52. GEOCHEMISTRY OF BASALTS FROM COSTA RICA RIFT SITES 504 AND 505 (DEEP SEA DRILLING PROJECT LEGS 69 AND 70)[1]

H.-W. Hubberten,[2] R. Emmermann,[3] and H. Puchelt, Institut für Petrographie und Geochemie, Universität Karlsruhe, Karlsruhe, Federal Republic of Germany

ABSTRACT

We obtained major and trace element data on 113 samples from basalts drilled during DSDP Legs 69 and 70 in the Costa Rica Rift area. The majority have major and trace element characteristics typical of ocean-ridge tholeiities. Most of the basalts are relatively MgO rich (MgO > 8 wt.%) and have Mg values (MgO/MgO + 0.85FeO × 100) of about 53, characteristics that clearly indicate that the various magmas underwent only a small amount of crystal fractionation before being erupted onto the seafloor. According to their normative mineralogies, the rocks are olivine tholeiites. A few samples plot close to the diopside–hypersthene join of the projected basalt tetrahedron.

Except for basalts from two thin intervals in Hole 504B, which differ significantly from all the other basalts of the hole, practically no chemical downhole variation could be established. In the two exceptional intervals, both TiO_2 and P_2O_5 contents are markedly enriched among the major oxides. The trace elements in these intervals are distinguished by relatively high contents of magmatophile elements and have flat to enriched chondrite-normalized distribution patterns of light rare earth elements (LREE). Most of the rocks outside these intervals are strongly depleted in large-ion-lithophile (LIL) elements and LREE. We offer no satisfactory hypothesis for the origin of these basalts at this time. They might have originated within pockets of mantle materials that were more primitive than the LIL-element-depleted magmas that were the source of the other basalts.

A significant change with depth in the type of alteration occurs in the 561 meters of basalt cored in Hole 504B. According to the behavior of such alteration-sensitive species as K_2O, H_2O^-, CO_2, S, Tl, and the iron oxidation ratio, the alteration is oxidative in the upper part and nonoxidative or even reducing in the lower part. The oxidative alteration may have resulted from low temperature basalt/seawater interaction, whereas hydrothermal solutions may be responsible for the nonoxidative alteration.

INTRODUCTION

During Legs 69 and 70 of the Deep Sea Drilling Project, several holes were drilled through sediments and into basalts where heat flow measurements (e.g., CRRUST, 1982) indicated the existence of contrasting geothermal regimes. The holes were south of the Costa Rica Rift (Fig. 1), the easternmost actively spreading segment of the Galapagos Spreading Center (Lonsdale and Klitgord, 1978). Sites with different geothermal characteristics were selected deliberately to permit the study of geothermal phenomena. Site 505 was in an area of low heat flow, and Site 504 was in an area of high heat flow.

Our investigation concentrates primarily on Hole 504B, which is located at 1°13.63′N, 38°43.8′W on crust 5.9 m.y. old. This hole reached a sub-bottom depth of 836 meters, with a total basement penetration of 561 meters. The basement section cored is made up of a sequence of massive flows (which become more abundant in deeper parts) and pillows or thin basalt flows. Most of the pillow or thin lava flows are highly fractured and allow the intensive circulation of solutions. A downflow of cold seawater at a rate of about 50 gal./hr. was induced by drilling. The water issued into the basement at a depth of 90 meters below the sediments (CRRUST, 1982).

The basalts recovered exhibit a wide range of textures, from glassy spherulitic in pillows or thin flows to ophitic intergranular in some of the massive lavas. Most of the samples are moderately phyric, with plagioclase and olivine as dominant phenocryst phases. Clinopyroxene phenocrysts are abundant in some units. Cr–spinel occurs in other units in minor amounts. Titanomagnetite is the dominant opaque mineral, and it is often accompanied by primary sulfide spherules. According to the Site 501/504 chapter (this volume), 49 lithologic units were defined in Hole 504B by the shipboard scientific parties on the basis of the distribution of the phenocryst assemblages observed in thin sections and hand specimens.

Alteration is slight to moderate in the massive units and moderate to high in the fractured basalts. A significant downhole change occurs in the type of alteration minerals. Reddish-brown iddingsites and iron oxy-hydroxides are characteristic alteration products in the upper part of the basement (down to 584 m sub-bottom), indicating oxidative alteration conditions; below this depth they are virtually absent (see Honnorez et al., this volume). Instead, pyrite, which is very rare in the upper part of the hole, becomes abundant. A third type of alteration, in which zeolites are abundant, occurs between 534.5 meters and 543.5 meters and is superimposed on the earlier oxidative alteration. This zone differs from that in the upper and the lower part of the hole in the nature and amount of the secondary minerals, which fill

[1] Cann, J. R., Langseth, M. G., Honnorez, J., Von Herzen, R. P., White, S. M., et al., *Init. Repts. DSDP*, 69: Washington (U.S. Govt. Printing Office).

[2] Present address: Instituto de Geología, Universidad Autónoma de Nuevo Leon, 67700 Linares, N.L., Mexico.

[3] Present address: Mineralogisch-Petrologisches Institut, Universität Giessen, Federal Republic of Germany.

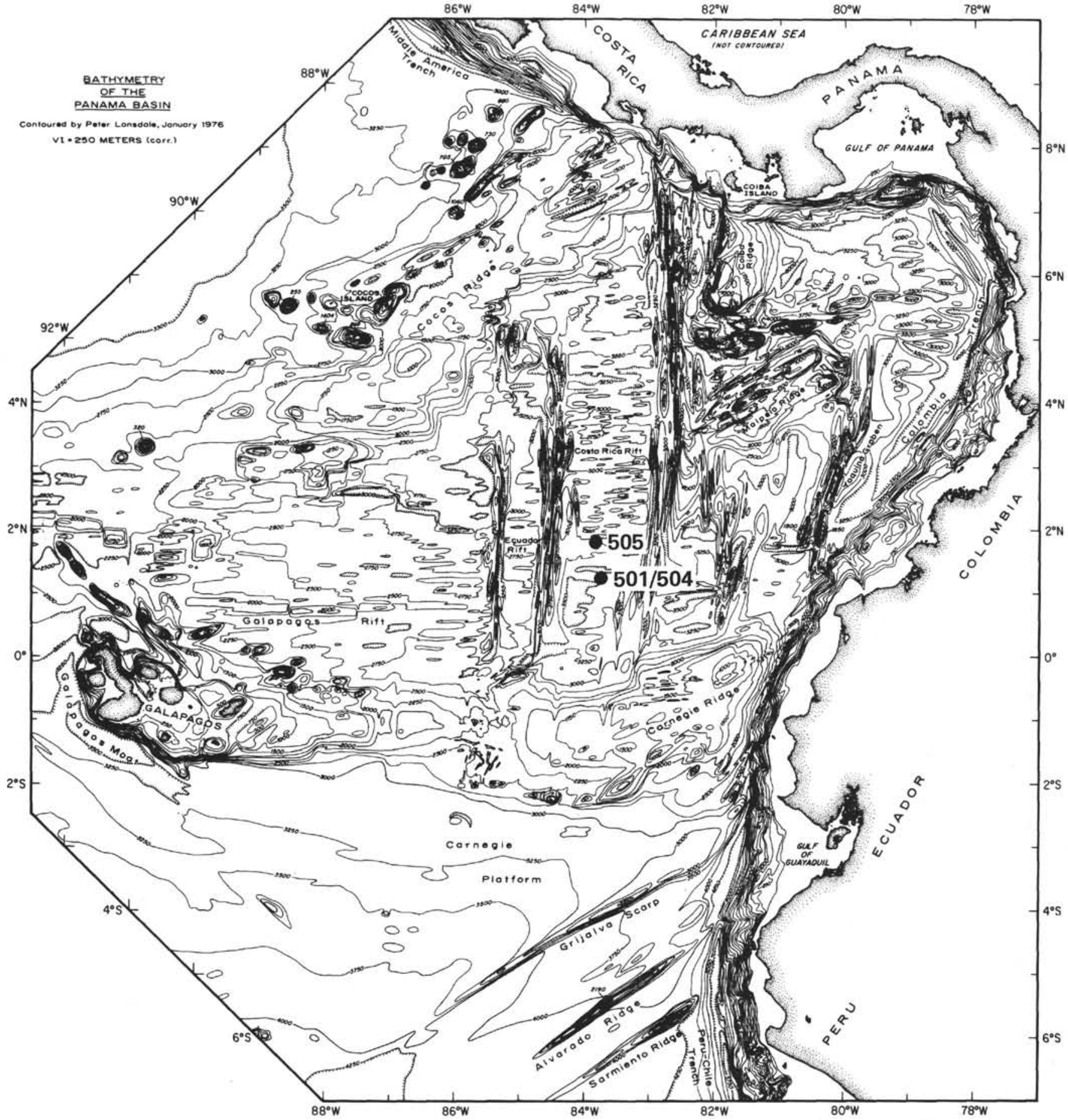

Figure 1. Location of Sites 501, 504, and 505. Bathymetry after Lonsdale and Klitgord (1978). Contour interval is 250 m.

all fractures and seal this part against circulating solutions. For a detailed description of alteration mineralogy see Honnorez et al. (this volume).

The main objective of this chapter is to define the bulk chemical characteristics of the material recovered from Hole 504B. Through detailed geochemical investigations we will try to answer the following questions:

1) What is the chemical composition and variation of the young crustal basalts at the Costa Rica Rift?

2) What conclusions can be reached with respect to their mode of formation?

3) Are there any significant chemical changes that can be related to alteration processes?

ANALYTICAL PROCEDURE

We selected 68 samples for analysis from the Leg 70 part of Hole 504B while we were on board ship. We also selected 27 samples from the upper part of Hole 504B and from Holes 504A, 505A, and 505B that were collected during Leg 69, to which we added another 18 Leg 69 samples that we chose during the post-cruise meeting at La Jolla. Sample density is such that each lithologic unit is represented by at least one sample. In order to determine the primary compositional variation of the basalts we took care to select the freshest material possible, that is, material devoid of smectite, carbonate, and so forth.

All the samples were renumbered in our laboratory. Table 1 lists the DSDP sample designations and the corresponding laboratory sample numbers. For the sake of brevity we will refer to the laboratory sample numbers in this paper.

After removing alteration rims the samples were cleaned with distilled water, crushed with the help of a pneumatic press, ground with an agate mill to <200 mesh, and dried at 105°C. All the samples were analyzed for their major components, including H_2O^+ and CO_2; in addition, 23 trace elements were determined on 27 samples. X-ray fluorescence analysis (XRF) was used for the determination of Si, Ti, Al, Fe, Mn, Mg, Ca, Na, K, P, Zr, Y, Sr, Zn, and Ni. The analyses were carried out on fused glass beads of lithium metaborate (rock-to-flux ratio: 1:4) by routine XRF techniques using a Philips PW 1450 computerized spectrometer. For concentration calculations the Philips "alphas" program was used.

Instrumental neutron activation analysis (INAA) was used for Fe, Mn, Na, Sc, Cr, Co, Hf, and Ta as well as the REE La, Ce, Nd, Sm, Eu, Gd, Tb, By, Yb, and Lu. The analytical procedure adopted has been described by Kramar and Puchelt (in press). Atomic absorption spectrometry (AAS), using a Varian AA6 spectrometer, was used to determine V, Cr, Ni, Cu, and Zn. Coulometric titration was used to determine CO_2 and S. H_2O^+ was measured by Karl Fischer titration after thermal decomposition of the rock. Ferrous iron was determined by manganometric titration.

Concentrations of the following elements were below detection limits (detection limit and method used are shown in parentheses): Rb (3 ppm, XRF), Nb (3 ppm, XRF), Ba (50 ppm, XRF), Cs (0.7 ppm, INAA), Sb (0.5 ppm, INAA), Th (<1 ppm, INAA) and U (<1 ppm, INAA). Precision was tested by duplicate measurements of selected samples; accuracy was always checked by carrying the reference rocks BCR-1 and BHVO-1 through the whole procedure along with the basalt samples. The values we obtained for BCR-1 and BHVO-1 are summarized in Table 2 (data from Puchelt and Kramar, 1981 and Kramar and Puchelt, in press).

This table also contains our data for the three samples used as interlaboratory standards; these samples were distributed to all the laboratories that participated in the analysis of Leg 69 and 70 basalts.

MAJOR AND TRACE ELEMENT CHEMISTRY

Major element analyses of the Hole 504A, 504B, 505A, and 505B basalts along with the normative mineralogies calculated from these data are given in Table 3. Table 4 presents trace element data for these samples. Table 5 shows the REE and some additional trace elements for 27 samples selected from these holes.

Before the chemical data can be evaluated, it is necessary to determine the extent to which the primary composition of the basalts analyzed has been affected by low temperature seawater interaction or hydrothermal alteration. The experience acquired in many previous investigations of ocean-floor basalts makes it possible to determine the freshness of the basalts from its concentrations of H_2O^+, CO_2, and K_2O and the degree of oxidation (expressed as $Fe_2O_3/FeO + Fe_2O_3$). The following limits can be defined for fresh basaltic material: $H_2O^+ < 0.5$ wt.%, $CO_2 < 0.15$ wt.%, $K_2O < 0.25$ wt.%, and $Fe^{3+}/Fe^{2+} < 0.15$ (Puchelt and Emmermann, in press). If these freshness criteria are applied to the basalts from Sites 504 and 505, all the samples from Site 504 are more or less altered. The Site 505 basalts represent the freshest samples cored at the Costa Rica Rift.

Thus, the composition of Hole 504B basalts must be discussed with the understanding that practically no fresh material was obtained from this hole.

Alteration-Sensitive Elements

The subdivision of Hole 504B into an upper and a lower part according to the presence or absence of specific secondary minerals (see Honnorez et al., this volume) is nicely reflected in the significant downhole variations of the degree of oxidation and the concentrations of K_2O, Tl, and S (Fig. 2). In the upper part of the hole Fe^{3+}/Fe^{2+} varies between 0.26 and 0.56, with an average of 0.41. Below a sub-bottom depth of 584 meters this ratio is consistently lower (between 0.22 and 0.45) and averages 0.31. This is in accordance with an assumption of nonoxidative or even reducing alteration conditions. The most pronounced changes between the upper and lower parts of the hole are in the concentrations of K_2O and Tl, both of which are very low and uniform in the lower part of the hole (averaging 0.02 wt.% and 3.4 ppb respectively) but have considerable scatter and clearly higher values in the oxidized part of the hole (0.16 wt.% and 34.1 ppb). Since the potassium enrichment of ocean-floor basalts has been proven to be one of the most consistent features of low temperature basalt/seawater interaction (Honnorez, 1980), the K_2O enrichment of the rocks recovered from the upper alteration zone is a strong argument in favor of the existence of this process. Tl, which geochemically behaves very much like K, seems to be an even more sensitive indicator of low temperature basalt/seawater interaction (McGoldrick et al., 1979), because the absolute concentration changes are much higher (from 1 to 10 ppb with an average of 3.4 in the lower part and from 1 to 201 ppb with an average of 34.1 in the upper part). CO_2 shows no significant change from the upper to the lower part of the hole, with mean values of 0.12 and 0.11 wt.%, respectively.

There are no obvious downhole variations in H_2O^+ concentration. The values found are between 0.44 and 1.40 wt.%, and their average is 0.72 wt.%.

Major Oxides

The downhole variation in the concentration of the major oxides is shown in Figure 3. In general, there are only small compositional fluctuations and no systematic concentration changes with increasing depth. The only notable exceptions to this very uniform picture occur in the concentrations of TiO_2 and P_2O_5, both of which become significantly enriched in Lithologic Units 5 and 36, two minor lithologic units at sub-bottom depths from 398.0 to 404.5 meters and from 672.7 to 715.2 meters, respectively. The following ranges of variation were found for the majority of the basalts: SiO_2, 48.7 to 50.9 wt.%; TiO_2, 0.77 to 1.14 wt.%; Al_2O_3, 14.1 to 17.4 wt.%, Fe_2O_3, 1.86 to 5.93 wt.%; FeO, 3.60 to 7.40 wt.%; MnO, 0.14 to 0.22 wt. %; MgO, 6.67 to 9.35 wt.%; CaO, 11.2 to 13.8 wt.%; Na_2O, 1.93 to 2.69 wt.%; K_2O, 0.01 to 0.39 wt.%; P_2O_5, 0.4 to 0.9 wt.%. The same ranges also apply to basalts from Lithologic Units 5 and 36, except that TiO_2 ranges between 1.27

Table 1. Correlation of DSDP sample designations and our laboratory sample numbers.

DSDP Sample Number Hole/Core/Section (interval in cm)	Piece Number	Laboratory Sample Number
Leg 69		
504A-6-1, 50–52	11	51 01
6-1, 134–138	25	51 02
6-2, 88–96	40	51 03
7-2, 48–52	81	51 04
504B-3-1, 16–19	241	51 05
4-1, 33–40	269	51 06
5-1, 106–109	370	51 07
6-2, 108–112	423	51 08
7-5, 63–65	515	51 09
8-1, 1–2	519	51 10
8-2, 43–45	528	51 67
8-4, 120–123	557	51 11
9-1, 31–33	571	51 68
9-2, 80–83	597	51 12
10-2, 12–14	628	51 13
11-1, 23–25	663	51 51
11-2, 128–130	693	51 52
12-1, 42–45	714	51 53
13-2, 102–103	782	51 54
13-2, 118–122	785	51 55
13-4, 22–26	804	51 56
13-4, 116–122	816	51 60
14-1, 86–89	848	51 57
15-2, 130–132	902	51 58
15-5, 3–5	946	51 59
16-2, 5–10	975	51 14
16-2, 110–112	983	51 61
17-2, 130–137	1069	51 15
18-1, 110–115	1095	51 16
19-1, 98–103	1126	51 17
19-2, 93–95	1146	51 18
20-1, 48–51	1165	51 62
21-1, 123–125	1191	51 63
21-2, 67–70	1209	51 64
21-3, 111–114	1233	51 65
23-1, 73–75	1320	51 19
25-1, 41–44	1403	51 66
25-2, 36–38	1425	51 20
27-1, 105–110	1473	51 21
28-4, 125–130	1553	51 22
29-1, 50–52	1569	51 23
Leg 70		
504B-32-1, 81–83	147	53 01
33-1, 12–14	182	53 02
36-1, 68–70	299	53 03
36-1, 91–110	301	53 04
36-3, 83–85	324	53 05
36-4, 68–70	332	53 06
37-2, 94–96	377	53 07
38-1, 90–92	420	53 08
39-1, 35–37	460	53 09
39-1, 106–110	470	53 10
39-3, 123–125	495	53 11
40-2, 72–88	532	53 12
40-4, 73–75	567	53 13
41-2, 17–19	599	53 14
41-3, 121–123	626	53 15
42-1, 9–11	642	53 16
42-2, 59–61	667	53 17
43-1, 63–65	679	53 18
43-2, 44–46	697	53 19
44-1, 128–130	716	53 20
44-1, 133–135	717	53 21

Table 1. (Continued).

DSDP Sample Number Hole/Core/Section (interval in cm)	Piece Number	Laboratory Sample Number
Leg 69		
45-1, 110–112	746	53 22
46-2, 129–131	791	53 23
46-3, 46–48	798	53 24
47-1, 129–131	820	53 25
47-2, 143–145	836	53 27
47-4, 49–51	854	53 28
48-1, 56–59	865	53 29
48-1, 24–26	862	53 30
48-2, 23–25	878	53 31
48-2, 40–42	880	53 32
48-3, 23–25	895	53 33
49-2, 69–73	944	53 34
49-2, 94–96	947	53 35
50-1, 32–34	962	53 36
51-1, 27–29	973	53 37
52-1, 58–61	995	53 38
52-4, 91–93	1049	53 39
54-1, 39–42	1062	53 40
54-1, 131–135	1071	53 41
55-1, 36–39	1083	53 42
55-2, 34–36	1098	53 43
56-1, 76–79	1108	53 44
57-1, 14–17	1127	53 45
57-3, 13–15	1161	53 46
58-2, 84–89	1215	53 47
59-1, 57–63	1252	53 48
60-1, 102–105	1266	53 49
61-2, 12–15	1299	53 50
62-1, 105–109	1323	53 51
62-2, 5–8	1332	53 52
63-2, 136–140	1374	53 53
63-2, 96–98	1368	53 54
63-4, 10–13	1392	53 55
63-4, 72–77	1399	53 56
64-1, 119–124	1417	53 57
64-2, 111–113	1434	53 58
64-3, 93–98	1451	53 59
64-3, 105–107	1452	53 60
65-1, 20–25	1476	53 61
66-1, 141–145	1505	53 63
66-2, 115–120	1520	53 64
66-2, 139–141	1523	53 62
67-1, 15–18	1525	53 65
68-1, 102–104	1538	53 66
69-1, 57–59	1543	53 67
69-1, 69–73	1544	53 68
70-1, 96–100	1559	53 69
70-2, 12–16	1564	53 70
Leg 69		
505A-1-1, 25–33	102	51 24
505B-2-1, 4–10	112	51 25
2-1, 119–121	124	51 26
2-1, 142–147	127	51 27

and 1.36 wt.% and P_2O_5 ranges between 0.15 and 0.20 wt.%.

Basalt Classification

The CIPW norm was used for the normative classification of the basalts. To avoid the effects of oxidation, the Fe_2O_3 content was fixed at a value of 1.5 wt.% in the

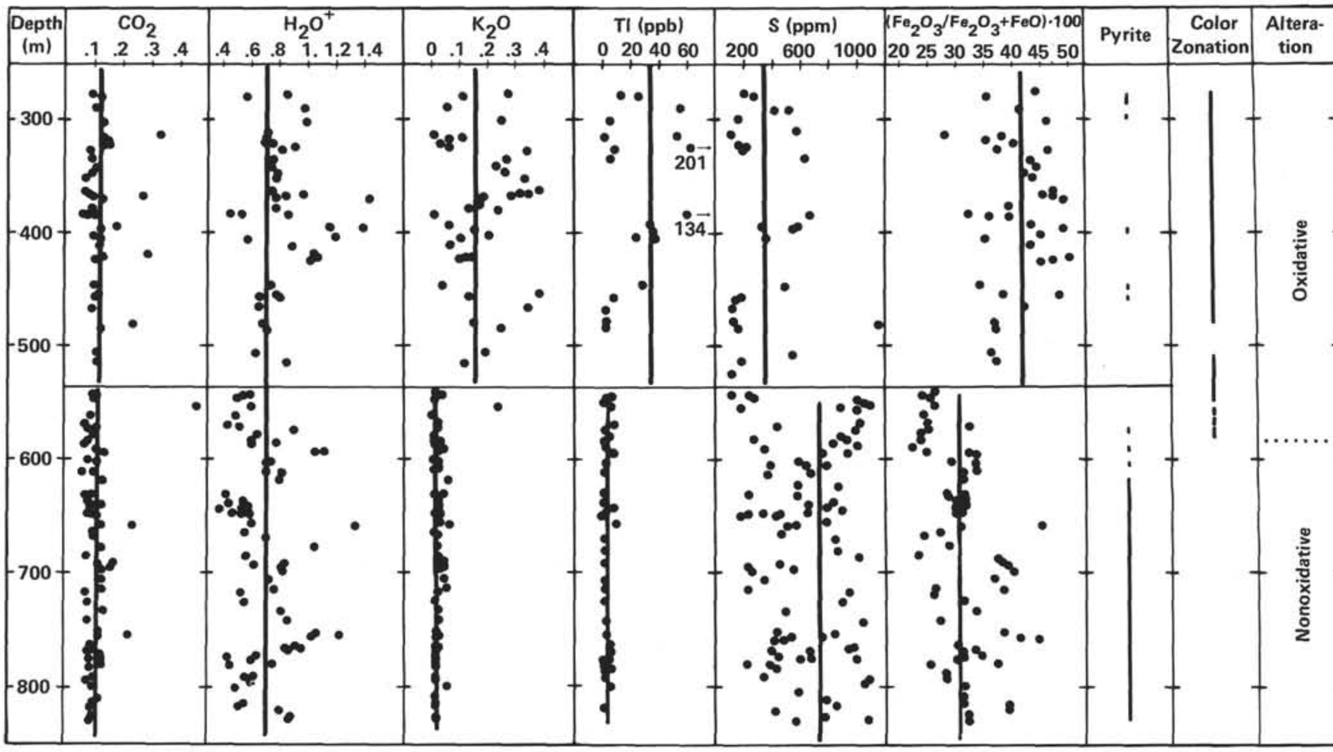

Figure 2. Downhole distribution of components sensitive to alteration of bulk rocks analyzed of "fresh" basalts. Tl data are from Erzinger (1981); S contents are from Hubberten (this volume).

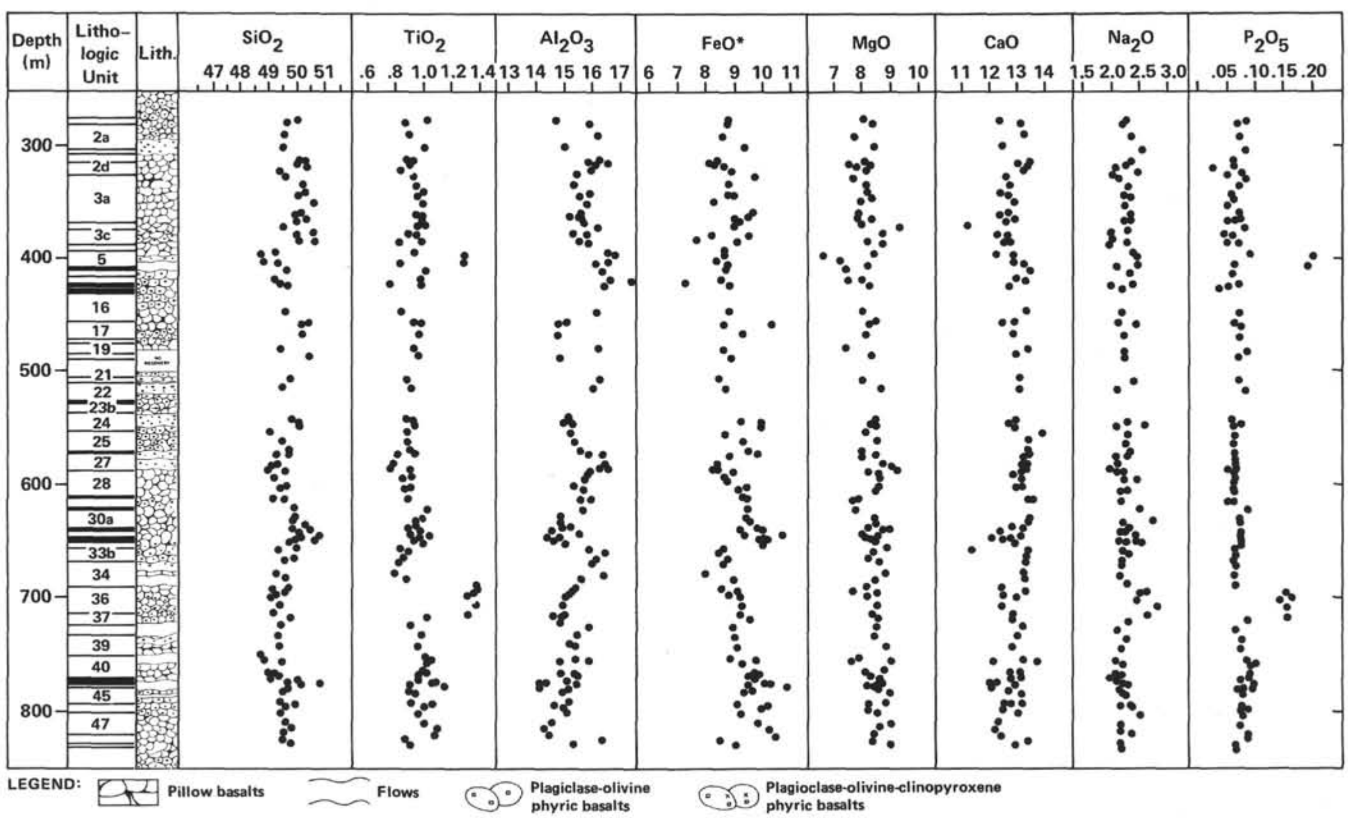

Figure 3. Major element distribution in relation to depth for freshest Hole 504B basalts.

Table 2. Major and trace element data obtained by our laboratory on BCR-1,[a] BHVO-1,[b] and the three samples used as interlaboratory standards.

	BCR-1	BHVO-1	IC 1	IC 2	IC 3
	Major Elements (wt.%)				
SiO_2	54.3	49.8	50.1	50.0	49.0
TiO_2	2.31	2.77	0.75	0.91	0.78
Al_2O_3	13.6	14.08	15.5	15.0	16.2
Fe_2O_3	3.82	3.16	1.83	2.38	1.89
FeO	8.63	8.10	7.01	7.25	6.64
CaO	7.03	11.53	13.7	12.6	13.2
MgO	3.57	7.42	8.39	8.32	8.78
MnO	0.19	0.17	0.16	0.17	0.15
Na_2O	3.33	2.26	1.99	2.31	2.09
K_2O	1.85	0.60	0.02	0.01	0.01
P_2O_5	0.35	0.31	0.05	0.06	0.03
H_2O^+	0.82	0.20	0.38	0.62	0.68
CO_2	<0.1	<0.1	0.18	0.14	0.14
	Trace Elements (ppm)				
Sc	31.8	31.6	42.4	46.6	—
V	400	311	250	291	270
Cr	13	276	425	377	462
Co	36.5	46.7	42.8	44.1	41.4
Ni	15	118	77	91	131
Cu	15	144	108	97	86
Zn	114	120	66	83	67
Zr	185	170	31	41	35
Y	n.d.	25	23	28	27
Hf	4.73	4.31	1.06	1.29	1.19
La	27.3	17.4	0.87	1.15	0.78
Ce	50.7	37.3	2.4	5.4	4.1
Nd	29.0	24	3.08	4.07	3.34
Sm	6.93	6.67	1.52	2.01	1.72
Eu	1.94	2.05	0.62	0.81	0.72
Gd	5.9	n.d.	2.90	3.59	2.74
Tb	1.16	0.91	0.48	0.65	0.52
Ho	1.33	n.d.	0.83	0.91	0.76
Tm	0.47	n.d.	0.41	0.46	0.37
Yb	3.42	2.10	2.19	2.91	2.48
Lu	0.49	—	0.32	0.46	0.37

[a] Kramar and Puchelt, in press.
[b] Puchelt and Kramar, 1981.

norm calculations, so normative magnetite always has a value of 2.18. As shown in Figure 4, most of the basalts have normative olivine and plot in the olivine-tholeiite field of the olivine-diopside-hypersthene-quartz tetrahedron, with only a few samples lying on the hypersthene-diopside join.

Trace Elements

The differences between the Lithologic Unit 5 and 36 basalts and all the other basalts in Hole 504B are even more pronounced in terms of their trace elements (Tables 4 and 5). The differences are particularly pronounced for Zr, Hf, Ta, and the light rare earth elements. The basalts from Lithologic Units 5 and 36 (Samples 51 16 and 53 40 in Tables 4 and 5) display values of Zr, Hf, and Ta of 101 and 107 ppm, 2.2 and 2.6 ppm, and 0.73 and 0.13 ppm, respectively. The values of Zr, Hf, and Ta for all the other basalts range from 32 to 66 ppm, 1.2 to 1.6 ppm, and 0.02 to 0.23 ppm, respectively. Most of the basalts from Hole 504B exhibit very similar chondrite-normalized REE patterns (Masuda, 1975), as shown in Figure 5A. These REE patterns are typical for mid-

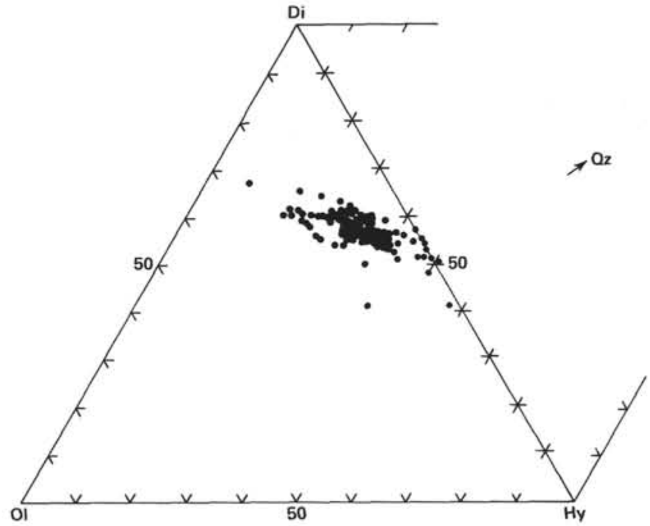

Figure 4. Olivine-diopside-hypersthene-quartz diagram for "fresh" basalts from Sites 504 and 505. For the norm calculations Fe_2O_3 was fixed at a value of 1.5 wt.%.

ocean-ridge basalts (MORB) and show a depletion of the light REE with a La/Sm_N ratio (chrondrite normalized) below 0.43 and almost unfractionated heavy REE with Yb_N values between 12.8 and 18.0.

In contrast, the basalts from Lithologic Units 5 and 36 are only slightly LREE depleted or are even enriched, with La/Sm_N ratios of 1.52 and 0.64, respectively (Fig. 5B). In addition to these basalts, Sample 51 05, which has "normal" major and trace element contents, has a La/Sm_N ratio above unity (1.03). No difference exists in the content of the HREE of these samples when compared with the "normal" Costa Rica Rift basalts.

DISCUSSION

From the large number of chemical analyses available three main points emerge:

1) The concentrations of some alteration-sensitive elements and the degree of iron oxidation allow a distinction to be made between two significantly different alteration zones. This is in accordance with mineralogical observations (see Honnorez et al., this volume).

2) The primary composition of the basement section drilled is remarkably uniform.

3) Two subordinate lava flows, Lithologic Units 5 and 36, have exceptional chemistry.

According to their H_2O^+ contents all the "fresh" basalts analyzed are more or less altered. The concentrations found for H_2O^+ range between 0.44 and 1.40 wt.%, with most samples close to 0.7 wt.%. H_2O^+ determinations on fresh basalt glasses dredged at different localities on the East Pacific Rise and the Galapagos Spreading Center revealed that the water content of fresh ocean-floor tholeiites is below 0.5 wt.%, depending on the degree of fractionation of the magmas (Puchelt and Emmermann, in press). Thus, at least part of the water content is due to alteration. The extent of this type of alteration seems to be mainly a function of the permeability of the basalts (massive versus fractured or pillowed sequences) rather than of depth.

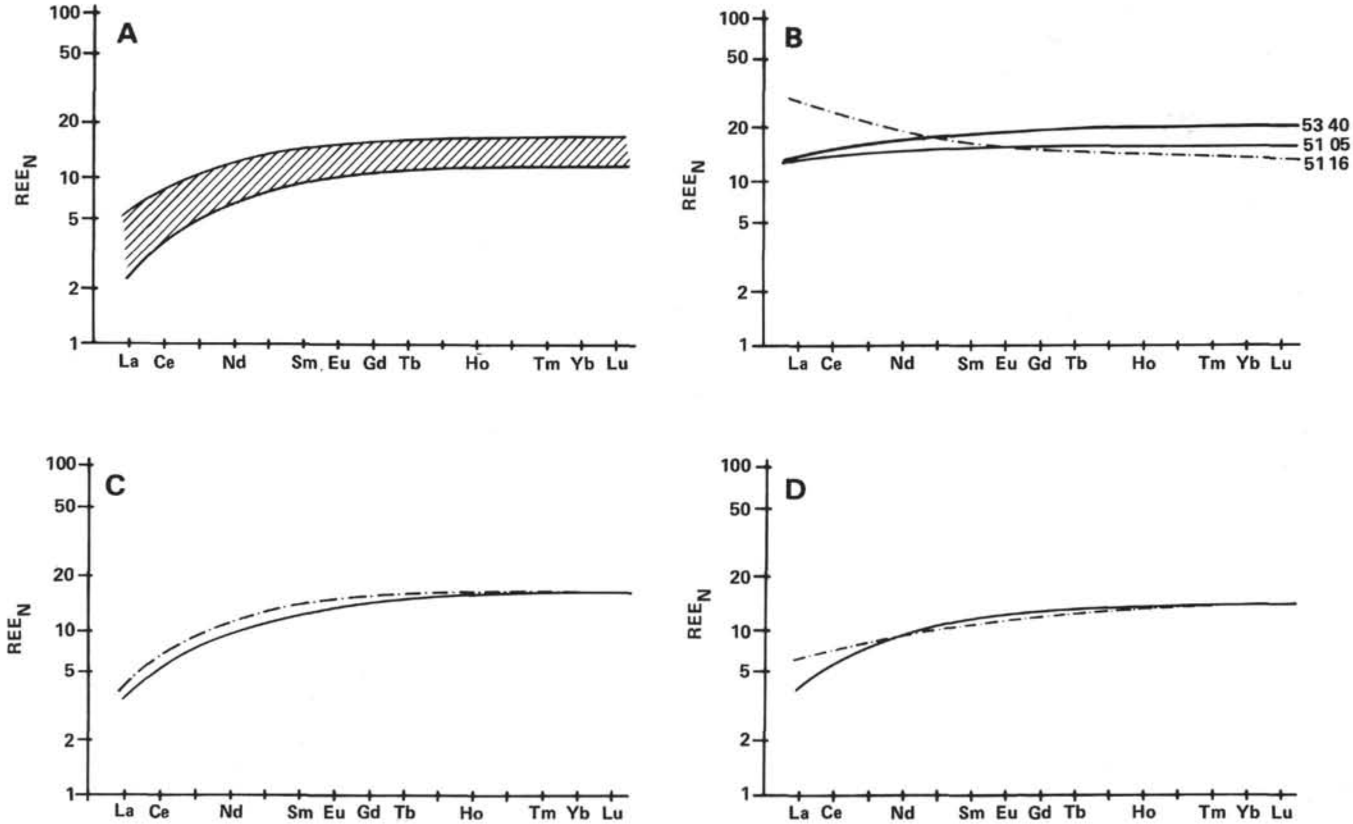

Figure 5. Chondrite-normalized REE patterns. A. Range of "normal" Hole 504B basalts. B. Samples 51 05, 51 16, and 53 40. C. Hole 504A basalts. D. Hole 505A and 505B basalts.

The CO_2 concentrations of the freshest possible rocks show a broader scatter in the upper part of the hole, but they do not decrease with depth.

The most pronounced differences between basalts from the upper and lower part of the hole have to do with the degree of iron oxidation and the concentrations of potassium, thallium, and sulfur (Fig. 2). All together, these four indicators of alteration allow a clear distinction to be made between two markedly different types of alteration. One is characterized by low sulfur contents, a high iron oxidation ratio, and potassium as well as thallium enrichment, and the other is not depleted in sulfur, has a low iron oxidation ratio, and is very low in K and Tl. The first alteration type prevails in the upper part of the basement section (down to a sub-bottom depth of 544.5 m), and the second occurs only in the lower part of the hole (below a sub-bottom depth of 544.5 m). According to shipboard visual observations of the cores, the last red halo indicating oxidative conditions of alteration (see Honnorez et al., this volume) occurs in Sample 504B-40-3 (130–135 cm), which is from a sub-bottom depth of 584.5 m. There is therefore a transitional zone in the hole 40 meters thick where the alteration mineralogy indicates that the rocks were oxidatively altered although the bulk rock chemistry is characteristic of suboxic or anoxic alteration.

Apart from these significant downhole variations, which are clearly produced by alteration processes and overprint the primary composition of the rocks to a certain extent, no systematic concentration changes with depth were found in either the major or the trace elements. On the other hand, this result indicates that at least as a first approximation, none of the other components analyzed were affected in terms of concentration by secondary processes in the so-called "fresh" basalts (Fig. 3).

This small degree of variation constitutes a strong argument that the single lava eruptions that built up this basement section were rather uniform in composition and are related by systematic variations in composition, a hypothesis also supported by Figures 6 and 7, which show variation diagrams for FeO^+ and Al_2O_3 with respect to TiO_2. Except for Lithologic Units 5 and 36, which differ chemically from all other basement rocks recovered, the basalts analyzed represent typical (i.e., LIL-depleted, MgO-rich, and K_2O-poor) mid-ocean-ridge tholeiites.

According to their MgO contents and their Mg values, which average 52.6, these rocks were generated from rather primitive, (i.e., unevolved) basaltic liquids, which had only undergone a small degree of crystal fractionation prior to being erupted. Because of their relatively high Mg and Ca and rather low Ti and Fe contents, the basalts from Hole 504B can be regarded as less fractionated than other basalts from the Galapagos spreading system (Anderson et al., 1975; Byerly et al., 1976; Melson et al., 1977; Emmermann et al., in press). The relatively narrow fluctuations in composition, most of

Table 3. Major element contents and CIPW norms for all investigated samples of "freshest" basalts.

	Leg 69, Hole 504A				Leg 69, Hole 504B														
	Sample																		
	51 01	51 02	51 03	51 04	51 05	51 06	51 07	51 08	51 09	51 10	51 67	51 11	51 68	51 12	51 13	51 51	51 52	51 53	51 54
	Major Elements (wt.%)																		
SiO_2	50.4	50.4	49.8	50.0	50.0	49.6	49.5	49.5	50.1	50.0	50.4	49.4	50.2	49.5	50.2	50.1	50.0	50.5	50.0
TiO_2	1.02	1.02	1.02	1.07	1.01	0.86	0.89	1.00	0.88	0.89	0.90	0.84	0.90	0.91	0.94	0.98	0.96	0.97	0.97
Al_2O_3	14.5	14.6	15.0	14.9	14.7	15.8	16.1	15.0	15.8	16.0	16.2	15.9	16.5	15.4	15.3	15.8	15.5	15.6	15.4
Fe_2O_3	3.33	3.24	4.12	3.45	4.49	3.14	3.64	4.47	2.34	3.47	2.95	3.67	3.12	4.64	3.98	4.04	3.93	3.69	4.58
FeO	7.08	7.19	6.09	5.65	5.78	5.89	5.33	5.29	5.94	5.53	5.42	5.51	5.35	5.41	5.24	5.16	5.34	4.94	5.19
MnO	0.19	0.18	0.18	0.18	0.18	0.18	0.18	0.18	0.17	0.16	0.15	0.19	0.18	0.18	0.17	0.17	0.16	0.16	0.16
MgO	8.04	7.84	7.91	8.60	8.03	8.34	7.75	8.46	8.06	7.72	8.26	8.15	7.56	7.66	8.08	8.22	8.26	8.43	7.94
CaO	12.6	12.5	12.6	12.5	12.4	13.1	13.2	12.5	13.4	13.2	13.0	13.2	13.3	12.6	12.7	12.4	12.7	12.7	12.6
Na_2O	2.27	2.20	2.27	2.60	2.26	2.20	2.35	2.53	2.35	2.26	2.07	2.46	2.03	2.15	2.28	2.43	2.35	2.24	2.33
K_2O	0.01	0.01	0.17	0.05	0.27	0.11	0.07	0.25	0.01	0.11	0.06	0.03	0.06	0.34	0.27	0.24	0.26	0.33	0.38
P_2O_5	0.08	0.08	0.08	0.08	0.08	0.07	0.07	0.08	0.06	0.06	0.04	0.06	0.05	0.08	0.07	0.06	0.06	0.05	0.07
H_2O^+	0.59	0.63	0.80	0.93	0.86	0.57	0.98	0.99	0.72	0.70	0.65	0.76	0.93	0.83	0.76	0.76	0.79	0.78	0.75
CO_2	0.13	0.08	0.10	0.13	0.09	0.12	0.10	0.13	0.33	0.13	0.13	0.15	0.13	0.08	0.09	0.10	0.09	0.07	0.07
Total	100.24	99.97	100.14	100.14	100.15	99.98	100.16	100.38	100.16	100.23	100.23	100.32	100.31	99.78	100.08	100.49	100.40	100.37	100.44
	CIPW Norm[a]																		
Q	—	0.10	—	—	—	—	—	—	—	—	0.12	—	0.58	—	—	—	—	—	—
or	0.06	0.06	1.06	0.30	1.60	0.65	0.41	1.48	0.06	0.65	0.35	0.18	0.35	2.02	1.60	1.42	1.53	1.95	2.24
ab	19.20	18.65	19.23	22.01	19.15	18.65	19.90	21.39	19.87	19.12	17.50	20.79	17.15	18.29	19.32	20.51	19.85	18.93	19.69
an	29.33	29.99	30.27	28.85	29.21	32.97	33.19	28.81	32.51	33.18	34.71	32.22	35.68	31.53	30.77	31.42	30.93	31.49	30.40
di	25.97	25.44	25.43	25.80	25.54	25.09	25.38	25.85	25.45	25.26	23.17	25.88	23.57	24.72	25.43	23.48	25.18	24.80	25.35
hy	18.92	20.64	14.67	10.99	15.36	12.43	10.44	7.35	14.08	13.80	19.23	7.45	17.44	14.05	14.38	12.35	11.55	14.91	11.32
ol	1.34	—	4.06	6.43	3.79	5.39	5.44	9.57	2.58	3.00	—	8.47	—	4.26	3.40	5.64	5.83	2.86	5.91
il	1.94	1.94	1.94	2.03	1.92	1.64	1.69	1.90	1.67	1.69	1.71	1.59	1.71	1.74	1.79	1.86	1.82	1.84	1.84
ap	0.19	0.19	0.19	0.19	0.19	0.17	0.17	0.19	0.14	0.14	0.09	0.14	0.12	0.19	0.17	0.14	0.14	0.12	0.17
cc	0.29	0.18	0.23	0.30	0.20	0.27	0.23	0.29	0.75	0.30	0.29	0.34	0.30	0.18	0.20	0.23	0.20	0.16	0.16

[a] Normative magnetite (mt), which was always a value of 2.18 because Fe_2O_3 was fixed at a value of 1.5% for the normal calculations, was omitted from the table.

Table 3. (Continued).

	Leg 69, Hole 504B		Leg 70, Hole 504B																
	Sample																		
	51 22	51 23	53 01	53 02	53 03	53 04	53 05	53 07	53 08	53 09	53 10	53 11	53 12	53 13	53 14	53 15	53 16	53 17	53 18
	Major Elements (wt.%)																		
SiO_2	49.4	50.4	48.8	49.5	49.9	50.1	50.1	49.1	49.5	49.7	49.7	49.3	49.3	49.1	49.1	49.6	49.2	49.2	49.6
TiO_2	0.92	0.95	0.89	0.91	0.89	0.91	0.92	0.88	0.87	0.90	0.93	0.81	0.78	0.77	0.78	0.90	0.91	0.85	0.88
Al_2O_3	16.1	14.8	16.2	16.0	15.1	15.0	15.2	15.2	15.3	15.5	15.8	16.3	16.4	16.5	16.2	15.9	15.7	15.7	15.3
Fe_2O_3	3.49	3.53	3.22	3.32	2.43	2.28	2.46	2.56	2.48	2.47	2.94	2.20	2.02	1.94	1.86	2.47	3.13	3.25	2.80
FeO	5.49	5.66	5.63	5.74	7.04	7.33	7.24	6.36	7.11	7.31	6.12	6.49	6.57	6.52	6.73	6.64	5.74	5.74	6.84
MnO	0.18	0.19	0.17	0.16	0.16	0.16	0.16	0.16	0.17	0.17	0.17	0.15	0.15	0.14	0.15	0.15	0.17	0.15	0.15
MgO	7.40	8.28	7.94	8.58	8.45	8.30	8.40	8.10	8.45	7.97	7.95	8.44	8.71	9.09	9.00	8.21	8.54	8.54	8.51
CaO	13.3	12.9	13.0	13.0	12.9	12.7	12.8	13.8	13.3	13.3	13.3	13.2	13.3	13.2	13.1	13.1	12.8	13.0	12.9
Na_2O	2.20	2.19	2.37	2.13	2.25	2.58	2.11	2.27	2.24	2.30	2.28	2.05	2.06	1.96	2.12	2.14	2.40	2.18	2.25
K_2O	0.15	0.24	0.19	0.11	0.01	0.03	0.01	0.23	0.01	0.02	0.02	0.02	0.01	0.01	0.03	0.01	0.04	0.02	0.01
P_2O_5	0.08	0.07	0.07	0.08	0.06	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.06	0.05	0.06	0.06	0.06	0.06	0.06
H_2O^+	0.70	0.72	0.63	0.86	0.60	0.55	0.51	0.61	0.49	0.44	0.63	0.91	0.66	0.77	0.79	0.61	1.12	1.06	0.75
CO_2	0.23	0.12	0.11	0.11	0.10	0.11	0.10	0.46	0.09	0.07	0.11	0.08	0.10	0.08	0.07	0.07	0.11	0.14	0.08
Total	99.64	100.05	100.22	100.49	99.89	100.12	100.07	99.79	100.07	100.21	100.01	100.01	100.12	100.07	99.99	99.86	99.92	99.89	100.13
	CIPW Norm[a]																		
Q	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
or	0.89	1.42	1.12	0.65	0.06	0.18	0.06	1.36	0.06	0.12	0.12	0.12	0.06	0.06	0.18	0.06	0.24	0.12	0.06
ab	18.72	18.56	20.05	17.97	19.08	21.82	17.86	19.27	18.96	19.44	19.32	17.36	17.42	16.58	17.95	18.15	20.36	18.50	19.04
an	33.80	29.89	32.99	33.67	31.14	29.25	31.98	30.70	31.67	31.87	32.86	35.24	35.45	36.18	34.61	33.83	32.03	33.09	31.62
di	24.87	26.78	24.61	23.84	25.98	26.51	24.83	28.14	27.14	27.07	26.09	23.81	23.84	22.98	23.91	24.75	24.74	24.57	25.60
hy	13.48	16.23	10.33	13.17	14.58	10.25	18.38	7.51	10.44	10.61	12.19	13.93	12.63	9.04	10.83	14.58	9.44	12.83	12.74
ol	2.88	1.98	5.99	5.52	4.32	7.13	2.10	7.36	7.07	6.27	4.45	4.60	5.92	6.34	7.77	3.83	7.78	5.58	6.03
il	1.76	1.81	1.68	1.72	1.69	1.73	1.75	1.68	1.65	1.71	1.77	1.54	1.48	1.46	1.48	1.71	1.73	1.62	1.67
ap	0.19	0.17	0.17	0.19	0.14	0.17	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.12	0.14	0.14	0.14	0.14	0.14
cc	0.53	0.27	0.25	0.25	0.23	0.25	0.23	1.05	0.20	0.16	0.25	0.18	0.23	0.18	0.16	0.16	0.25	0.32	0.18

which coincide with lithostratigraphic boundaries, can plausibly be interpreted as the result of slightly different degrees of fractionation. The very limited extent of crystal fractionation is also apparent in the AFM diagram (Fig. 8), which shows a point cluster rather than any obvious trend.

The occurrence of two chemically exceptional lava flows, Lithologic Units 5 and 36, within this rather uniform basement sequence poses a major problem. According to their Mg values these basalts display the same degree of fractionation as all the other rocks recovered. No differences exist between these basalts and those in the rest of the hole with respect to any of their major components except for Ti and P, which are markedly enriched (see Fig. 9). They are furthermore characteristically enriched in magmatophile trace elements, such

Table 3. (Continued).

Leg 69, Hole 504B																			
Sample																			
51 55	51 56	51 60	51 57	51 58	51 59	51 14	51 61	51 15	51 16	51 17	51 18	51 62	51 63	51 64	51 65	51 19	51 66	51 20	51 21
Major Elements (wt.%)																			
49.8	50.1	49.9	49.3	50.5	49.9	50.6	50.1	49.2	48.7	48.8	49.5	49.6	49.3	49.3	49.6	49.6	49.7	50.4	50.2
0.97	0.97	0.94	0.95	0.89	0.87	0.97	1.00	0.93	1.28	1.27	0.83	1.00	0.98	0.75	0.98	0.84	0.95	0.95	0.96
15.4	15.5	15.6	16.1	15.6	15.2	15.8	15.6	16.5	16.7	16.5	16.1	16.3	16.6	17.4	15.8	16.1	14.7	15.0	14.7
5.65	4.29	4.44	4.56	3.18	3.09	2.91	3.64	3.62	4.41	3.92	3.15	3.85	4.56	3.78	4.12	3.13	5.14	3.45	4.01
4.44	5.15	5.03	4.80	5.27	6.69	5.08	5.79	4.88	4.64	4.79	5.87	5.18	4.47	4.32	5.11	5.93	5.62	5.50	5.63
0.15	0.18	0.17	0.14	0.15	0.20	0.18	0.17	0.17	0.18	0.21	0.19	0.20	0.17	0.14	0.21	0.18	0.18	0.16	0.18
7.88	8.15	7.97	9.35	8.74	8.69	8.70	8.20	8.42	6.67	7.21	8.20	7.40	7.50	7.99	8.09	8.02	8.27	8.41	8.12
12.3	12.8	12.7	11.2	12.9	13.1	12.5	13.1	12.2	12.8	12.8	13.2	13.4	12.9	13.3	13.2	13.2	12.4	12.8	12.8
2.33	2.25	2.23	2.28	2.01	2.00	2.27	1.93	2.34	2.43	2.45	2.10	2.29	2.36	2.00	2.15	2.15	2.12	2.41	2.22
0.34	0.28	0.24	0.18	0.17	0.12	0.01	0.24	0.06	0.15	0.20	0.10	0.07	0.14	0.13	0.10	0.04	0.39	0.13	0.34
0.07	0.06	0.05	0.08	0.04	0.06	0.07	0.05	0.09	0.20	0.19	0.06	0.06	0.07	0.04	0.06	0.07	0.06	0.07	0.07
0.98	0.78	0.83	1.44	0.79	0.46	0.87	0.53	1.16	1.40	1.20	0.58	0.90	1.05	1.07	1.02	0.73	0.80	0.67	0.63
0.08	0.09	0.27	0.13	0.09	0.06	0.10	0.06	0.18	0.12	0.10	0.12	0.12	0.29	0.13	0.10	0.10	0.10	0.10	0.09
100.39	100.60	100.37	100.51	100.33	100.44	100.06	100.41	99.75	99.68	99.64	100.00	100.37	100.39	100.35	100.54	100.09	100.23	100.05	99.85
CIPW Norm[a]																			
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
2.01	1.65	1.42	1.06	1.00	0.71	0.06	1.42	0.36	0.89	1.18	0.59	0.41	0.83	0.77	0.59	0.24	2.30	0.77	2.00
19.72	18.98	18.86	19.25	16.98	16.88	19.22	16.30	19.89	20.69	20.64	17.80	19.35	19.95	16.90	18.14	18.21	17.93	20.42	18.69
30.56	31.27	31.82	33.10	32.99	32.05	32.92	33.13	34.50	34.43	33.28	34.26	33.94	34.26	38.07	33.07	34.19	29.42	29.77	29.00
24.06	25.25	23.67	17.00	24.30	26.01	22.61	25.21	19.87	22.31	22.91	24.50	25.46	22.27	21.63	25.35	24.58	25.34	26.53	27.08
12.85	13.10	15.52	16.86	19.25	15.31	19.81	17.52	14.73	11.37	7.90	13.51	11.68	12.13	14.17	13.35	14.07	13.98	13.58	12.84
5.45	4.62	3.20	6.83	0.54	4.49	0.10	1.57	4.92	3.53	7.67	4.58	3.77	4.65	3.41	4.08	3.83	5.87	3.89	5.40
1.84	1.84	1.78	1.80	1.69	1.65	1.84	1.90	1.77	2.45	2.40	1.58	1.90	1.86	1.42	1.86	1.60	1.80	1.81	1.81
0.17	0.14	0.12	0.19	0.09	0.14	0.17	0.12	0.21	0.48	0.45	0.14	0.14	0.17	0.09	0.14	0.17	0.14	0.17	0.16
0.18	0.20	0.61	0.30	0.20	0.14	0.23	0.14	0.41	0.27	0.23	0.27	0.27	0.66	0.29	0.23	0.23	0.23	0.23	0.20

Table 3. (Continued).

Leg 70, Hole 504B																			
Sample																			
53 19	53 20	53 21	53 22	53 23	53 25	53 26	53 28	53 29	53 30	53 31	53 32	53 33	53 34	53 35	53 36	53 37	53 38	53 39	53 40
Major Elements (wt.%)																			
49.4	49.2	49.6	49.9	49.9	50.4	49.9	50.1	50.1	50.8	50.0	50.7	49.8	50.0	49.4	49.9	49.6	49.3	49.6	49.7
0.87	0.88	0.87	1.12	0.95	0.94	0.89	0.89	0.97	1.03	0.96	0.96	0.99	0.83	0.84	0.86	0.83	0.80	0.88	1.36
15.6	15.8	15.6	15.6	14.8	14.9	15.2	15.4	14.7	14.3	14.7	14.5	15.0	15.8	16.2	16.0	15.9	16.3	15.5	15.3
3.09	3.19	3.04	3.02	2.72	2.64	2.74	2.58	3.38	3.21	3.08	3.18	3.18	4.01	2.94	2.41	2.08	2.50	2.14	3.22
6.27	6.36	6.61	6.73	7.00	7.40	6.69	7.01	7.00	7.70	7.32	7.00	7.04	4.98	5.84	6.53	6.69	5.67	7.03	5.58
0.16	0.17	0.17	0.17	0.18	0.17	0.17	0.16	0.17	0.18	0.17	0.16	0.18	0.14	0.16	0.16	0.16	0.15	0.16	0.18
8.45	7.80	7.67	7.72	8.40	8.13	8.86	7.98	8.45	8.06	8.41	8.25	8.43	8.81	8.22	8.21	8.57	8.74	8.43	8.15
13.1	13.3	13.5	12.0	13.3	12.7	13.1	13.0	12.6	12.4	12.8	12.4	12.8	11.3	13.3	13.2	13.2	13.1	13.2	12.4
2.15	2.20	2.17	2.47	2.69	2.28	2.14	2.41	2.21	2.41	2.09	2.50	2.21	2.24	2.34	2.13	2.16	2.14	2.24	2.53
0.02	0.02	0.01	0.06	0.04	0.02	0.02	0.02	0.02	0.02	0.01	0.02	0.02	0.06	0.03	0.01	0.02	0.02	0.02	0.04
0.06	0.06	0.05	0.08	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.07	0.06	0.06	0.06	0.06	0.06	0.06	0.15
0.81	0.84	0.72	0.81	0.44	0.56	0.46	0.55	0.57	0.48	0.55	0.48	0.61	1.34	0.61	0.57	0.71	1.06	0.58	0.86
0.11	0.10	0.06	0.13	0.09	0.08	0.09	0.09	0.09	0.08	0.08	0.09	0.11	0.23	0.13	0.10	0.10	0.13	0.08	0.17
100.09	99.92	100.07	99.81	100.58	100.29	100.33	100.26	100.33	100.74	100.24	100.31	100.44	99.80	100.07	100.14	100.08	99.97	99.92	99.64
CIPW Norm[a]																			
—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
0.12	0.12	0.06	0.36	0.23	0.12	0.12	0.12	0.12	0.12	0.06	0.12	0.12	0.36	0.18	0.06	0.12	0.12	0.12	0.24
18.20	18.66	18.38	20.97	22.66	19.26	18.07	20.36	18.67	20.28	17.67	21.12	18.65	19.04	19.82	18.02	18.27	18.13	18.98	21.52
32.88	33.26	32.82	31.41	28.06	30.31	31.74	31.10	30.09	27.98	30.67	28.24	30.87	33.03	33.64	34.05	33.62	34.86	32.23	30.44
25.23	25.96	27.33	21.99	29.77	25.79	26.04	26.29	25.23	26.37	25.95	26.23	25.52	17.35	25.28	24.66	24.97	23.41	26.35	23.75
13.14	11.56	12.58	16.86	3.41	17.18	14.20	12.29	17.09	17.64	17.98	15.83	14.87	23.96	9.05	15.53	12.98	13.07	11.62	14.44
5.39	5.38	4.03	2.81	11.08	2.49	5.14	5.06	3.55	2.67	2.77	3.62	4.90	0.49	7.22	2.94	5.21	5.22	5.95	3.25
1.65	1.67	1.65	2.13	1.80	1.78	1.69	1.67	1.84	1.95	1.82	1.82	1.88	1.58	1.60	1.63	1.58	1.52	1.67	2.60
0.14	0.14	0.12	0.19	0.16	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.14	0.14	0.14	0.14	0.14	0.14	0.36
0.25	0.23	0.14	0.30	0.20	0.18	0.20	0.20	0.20	0.18	0.18	0.20	0.25	0.53	0.30	0.23	0.23	0.30	0.18	0.39

as Sr, Zr, Hr, and the rare earths. This is especially well documented in the chondrite-normalized rare earth distribution patterns, which are almost chondritic or even enriched in the light rare earths (see Fig. 5B). Since the Mg values and the Cr and Ni concentrations indicate that the degree of fractionation of the melts from which Lithologic Units 5 and 36 were derived was comparable to that in the magmas from which all the other basalts were generated, it is likely that the starting liquids were derived from a chemically different mantle source. For the generation of the melts that produced the Lithologic Units 5 and 36 basalts, the possibility of a LIL-element-enriched ("plume") mantle source has to be taken into consideration. Natland and Melson (1980) suggested the existence of localized pockets of less depleted mantle to explain similar basalts in and near the Siqueiros Frac-

Table 3. (Continued).

	Leg 70, Hole 504B																			
	Sample																			
	53 41	53 42	53 43	53 44	53 45	53 46	53 47	53 48	53 49	53 50	53 51	53 52	53 53	53 54	53 55	53 56	53 57	53 58	53 59	53 60
	Major Elements (wt.%)																			
SiO_2	49.2	49.6	49.2	49.4	49.2	49.8	49.5	49.4	49.4	48.8	48.9	49.5	49.1	49.2	49.4	49.1	50.1	50.2	49.7	49.7
TiO_2	1.36	1.34	1.31	1.33	1.30	1.02	0.91	0.98	0.96	1.01	1.04	1.01	1.01	0.92	0.97	0.96	1.10	1.14	0.90	0.90
Al_2O_3	15.2	15.1	15.0	14.9	14.9	14.8	15.8	15.4	15.4	15.3	15.8	14.8	15.3	14.8	15.4	15.1	14.2	14.1	15.3	15.1
Fe_2O_3	3.69	3.53	3.80	3.40	3.66	2.58	2.65	3.10	2.48	3.84	4.20	4.24	3.22	3.00	3.23	3.06	3.60	3.42	2.91	3.62
FeO	5.80	5.58	5.72	6.10	5.88	7.19	6.54	6.15	6.83	6.35	5.94	5.39	6.84	6.97	6.51	6.88	3.60	7.65	6.79	6.26
MnO	0.18	0.18	0.18	0.19	0.18	0.17	0.16	0.18	0.16	0.18	0.18	0.17	0.17	0.17	0.19	0.17	0.18	0.18	0.17	0.16
MgO	7.66	8.44	8.10	8.42	8.31	8.42	8.38	8.36	8.66	7.79	7.03	8.93	8.10	8.65	8.16	8.51	8.42	8.02	8.29	8.49
CaO	13.2	12.4	12.9	12.4	12.7	12.7	13.0	12.9	12.7	13.1	13.6	12.1	13.0	12.6	13.0	12.7	12.0	11.9	12.8	12.6
Na_2O	2.48	2.45	2.39	2.73	2.59	2.25	2.08	2.22	2.16	2.06	2.17	2.03	2.10	2.05	2.04	1.94	2.20	2.26	2.11	2.14
K_2O	0.03	0.04	0.03	0.04	0.05	0.02	0.01	0.02	0.02	0.01	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.01	0.01
P_2O_5	0.15	0.16	0.14	0.15	0.15	0.08	0.06	0.07	0.07	0.08	0.08	0.09	0.08	0.08	0.07	0.07	0.08	0.09	0.07	0.07
H_2O^+	0.64	0.81	0.82	0.72	0.79	0.54	0.57	0.82	0.88	1.08	1.02	1.34	0.85	0.92	0.87	0.95	0.65	0.47	0.62	0.76
CO_2	0.12	0.16	0.13	0.13	0.13	0.07	0.08	0.14	0.08	0.12	0.12	0.22	0.10	0.09	0.11	0.09	0.13	0.09	0.13	0.13
Total	99.71	99.79	99.72	99.91	99.84	99.64	99.77	99.74	99.80	99.72	100.10	99.83	99.84	99.53	99.96	99.54	99.68	99.53	99.80	99.91
	CIPW Norm[a]																			
Q	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
or	0.18	0.24	0.18	0.24	0.30	0.12	0.06	0.12	0.12	0.06	0.12	0.06	0.12	0.06	0.06	0.06	0.06	0.06	0.06	0.06
ab	21.09	20.82	20.33	23.17	22.00	19.13	17.66	18.86	18.33	17.52	18.39	17.25	17.83	17.46	17.30	16.52	18.72	19.25	17.92	18.16
an	30.41	30.21	30.27	28.36	28.99	30.37	33.86	32.13	32.36	32.64	33.37	31.38	32.23	31.35	32.90	32.67	28.30	28.49	32.36	31.66
di	27.38	23.88	26.24	25.57	26.34	26.01	24.44	24.99	24.23	25.64	26.97	21.84	25.53	24.78	24.89	24.17	24.07	24.38	24.48	24.21
hy	9.21	14.61	11.63	7.79	8.16	15.39	15.43	14.03	14.90	14.40	11.25	22.42	14.29	17.09	16.72	18.30	21.96	22.22	17.49	17.48
ol	5.70	3.97	5.23	8.80	8.13	3.98	3.75	4.51	4.83	4.09	4.27	0.88	4.63	3.89	2.83	2.95	0.78	0.36	2.72	3.31
il	2.60	2.56	2.50	2.53	2.48	1.95	1.73	1.87	1.83	1.93	1.98	1.93	1.93	1.89	1.85	1.84	2.10	2.18	1.72	1.71
ap	0.36	0.38	0.33	0.36	0.36	0.19	0.14	0.17	0.17	0.19	0.19	0.21	0.19	0.19	0.17	0.17	0.19	0.22	0.17	0.17
cc	0.27	0.37	0.30	0.30	0.30	0.16	0.18	0.32	0.18	0.27	0.27	0.50	0.23	0.21	0.25	0.21	0.30	0.21	0.30	0.30

Table 3. (Continued).

	Leg 70, Hole 504B											Leg 69, Hole 505A	Leg 69, Hole 505B		
	Sample														
	53 61	53 63	53 64	53 62	53 65	53 66	53 67	53 68	53 69	53 70	53 71	51 24	51 25	51 26	51 27
	Major Elements (wt.%)														
SiO_2	49.6	49.5	49.8	50.0	49.5	49.6	49.8	49.6	49.1	49.3	50.9	49.5	50.1	49.4	49.3
TiO_2	0.92	0.92	1.00	1.03	0.96	1.00	1.08	1.07	0.87	0.90	1.07	0.94	0.93	0.92	0.93
Al_2O_3	14.9	15.1	14.9	14.6	15.0	14.5	14.3	14.4	16.2	15.3	14.1	16.1	16.1	16.0	16.1
Fe_2O_3	2.45	2.68	3.18	2.92	2.96	3.99	4.21	3.88	2.89	3.01	3.35	2.29	2.61	2.46	2.34
FeO	7.11	6.67	7.07	7.54	6.51	6.15	6.21	6.89	5.88	6.29	7.07	6.61	6.04	6.31	6.60
MnO	0.17	0.19	0.17	0.17	0.19	0.19	0.21	0.22	0.22	0.17	0.16	0.17	0.14	0.17	0.17
MgO	8.88	8.71	8.13	8.09	8.45	8.89	8.52	8.33	8.30	8.90	8.61	8.49	8.21	8.94	8.78
CaO	13.0	13.0	12.4	12.4	12.9	12.2	12.1	12.3	13.2	12.8	11.9	13.0	12.8	12.7	12.9
Na_2O	2.20	2.13	2.30	2.35	2.48	2.11	2.12	2.30	2.12	2.12	2.15	2.36	2.29	2.28	2.24
K_2O	0.01	0.01	0.01	0.01	0.05	0.01	0.01	0.01	0.01	0.01	0.01	0.05	0.11	0.02	0.05
P_2O_5	0.07	0.07	0.07	0.07	0.07	0.07	0.08	0.08	0.06	0.06	0.08	0.07	0.06	0.07	0.07
H_2O^+	0.46	0.57	0.63	0.61	0.51	0.81	0.66	0.61	0.89	0.89	0.66	0.57	0.49	0.65	0.40
CO_2	0.09	0.10	0.08	0.08	0.10	0.12	0.10	0.09	0.10	0.09	0.12	0.07	0.07	0.15	0.05
Total	99.86	99.65	99.74	99.87	99.68	99.64	99.40	99.78	99.84	99.84	100.18	100.22	99.95	100.07	99.93
	CIPW Norm[a]														
Q	—	—	—	—	—	—	—	—	—	—	0.76	—	—	—	—
or	0.06	0.06	0.06	0.06	0.30	0.06	0.06	0.06	0.06	0.06	0.06	0.29	0.65	0.12	0.30
ab	18.66	18.11	19.55	19.94	21.08	17.91	18.10	19.55	17.99	18.00	18.19	19.94	19.41	19.30	18.98
an	30.82	31.76	30.43	29.34	29.79	30.29	29.72	29.07	34.76	32.30	28.79	33.14	33.38	33.37	33.78
di	26.62	25.92	24.79	25.63	27.15	24.15	24.17	25.53	24.24	24.67	23.60	24.61	23.81	22.84	23.93
hy	12.78	14.44	16.42	16.30	8.43	16.61	21.55	15.79	12.61	14.28	23.26	9.35	14.45	12.31	10.54
ol	6.30	4.81	3.69	3.64	8.34	7.73	1.06	4.88	5.25	5.56	—	7.82	3.57	6.98	7.86
il	1.75	1.76	1.91	1.96	1.83	1.91	2.07	2.04	1.66	1.72	2.03	1.78	1.77	1.75	1.77
ap	0.17	0.17	0.17	0.17	0.17	0.17	0.19	0.19	0.14	0.14	0.19	0.17	0.14	0.17	0.17
cc	0.21	0.23	0.18	0.18	0.23	0.28	0.23	0.21	0.23	0.21	0.27	0.16	0.16	0.34	0.11

ture Zone of the East Pacific Rise. As a working hypothesis we suggest that the Lithologic Units 5 and 36 basalts represent melt products generated within such pockets of more primitive mantle material.

CONCLUSIONS

The crustal section in Hole 504B can be roughly subdivided into an upper and a lower part on the basis of changes in chemistry due to alteration. The alteration solution in the upper part of the hole consists of seawater at low temperatures and results in an enrichment in K and Tl, a higher iron oxidation ratio, and a depletion of S in the "fresh" basalts. The alteration solutions in the lower part were less oxidative, as shown by the higher S contents and the lower iron oxidation ratio. Elements such as K and Tl show very low concentrations in the lower part of the hole.

Most of the basalts encountered at the Costa Rica Rift display the petrological and chemical characteristics typical of LIL-element-depleted ocean-ridge tholei-

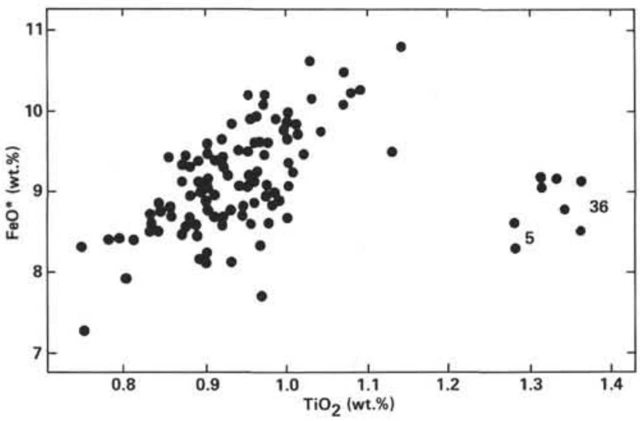

Figure 6. FeO* plotted versus TiO_2. FeO* is total iron as FeO.

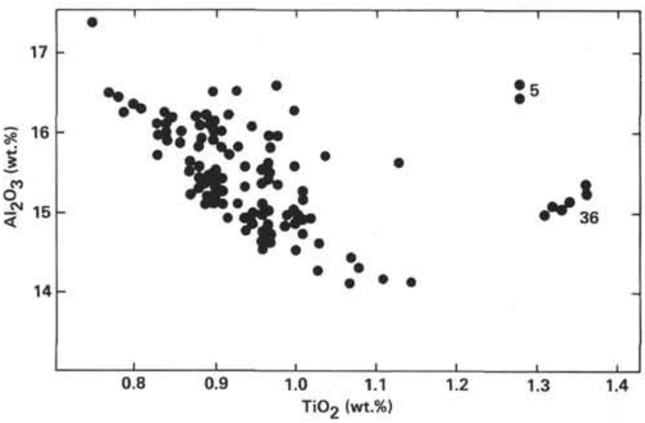

Figure 7. Al_2O_3 plotted versus TiO_2.

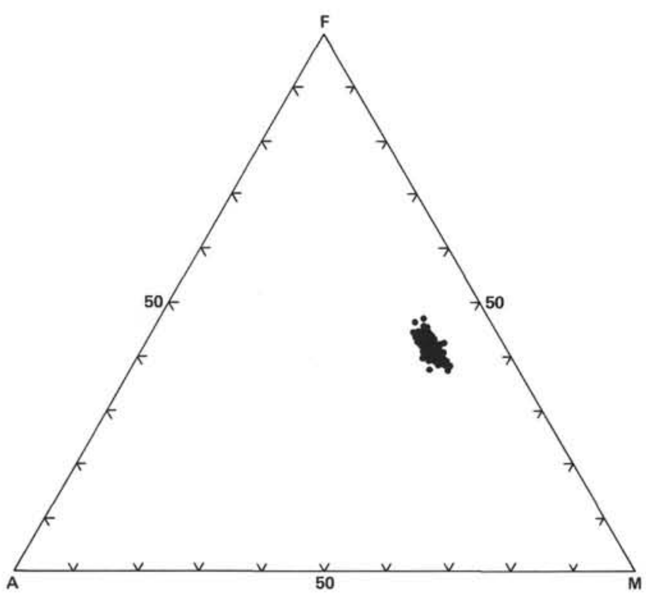

Figure 8. AFM diagram for Hole 504B.

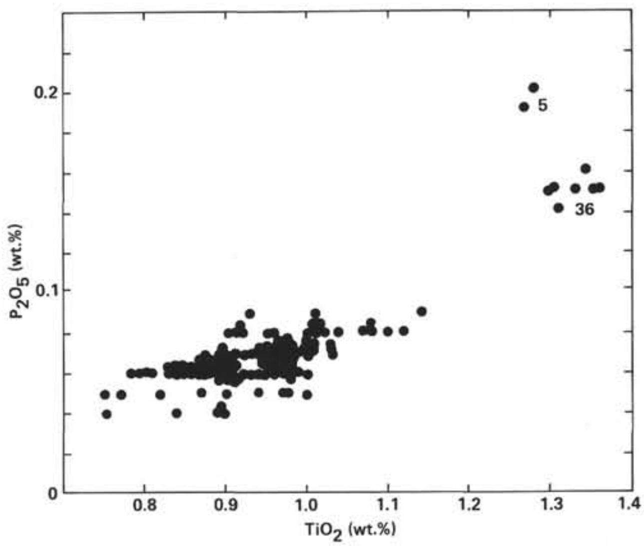

Figure 9. P_2O_5 plotted versus TiO_2.

ites. They can almost all be classified as olivine tholeiites according to their normative mineralogy. No significant chemical downhole variation could be observed. These normal Costa Rica Rift basalts were probably formed by olivine-plagioclase fractionation of a magma derived from a depleted mantle source.

The basalts of Lithologic Units 5 and 36 are almost identical to the others with respect to their major element composition and their normative mineralogy. However, they are less depleted in LIL elements than the other basalts and are believed to have formed from magmas derived from localized pockets of a less depleted mantle.

ACKNOWLEDGMENTS

This investigation was supported by a grant from the Deutsche Forschungsgemeinschaft. Neutron activation analyses were carried out with equipment provided by the Bundesministerium für Forschung und Technologie. The manuscript was reviewed by J. H. Natland.

REFERENCES

Anderson, R. N., Clague, D. A., Klitgord, K. D., Marshall, M., and Nushimori, R. K., 1975. Magnetic and petrologic variations along the Galapagos Spreading Center and their relation to the Galapagos melting anomaly. *Geol. Soc. Am. Bull.*, 86:683–694.

Byerly, G. R., Melson, W. G., and Vogt, P. R., 1976. Rhyodacites, andesites, ferro-basalts and ocean tholeiites from the Galapagos Spreading Center. *Earth Planet. Sci. Lett.*, 30:215–221.

CRRUST, 1982. Geothermal regimes of the Costa Rica Rift, East Pacific, investigated by drilling, DSDP-IPOD Legs 68, 69 and 70. *Geol. Soc. Am. Bull.*, 93:862–875.

Emmermann, R., Hubberten, H.-W., and Puchelt, H., in press. Geochemistry of basalts erupted at the Galapagos Spreading Center between 85-87°W. *In* Honnorez, J., Von Herzen, R. P., et al., *Init. Repts. DSDP*, 70: Washington (U.S. Govt. Printing Office).

Erzinger, J., 1981. Zur Geochemie von Selen und Thallium in magmatischen Gesteinen—mit einem Beitrag zur Analytik von Selen in geochemischen Matrizes [Ph.D. dissert.]. University of Karlsruhe, Karlsruhe, Germany.

Honnorez, J., 1980. The aging of the oceanic crust at low temperature. *In* Emiliani, C. (Ed.), *The Sea* (Vol. 7): New York (Wiley Interscience), 528–587.

Kramar, U., and Puchelt, H., in press. Reproduciblity for INAA trace element determinations with AGV, BCR and GSP and new data for 18 geochemical reference materials. *Geostandards Newslet.*

Lonsdale, P., and Klitgord, K. D., 1978. Structure and tectonic history of the Eastern Panama Basin. *Geol. Soc. Am. Bull.*, 89:981–999.

Masuda, A., 1975. Abundances of monoisotopic REE, consistent with the Leedey chondrite value. *Geochem. J.*, 9:183–184.

McGoldrick, P. J., Keays, R. R., and Scott, B. B., 1979. Thallium: a sensitive indicator of rock/seawater interaction and of sulfur saturation of silicate melts. *Geochim. Cosmochim. Acta*, 43:1303–1311.

Melson, W. G., Byerly, G. R., Nelen, J. A., O'Hearn, T., Wright, T. L., and Vallier, T., 1977. A catalog of the major element chemistry of abyssal volcanic glasses. *In* Mason, B. (Ed.), *Mineral Sciences Investigations, 1974–1975, Smithson. Contrib. Earth Sci.*, 19:31–60.

Natland, J. H., and Melson, W. G., 1980. Compositions of basaltic glasses from the East Pacific Rise and Siqueiros Fracture Zone, near 9°N. *In* Rosendahl, B. R., Hekinian, R., et al., *Init. Repts. DSDP*, 54: Washington (U.S. Govt. Printing Office), 705–723.

Puchelt, H., and Emmermann, R., in press. Petrogenetic implications from tholeiite basalt glasses from the East Pacific Rise and the Galapagos Spreading Center. *Chem. Geol.*

Puchelt, H. and Kramar, U., 1981. New analytical data and homogeneity of BHVO-1. *Geostandards Newslet.*, 5:87–94.

Table 4. Trace element contents, the oxidation ratio, and the Mg value for all investigated samples of "freshest" basalts.

Sample	Ni (ppm)	Zn (ppm)	Y (ppm)	Sr (ppm)	Zr (ppm)	S (ppm)	Tl (ppb)	Oxidation Ratio[a]	Mg[b]
51 01	64	81	30	76	61	1221	—	32	48.4
51 02	71	82	31	80	57	1197	—	31	47.7
51 03	92	83	29	76	54	229	—	40	48.7
51 04	102	90	28	81	55	1224	—	38	53.6
51 05	65	82	27	79	56	200	13	44	49.0
51 06	112	71	26	77	48	272	26	35	52.9
51 07	119	74	34	82	47	525	56	41	51.5
51 08	85	81	31	83	59	160	5	46	51.6
51 09	111	74	24	79	50	578	53	28	54.1
51 10	116	69	29	81	50	106	1	38	51.2
51 67	n.d.	n.d.	n.d.	n.d.	n.d.	762	—	35	54.6
51 11	130	73	25	78	45	891	201	40	52.1
51 68	n.d.	n.d.	n.d.	n.d.	n.d.	547	—	37	52.1
51 12	62	82	31	65	33	157	8	46	48.5
51 13	82	79	30	91	49	193	6	43	51.9
51 51	n.d.	n.d.	n.d.	n.d.	n.d.	300	—	44	52.4
51 52	n.d.	n.d.	n.d.	n.d.	n.d.	218	—	42	52.3
51 53	n.d.	n.d.	n.d.	n.d.	n.d.	154	—	43	54.3
51 54	n.d.	n.d.	n.d.	n.d.	n.d.	139	—	47	50.1
51 55	n.d.	n.d.	n.d.	n.d.	n.d.	157	—	56	49.3
51 56	n.d.	n.d.	n.d.	n.d.	n.d.	195	—	45	51.5
51 60	n.d.	n.d.	n.d.	n.d.	n.d.	172	—	47	51.0
51 57	n.d.	n.d.	n.d.	n.d.	n.d.	338	—	49	55.3
51 58	n.d.	n.d.	n.d.	n.d.	n.d.	138	—	38	55.8
51 59	n.d.	n.d.	n.d.	n.d.	n.d.	495	—	32	51.9
51 14	173	85	30	74	48	635	134	36	57.1
51 61	n.d.	n.d.	n.d.	n.d.	n.d.	75	—	39	51.6
51 15	133	73	28	101	53	663	33	43	54.9
51 16	112	74	30	175	101	576	35	49	47.7
51 17	108	71	27	176	101	559	37	45	50.5
51 18	122	69	25	75	44	348	24	35	52.6
51 62	n.d.	n.d.	n.d.	n.d.	n.d.	788	—	43	50.2
51 63	n.d.	n.d.	n.d.	n.d.	n.d.	152	—	50	50.7
51 64	n.d.	n.d.	n.d.	n.d.	n.d.	363	—	47	54.9
51 65	n.d.	n.d.	n.d.	n.d.	n.d.	668	—	45	51.9
51 19	99	71	27	70	41	479	28	34	51.9
51 66	n.d.	n.d.	n.d.	n.d.	n.d.	189	—	48	48.7
51 20	97	83	30	78	52	173	8	38	53.5
51 21	85	83	29	75	51	116	2	42	50.8
51 22	108	76	32	69	53	130	3	39	50.2
51 23	95	76	34	76	54	163	3	39	52.5
53 01	103	65	27	52	48	538	—	36	52.3
53 02	121	60	30	83	53	191	—	37	53.8
53 03	95	56	25	66	43	994	7	26	51.8
53 04	90	65	21	63	51	1040	4	24	51.0
53 05	93	59	28	58	44	1087	2	25	50.5
53 07	126	55	24	86	41	175	6	26	52.3
53 08	97	57	23	67	44	996	—	24	51.6
53 09	82	59	26	62	42	1009	9	25	49.7
53 10	78	59	31	69	47	421	—	32	51.6
53 11	107	48	27	71	36	980	2	25	54.0
53 12	131	51	29	62	42	880	4	23	55.0
53 13	125	48	22	65	36	920	2	23	56.4
53 14	113	53	26	67	37	820	—	22	55.8
53 15	79	45	36	66	47	990	2	27	52.1
53 16	87	56	34	66	47	340	—	35	54.0

[a] Oxidation ratio is $(Fe_2O_3/Fe_2O_3 + FeO) \times 100$.
[b] Mg value is $(MgO/MgO + 0.85\ FeO^*) \times 100$, where FeO^* is total iron as FeO.

Table 4. (Continued).

Sample	Ni (ppm)	Zn (ppm)	Y (ppm)	Sr (ppm)	Zr (ppm)	S (ppm)	Tl (ppb)	Oxidation Ratio[a]	Mg[b]
53 17	104	49	24	65	34	748	9	36	53.7
53 18	94	60	19	63	46	579	—	29	51.7
53 19	96	63	18	66	35	619	3	33	52.4
53 20	105	60	29	64	43	657	—	33	49.8
53 21	103	51	33	66	46	335	2	31	49.1
53 22	93	73	39	63	53	565	—	31	48.9
53 23	87	56	28	67	49	232	1	28	51.3
53 25	70	67	31	58	40	808	—	31	49.5
53 26	89	52	27	61	42	643	1	31	53.3
53 28	67	63	22	61	39	893	—	34	50.2
53 29	62	68	27	60	48	452	2	32	49.8
53 30	47	80	27	57	48	737	—	29	47.4
53 31	79	65	26	57	46	215	1	30	49.6
53 32	74	67	29	56	51	422	—	31	49.7
53 33	81	66	28	61	49	175	—	31	52.8
53 34	84	51	27	56	41	778	—	45	54.6
53 35	91	57	29	57	38	552	10	33	53.3
53 36	100	56	25	69	35	460	—	27	52.6
53 37	106	49	28	66	32	934	2	24	54.1
53 38	100	49	32	66	45	943	—	31	56.5
53 39	93	53	31	70	44	1000	2	23	52.5
53 40	77	64	42	115	107	443	—	37	53.0
53 41	72	63	39	116	106	224	2	38	49.6
53 42	71	60	35	116	100	542	—	39	53.1
53 43	79	68	33	111	103	243	2	40	51.0
53 44	75	64	34	119	100	341	—	36	51.1
53 45	72	65	34	110	103	221	2	38	51.6
53 46	86	63	27	77	61	927	—	26	49.6
53 47	80	54	24	63	47	890	2	31	52.4
53 48	95	53	25	83	61	494	—	33	52.3
53 49	97	56	25	78	54	1022	3	27	52.9
53 50	115	67	26	59	50	808	—	38	48.2
53 51	109	66	23	56	52	731	3	41	46.0
53 52	94	68	27	57	47	460	—	44	53.2
53 53	116	63	32	58	48	969	6	32	49.4
53 54	103	63	32	60	44	955	—	30	51.0
53 55	125	60	31	61	43	395	6	33	50.5
53 56	127	64	37	63	45	648	—	31	50.8
53 57	68	76	36	66	47	424	5	34	49.1
53 58	56	70	35	69	56	988	—	31	46.7
53 59	81	60	24	62	45	210	2	30	50.9
53 60	83	66	31	63	41	376	—	37	51.2
53 61	92	61	26	74	47	419	5	25	47.3
53 63	90	63	21	77	48	325	3	28	52.9
53 64	86	68	36	67	52	1067	—	31	49.0
53 62	64	66	25	65	49	1043	—	28	48.3
53 65	98	59	35	76	45	572	6	31	51.9
53 66	94	71	34	66	44	772		31	51.7
53 67	64	65	25	70	49	843	1	39	49.9
53 68	71	70	26	68	43	411		39	48.5
53 69	120	55	22	73	38	768		32	53.5
53 70	147	55	31	72	39	1066		32	53.7
51 24	122	68	25	88	57	669		26	53.5
51 25	132	65	25	84	66	780		30	53.5
51 26	133	70	26	84	55	971		28	55.2
51 27	137	74	31	85	61	509		26	54.3

Table 5. REE and additional trace element contents of selected samples.

Hole		504A		504B										
Sample		51 01	51 04	51 05	51 07	51 13	51 16	51 18	51 20	51 22	53 01	53 04	53 09	53 10
	Sc	48	51	48	42	43	38	40	48	44	43	47	46	48
	Cr	236	235	206	428	336	316	386	289	302	291	377	351	363
	Co	45	54	48	47	44	41	50	48	46	54	44	48	48
	La	1.1	1.3	3.8	1.6	1.2	8.6	1.1	1.4	0.90	1.3	1.2	1.1	1.1
	Ce	4.8	5.9	12.3	3.5	4.7	15.8	3.4	3.6	4.5	2.6	5.4	3.5	3.1
	Nd	4.8	6.9	6.7	5.1	4.1	11.0	4.3	6.4	5.1	5.0	4.1	4.1	4.3
	Sm	2.3	2.4	2.6	2.3	2.3	3.4	2.0	2.4	2.3	2.2	2.0	2.2	2.1
Element	Eu	0.89	0.95	0.92	0.77	0.83	1.1	0.75	0.88	0.86	0.77	0.81	0.77	0.73
	Gd	4.7	4.6	4.6	3.7	3.6	5.1	3.4	4.0	4.4	5.0	3.6	3.9	3.7
	Tb	0.72	0.76	0.77	0.65	0.65	0.71	0.52	0.65	0.61	0.61	0.65	0.58	0.59
	Ho	0.80	1.2	0.99	1.3	1.0	0.93	0.97	1.0	0.75	1.1	0.91	1.1	0.96
	Yb	3.3	3.6	3.2	2.9	2.8	2.9	2.7	3.0	3.0	2.9	2.9	2.7	3.0
	Lu	0.47	0.54	0.46	0.40	0.37	0.39	0.38	0.42	0.45	0.42	0.46	0.39	0.41
	Hf	1.8	1.8	1.5	1.6	1.5	2.2	1.2	1.5	1.4	1.5	1.3	1.2	1.2
	Ta	0.06	1.1	0.11	0.16	0.08	0.73	0.08	0.04	0.23	—	0.02	—	—

Table 5. (Continued).

	504B											505A	505B	
	53 12	53 18	53 22	53 25	53 31	53 35	53 40	53 49	53 56	53 64	53 70	51 24	51 25	51 27
Sc	40	45	48	43	46	44	49	41	42	45	42	41	41	44
Cr	462	343	181	163	149	261	262	334	288	232	349	456	454	484
Co	41	47	52	47	50	46	47	47	48	48	48	41	42	45
La	0.78	1.1	1.4	1.2	1.6	—	3.9	1.4	1.3	1.3	1.4	1.4	2.1	1.3
Ce	4.1	4.0	6.2	4.3	3.4	2.6	10.6	4.2	3.5	5.6	3.7	4.7	5.9	5.8
Nd	3.3	4.5	6.9	5.6	5.0	4.8	9.9	6.3	5.7	5.5	3.7	5.3	4.5	5.0
Sm	1.7	2.1	2.8	2.2	2.3	2.1	3.7	2.4	2.4	2.5	2.2	2.1	2.1	2.3
Eu	0.72	0.73	0.96	0.80	0.83	0.74	1.3	0.82	0.79	0.87	0.77	0.88	0.82	0.82
Gd	2.7	4.0	6.0	3.7	3.9	3.9	5.7	3.5	3.7	3.6	3.6	3.5	3.5	3.5
Tb	0.52	0.64	0.72	0.61	0.67	0.60	0.87	0.64	0.62	0.65	0.55	0.58	0.51	0.65
Ho	0.76	1.1	1.2	0.96	0.85	0.91	1.2	1.1	0.92	1.0	1.0	0.82	0.94	0.83
Yb	2.5	2.8	3.5	3.2	3.1	2.7	3.7	2.7	2.9	3.2	2.7	2.8	2.8	3.0
Lu	0.37	0.41	0.49	0.41	0.45	0.36	0.55	0.43	0.46	0.41	0.46	0.39	0.42	0.40
Hf	1.2	1.2	1.8	1.5	1.6	1.2	2.6	1.7	1.6	1.6	1.3	1.6	1.5	1.4
Ta	0.02	—	—	—	0.03	—	0.13	0.04	—	—	—	0.07	0.09	0.14