

## 5. TRACE ELEMENT AND ISOTOPIC EVIDENCE FOR MAGMA MIXING IN ALKALIC AND TRANSITIONAL BASALTS NEAR THE EAST PACIFIC RISE AT 8°N

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### ABSTRACT

Trace element abundances and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of Mg-rich tholeiites, alkalic basalts, and transitional basalts from very young oceanic crust near the East Pacific Rise at 8°N show wide variability. The tholeiites are depleted in large-ion-lithophile (LIL) elements and have  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70270$ . The alkalic basalts are LIL-enriched, and fresh samples have  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70300$ . Chemical and isotopic effects of alteration, fractional crystallization, "dynamic melting," and mantle heterogeneity are observed in each group. Fresh transitional basalts have intermediate LIL-enrichment and  $^{87}\text{Sr}/^{86}\text{Sr} = 0.70287$ . These basalts are hybrid and originate by mixing of tholeiitic and alkalic basalt near the East Pacific Rise.

### INTRODUCTION

Numerous petrologic and geophysical studies have recently been carried out in the Siqueiros area of the East Pacific Rise (EPR) (Figure 1) at about 8°N (Batiza et al., 1977; Johnson, 1979; Scientific Staff, 1977; Rosendahl et al., 1976; Orcutt et al., 1976; Lonsdale, 1979; Rosendahl, 1976; Crane, 1976). The geophysical studies have established that the crest of the EPR is underlain by a narrow crustal low-velocity zone which is probably a magma chamber. This magma chamber provides a locus for production of a wide range of crystal fractionation products from an Mg- and Ni-rich, and large-ion-lithophile (LIL) element depleted parental tholeiite liquid. Abundant Fe- and Ti-rich tholeiites of this type have been recovered from the Siqueiros area (Batiza et al., 1977; Johnson, 1979; Scientific Staff, 1977). In addition, Ne-normative, less LIL element depleted alkalic basalts have been dredged in the Siqueiros area (Batiza et al., 1977). Basalts that are chemically and isotopically intermediate between Mg- and Ni-rich, LIL element depleted tholeiite and these alkalic basalts have also been recovered (Johnson, 1979). In this report we present additional trace-element and isotopic data supporting the hypothesis that these transitional basalts are hybrid magmas produced by the mixing of tholeiitic and alkalic basalt melts. These data also provide additional constraints on the origin of the Siqueiros alkalic basalts and on the nature of chemical

and isotopic mantle heterogeneities below very young crust at the EPR.

### RESULTS

Major oxide, trace element, and isotopic data for the tholeiites, alkalic basalts, and transitional basalts are given in Table 1. Rare earth element (REE) abundances are shown normalized to chondrites (Haskin et al., 1968) in Figure 2. The tholeiites are typical of light rare earth element (LREE) depleted mid-ocean ridge basalt (Engel et al., 1965; Tatsumoto et al., 1965; Frey et al., 1974 and references therein; and Kay and Hubbard, 1978 and references therein). They are Ol-Hy normative, have very low concentrations of LREE, Rb, Sr, Zr, Hf, and U, and have  $^{87}\text{Sr}/^{86}\text{Sr} = 0.7027$ . The Sm/Nd and  $^{143}\text{Nd}/^{144}\text{Nd}$  of these samples (Carlson et al., 1977, 1978) is also within the range of mid-ocean ridge basalts, which are thought to be produced from "depleted" portions of the sub-oceanic upper mantle (Gast, 1968; DePaolo and Wasserburg, 1977).

The alkalic basalts, on the other hand, are enriched in LREE, other LIL elements, and  $^{87}\text{Sr}$  relative to the tholeiites. The enrichments of LIL elements in the alkalic basalts are not as large as those observed for oceanic island alkalic basalts (Sun and Hanson, 1975; Gast, 1968), nor do these basalts have as much normative Ne as typical alkalic island basalts have (Batiza et al., 1977). They have higher abundances of heavy rare earth elements (HREE) and less Sr than is typical of island

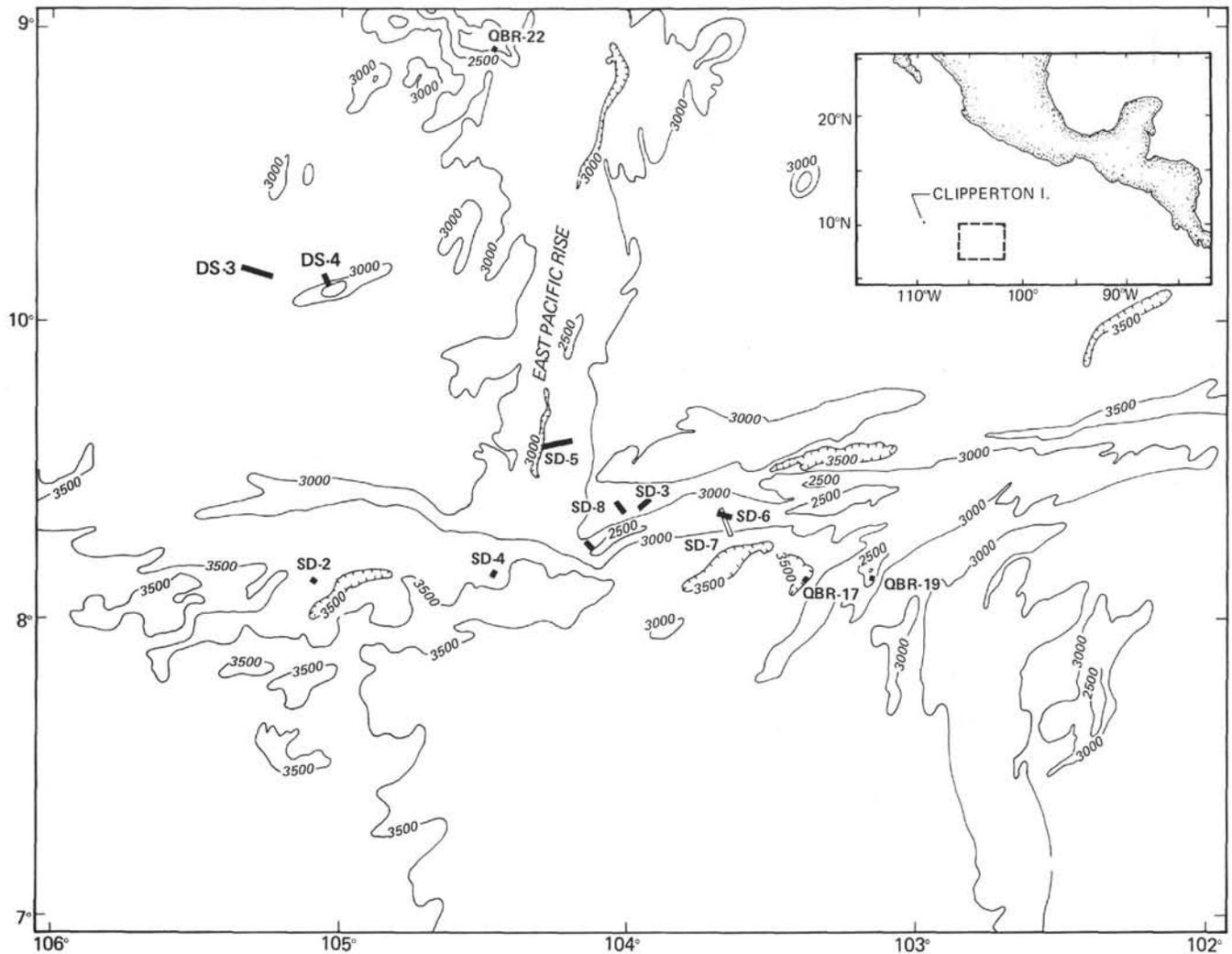


Figure 1. Bathymetric map of the Siqueiros area showing locations of dredge hauls. Rocks from SD-8, DS-3, and DS-4 are described in this paper.

alkalic basalts, but their Sm/Nd and  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios are comparable to ocean island values (Carlson et al., 1977, 1978).

The major oxide and trace element abundances of the transitional basalts are intermediate between those of the tholeiites and the alkalic basalts (Table 1 and Figure 2). The  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of the transitional basalts have a range that overlaps the values obtained for the alkalic basalts. The Siqueiros transitional basalts have  $^{143}\text{Nd}/^{144}\text{Nd}$  ratios intermediate between alkalic and tholeiitic values (Carlson et al., 1977, 1978). The chemical composition of the transitional basalts in the Siqueiros area is very similar to that of samples drilled on DSDP Leg 2 in the Atlantic (Frey et al., 1974), indicating that such basalts may not be altogether rare. Similar basalts have also been sampled in the North Atlantic (Wood et al., 1979 and references therein).

#### DISCUSSION

The chemical effects of several individual processes can be identified within the basalt from the Siqueiros

area. These processes include: alteration, fractional crystallization, mantle heterogeneity, dynamic melting, and mixing. Evidence for each of these will be briefly discussed.

#### Alteration

Effects of sea-water alteration on the major oxide chemistry of the Siqueiros basalts have been discussed by Batiza et al. (1977) and Johnson (1979). There is additional evidence that the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of some of the samples has been elevated by sea-water interaction. Even without petrographic evidence of extensive alteration, it has been clearly demonstrated that such interaction can significantly raise the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio of submarine volcanic rocks (DePaolo and Wasserburg, 1977; Dasch et al., 1973; Hart et al., 1974). Figure 3 shows there is good correlation between the  $\text{Fe}^{+3}/\text{Fe}^{+2}$  and  $^{87}\text{Sr}/^{86}\text{Sr}$  ratios of some of the basalt samples from the Siqueiros area, although there is no corresponding extensive visible alteration in the rocks. If only the lowest values of the  $^{87}\text{Sr}/^{86}\text{Sr}$  ratio obtained for each rock

TABLE 1  
Major Oxide and Trace Element and Isotopic Data<sup>a</sup>

Oxide or Element	SD 8-3	DS 3-3	DS <sup>b</sup> 4-1a	DS <sup>b</sup> 4-6	DS <sup>b</sup> 4-14	DS <sup>b</sup> 4-15	SD 8-5	DS 8-6
wt. %								
SiO <sub>2</sub>	50.3	49.1	49.2	48.8	50.1	48.2	47.6	48.2
TiO <sub>2</sub>	0.93	0.91	1.90	1.87	1.90	1.86	2.45	2.52
Al <sub>2</sub> O <sub>3</sub>	15.6	17.6	16.5	16.4	16.5	16.2	16.1	15.2
Fe <sub>2</sub> O <sub>3</sub>	1.27	2.3	2.89	2.89	—	—	2.32	2.31
FeO	7.45	6.1	6.4	6.5	9.32	9.20	7.70	8.56
MnO	0.14	0.16	0.15	0.17	0.16	0.16	0.13	0.17
MgO	9.80	9.74	8.14	8.51	8.38	9.08	6.80	7.15
CaO	12.77	12.45	10.75	10.75	10.83	10.57	9.38	9.69
Na <sub>2</sub> O	2.15	2.5	2.7	3.2	3.1	3.1	3.58	3.79
K <sub>2</sub> O	0.05	0.08	0.60	0.56	0.43	0.38	1.23	0.90
P <sub>2</sub> O <sub>5</sub>	0.09	0.09	0.29	0.28	0.29	0.28	0.12	0.44
H <sub>2</sub> O	—	1.0	1.5	1.4	—	—	—	—
Total	100.55	102.03	99.23	99.64	101.01	99.03	97.41	98.93
ppm								
La	1.59	1.38	9.70	10.13	10.12	9.46	23.54	18.48
Ce	5.41	4.22	25.95	25.19	25.2	24.90	51.15	41.19
Sm	2.07	2.09	4.73	4.95	4.78	4.79	6.77	6.67
Eu	0.80	0.83	1.63	1.51	1.62	1.46	2.12	2.02
Tb	0.57	0.48	0.81	0.85	0.99	0.86	1.21	1.17
Yb	2.23	2.00	3.18	3.37	3.19	3.12	3.12	3.68
Lu	0.37	0.30	0.49	0.49	0.48	0.47	0.43	0.54
Rb	0.40	—	—	—	5.51	6.90	13.54	13.09
Sr	125	99	169	180	199	223	380	342
Zr	—	42	206	229	224	—	344	289
Hf	1.4	1.5	4.0	3.9	4.0	4.0	5.5	5.2
U	0.027	0.014	0.224	0.237	0.224	0.228	0.660	0.359
Co	46	60.2	59.7	48	47.4	70	39.5	43
Cr	478	427	406	307	310	349	157	196
Ni	130	176	143	133	129	142	—	113
Cu	82	72	48	48	60	60	—	44
Zn	80	69	110	93	90	78	80	97
Sc	44.6	29.9	33.1	32.1	33	32.3	25.7	28.8
<sup>87</sup> Sr/ <sup>86</sup> Sr	0.70270	—	—	—	0.70312	0.70287	0.70307	0.70300

<sup>a</sup>Major oxide data are from Batiza et al. (1979), and Johnson (1979), where the determinative procedures and their accuracy are discussed. REE were determined by instrumental neutron activation (Jacobs et al., 1977), as were Hf, Zn, and Sc. Rb was determined by isotope dilution mass spectrometry. Sr, Zr, Co, Cr, and Ni were determined by both INAA and atomic absorption spectrophotometry. Agreement was found to be within 2 per cent of the atomic absorption method (Batiza et al., 1977), and values obtained by both methods were averaged. Cu was determined by AA. U was determined by induced fission track methods. <sup>87</sup>Sr/<sup>86</sup>Sr was determined by mass spectrometry; <sup>87</sup>Sr/<sup>86</sup>Sr values were normalized to an <sup>86</sup>Sr/<sup>88</sup>Sr value of 0.1194, and values are ±0.00006.

<sup>b</sup>From Johnson, 1979.

group are used, then the transitional basalts have <sup>87</sup>Sr/<sup>86</sup>Sr ratios intermediate between the alkalic basalt and the tholeiite values. Samples with lowest <sup>87</sup>Sr/<sup>86</sup>Sr ratios have Fe<sup>+3</sup>/Fe<sup>+2</sup> = ~0.2. Isotopes of Nd are less subject to alteration by sea-water interaction; indeed, Carlson et al. (1977, 1978) have shown that the Siqueiros transitional basalts have <sup>143</sup>Nd/<sup>144</sup>Nd ratios intermediate between alkalic and tholeiitic values.

### Fractional Crystallization

The importance of shallow-level crystal fractionation in the production of Fe- and Ti-rich basalts in the Siqueiros area has been confirmed by the work of Batiza et al. (1977) and is further supported by trace element and isotopic data (Batiza, unpublished data). However, shallow fractional crystallization of a single parental liquid cannot be responsible for the production of tholei-

ites, alkalic basalts, and transitional basalts (Johnson, 1979). First, the isotopic data preclude such an origin for the three basalt types, and secondly no quantitative fractionation models using low-pressure phase assemblages can be made to fit the observed major oxide and trace element abundances in the lavas. The alkalic and transitional basalts cannot be related to either an Mg-rich tholeiitic liquid or fractionated tholeiitic liquid by fractional crystallization unless other processes are invoked to account for discrepancies in the isotopic and chemical data.

### Mantle Heterogeneities

The Sr and Nd isotopic data for alkalic and tholeiitic basalts in the Siqueiros area indicate that the mantle below is isotopically heterogeneous. Also, chemical heterogeneity is indicated by large differences in La/Sm,

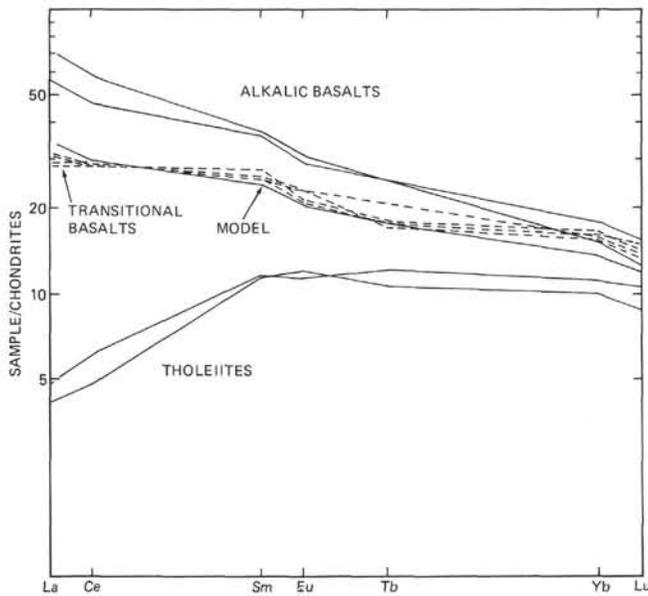


Figure 2. REE abundance patterns of the samples from Table 1 normalized to chondrites (Haskin et al., 1968). Also shown is the pattern resulting from the mixing model described in the text. (Transitional basalt patterns are dashed.) Note similarity between the mixing model and the observed REE abundances of the transitional basalts.

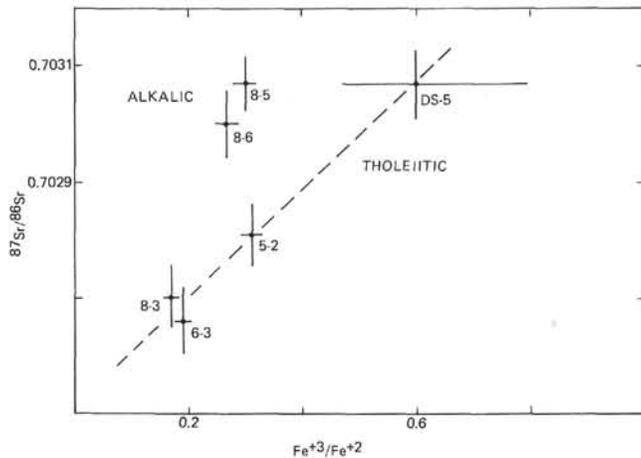


Figure 3. Plot of  $Fe^{+3}/Fe^{+2}$  and  $^{87}Sr/^{86}Sr$  ratios for alkalic and tholeiitic basalts. Most of the tholeiite data are unpublished but are available from the authors.

K/Rb, and Zr/U ratios between alkalic and tholeiitic basalts (Table 1). Smaller differences in such ratios are observed between individual samples within the tholeiitic and alkalic groups (Table 1) and indicate smaller-scale heterogeneity in the sources of both tholeiites and alkalic basalts (Church and Tatsumoto, 1975; Langmuir et al., 1977).

### Dynamic Melting

Evidence for "dynamic melting" (Langmuir et al., 1977) in the upper mantle in the Siqueiros area comes from the crossing chondrite-normalized REE patterns of the alkalic basalts (Figure 2). Langmuir et al. (1977) have shown that such patterns cannot result simply from one-step mantle or crustal processes. Instead, they propose that simultaneous action of several simple processes produces a wide range of trace-element abundance patterns from a single mantle source. Thus, assuming that a single source was melted to produce the alkalic basalts from the Siqueiros area, it is necessary to adduce a process such as dynamic melting for the variable LREE and HREE abundances in samples SD 8-5 and SD 8-6. Other mechanisms, such as batch processing, could produce similar patterns (O'Hara, 1977). The isotopic differences between these two samples are not significant (Table 1 and Figure 3).

### Mixing

Figure 4 and Table 2 provide strong evidence that the transitional basalts originated by mixing, whose effects are most clearly seen in the transitional basalts. Johnson (1979) proposed that mixing of little-fractionated tholeiitic and alkalic basalt could produce the transitional basalts of the Siqueiros area. Mixing did *not* occur between strongly fractionated East Pacific Rise ferrobasalt and alkali basalts. Furthermore, it is possible to place quantitative constraints on the composition of the mixing end members using the graphical methods outlined by Langmuir et al. (1978). Not only does Figure 4 show that mixing occurred, but also that probably true magma mixing occurred rather than mixing of sources prior to melting. This hypothesis was put to a quantitative test for all oxides and trace elements (see Table 2), the results showing remarkably good agreement with observed major oxide and trace element abundances and isotope ratios, in the transitional basalts.

Averages of little-fractionated tholeiitic basalts, alkalic basalts, and transitional basalts were employed in this test in hopes of eliminating the chemical effects of other processes discussed previously. This averaging has little influence on the validity of the test, since individual samples within each group do not vary greatly in their chemistry. In addition to the elements used in Figure 4, many other element and isotope ratio-ratio and element-ratio pairs are consistent with the mixing hypothesis. The results of these graphic methods indicate that the end-member compositions are very close to those of the averaged alkalic and tholeiitic basalts of Table 2. The large geographic distances between dredges SD-8, DS-3, and DS-4, however, preclude mixing of these particular samples. The modeling, though, provides strong evidence that hybridization of alkalic and tholeiitic basalts did actually occur. Further, the close chemical similarity between the various transitional basalt samples, as well as the small inferred volumes of

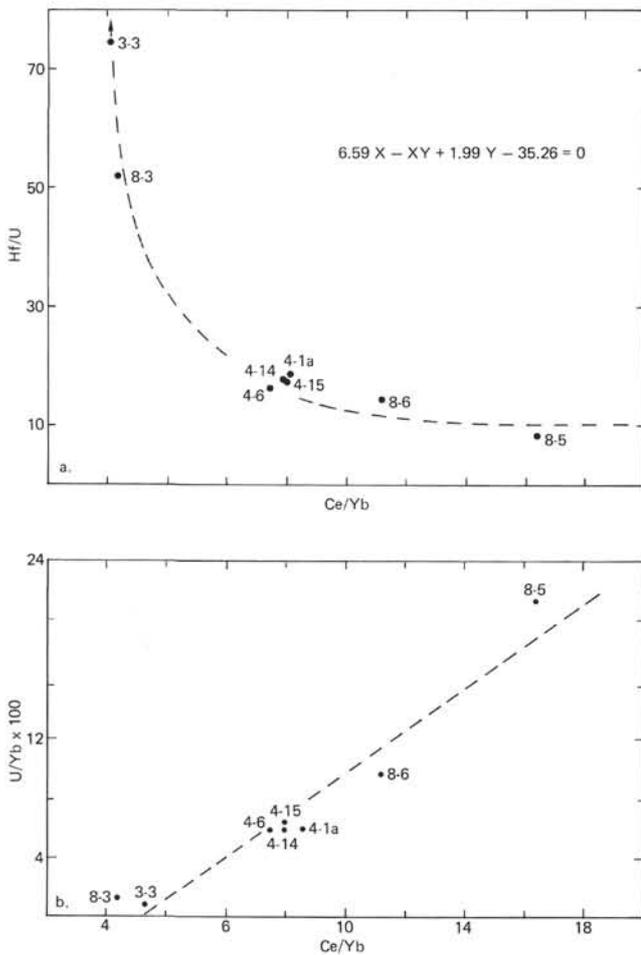


Figure 4. Plots of  $Hf/U$  versus  $Ce/Yb$  (a) and  $U/Yb$  versus  $Ce/Yb$  (b) for the basalts of this study. As shown by Langmuir et al. (1978), such data arrays can be used to interpret the role of mixing in magmatic processes. The linearity of the  $U/Yb$  -  $Ce/Yb$  data array (b) (which is the "companion plot" of the  $Hf/U$  versus  $Ce/Yb$  plot [a]) indicates that magma mixing rather than source mixing prior to melting occurred in these samples. Note also that samples SD 8-5 and DS 3-3 are very close to the asymptotes of the hyperbolic mixing curve, and are thus close to the actual mixing end members.

such rocks (Johnson, 1979), suggests that the dredging has sampled the products of only one mixing event. Since the model shows some significant discrepancies (e.g., Zr; Table 2), it is improbable that the actual mixing end members have been recovered and analyzed. The general good fit of the model, however, suggests that the analyzed samples are very similar to actual liquids involved.

### Implications

If the mixing hypothesis for the origin of the transitional basalts in the Siqueiros is correct, then it holds several implications for magmatic processes at the EPR and perhaps other oceanic ridges and also for the size of

TABLE 2  
Mixing Model Data<sup>a</sup>

Oxide or Element	Average Tholeiite	Average Alkali Basalt	Average Transitional Basalt	50:50 Mixing Model	R <sup>2</sup>
SiO <sub>2</sub>	49.7	47.9	49.1	48.8	0.090
TiO <sub>2</sub>	0.92	2.49	1.89	1.71	0.032
Al <sub>2</sub> O <sub>3</sub>	16.6	15.6	16.4	16.1	0.090
FeO*	8.39	10.21	9.16	9.30	0.020
MnO	0.15	0.15	0.16	0.15	0.001
MgO	9.77	6.98	8.53	8.38	0.023
CaO	12.62	9.54	10.73	11.08	0.123
Na <sub>2</sub> O	2.33	3.69	3.03	3.01	0.002
K <sub>2</sub> O	0.07	1.07	0.49	0.54	0.002
P <sub>2</sub> O <sub>5</sub>	0.09	0.28	0.28	0.19	0.008
Total	100.64	97.77	99.77	99.26	0.39
					% Difference
La	1.48	21.01	9.85	11.25	12
Ce	6.07	46.17	25.68	26.12	2
Sm	2.08	6.72	4.81	4.40	-9
Eu	0.81	2.07	1.55	1.43	-8
Tb	0.52	1.19	0.87	0.85	-2
Yb	2.11	3.40	3.21	2.76	-14
Lu	0.34	0.49	0.48	0.41	-15
Rb	0.40	13.32	6.21	6.86	9
Sr	110	354	208	232	10
Zr	42	316	219	176	-18
Hf	1.4	5.3	4.0	3.35	-16
U	0.020	0.509	0.228	0.264	14
V	210	297	266	253	-5
Co	53	41	55	47	-15
Cr	441	183	319	312	-2
Ni	152	113	135	132	-2
Cu	77	44	54	60	10
Zn	74	88.5	92	81.5	-11
Sc	37.3	27.2	32.5	32.2	-1
<sup>87</sup> Sr/ <sup>86</sup> Sr	0.70270	0.70303	0.70287	0.70295	

<sup>a</sup>The tholeiite column is an average of analyses DS 3-3 and SD 8-3. The alkalic basalt column is an average of SD 8-5 and SD 8-6. The transitional basalt column is an average of the four transitional basalts from Table 1. The 50:50 mixing model column represents a mix of equal weights of tholeiitic and alkalic basalt. These proportions were determined by obtaining the mean of the individual proportions required for fitting each element. Iterative computer methods yield essentially the same result. Note the excellent agreement between observed and calculated chemical and isotopic composition of the transitional (hybrid) basalts. Residuals for the major oxides are given in the last column (R<sup>2</sup>); the sum of R<sup>2</sup> = 0.39. Also given are the percentage differences for each trace element. The lava compositions were averaged in order to minimize the effects of differences in degree of partial melting, small-scale mantle heterogeneity, and crystal fractionation. Complications arising from these processes are discussed in the text.

mantle heterogeneities in the sub-oceanic mantle. The transitional basalts from Siqueiros occur on oceanic crust dated with sea-floor magnetic anomalies to be 1.6 m.y. old (Johnson, 1979), but they could be much younger. The alkalic basalts occur on crust <0.5 m.y. old (Batiza et al., 1977). This indicates that production of alkalic basalts, their eruption, and mixing with tholeiitic basalt liquids occur very close to the ridge crest. The low Sr and high HREE abundances in these alkalic basalts compared with other oceanic alkali basalts suggest that plagioclase rather than garnet is the dominant Al-rich phase in the zone of melt production. If so, the depth of production of these melts is  $\leq 9-10$  Kbar (Yoder, 1976, p. 27). This implies that isotopic and chemical heterogeneities of relatively great magnitude are present in the upper mantle very close to the zone of production of mid-ocean ridge tholeiite. The exact nature, size, geometric arrangement, and cause of these heterogeneous mantle sources are subjects of considerable debate (Tatsumoto, 1978). The results of this

study indicate that many of these heterogeneous domains may be small, as shown by the low volumes of melt produced, and that these small-size heterogeneities are spatially and temporally closely related to the source of normal ridge crest tholeiitic volcanism.

### CONCLUSIONS

The major conclusions of this study are:

1) Isotopic and chemical heterogeneities of variable magnitude occur very close to the EPR in the vicinity of the Siqueiros transform fault.

2) The effects of such heterogeneity are clearly evident in the chemistry of the basalts, as are the effects of fractional crystallization, sea-water alteration, and complex melting phenomena.

3) The origin of the transitional basalts of the Siqueiros area is almost certainly due to mixing of tholeiitic and alkalic basalt; the transitional basalts are hybrid liquids.

### ACKNOWLEDGMENTS

We thank J. D. Macdougall for providing the fission track U data and R. Carlson for supplying a preprint. We are especially indebted to C. Hedge and K. Futa of the USGS Isotope Geology Branch and to L. Haskin, J. Jacobs, W. Day, M. Lindstrom, and D. Lindstrom for their generosity in allowing use of their facilities and providing assistance in collecting the mass spectrometric and INAA data, respectively. The work was supported by the McDonnell Center for Space Sciences, St. Louis, Missouri, and NSF Grant OCE 77-27001 to R. B. An earlier draft of this paper was improved by the review comments of W. B. Bryan and J. H. Natland.

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