ABSTRACT

Trace element abundances and $^{87}$Sr/$^{86}$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 $^{87}$Sr/$^{86}$Sr = 0.70270. The alkalic basalts are LIL-enriched, and fresh samples have $^{87}$Sr/$^{86}$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 $^{87}$Sr/$^{86}$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 from 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 $^{87}$Sr/$^{86}$Sr = 0.7027. The Sm/Nd and $^{143}$Nd/$^{144}$Nd of these samples (Carlson et al., 1977, 1978) is also within the range of mid-ocean ridge basalt, 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 $^{87}$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
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
group are used, then the transitional basalts have $^{87}$Sr/$^{86}$Sr ratios intermediate between the alkalic basalt and the tholeiite values. Samples with lowest $^{87}$Sr/$^{86}$Sr ratios have Fe$^{3+}$/Fe$^{2+}$ = ~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 $^{143}$Nd/$^{144}$Nd ratios intermediate between alkalic and tholeiite 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 tholeiites, 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 $\text{Fe}^{+3}/\text{Fe}^{+2}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ 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 tholeites 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
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 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 alkaline basalts occur on crust <0.5 m.y. old (Batiza et al., 1977). This indicates that production of alkaline 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 ~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 basaltas, 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.

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