations in terms of magma mixing is not unique. The variable La/Ta ratios might equally well reflect source mixing (less than 0.1% enriched component) or local source heterogeneities that are too small to affect the ratios of other incompatible elements.

Mixing Relations in the Leg 82 E-MORBs

Two models have been proposed to explain the occurrence of E-MORBs along the Mid-Atlantic Ridge between 30 and 40°N. The first one invokes binary mixing between "normal" depleted MORB (or their source regions) and Azores Mantle Plume magmas enriched in incompatible trace elements and radiogenic Sr, Nd, and Pb isotopes (Schilling, 1975; White and Schilling, 1978). The second model postulates the existence of regional chemical and isotopic heterogeneities in the subocean mantle, whose origins might be unrelated to the Azores volcanism (O'Nions et al., 1978; Wood et al., 1979; Davies, 1981). Because of its conceptual simplicity, the Azores Mantle Plume mixing hypothesis can be tested quite rigorously. To do so we will investigate whether or not the trace element variations in the E-MORBs are consistent with magma or source mixing and whether or

not the Azores magma are plausible enriched end-members.

Before proceeding with the discussion of mixing relations, we would like to call attention to two chemical aspects of the Leg 82 E-MORBs. Firstly, the MgO (Fig. 4), Cr (Table 1), and Ni (Sachtleben et al., this volume) contents are generally higher than in the Leg 82 N-MORBs. This precludes crystal fractionation being of any importance in establishing the trace element characteristics of the Leg 82 E-MORBs. (The fractionated basalts from Hole 557 are an exception). Secondly, there is no correlation between LREE enrichment and HREE abundance in the Leg 82 E-MORBs. Crossing REE patterns, as observed in the Hole 558 E-MORBs, are the hallmark of the "dynamic melting" model proposed by Langmuir et al. (1977) for basalts from the FAMOUS area. However, no indication for dynamic melting could be found in the REE systematics of the Leg 82 N-MORBs. Because there is no obvious reason why dynamic melting should be restricted to particular areas along a ridge, or to enriched sources for that matter, we cannot accept dynamic melting as the preferred model.

Two mixing models will be explored: (1) mixing between N-MORB magmas and alkaline magmas; and (2) mixing of depleted N-MORB mantle sources with alkaline magmas. For the sake of clarity, the alkali basalt F33 from Faial Island, Azores, (White et al., 1979) has been chosen to represent alkaline magmas for both models.

We will first consider the mixing relations in the chondrite-normalized La/Yb versus La/Sm diagram (Fig. 6). With the exception of the basalts from Holes 557 and 561, the Leg 82 E-MORBs fit reasonably well to the mixing curve between N-MORB magmas and the alkali basalt F33. The magma mixing model predicts 8 to 40% alkaline component for the Hole 558 E-MORBs, 13 to 14% for the Hole 559 E-MORBs, and less than 3% for the transitional MORBs from Holes 562, 563, and 564. If we consider the magma mixing curve, crystal fractionation after magma mixing does not appear to be a plausible explanation for the deviation of the E-MORBs from Holes 557 and 561, because crystallization of moderate amounts of olivine, plagioclase, and clinopyroxene does not significantly change the La/Sm and La/Yb ratios. So, if the REE geochemistry of these samples is due to mixing, the enriched end-members must have been different. The alignment of the Leg 82 E-MORBs along a mixing line can also be explained in terms of source mixing. The heavy arrows in Figure 6 indicate the calculated La/Sm and La/Yb ratios of magmas generated by 20% partial melting of N-MORB sources "contaminated" with 1.5, 3, and 5% F33 alkaline component. The following assumptions were made for Sm: a concentration of 0.32 ppm ($1.5 \times$ chondrites) in the N-MORB source and partition coefficients of 0.001, 0.01, and 0.15 for olivine, orthopyroxene, and clinopyroxene. The other input parameters of the melting model were the same as used in the preceding section for modeling the La/Yb variation in the N-MORBs. Results of this source mixing/partial melting model will be discussed more in detail in subsequent paragraphs.

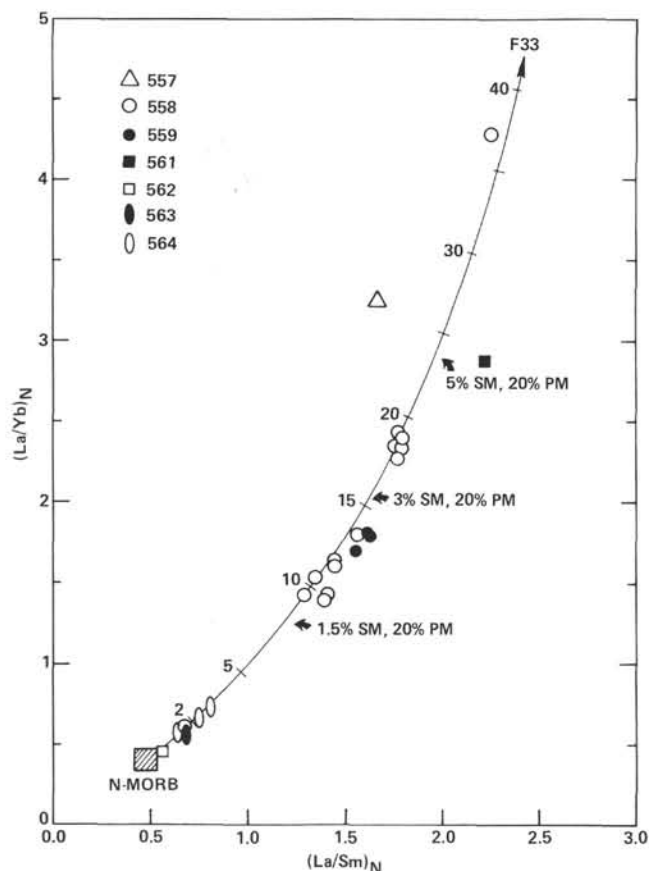


Figure 6. La/Yb versus La/Sm for Leg 82 basalts; both ratios are normalized to chondrites. The N-MORBs fall within a very narrow field (hatched square). The position of the E-MORBs (except for Holes 557 and 561) is consistent with either magma or source mixing. The mixing curve is calculated for magma mixing between Sample 556-8-2, 27–29 cm and alkali basalt F33 from Faial Island, Azores (White et al., 1979); numbers along the mixing curve refer to percentage of F33 component. The three heavy arrows indicate the calculated position of magmas derived by 20% partial melting (PM) of N-MORB sources mixed with 1.5, 3, and 5% of F33 component.

Plots involving ratios of incompatible and slightly compatible elements, such as Figures 5 and 6, do not distinguish between magma or source mixing for the Leg 82 E-MORBs. It might, therefore, be instructive to consider mixing plots involving absolute concentrations, such as Figures 7–9.

The percentages of magma mixing indicated by the La versus La/Ta plot (Fig. 7) are not inconsistent with the amounts predicted by Figure 6, if allowance is made for minor variations in the composition of the depleted and enriched end-members and for changes in the La contents by moderate degrees of crystal fractionation after magma mixing. However, when the E-MORBs from the FAMOUS area (Bougault et al., 1979) and Hole 332B (Bougault, 1980) are considered, it appears that the chemistry of the E-MORBs has been controlled by source mixing rather than magma mixing. Indeed, the majority of the Hole 332B and FAMOUS MORBs plot well off magma mixing curves between common N-MORB and alkaline magmas. The near-vertical array of the Hole

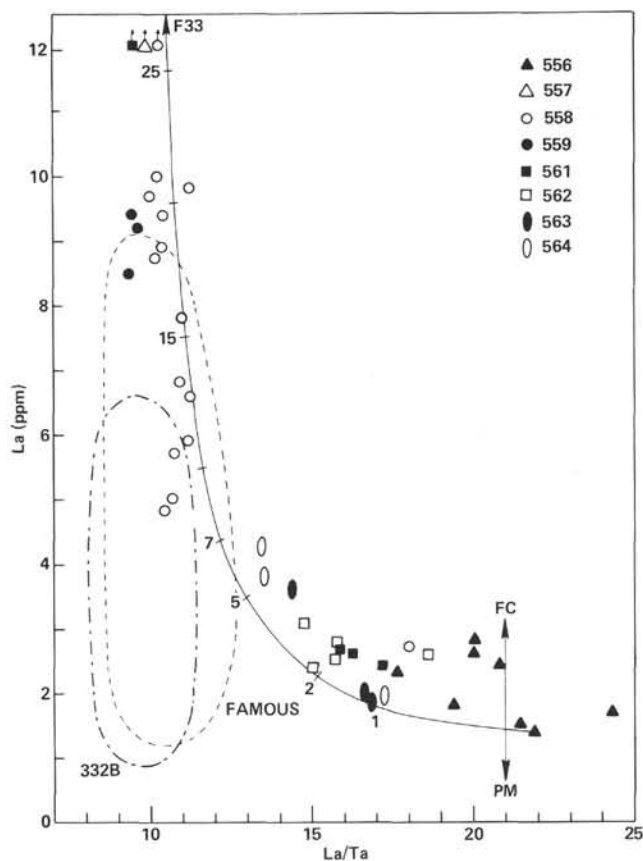


Figure 7. La versus La/Ta for Leg 82 basalts. As the La/Ta ratio is not changed by fractional crystallization (FC) or partial melting (PM), the variation of the La/Ta ratio must be ascribed to mixing or source heterogeneity. End-members of the mixing curve are the same as in Figure 6. The moderately enriched MORBs from Hole 332B (Bougault, 1980) and the FAMOUS area (Bougault et al., 1979) fall well off magma mixing curves between Azores alkaline magmas and N-MORBs. This suggests that the trace element chemistry of the E-MORBs is controlled by source mixing rather than by magma mixing.

332B, FAMOUS, and Leg 82 E-MORBs in Figure 7 is more readily explained by different degrees of partial melting of N-MORB sources contaminated with $\geq 1.5\%$ alkaline magma.

To further explore mixing relations, magma mixing curves have been superimposed on the Yb versus La/Yb and TiO_2 versus La plots (Figs. 8 and 9). It is immediately apparent that the REE systematics and La/Ti variation of the Leg 82 E-MORBs are not consistent with magma mixing involving a unique depleted end-member. The whole array of N-MORB magmas must be considered as depleted end-members, and the magma mixing curves shown in Figures 8 and 9 are examples from a whole family of mixing curves converging towards the composition of basalt F33. Here again, source mixing offers an explanation that is at least as viable. The dashed, near-vertical lines in Figures 8 and 9 are batch partial melting paths calculated for depleted N-MORB sources contaminated with 1.5% (line A) and 3% (line B) F33 alkaline component. The numbers along the melting curves refer to the percentage of batch melting. (The melt-

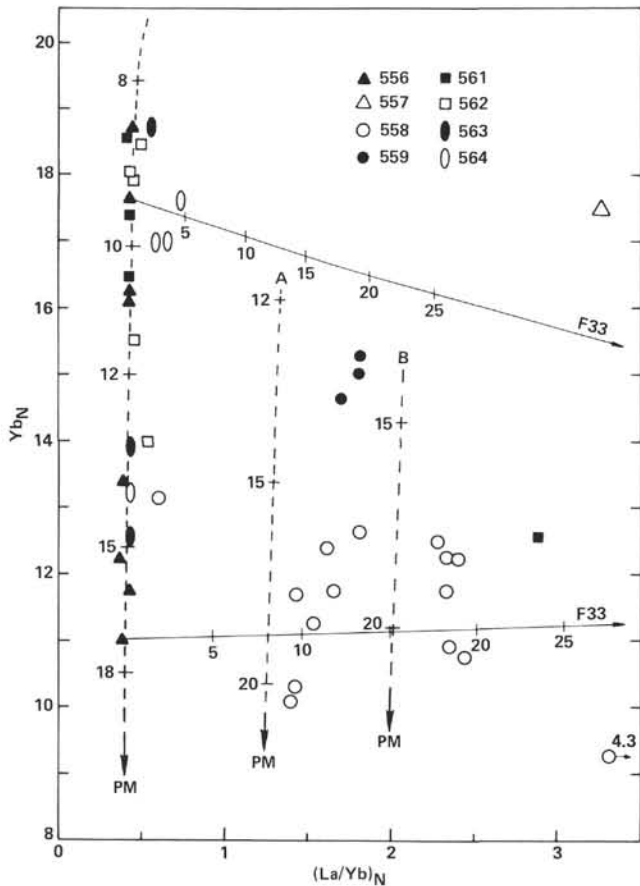


Figure 8. Yb versus La/Yb ratio normalized to chondrites for Leg 82 basalts. The twofold variation of rare earth element (REE) content in the Leg 82 N-MORBs ($La/Yb \leq 0.5$) is primarily due to different degrees (8 to 18%) of partial melting (PM). The dashed curve passing through the N-MORBs is a calculated batch partial melting path; see text for input parameters of the melting model. The REE systematics of the Leg 82 E-MORBs can be interpreted in terms of magma or source mixing. The full lines are two examples from a whole family of magma mixing curves between N-MORB magmas and Azores alkali basalt F33; numbers along mixing curves refer to percentage of F33 component. The dashed lines marked A and B are calculated partial melting paths for N-MORB mantle sources mixed with 1.5% (line A) and 3% (line B) F33 magma; numbers refer to percentage of partial melting.

ing paths from Figure 9 are based on the reasonable assumptions that the La/Ti ratio of the N-MORB source was identical to the La/Ti ratio of the N-MORBs and that Ti behaved as an incompatible element after exhaustion of clinopyroxene from the mantle sources.) Our analysis of the data shows that the geochemistry of the transitional and enriched Leg 82 MORBs is consistent with ≥ 0.5 to 5% admixture of alkaline component.

Whereas the trace element characteristics of the Leg 82 E-MORBs can be used to promote both the magma and source mixing models, there is some evidence to definitely favor the source mixing model:

1. The Nd isotopic data are not easily reconciled with magma mixing, even if allowance is made for variability in the isotopic and trace element composition of the end-members (Jenner et al., this volume).

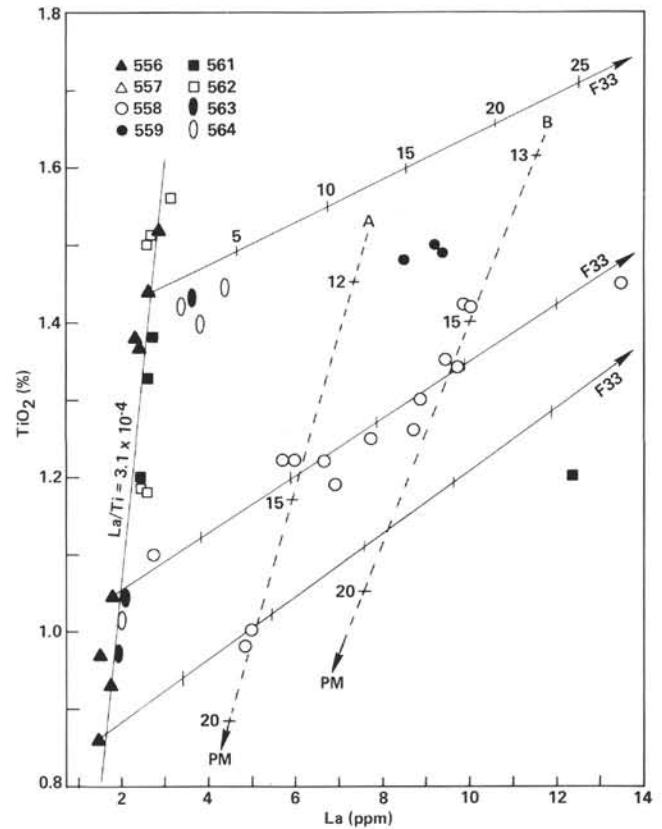


Figure 9. TiO_2 versus La for Leg 82 basalts. Note the constant La/Ti ratio of the N-MORBs. The full lines marked F33 are magma mixing curves, the dashed lines marked A and B are partial melting paths; see Figure 8 caption for further explanations.

2. Magma mixing does not appear to be a viable model for the moderately enriched FAMOUS and Hole 332B MORBs (Fig. 7), and there is no obvious reason to invoke special circumstances for either the Leg 82 or the FAMOUS and Hole 332B basalts.

3. The LREE-depleted basalt from Hole 558 (Sample 558-28-3, 118–120 cm) might provide an important clue. Its $^{143}Nd/^{144}Nd$ ratio is within the range of E-MORBs (Jenner et al., this volume), although source or magma mixing calculations point to a much smaller admixture of enriched component. This sample apparently derives from an enriched source that lost a small fraction of melt before the main melting event. In contrast, it is not so easy to imagine a simple process that can deplete a melt in incompatible trace elements.

We are still left with the question of whether the source mixing process is directly related to the Azores Mantle Plume magmatism. The Azores magmas indeed appear to be suitable enriched end-members, but any alkaline or nephelinitic melt generated in the subocean mantle is probably quite similar to the Azores magmas with respect to trace element geochemistry. It seems reasonable to attribute the occurrence of E-MORBs in Hole 557 to Azores plume input, but the correlation of light REE enrichment with distance from the Azores Triple Junction is tenuous at best for the other Leg 82 holes. This

REFERENCES

observation favors alternative models, such as episodic source mixing with "fracture zone-derived" enriched magmas (Flower, 1981).

Finally, there is the problem of recent mixing versus long-lived mantle heterogeneities (O'Nions et al., 1978; Wood et al., 1979; Davies, 1981). Although trace element concentrations do not provide information on the timing of the enrichment event, the data for the Leg 82 basalts may indirectly have a bearing on this question. Indeed, N-MORBs with amazingly constant La/Sm (Fig. 6), La/Yb (Fig. 8), and La/Ti (Fig. 9) ratios have been derived from a large, homogeneous mantle source over a distance of 1200 km along the Mid-Atlantic Ridge during a period of approximately 20 Ma (37–15 Ma). These data seem to be at variance with the recent emphasis on small-scale mantle heterogeneity in the area under study.

CONCLUSIONS

The almost twofold variation of absolute concentrations of incompatible trace elements in the Leg 82 N-MORBs is primarily due to different degrees (8 to 18%) of batch partial melting. The Leg 82 N-MORBs have MgO and Ni contents that are too low to qualify the MORBs as primary mantle melts; they most likely evolved from a sequence of more primitive magmas by 5 to 15% olivine fractionation before eruption. The remarkably constant La/Yb, La/Sm, and La/Ti ratios of the Leg 82 N-MORBs apparently require a large, homogeneous mantle source underneath a segment (1200 km long) of the Mid-Atlantic Ridge.

The variation of highly to moderately incompatible elements (REE, HF, Ta, Ti) in the Leg 82 E-MORBs is consistent with magma or source mixing between N-MORB magmas or sources and an enriched component similar to Azores alkali basalts. However, the combined trace element and Nd isotopic data (Jenner et al., this volume) strongly favor source mixing (≥ 0.5 to 5% enriched component). The association of depleted MORBs with transitional and enriched MORBs in Holes 561, 563, and 564 underscores the episodic and localized nature of mixing processes.

The absence of a regular spatial distribution of Leg 82 E-MORBs as a function of distance from the Azores Triple Junction casts serious doubts on the validity of Azores Mantle Plume mixing models advocated by Schilling (1975) and White and Schilling (1978). The enriched alkaline magmas involved in the source mixing are probably not directly related to the Azores magmatism.

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