Chemistry of seamounts near the East Pacific Rise: Implications for the geometry of subaxial mantle flow

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ABSTRACT

The volcanically active axes of mid-ocean ridges are very narrow (<1 km), so existing theoretical models to explain magma supply to active mid-ocean ridges feature either a narrow zone of mantle upwelling beneath the axis or a broader zone of upwelling, with an additional process needed to focus melt migration narrowly at the axis. Seamounts near active mid-ocean ridges also represent zero-age active volcanism in the plate-boundary zone. Their distribution and lava chemistry tend to favor a broad axial zone of upwelling. Furthermore, average near–East Pacific Rise seamount lavas apparently result from shallower mantle melting than the East Pacific Rise axis lavas. This suggests that mantle upwelling beneath the axis is not perfectly adiabatic. Instead, the broad mantle upwelling is cooler at the edges than in the center.

INTRODUCTION

The geometry of mantle flow and melt migration beneath active mid-ocean ridges is currently unknown, but it is of fundamental importance to understanding the generation of ocean crust and oceanic lithosphere. The very narrow (<1 km) width of the axial volcanic zone at ridges provides information on mantle flow patterns and melt migration paths. Furthermore, seismic evidence suggests that the ocean crust achieves its full thickness (5–7 km) within a few kilometres of the axis (Detrick et al., 1987), indicating that off-axis additions to the crust are generally small. Two general explanations for the narrowness of the crustal accretion zone have been proposed. (1) The mantle upwelling zone is broad, as suggested by models for passive mantle upwelling in response to plate separation, but the melt produced during upwelling migrates toward the axis (Spiegelman and McKenzie, 1987; Phipps-Morgan, 1987; Sleep, 1988; Ribe, 1988). These models suggest that flow of melt converges toward the axis, whereas mantle flow lines of the solid residue diverge outward and away from the axis. (2) The mantle upwelling zone is narrow, an explanation that circumvents the difficulty of focusing melt flow. There are also self-consistent models that feature a narrow upwelling zone (Bottinga and Allègre, 1978; Scott and Stevenson, 1989; Buck and Su, 1989; Sotin and Parmentier, 1989; Rabinowicz et al., 1987).

The existence of active volcanoes near the axes of mid-ocean ridges (Batiza and Vanko, 1984; Batiza et al., 1989a) places additional limits on the processes of mantle flow and melt migration because, like the neovolcanic ridge axis, these seamounts represent zero-age volcanism in a broad (~100 km) zone near the axis. The value of near-axis seamounts has been recognized (e.g., Sleep, 1984; Richter and Daly, 1989), particularly because the petrologic and isotopic contrasts between axial and near-axis seamount lavas can provide additional information on melting and melt-segregation processes (Allan et al., 1987, 1989).

In this paper we present new data on the chemistry and distribution of seamount chains near the axis of the East Pacific Rise. These data were obtained on a cruise of the R/V *Thomas Washington* in 1988 (RAIT 02), near the rise, during which we surveyed (with Seabeam) and sampled 55 seamounts between lat 5° and 15°N that were previously unsampled. Data show that whereas there are scattered individual seamounts near the East Pacific Rise, most volcanoes belong to linear seamount chains. On both the Cocos and Pacific plates, these chains trend parallel to either relative plate motion or absolute plate motion. Chemical analyses show that systematic differences in lava chemistry are found between the rise axis and the seamount chains. East Pacific Rise axis lavas are systematically more evolved (lower temperature) than seamount lavas. This is probably the result of cooling in subaxial magma chambers. New data show that once these effects are removed, the East Pacific Rise axis lavas result from deeper

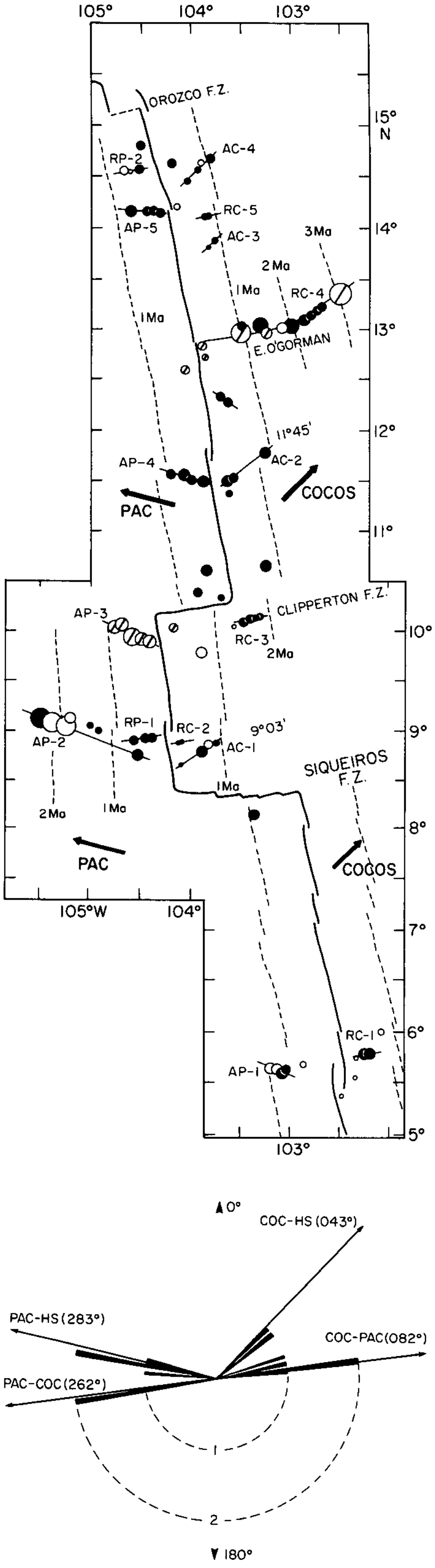

Figure 1. East Pacific Rise axis (heavy line) and vicinity showing seamounts present (circles). Sizes of circles are proportional to seamount sizes. Inferred seamount chains are shown as lines and are labeled as in Table 1. Solid black circles are newly sampled seamounts; circles with diagonal line are previously sampled seamounts; white circles are unsampled seamounts. Dashed lines are crustal isochrons; large arrows show absolute motion of Pacific (PAC) (283°) and Cocos (COC) (043°) plates. Relative plate motion is normal to East Pacific Rise (Cocos ~083°; Pacific ~263°). F.Z. = fracture zone. Rose diagram shows that most chains are parallel to relative or absolute plate motion. Sources of data for location of East Pacific Rise axis and seamounts are Macdonald et al. (1984, 1988); Lonsdale (1985a, 1985b); Madsen et al. (1988); Fornari et al. (1984, 1987a, 1987b, 1988); J. Mclain (1988, personal commun.); and new data from RAIT 02.

initial melting and larger extents of melting than seamount lavas. These new results tend to favor a broad zone of mantle upwelling beneath the axis and provide additional information on melting and melt segregation-extraction processes.

RESULTS

Figure 1 shows the locations of seamounts near the East Pacific Rise. Most are members of linear seamount chains that trend parallel to the relative or absolute plate motion of the Pacific and Cocos plates. Most of the chains can be identified with confidence because they consist of numerous volcanoes. A few consist of only two volcanoes or else have gaps with no volcanoes; that these compose chains is debatable, and thus we identify them only tentatively. The trends of the chains (Table 1) were estimated from best-fit lines through the seamounts. Measurement error is only ±2°; however, the total uncertainty in trends is larger, because most chains are not perfectly colinear. Nevertheless, the trends of the chains are very close to Pacific and Cocos relative and absolute motions (mean deviation is only 3.6°). On the Pacific plate, the absolute and relative plate motions differ by 16°; however, on the Cocos plate, the difference is 40° and the chains clearly cluster near the trends of relative and absolute plate motion (Fig. 1, Table 1). If we assume that the identification of the chains in this area (lat 5°–15°N) is valid, the Pacific plate has five chains parallel to absolute plate motion (absolute), and two chains parallel to relative plate motion (relative), whereas the Cocos plate has four absolute and five relative chains. The average spacing of absolute-motion parallel chains is thus ~250 km on each plate. Chains near the East Pacific Rise that have trends significantly different from directions of either relative or absolute plate motion are well documented (e.g., lat 21°N; Allan et al., 1987); however, within the lat 5°–15°N area, there are no such oblique chains.

Table 2 presents a summary of selected chemical data for each chain and contains new data for 253 samples from 52 dredges of 42 volcanoes. Some chains such as the East O'Gorman (Batiza and Vanko, 1984; Batiza et al., 1989b) and the Lamont chain (Fornari et al., 1988; Allan et al., 1989) were previously well studied. These are type examples of relative- and absolute-plate-motion parallel chains and are included in our compilation. Data for the East Pacific Rise in Table 2 include data from CHEPR (Langmuir et al., 1986; Joint Oceanographic Institutions, 1989) and RAIT 02. In Table 2 we have tabulated Mg# (Mg/Mg+Fe^{2+}), $Fe_{8.0}$, $Na_{8.0}$, and K_2O/TiO_2 because they are useful indicators of, respectively, eruption temperature (e.g., Nielsen, 1988), depth of melting, extent of melting (Klein and Langmuir, 1987), and mantle source characteristics (enriched vs. depleted).

The K_2O/TiO_2 ratios of East Pacific Rise axial basalts, and basalts from seamount chains parallel to relative and absolute plate motion are not significantly different; therefore, the mantle sources of axial and seamount lavas are probably not systematically different. This is supported by isotopic data (Zindler et al., 1984; Graham et al., 1988; Fornari et al., 1988) which, taken together, show no *systematic* differences between the mantle sources of the rise axial basalts and seamount lavas. While the mantle sources of axial and near-axis seamount samples are similar, there are systematic chemical differences between seamount and axial lavas. Figure 2 shows percent-frequency histograms for the

TABLE 1. SMALL SEAMOUNT CHAINS NEAR THE EAST PACIFIC RISE

Latitude (~°N)	Designation*	Trend (°)	Name	Number of seamounts
5°30′	RC-1	082	None	3
9°	RC-2	078	None	2
9°	RP-1	260	None	3
10°	RC-3	082	Watch stander/ late night seamounts	4
13°	RC-4	083 to 055 (small circle)	East O'Gorman	12
14°	RC-5	072	None	2
14°30′	RP-2	260	None	3
5°30′	AP-1	281	None	4
9°	AC-1	052	None	4
9°	AP-2	281	OCP ridge	8
10°	AP-3	282, 294	Lamont seamounts	3, 5
11°30′	AP-4	280	Cerveza seamounts	4
11°30′N	AC-2	050	Gaucho-Moana Wave	3
14°	AC-3	046	None	2
14°30′	AP-5	274	None	4
14°30′	AC-4	045	None	4

* R = relative, A = absolute, C = Cocos plate, P = Pacific plate. Seamounts trend parallel to relative (Cocos, 083°; Pacific, 263°) or absolute (Cocos, 043°; Pacific, 283°) plate motions.

TABLE 2. CHEMICAL DATA FOR EAST PACIFIC RISE SEAMOUNT CHAINS

Chain	No. of dredges	No. of analyses	Mg/Mg+Fe^{2+} (wt%)	$Fe_{8.0}$ (wt%)	$Na_{8.0}$ (wt%)	K_2O/TiO_2
RC-1	2	13	66.2 ±4.3	9.72 ±0.70	2.55 ±0.07	0.05 ±0.04
RC-2	2	10	62.1 ±0.8	9.21 ±0.22	2.32 ±0.10	0.07 ±0.01
RP-1	3	14	60.4 ±5.9	7.90 ±1.02	2.53 ±0.07	0.23 ±0.13
RC-3	3	11	69.1 ±3.1	10.39 ±0.88	2.78 ±0.13	0.06 ±0.02
RC-4	14*	196	62.5 ±3.8	7.91 ±1.70	2.72 ±0.30	0.15 ±0.15
RC-5	2	29	63.7 ±2.2	9.04 ±0.28	2.67 ±0.14	0.06 ±0.01
RP-2	1	2	58.8 ±0.35	8.98 ±0.09	2.21 ±0.03	0.06 ±0.00
Total RP	4	16	60.2 ±5.5	8.03 ±1.02	2.49 ±0.12	0.20 ±0.13
Total RC	--	259	62.9 ±5.4	8.25 ±1.82	2.68 ±0.33	0.13 ±0.18
Total R	NA	275	62.7	8.23	2.66	NA
AP-1	2	7	59.3 ±6.0	8.37 ±0.99	2.58 ±0.05	0.14 ±0.07
AC-1	3	24	65.6 ±2.7	9.47 ±0.43	2.57 ±0.15	0.08 ±0.03
AP-2	5	22	65.3 ±4.1	8.04 ±1.40	2.91 ±0.20	0.30 ±0.20
AP-3	8†	122	65.6 ±3.0	9.56 ±0.56	2.77 ±0.27	0.04 ±0.02
AP-4	7	22	64.0 ±1.4	8.44 ±0.64	2.83 ±0.16	0.14 ±0.11
AC-2	3	14	66.4 ±1.3	9.50 ±1.25	2.56 ±0.21	0.14 ±0.22
AC-3	2	20	62.6 ±1.8	7.86 ±0.41	2.78 ±0.16	0.08 ±0.07
AP-5	5	35	61.7 ±5.8	7.84 ±1.02	2.69 ±0.18	0.21 ±0.10
AC-4	2	16	62.9 ±3.6	8.91 ±1.18	3.15 ±0.30	0.07 ±0.04
Total AP	NA	208	64.5 ±4.1	8.95 ±1.08	2.77 ±0.24	0.11 ±0.12
Total AC	NA	74	64.4 ±3.0	8.91 ±1.06	2.75 ±0.30	0.09 ±0.10
Total A	NA	282	64.5	8.93	2.76	NA
EPR (5°-15°N)	NA	850	59.0 ±5.4	9.75 ±0.57	2.59 ±0.20	0.10 ±0.10

Note: EPR is East Pacific Rise.
*Plus 17 ALVIN dives; includes seamount 6. NA = not applicable.
†Plus 14 ALVIN dives.

East Pacific Rise and seamounts (both relative and absolute chains). Seamounts have higher Mg# than rise axial basalts (Batiza and Vanko, 1984), probably due to cooling of axial magmas in shallow subaxial chambers (Detrick et al., 1987).

Figure 2 also shows that seamount lavas have lower $Fe_{8.0}$ and higher $Na_{8.0}$ than do East Pacific Rise axial lavas. The systematic differences between lavas of absolute chains and the East Pacific Rise shown in Figure 2 are significant at better than 99% confidence on the basis of several statistical tests, whereas differences between absolute and relative chains are less significant. All but a few samples in our data set are normal mid-ocean ridge basalt (MORB) type. Fewer than 20 seamount samples are alkalic basalts and alkalic differentiates (Batiza and Vanko, 1984; Graham et al., 1988), but omitting them from the data set has no effect on the patterns in Table 2 and Figure 2.

INTERPRETATION AND DISCUSSION

Some important points bear on the characteristics of our data set. First, there are large differences in the number of samples per volcano. Some volcanoes, such as those of the East O'Gorman chain and the Lamont chain, are very well sampled (30–40 analyses per seamount), whereas others have only one analysis. Second, Batiza et al. (1989b) showed that single volcanoes may exhibit systematic changes in lava chemistry with elevation, but it is not known how common this is. These two effects limit our ability to confidently interpret intrachain and interchain chemical differences. Third, we lack quantitative age determinations, because almost all the samples of this study are normal MORB, which currently are difficult to date by any technique. Sample freshness, sediment cover, and other qualitative age indicators show that most seamounts on sea floor <1 Ma have probably been recently active. In addition, samples from seamounts of relative chains located on older crust (2–3 Ma) appear to be fresh (Batiza et al., 1989b), whereas those on old parts of absolute chains are weathered and thickly covered with manganese. This suggests that relative chains may remain volcanically active for longer periods than absolute chains.

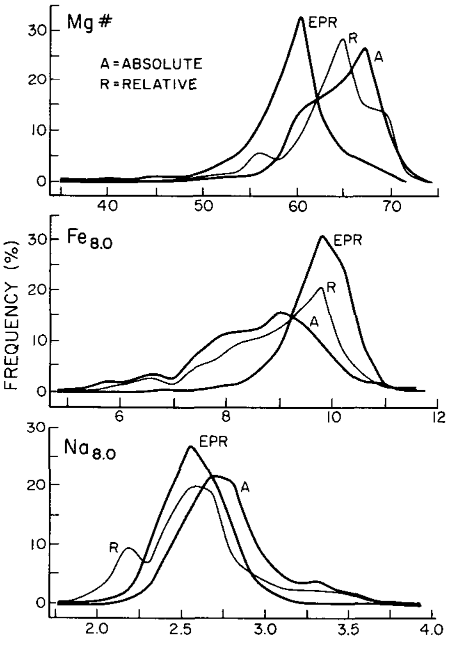

Figure 2. Frequency percent histograms for Mg#, $Fe_{8.0}$, and $Na_{8.0}$ for East Pacific Rise and relative and absolute motion parallel seamount chains. Data are from Table 2 and were binned by intervals of 2.25 for Mg#, 0.4 for $Fe_{8.0}$, and 0.125 for $Na_{8.0}$ for plotting histograms. There is significant difference in Mg#, $Fe_{8.0}$, and $Na_{8.0}$ between East Pacific Rise and seamount chains.

Despite these caveats, there are several first-order chemical systematics shown in Table 2 and Figure 2. The systematic difference in Mg# between East Pacific Rise axial lavas and seamount lavas (Fig. 2) was recognized by Batiza and Vanko (1984). This difference suggests that seamount lavas rise from their mantle source region with less heat loss and fractionation than East Pacific Rise axial lavas. This is consistent with the notion that axial magmas commonly pass through and evolve within axial magma chambers (Detrick et al., 1987). Seamount lavas also are more diverse chemically than rise axial lavas (e.g., Allan et al., 1987, 1989). This is illustrated by comparing the K_2O/TiO_2 data (mean and standard deviation) for the East Pacific Rise with both absolute and relative seamount chains (Table 2). This comparison indicates that seamounts tap the same (heterogeneous) mantle material as the East Pacific Rise, but that seamount lavas are less commonly mixed and homogenized than East Pacific Rise axial lavas. This conclusion is well documented (Batiza and Vanko, 1984; Zindler et al., 1984; Allan et al., 1987, 1989; Fornari et al., 1988; Graham et al., 1988) and is consistent with crustal mixing of axial magmas in shallow chambers.

An interesting result of this study (Table 2) is that, despite the diversity of seamount lavas, there is no significant difference in the K_2O/TiO_2 of East Pacific Rise and seamount lavas. This indicates that seamount and axial magmas are derived from the same mantle source. This is not surprising, given the geographic proximity of seamounts to the East Pacific Rise axis. The chemical diversity of seamount lavas is also illustrated by the $Na_{8.0}$ and $Fe_{8.0}$ data. Klein and Langmuir (1987) showed that $Na_{8.0}$ and $Fe_{8.0}$ contents (the Na_2O and FeO contents back-tracked along liquid line of descent to MgO = 8.0 wt%) are good indicators of, respectively, the extent of partial melting and initial melting depth. If this is true, Table 2 shows that seamount lavas vary in initial depth and extent of partial melting.

The chemical diversity of seamount lavas vs. East Pacific Rise axial lavas, like the systematic differences in Mg#, can be explained by cooling, mixing, and homogenization of rise axial lavas in subaxial chambers. However, shallow processes probably cannot produce large differences in $Fe_{8.0}$ and $Na_{8.0}$. Using the single-column melting model of Klein and Langmuir (1987), these differences can be interpreted as being due to differences in the initial depth of melting (which is related to mantle temperature; e.g., McKenzie, 1984) and the total extent of melting. East Pacific Rise lavas would be produced by deeper initial melting and higher extents of melting than seamount lavas.

This pattern is consistent with the East Pacific Rise axial melts being produced from hotter mantle than near-axis seamounts (Fig. 3). Thus, our new data support a pattern of mantle upwelling in which the axial magmas are produced from the hotter center of the upwelling. In contrast, seamounts are produced by shallower initial melting and less total melting of the cooler edges of the upwelling (Fig. 3). This pattern of mantle temperature and melting would be expected if the upwelling does not rise perfectly adiabatically but instead loses some heat to the cooler surrounding asthenosphere. The chemical diversity of seamount melts produced at the edges of the upwelling suggests that they probably segregate into veins and dikes (Sleep, 1988; Stevenson, 1989) and erupt in small batches.

Whereas this model favors a broad subaxial upwelling zone, an alternative possibility is that the upwelling zone is narrow. Under such conditions, especially with a two-dimensional rolling-mill circulation as in the models of Rabinowicz et al. (1987) and Scott and Stevenson (1989), it is more difficult to imagine how off-axis seamount melts could be generated. It is possible that residual porosity in the mantle, from inefficient melt extraction exactly at the axis, could supply melts to seamounts, but it is difficult to

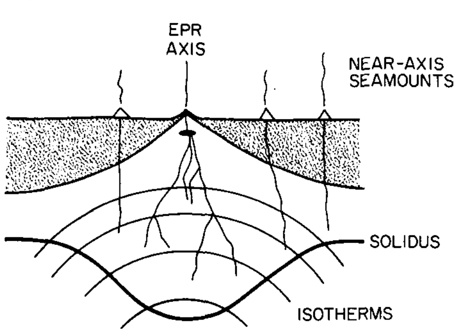

Figure 3. Observed distributions of seamounts near East Pacific Rise (EPR) together with observed differences in $Fe_{8.0}$ and $Na_{8.0}$ can be interpreted in terms of across-axis differences in temperature of upwelling mantle (thin solid lines). Initial melting to produce axial lavas occurs deeper (Klein and Langmuir, 1987) than melting to produce seamount lavas from cooler edges of upwelling. Axial lavas also result from greater extents of melting than seamount lavas.

explain the systematic differences in $Fe_{8.0}$ and $Na_{8.0}$ between axial and seamount melts. Furthermore, a rolling-mill circulation near the axis might be expected to result in a wide zone of *no* off-axis eruptions above the downwelling limb of the circulation. There is no evidence for such a zone, although it is possible that some of the gaps in the chains near the axis could be the result of such a process. Overall, however, for the very reason that they are an appealing explanation for a narrow axial eruption zone, narrow-upwelling models have difficulty producing near-axis seamounts. The presence of near-axis seamounts as well as the systematic chemical difference between seamount and axial lavas thus favors a broad zone of upwelling beneath the East Pacific Rise.

CONCLUSIONS

1. Most seamounts near the East Pacific Rise are members of seamount chains that parallel absolute and relative plate motions.
2. Seamount lavas are more primitive than East Pacific Rise axial lavas, reflecting differences in low-pressure cooling and fractionation histories. Seamount lavas are also more diverse, consistent with less homogenization, than East Pacific Rise axial melts. Despite these differences, however, the vast majority of seamount samples are depleted normal MORB, otherwise similar to axial normal MORB. Seamounts tap the same (heterogeneous) mantle material as the axis.
3. Seamount lavas have systematically lower $Fe_{8.0}$ and higher $Na_{8.0}$ than East Pacific Rise axial lavas. This is best explained by across-axis temperature differences between the center and edges of a broad zone of upwelling mantle.
4. Results tend to favor a broad zone of mantle upwelling (>100 km) beneath the East Pacific Rise.

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