

9. RARE EARTH AND LARGE-ION LITHOPHILE (Sr AND Ba) ELEMENT GEOCHEMISTRY OF DIABASE DIKES, HOLE 504B, COSTA RICA RIFT, LEG 140¹

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ABSTRACT

Hole 504B is located in Panama Basin approximately 200 km south of the Costa Rica Rift within a tectonically undisturbed oceanic crust formed at the Costa Rica Rift spreading center. The hole was drilled in several Deep Sea Drilling Project (DSDP)/Ocean Drilling Program (ODP) legs, including ODP Leg 140. The 378.9 m of core drilled at Hole 504B during Leg 140 continues the dike complex recovered previously during DSDP Leg 83. All the rocks drilled during Leg 140 are fragments of variably metamorphosed dikes composed of olivine-plagioclase-clinopyroxene-, olivine-plagioclase-, and olivine-plagioclase-clinopyroxene-spinel-bearing basalts.

We report results of determination of rare earth elements (REE) and large-ion lithophile (LIL) elements in 28 representative samples from the major units of the Hole 504B dike complex. Analyzed samples display relatively uniform REE patterns with only a slight difference in the extent of light REE depletion. LIL elements show large variations independent from other incompatible (Zr and Y), compatible (Cr, Ni, Co), and rare earth elements.

Observed REE variations indicate that metamorphism has changed LIL distribution, but has not affected REE patterns. Variable REE depletions are believed to represent original magmatic characteristics of the Costa Rica Rift oceanic crust. LIL distribution favors Ba redistribution due to the fluid-rock interaction in the lower oceanic crust. REE systematics define various degree of depletion in Leg 140 diabase dikes consistent with their derivation from a variably depleted MORB-type source.

INTRODUCTION

The geochemical stratigraphy of oceanic crust and particularly the composition of its deeper layers are poorly understood because of the apparent scarcity of preserved intact sections of the oceanic crust, untouched by later tectonic processes. Recent studies of crustal sections exposed within mid-ocean ridges and major fracture zones revealed their tectonic complexity and geochemical diversity resulted from a variety of tectonic and petrogenetic processes interplaying during the birth and subsequent evolution of oceanic crust (Mével and Cannat, 1991; Hekinian et al., 1992). Primary stratigraphy of oceanic crust is obscured by faulting, block rotation, vertical tectonism and early crustal slicing in the vicinity of the mid-ocean spreading center (Bonatti, 1978; Auzende et al., 1990; Mével et al., 1991; Karson, 1991; Dick et al., 1991). Consequently, the inferences about the chemical structure of the oceanic crust were made on the basis of ophiolite studies assuming that ophiolite stratigraphy resembles that of normal oceanic crust (Karson, 1991). The character of metamorphism operating in the oceanic crust also changes with depth (Stern and Elthon, 1979; Alt et al., 1986; Alt et al., 1989), which may variably affect the distribution of certain mobile trace elements in upper volcanics, dikes and lower plutonic rocks.

Despite the fact, that several blocks of oceanic crust with apparently normal stratigraphy (volcanics, dikes, and gabbros) have been recently discovered in oceanic fracture zones, such as the Vema Fracture Zone (Auzende et al., 1990), this oceanic environment is likely to be affected by a variety of tectonic processes. This is supported by recent drilling results in the vicinity of Kane Fracture Zone (Mid-Atlantic Ridge) and Atlantis II Fracture Zone (Southwest Indian Ridge) (Dick et al., 1991). Hole 504B is located on the 6-m.y.-old oceanic crust away from the major fracture zones within a tectonically quiet area, thus offering an opportunity to study the chemical composition of the upper 2 km of in-situ oceanic crust. Previous drilling

established simple igneous stratigraphy that changes from massive and pillow lava flows on top through transitional into typical sheeted dike complex at the bottom of the Hole 504B (Anderson, Honnorez, Becker, et al., 1985; Becker, Sakai, et al., 1989).

We present results of geochemical investigation of diabase dikes drilled during the Ocean Drilling Program (ODP) Leg 140 with particular reference to large-ion lithophile (LIL) and rare earth elements (REE). We also discuss possible effects of metamorphism on the mobility of certain trace elements as a function of extent and style of alteration in the dikes. The primary magmatic evolution of the Leg 140 diabase dikes is also finally evaluated.

DRILLING HISTORY AND STRATIGRAPHY OF HOLE 504B, COSTA RICA RIFT

Hole 504B is located in the Panama Basin approximately 200 km south of the Costa Rica Rift (Hobart et al., 1985). The age of the oceanic crust drilled at Hole 504B is around 6 Ma estimated from the magnetic anomaly patterns (Lonsdale and Klitgord, 1978). The magnetic anomaly pattern defines an absence of an active fracture zones in the vicinity of Hole 504B at least for the last 10 Ma (Lonsdale and Klitgord, 1978), which implies quiet tectonic conditions and suggests the existence of an undisturbed crustal sequence in this portion of oceanic crust which was generated at intermediate (half-spreading rate of 3.6 cm/yr) Costa Rica Rift.

The summary of drilling results at Hole 504B is presented in Becker, Sakai, et al. (1989). Basement rocks recovered during previous Deep Sea Drilling Project (DSDP)/ODP legs include aphyric to porphyritic basalts which could be further subdivided into aphyric, olivine-plagioclase-clinopyroxene-, olivine-plagioclase-, and olivine-plagioclase-clinopyroxene-spinel-bearing basalts on the basis of modal proportions of the constituent phenocrysts (Autio and Rhodes, 1983; Autio et al., 1989). No significant chemical differences between upper pillow and massive lava flows and lower dikes were observed, and only few basaltic units include enriched or transitional-type oceanic basalts (Autio and Rhodes, 1983; Etoubleau et al., 1983). The majority of the basalts in the Hole 504B igneous sequence are depleted mid-ocean ridge basalts (MORB), with variable extents of light rare-earth element (LREE) depletion (Autio et al., 1989).

¹ Erzinger, J., Becker, K., Dick, H.J.B., and Stokking, L.B. (Eds.), 1995. *Proc. ODP, Sci. Results*, 137/140: College Station, TX (Ocean Drilling Program).

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Table 1. REE analyses of international geochemical standards.

Standard: Results (ppm):	AGV-1		W-2		BCR-1	
	Measured	Reported	Measured	Reported	Measured	Reported
La	39	37	12	11.4	0.9	0.88
Ce	68	66	24	24	2.4	2.5
Nd	33	34	15	14	2.5	2.5
Sm	6.1	5.9	3.1	3.25	1.7	1.8
Eu	1.7	1.66	1.2	1.1	0.51	0.54
Gd	5.1	5.2	3.6	3.6	1.8	1.9
Er	1.6	1.6	2.4	2.5	1.8	1.8
Yb	1.6	1.7	2	2.05	1.7	1.7

Note: Reported values for international standard samples are from Gladney et al. (1983).

Lithologic units in Leg 140 core were classified on the basis of the abundance of phenocrysts following the scheme developed during previous DSDP/ODP legs (Shipboard Scientific Party, 1992). The 378.9 m drilled at Hole 504B during Leg 140 continued the recovery of the dike complex previously drilled during DSDP Leg 83 (Anderson, Honnorez, Becker, et al., 1985) and ODP Leg 111 (Becker, Sakai, et al., 1989). All the rocks recovered are fragments of dikes. Grain-size variations observed in the lower portion of Hole 504B are explained by variation in a cooling rate between individual dikes and dike packages similar to grain-size variations observed in ophiolite dike complexes (Shipboard Scientific Party, 1992).

All rocks are altered to some extent and exhibit a pervasive background alteration (Shipboard Scientific Party, 1992). More intensively altered areas occur in the vicinity of hydrothermal veins. Olivine in dikes is commonly replaced by talc, chlorite, and magnetite. Clinopyroxene is partly replaced by actinolite. Plagioclase in several cases is replaced by albite and chlorite, but is commonly fresh. In general, Leg 140 dikes are more altered than the previously recovered rocks from Hole 504B, with the greater proportion of actinolite among the metamorphic minerals (Shipboard Scientific Party, 1992).

ANALYTICAL METHODS

Trace element analyses were performed on 28 selected samples which represent 17 units from the dike sequence from the lowest 500 m of Hole 504B.

Cr, Ni, and Co concentrations were measured by atomic absorption spectrophotometry (AAS) using a PERKIN ELMER 5000 instrument. The measurements were performed on triplicate preparations following dissolution of 1 g of the rock in HF-HNO₃-HClO₄. Concentration calibrations were employed using carefully selected geological reference samples of mafic composition. Precision and accuracy are generally better than 1% (relative) when the element concentrations are well above their detection limits.

Ba and Sr were determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES) using Hilger Analytical MONO-SPEC 1000 spectrometer. Twenty mg of the rock was fused with H₃BO₃-Li₂CO₃ flux with subsequent dissolution in 0.6N HCl. The sensitivity of the method is 1 ppm for both Ba and Sr, with precision of 1% (relative) for Ba and 3% (relative) for Sr.

Rare earth elements (REE) were analyzed by ICP-AES using the same spectrometer with preliminary concentration of REEs on the ion-exchange resins following the technique of Kepezhinskas et al. (1990). Five hundred mg of the sample was dissolved in HF-HNO₃-HClO₄. The DOWEX-HCR-W2 ion-exchange resin saturated in 2N HCl was used in chromatographic columns with a final solution volume of 10 mL and a rate of less than 1 mL per min. Emission was measured along the following plasma spectra: La = 333.749, Ce = 413.765, Nd = 406.109, Eu = 412.93, Gd = 342.247, Er = 349.910, and Yb = 328.937 nm. International standard samples BCR-1, W-2, and AGV-1 were run along with the unknowns, and the precision estimated during the course of the study was better than 2% (relative)

for all rare earth elements. Results of REE determination in standard samples are listed in Table 1.

RESULTS

Compatible Elements (Cr, Ni, and Co)

Concentrations of compatible elements in Leg 140 core are generally high (Table 2), which is consistent with the primitive, unfractionated nature of diabase dikes from Hole 504B. Cr and Ni show slight variation with degree of alteration plotted as a total percentage of the secondary phases from the shipboard alteration log (Shipboard Scientific Party, 1992; Fig. 1). Both Cr and Ni show a slight increase in concentrations (Fig. 1B, -C). Co displays less clear correlation (if any) with degree of alteration (Fig. 1C).

Large-ion Lithophile Elements (Sr and Ba)

Large-ion lithophile elements (Ba, in particular) show significant variations correlated with degree of alteration as well as with other trace element contents (Table 2).

Ba shows a rough increase with increasing alteration (Fig. 2A), which suggests its mobility under metamorphic conditions observed in oceanic crust below the Costa Rica Rift. The analyzed samples may be divided into a low-Ba group with Ba concentrations lower or similar to that in average N-MORB (10 ppm; Viereck et al., 1989) and a high-Ba group that also has a higher modal content of metamorphic minerals, such as albite, actinolite, and chlorite (except the high-Ba, less altered Sample 140-210R-1, 36–39 cm, with Ba = 23 ppm at alteration of 24%; Shipboard Scientific Party, 1992). Sr follows the same trend, with concentrations roughly increasing with higher degree of alteration. Although Sr contents measured by ICP-AES are in several samples higher than the shipboard X-ray fluorescence (XRF) values (Table 2), both data sets displays similar correlations between Sr contents and alteration (Fig. 3).

Correlations between LIL and compatible elements are less clear, although Ba appears to be generally weakly correlated with Cr (Fig. 4A). Sr shows no evident correlation with degree of fractionation, measured by Cr content of diabase (Fig. 4B), which may result from primary igneous geochemical complexities as well as metamorphic effects.

Ba also displays a weak increase with increasing Mg# (Mg/Mg+Fe) of diabase dikes, which confirms the general existence of correlated behavior of compatible elements (Cr and Ni) and LIL elements (Ba). This suggests that at least in part, the observed budget of LIL elements in the core drilled during Leg 140, is the result of magmatic processes. This is consistent with the positive correlation between Ba contents and Zr/Y ratios, which are thought to represent the degree of mantle source depletion/enrichment, as well as the extent of crystal fractionation (Pearce and Norry, 1979). Ba concentrations increase with an increasing Zr/Y ratio, suggesting that either Ba distribution is to some extent controlled by the magmatic processes that formed the dike sequence, or that both Ba, on one hand, and Zr and Y, on the other, are mobile under observed metamorphic conditions.

Rare Earth Elements

Rare earth element data are listed in Table 2 and are presented as chondrite-normalized patterns (Fig. 5A–Q) normalized to average ordinary chondrite using values of Nakamura (1974). The brief summary of results from 30 representative diabase samples and their chemical variability with depth is presented below.

Unit 213 samples display a slight heavy rare-earth element (HREE) depletion coupled with relatively high concentrations of light rare earths (6–7× chondrite values) (Fig. 5A). Unit 218 samples exhibit relatively strong depletion in LREEs (1–3× chondrite) at variable HREE concentrations (7–12× chondrite) (Fig. 5B). The two samples from Unit 220 (140-194R-1, 115–118 cm, and 140-193R-1, 28–31 cm) show similar LREE concentrations (3–4× chondrite) at different middle REE (MREE) and HREE contents (Fig. 5C). Sample 140-197R-2, 33–38 cm, is characterized by strong LREE depletion (La concentrations are less than 2× chondrite) typical of the highly depleted basalts from the upper portion of the dike sequence drilled during previous DSDP/ODP legs (Autio et al., 1989).

Samples from Units 221, 227, 229, 232, and 235 show smooth, moderately depleted REE pattern typical of N-MORB compositions (Fig. 5E–I). LREE concentrations are 4–6× chondrite resembling the majority of depleted basalt compositions from the Hole 504B (Etoubeau et al., 1983; Emmermann, 1985; Autio et al., 1989).

Sample 140-208R-3, 7–10 cm (Unit 239), shows a strong depletion in LREEs (close to chondrite concentrations) accompanied by generally low contents of all other REEs (around 5× chondrite) suggesting that this particular sample was derived from a highly refractory source. Surprisingly, this sample has extremely high LILE contents (Sr = 118 and Ba = 26 ppm, Table 1), suggesting the possible addition of potentially mobile LILE during alteration (Humphris and Thompson, 1978a; Humphris and Thompson, 1978b). REE behavior in this particular case does not follow the alteration pattern, showing no major concentration spikes (Fig. 5J).

Samples from Units 240, 241, 244, and 256 have similar concentrations of middle (Sm–Gd) and heavy (Er and Yb) REE (7–8× chondrite), but variable light REE contents (Fig. 5K–N). These diabases are only slightly different in their LILE contents (in fact, Sr content is similar, whereas Sample 140-210R-1, 36–39 cm, contains twice as much Ba).

Sample 140-224R-1, 21–24 cm (Unit 258), has a strongly LREE-depleted pattern (Fig. 5O) coupled with slight depletion in HREEs. This feature appears to be typical of many depleted basalts in the dike complex drilled in Hole 504B. In this particular case, depletion is accompanied by fairly low LILE contents (Sr = 62 and Ba = 2.5 ppm, Table 1). HREEs are thought to be immobile under conditions of oceanic metamorphism, therefore, suggesting that the chemical depletions observed in this portion of Leg 140 core probably represent source characteristics rather than metamorphic processes (Hajash, 1984).

Samples from Units 259 and 260 have similar REE patterns (Fig. 5P, –Q), showing a well-defined LREE depletion (LREE concentrations are 2–4× chondrite) and a weak negative Eu anomaly. They also show variable Ba (2.5–11 ppm) contents coupled with nearly constant Sr contents, indicating that these characteristics probably resemble those of parental magma.

Magmatic vs. Metamorphic Input in the REE Budget at Hole 504B

Rare earth elements show only a slight correlation with the degree of alteration, suggesting their relative immobility under conditions of oceanic metamorphism. La is fairly constant during increasing alteration (Fig. 2B), while Ce increases as alteration progresses (Fig. 2C). MREEs, such as Sm, which are of particular importance because of their strong preferential partitioning into hornblende (Drummond and Defant, 1990), show no significant correlation with alteration (Fig.

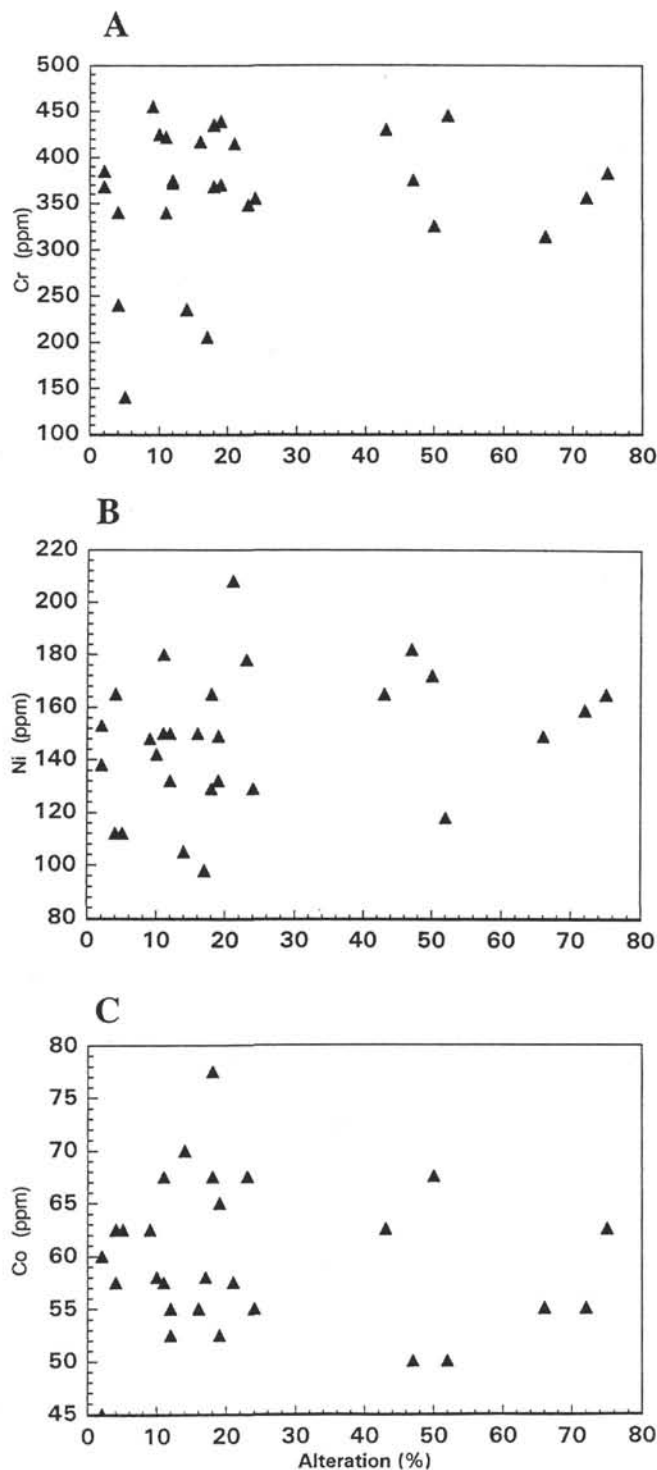


Figure 1. Degree of alteration (total percent secondary phases) vs. Cr (A), Ni (B), and Co (C) contents in Leg 140, Hole 504B, diabase dikes.

2D). Chondrite-normalized intra-REE ratios, such as $(La/Sm)_N$ and $(La/Yb)_N$, which are thought to indicate the source for basaltic magmas, are not affected by alteration and show no increase with increasing alteration in the lower diabase portion of Hole 504B (Fig. 2E, –F).

This is consistent with $(La/Sm)_N$ and $(La/Yb)_N$ variations compared with compatible element distribution in Leg 140 core. $(La/Sm)_N$ shows no increase or decrease with increasing Cr content (Fig. 6A), suggesting that this constantly low ratio in Leg 140 diabase dikes is charac-

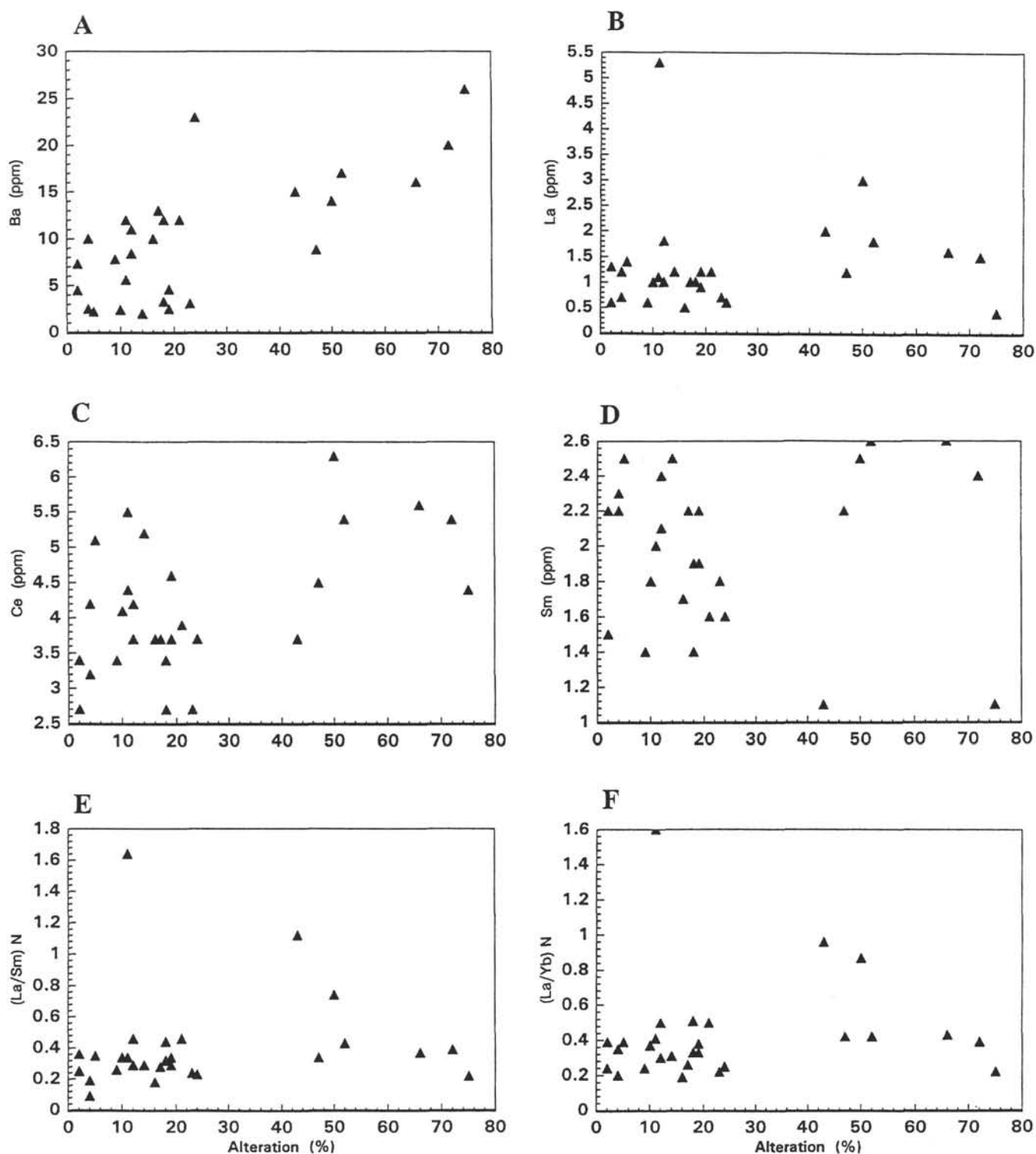


Figure 2. Degree of alteration vs. Ba (A), La (B), Ce (C), Sm (D), $(La/Sm)_N$ (E), and $(La/Yb)_N$ (F) in Leg 140, Hole 504B, diabase dikes.

teristic of the source rather than process. The same uniform pattern observed on a $(La/Sm)_N$ -Zr/Y plot (Fig. 6B) confirms the generally depleted nature of Leg 140 diabases which is consistent with the earlier model of Autio et al. (1989). The chondrite-normalized La/Yb ratio is constant (except for the three samples with transitional-type MORB REE patterns discussed above) with a large range of Cr (Fig. 7A) and Ni (Fig. 7B) concentrations, indicating that the REE patterns

are characteristic of a mantle source and are not significantly affected by the crystal fractionation process nor by late metamorphic events.

DISCUSSION

Judging from their REE compositions, the Leg 140 cores display few chemical variations with depth. Diabase samples that have been

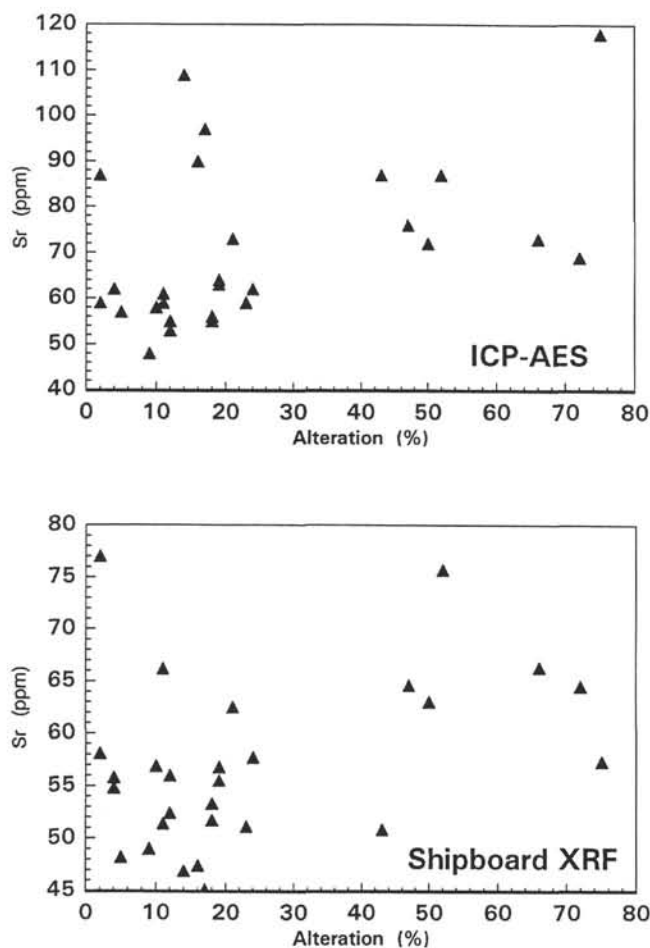


Figure 3. Degree of alteration vs. Sr contents in diabase dikes, Leg 140, Hole 504B, analyzed by ICP-AES and shipboard XRF techniques.

analyzed for REEs show relatively homogeneous compositions with a slight variation in a degree of depletion in light REEs. The majority of samples are moderately depleted and are similar to N-MORBs in many respects. They commonly display low LILE (especially Ba) concentrations which are typical of N-MORB compositions worldwide (Sun et al., 1979; Schilling et al., 1983; Viereck et al., 1989). Some samples in Units 218, 220, 239, 241, 244, 258, and 260 exhibit low LREE concentrations (2–3× chondrite) at low absolute concentrations of rare earth and LIL elements, suggesting their derivation from a refractory mantle source (Autio and Rhodes, 1983; Autio et al., 1989). A few samples (Units 213, 220, 221, 227, 229, 256, and 259) show a small degree of depletion resembling transitional-type MORBs described previously among some pillow and massive lava flows in the upper portion of Hole 504B (Etoubeau et al., 1983).

In many cases, these REE variations (tiny, but detectable) are not accompanied by well-defined LILE variations. Ba shows wide variations in the drilled sequence, suggesting an input of high-Ba fluid component in some units (213, 218, 227, 232, 239, 241, and 259) and leaching of Ba in other units characterized by extremely low Ba contents (Units 220, 221, 222, 240, 258, and 260). Average N-MORB has a Ba content of approximately 10 ppm (Viereck et al., 1989) and average deep-water sediment from the Pacific Ocean has a Ba content of approximately 300 ppm (Murray et al., 1992). Using Ba concentrations in deep-sea sediments as a basis, we can estimate Ba content in Pacific Ocean seawater to be on the order of 100–500 ppm. Direct

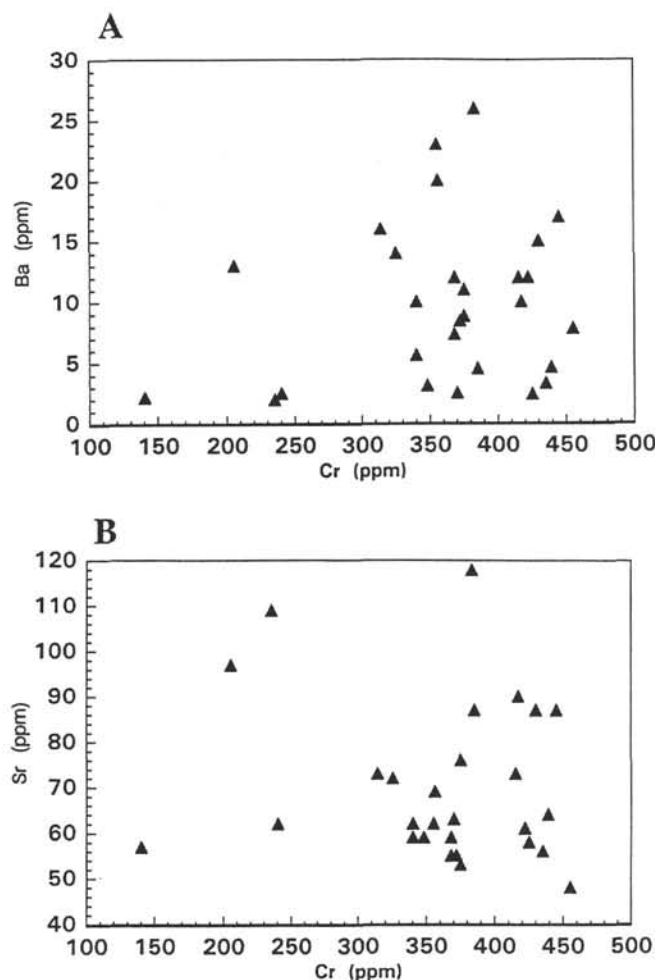


Figure 4. Ba vs. Cr (A) and Sr vs. Cr (B) variations in Leg 140, Hole 504B, diabase dikes.

measurement of Ba content in the nanofossil chalk above the lava surface in Hole 504B yields a concentration of 604 ppm (Murray et al., 1992) suggesting that seawater can account for observed Ba enrichments in several dike units drilled during Leg 140, even taking into account the possible effect of Ba sorption during sediment deposition. Staudigel and Hart (1983) have analyzed palagonite selvages in basaltic glass from Hole 417 and have shown that Ba is efficiently sorbed by altered surfaces of MORB glasses, and that the enrichment factor for Ba will be approximately +160%. Their estimation of average Ba content in fresh MORB glass (8.46 ppm) is similar to that of Viereck et al. (1989), suggesting that various degrees of seawater-basalt interaction can account for the range of Ba concentrations observed in Leg 140 diabase dikes. As Ba is mainly sorbed along the water-basalt interfaces (Staudigel and Hart, 1983), the bulk depletion or enrichment of this element will be a function of the percentage of alteration veins, as is also suggested by a plot of Ba concentration vs. the extent of alteration in Leg 140 diabase dikes (Fig. 2A). Sr appears to be less mobile under conditions of metamorphism observed at a depth of 2 km in oceanic crust, which can be partially explained by the fact that Sr concentration in the potential metamorphic fluid (seawater) is comparable to Sr content of oceanic basalt. Sr content of seawater ranges from tens to hundreds of ppm, while average Sr content in fresh MORB is approximately 95 ppm (Viereck et al., 1989). The resulting Sr_{fluid}/Sr_{crust} ratio can be roughly estimated as 0.7 to 3, with an average of 1.5, while the Ba_{fluid}/Ba_{crust} ratio exceeds 30

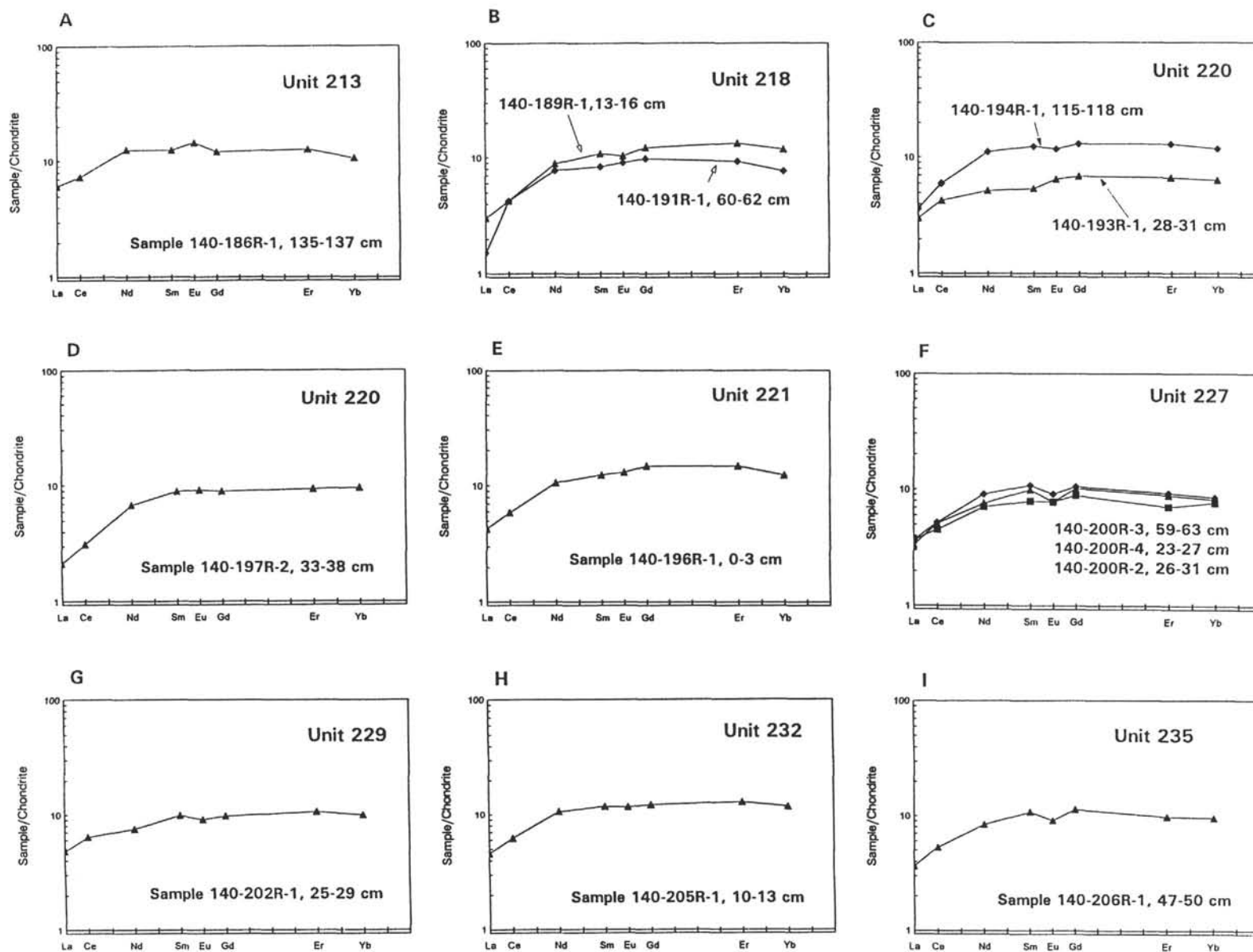


Figure 5. Chondrite-normalized rare earth element patterns for selected diabase samples from Leg 140. Normalizing values are from Nakamura (1974).

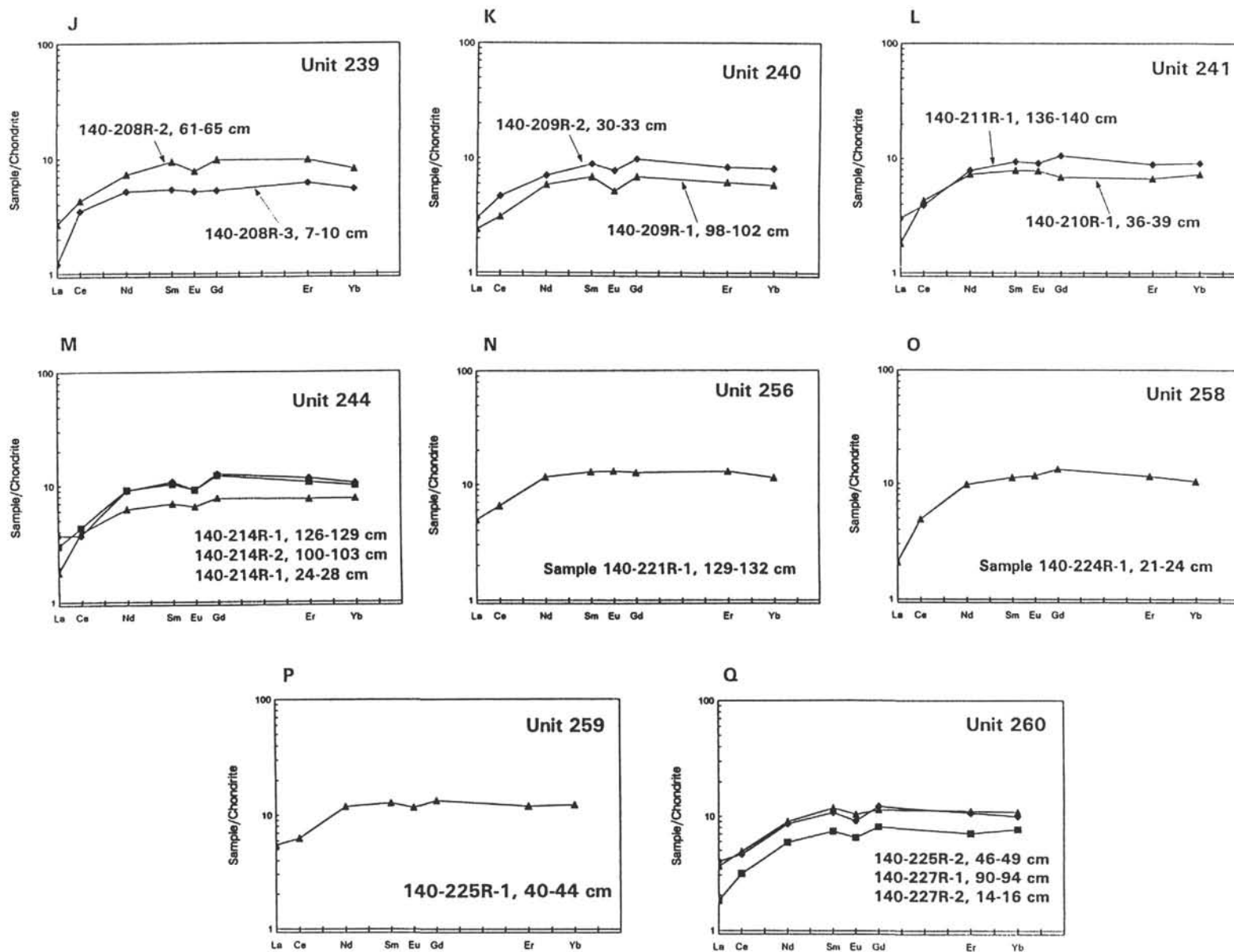


Figure 5 (continued).

Table 2. Representative major (wt%) and trace (ppm) element analyses of diabase dikes, Leg 140, Hole 504B.

Core, section:	186R-1	189R-1	191R-1	193R-1	194R-1	196R-1	197R-2	200R-2	200R-3	200R-4	202R-1	205R-1	206R-1	208R-2
Interval (cm):	135–137	13–16	60–62	28–31	115–118	0–3	33–38	26–31	59–63	23–27	25–29	10–13	47–50	61–65
Unit:	213	218	218	220	220	221	222	227	227	227	229	232	235	239
Depth (mbsf):	1627.66	1651.145	1662.01	1674.795	1681.565	1696.525	1698.375	1730.385	1732.21	1733.35	1747.47	1757.115	1761.185	1780.13
Alteration (%):	50	17	16	43	14	5	23	11	47	21	11	72	19	19
SiO ₂	48.28	50.43	50.08	50.45	50.26	50.50	49.30	49.22	49.33	50.44	49.62	48.66	49.47	49.52
TiO ₂	0.97	0.94	0.77	0.43	0.95	1.10	0.75	0.71	0.73	0.93	0.82	0.94	0.76	0.69
Al ₂ O ₃	15.90	14.88	15.75	15.61	15.01	14.45	15.89	16.11	16.46	14.63	15.50	16.17	16.08	16.52
Fe ₂ O ₃	10.05	10.60	9.50	8.95	10.80	11.21	9.72	9.08	9.05	10.57	9.99	9.33	9.11	8.71
MnO	0.16	0.18	0.16	0.15	0.18	0.18	0.16	0.15	0.15	0.19	0.18	0.15	0.16	0.15
MgO	9.25	7.81	8.73	9.12	7.85	8.06	9.35	10.01	9.28	8.27	8.76	8.99	9.02	8.94
CaO	13.42	12.64	13.04	12.50	12.83	12.18	12.91	12.95	13.23	12.71	13.12	13.82	13.21	13.40
Na ₂ O	1.66	1.74	1.80	2.06	1.79	2.03	1.81	1.76	1.79	2.01	1.81	1.73	1.76	1.83
K ₂ O	0.00	0.01	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.00	0.00
P ₂ O ₅	0.08	0.10	0.06	0.02	0.06	0.08	0.04	0.04	0.05	0.08	0.04	0.12	0.05	0.04
Total	99.70	99.32	99.89	99.31	99.73	99.79	99.94	100.04	100.08	99.83	99.84	99.91	99.61	99.80
Cr (XRF)	369	229	407	402	255	164	352	427	392	409	369	361	445	375
Cr (AAS)	325	205	417	430	235	140	348	422	375	415	340	356	439	370
Ni (XRF)	132	82	122	113	87	87	155	189	160	177	115	143	145	122
Ni (AAS)	172	98	150	165	105	112	178	180	182	208	150	159	149	132
Co (AAS)	67.5	58	55	62.5	70	62.5	67.5	57.5	50	57.5	67.5	55	52.5	65
V (XRF)	291.1	338.2	277	224.7	331.9	344.9	247.3	217.9	224.9	233	382.4	289	258.7	236.3
Sr (XRF)	63	45.1	47.4	50.8	46.9	48.2	51.1	66.2	64.6	62.5	51.4	64.5	56.8	55.5
Sr (ICP)	72	97	90	87	109	57	59	61	76	73	59	69	64	63
Ba (ICP)	14	13	10	15	2	2.2	3.1	12	8.8	12	5.6	20	4.6	2.5
La (ICP)	2	1	0.5	1	1.2	1.4	0.7	1.1	1.2	1.2	1.6	1.5	1.2	0.9
Ce (ICP)	6.3	3.7	3.7	3.7	5.2	5.1	2.7	4.4	4.5	3.9	5.5	5.4	4.6	3.7
Nd (ICP)	7.8	5.6	4.9	3.3	7	6.7	4.3	4.8	5.7	4.5	4.7	6.7	5.3	4.6
Sm (ICP)	2.5	2.2	1.7	1.1	2.5	2.5	1.8	2	2.2	1.6	2	2.4	2.2	1.9
Eu (ICP)	1.1	0.8	0.7	0.5	0.9	1	0.7	0.6	0.7	0.6	0.7	0.9	0.7	0.6
Gd (ICP)	3.4	3	2.4	1.7	3.2	3.6	2.2	2.5	2.6	2.2	2.4	3	2.8	2.4
Er (ICP)	2.8	3	2.1	1.5	2.9	3.3	2.1	2	2.1	1.6	2.4	2.9	2.2	2.2
Yb (ICP)	2.3	2.6	1.7	1.4	2.6	2.4	2.1	1.8	1.9	1.7	2.2	2.6	2.1	1.8
Mg#	0.67	0.62	0.67	0.69	0.62	0.61	0.68	0.71	0.69	0.63	0.66	0.68	0.69	0.69
Zr/Y	2.29	1.84	1.77	1.44	1.81	1.95	1.75	2.04	2.06	2.07	1.76	2.35	1.98	1.87

Notes: XRF shipboard major-element analyses are from the Shipboard Scientific Party (1992). Mg# is the molar ratio MgO/MgO + FeO, where FeO = 0.9 × total Fe as Fe₂O₃.

Table 2 (continued).

Core, section:	208R-3	209R-1	209R-2	210R-1	211R-1	214R-1	214R-1	214R-2	221R-1	224R-1	225R-1	225R-2	227R-1	227R-2
Interval (cm):	7–10	98–102	30–33	36–39	136–140	24–28	126–129	100–103	129–132	21–24	40–44	46–49	90–94	14–16
Unit:	239	240	240	241	241	244	244	244	256	258	259	260	260	260
Depth (mbsf):	1781.085	1788.5	1789.315	1795.275	1799.88	1818.86	1819.875	1821.11	1885.9	1903.9	1912.6	1914.2	1925.4	1926.2
Alteration (%):	75	18	10	24	18	9	4	12	66	4	52	12	2	2
SiO ₂	50.00	49.34	48.96	49.73	49.33	49.13	49.05	49.02	48.68	49.90	49.69	49.81	49.23	50.80
TiO ₂	0.56	0.39	0.67	0.82	0.78	0.53	0.80	0.79	1.05	0.91	0.95	0.79	0.76	0.57
Al ₂ O ₃	16.35	15.99	17.87	15.78	15.59	15.92	16.66	16.16	16.73	15.14	15.35	15.63	16.56	16.32
Fe ₂ O ₃	10.03	11.15	8.14	9.55	9.82	9.86	9.57	9.60	9.96	10.55	10.09	10.00	9.51	8.85
MnO	0.16	0.16	0.14	0.16	0.16	0.13	0.15	0.16	0.15	0.18	0.17	0.17	0.16	0.14
MgO	8.69	9.22	8.25	8.65	8.77	9.67	8.29	8.70	9.03	8.25	8.65	8.94	8.74	8.30
CaO	11.86	11.54	13.61	13.11	12.96	12.10	13.00	13.12	12.78	12.93	13.11	13.08	13.12	11.91
Na ₂ O	1.83	1.82	1.83	1.92	1.83	1.73	1.81	1.77	1.76	1.83	1.94	1.86	1.83	2.52
K ₂ O	0.01	0.02	0.00	0.00	0.00	0.02	0.00	0.00	0.01	0.00	0.01	0.01	0.01	0.02
P ₂ O ₅	0.03	0.01	0.04	0.04	0.04	0.10	0.11	0.09	0.07	0.05	0.06	0.08	0.08	0.03
Total	99.52	99.64	99.51	99.75	99.28	99.19	99.44	99.42	100.21	99.74	100.03	100.37	100.00	99.43
Cr (XRF)	396	418	424	361	361	473	335	381	308	262	415	371	364	391
Cr (AAS)	383	435	425	355	368	455	340	372	314	240	445	375	368	385
Ni (XRF)	125	135	137	121	124	166	137	144	140	100	112	129	154	136
Ni (AAS)	165	165	142	129	129	148	165	150	149	112	118	132	153	138
Co (AAS)	62.5	67.5	58	55	77.5	62.5	57.5	52.5	55	62.5	50	55	60	45
V (XRF)	201.8	197.8	221	248.6	269.3	213	266.8	251.4	286	300	282	252	241	221
Sr (XRF)	57.3	51.7	56.9	57.7	53.3	49	55.8	52.4	66.3	54.8	75.7	56	58.1	77
Sr (ICP)	118	56	58	62	55	48	62	55	73	62	87	53	59	87
Ba (ICP)	26	3.3	2.4	23	12	8	10	8.4	16	2.5	17	11	7.3	2.5
La (ICP)	0.4	0.8	1	0.6	1	0.6	1.2	1	1.6	0.7	1.8	1.2	1.3	0.6
Ce (ICP)	3	2.7	4.1	3.7	3.4	3.4	3.2	3.7	5.6	4.2	5.4	4.2	4	2.7
Nd (ICP)	3.3	3.7	4.5	4.6	5	3.9	5.7	5.7	7.3	6.2	7.5	5.7	5.4	3.7
Sm (ICP)	1.1	1.4	1.8	1.6	1.9	1.4	2.2	2.1	2.6	2.3	2.6	2.4	2.2	1.5
Eu (ICP)	0.4	0.4	0.6	0.6	0.7	0.5	0.7	0.7	1	0.9	0.9	0.8	0.7	0.5
Gd (ICP)	1.3	1.7	2.4	1.7	2.6	1.9	3.1	3	3.1	3.3	3.3	2.8	3	2
Er (ICP)	1.4	1.4	1.9	1.5	2	1.7	2.6	2.4	2.9	2.6	2.7	2.5	2.4	1.6
Yb (ICP)	1.2	1.3	1.8	1.6	2	1.7	2.3	2.2	2.5	2.3	2.7	2.4	2.2	1.7
Mg#	0.66	0.65	0.69	0.67	0.66	0.68	0.66	0.67	0.67	0.63	0.65	0.66	0.67	0.67
Zr/Y	2.2	1.76	1.92	1.98	1.76	1.76	1.85	1.79	2.57	1.89	2.45	1.75	1.8	1.83

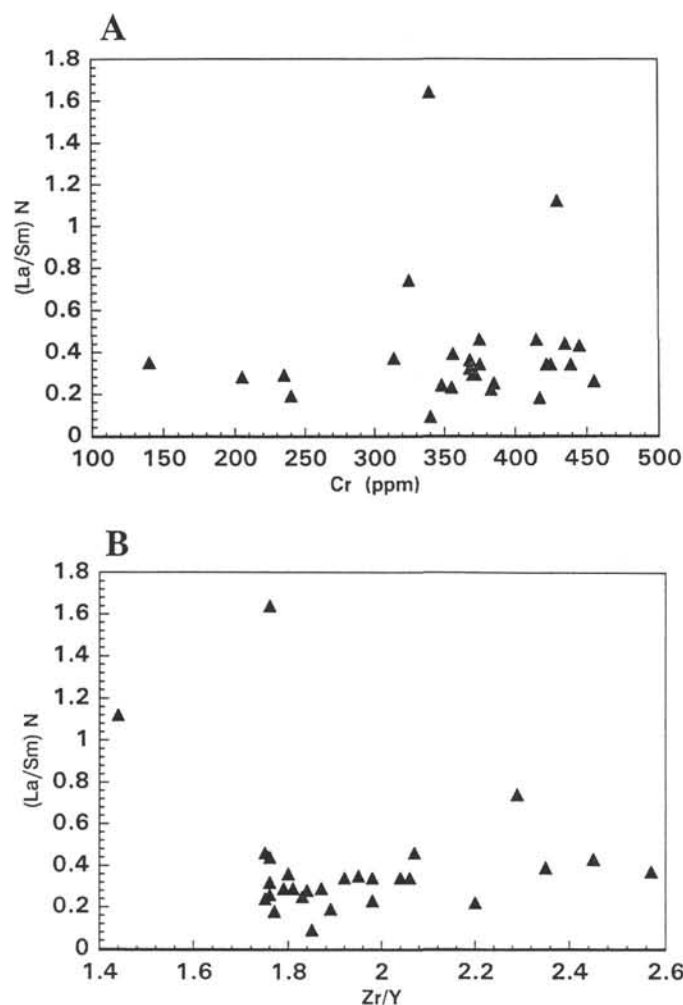


Figure 6. $(\text{La}/\text{Sm})_N$ vs. Cr content (A) and Zr/Y (B) ratio in Leg 140, Hole 504B, diabase dikes.

and can reach 50–60. Although these estimates are approximate, the difference in relative concentrations will probably lead to a difference in enrichment factors and, consequently, to higher relative mobility of Ba and “immobility” of Sr.

REE patterns observed in diabase dikes in Hole 504B are interpreted to represent their original igneous characteristics. Little or no variation is observed with various degrees of alteration, suggesting that both LREE and HREE are immobile under mid-crustal metamorphic conditions. This conclusion is consistent with experimental results of Hajash (1984) and implies that even if LREE (especially Ce) may be mobile at fluid-rock interfaces, this localized process cannot change the bulk REE pattern of considerable rock volumes.

CONCLUSIONS

1. Analyzed diabase samples from Hole 504B (Leg 140) have relatively uniform REE compositions with only a slight difference in the extent of LREE depletion. Instead, LIL elements (especially Ba) show large variations independently from other incompatible elements, compatible elements (Cr, Ni, and Co), and REEs.

2. Observed REE variations suggest that alteration has affected LILE distribution, but left REE patterns untouched, representing original igneous characteristics of Costa Rica Rift oceanic basalts.

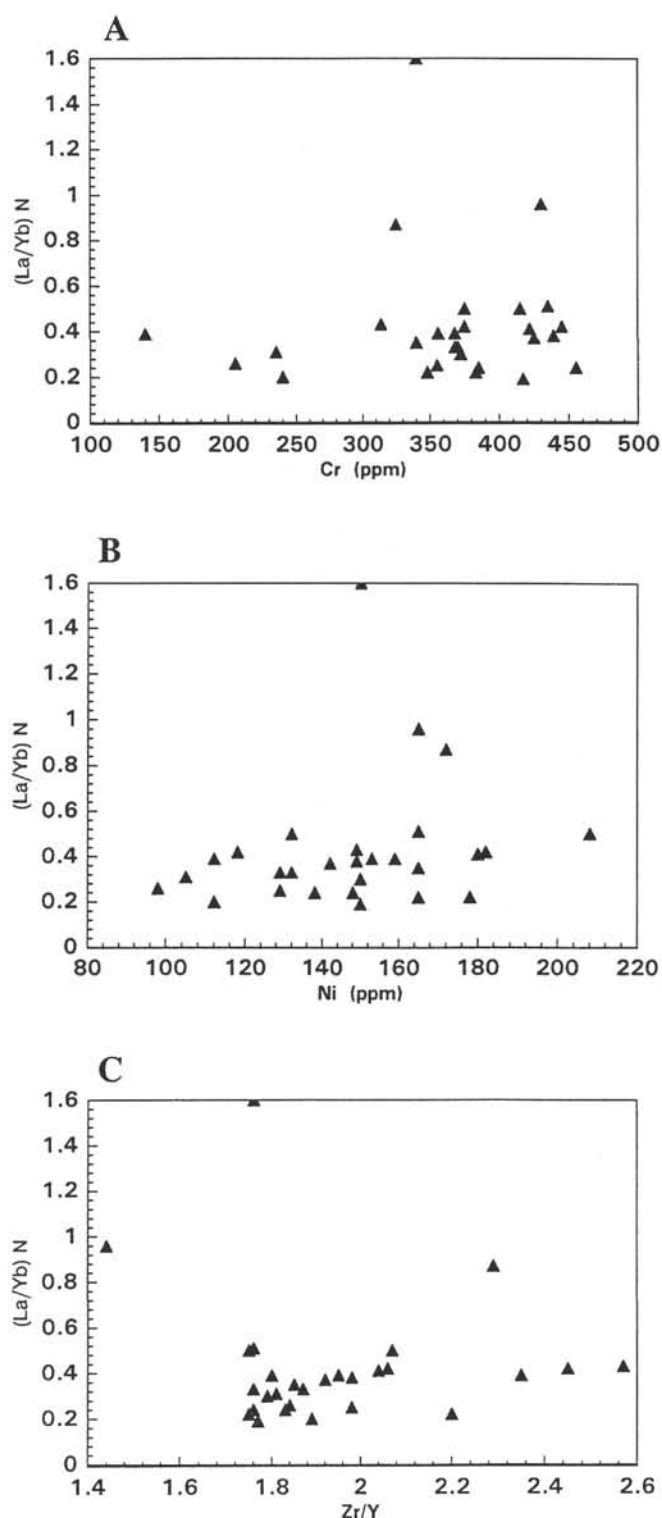


Figure 7. $(\text{La}/\text{Yb})_N$ vs. Cr (A), Ni (B), and Zr/Y ratio (C) in diabase dikes from Leg 140, Hole 504B.

3. LILE variations suggest addition of Ba in some units and leaching from others because of heterogeneous fluid-rock interaction under disequilibrium conditions.

4. Primary REE patterns define various degrees of depletion in Leg 140 diabase dikes consistent with their derivation from a variably depleted MORB-type source.

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* Abbreviations for names of organizations and publications in ODP reference lists follow the style given in *Chemical Abstracts Service Source Index* (published by American Chemical Society).

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