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Composition of Basaltic Glasses Dredged from Seven Seamounts Offshore Southern California on R/V *Farnella* Cruise F7-87-SC

by

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INTRODUCTION

Basaltic rock, hyaloclastite, and volcaniclastic breccia were dredged from seven seamounts offshore southern California during the U.S. Geological Survey cruise F7-87-SC of the R/V *Farnella* (Table 1, Fig. 1). Many of the pillow and sheet flow fragments recovered have fresh glassy rinds. The hyaloclastite and breccia samples also commonly contain fresh glass fragments.

This report presents major and minor element contents of 47 glasses from these seamounts and compares them to basalt compositions from seamounts near the East Pacific Rise (EPR) and from the northeast Pacific.

GEOLOGIC SETTING

Volcanic seamounts are abundant offshore southern California. Many of these volcanic edifices are small, circular in plan view, and appear morphologically similar to small volcanic cones formed near the flanks of the EPR (Lonsdale and Batiza, 1980; Batiza and Vanko, 1984; Batiza and others, 1984). Other volcanic edifices offshore California are large, elongate, composite volcanoes. Typically the elongation is in a NE-SW direction, which is the orientation of tensional fractures produced by right-lateral shearing along the continental margin (Lonsdale, 1989). All of the seamounts mapped on the continental slope off southern California have this NE-SW elongation (Lonsdale, 1989). Of the seven edifices sampled during cruise F7-87-SC, Rodriguez guyot and San Marcos seamount have this orientation (Fig. 1). Rodriguez is a small, elliptical guyot, located on the lower continental slope. San Marcos is a much larger edifice southwest of San Juan seamount, an even larger edifice located at the base of the Patton Escarpment (Fig. 1). Hoss, Adam, Ben, and Little Joe seamounts are small, round to elliptical seamounts comprising the Bonanza seamount group. Unlike many age-progressive, linear island chains in the central Pacific Ocean, the Bonanza seamounts do not lie along a simple linear trend. The seventh edifice studied, Flint seamount, lies NW of Jasper and Opal seamounts, but, similar to the Bonanza seamounts, these edifices form no simple linear chain. Instead, Flint, Opal, and some unnamed seamounts are arranged in a semi-circle around Jasper seamount, the largest of the edifices. (Fig. 1)

METHODS

Fragments of glass were selected from samples of each dredge for major and minor element analyses by electron microprobe. The glass fragments were washed in distilled water, mounted in epoxy resin and polished. All glass samples were analyzed with an ARL - SEMQ microprobe with an accelerating voltage of 15 kv and a sample current of 10 nAmps and count times of 50 seconds for each spot. Six spots were averaged for each individual glass chip. Natural basalt glasses VG-2 and A-99 and andesitic glass GSC were used as standards. Standards were run at the beginning and interspersed throughout the analyses. Precision and accuracy of major elements are better than ±2%, and are usually good to ±1% for all major elements except Na and Si. For K, P, and S, accuracy and precision are probably not better than ±5%. All microprobe data were reduced using a modified version of the Bence-Albee method (Bence and Albee, 1968).

GLASS COMPOSITIONS

Compositions of 47 basaltic glasses are shown in Table 2 and selected oxide variation diagrams are shown in figures 2 to 5. If all elements are within analytical precision, the Glasses recovered from the same site have been grouped into flow units. Compositional variations between some flow units (e.g. D17) are small and may actually represent variations caused by crystal fractionation within larger flows.

Compositions are classified as tholeiitic or alkalic based on the alkali versus SiO_2 plot (Fig. 2), using the boundary established by Macdonald and Katsura (1964) for volcanic rocks from Hawaii. Normative mineralogy and Mg-number (atomic 100Mg/(Mg+Fe^{2+}) were calculated assuming Fe^{2+}= 0.9 FeO total. For the MORB-like compositions such a ferric to ferrous iron ratio is probably appropriate (Christie and others, 1986). However, the alkalic compositions are undoubtedly less reduced. Since total iron is highly variable for alkalic samples at a comparable degree of fractionation (Fig. 3c), the Fe^{3+}/Fe^{2+} ratio may also be variable. An increase in ferric iron would reduce the amount of normative nepheline (Ne) and correspondingly increase normative hypersthene (Hy). All of the samples that plot in the tholeiitic field on the alkali versus SiO_2 plot (Fig. 2) are HY normative. Strongly alkalic compositions have more than 5% normative Ne. However, mildly alkalic compositions on this plot may be either Hy or Ne normative.

Rodriguez Guyot

Four of the five glass analyses from Rodriguez guyot are of centimeter-size or smaller glass chips from volcanic breccias. The remaining sample (D3-20) is the glassy rind of a vesicular pillow wedge. The breccias consist of angular to sub-rounded glass and lithic fragments in a brown, poorly consolidated, sandy matrix, that shows no bedding. All five compositions are similar and appear to represent the same flow unit. Samples from another dredge (D4), that did not recover fresh glass, are petrographically distinct with variable vesicle and plagioclase phenocryst contents, indicating that multiple lithologies are present on the edifice. The glass compositions are differentiated (Mg#s 57-58), strongly alkalic basalt (Ne 6-7%). Sulfur content is low (600-700 ppm), indicating that samples are partially degassed.

San Marcos Seamount

Of the thirteen glass analyses from San Marcos seamount, six are glass shards from volcaniclastic breccia samples that are morphologically similar to those from Rodriguez. Six glasses are rinds on pillow or sheetflow fragments of moderately vesicular basalt. One glass chip (D5-3d) is from a peperite, consisting of black, angular glass fragments in a white, calcareous matrix. The elongated, curved glass shards in the peperite show a pronounced flow alignment. Glass compositions indicate that three flow units were sampled. Flow unit 1, represented by the peperite and by the rind of one big pillow, was recovered only in the deep-water dredge 5. The other two flow units were sampled by both dredges 5 and 6. The two flow units sampled by both dredges are moderately to strongly alkalic basalt (Ne 4-6%), but the flow unit recovered from deeper water (>300 m) is only mildly alkalic (Hy ~1%). Sulfur contents (800-1300 ppm) are higher than in Rodriguez samples, with the mildly alkalic lava twice as high, indicating that it is undegassed. Dredge depth is also nearly twice that of Rodriguez samples (Table 1). All three flow units are moderately fractionated with MgO contents of about 5 to 6.5%. The only significant difference between flow units 2 and 3 is in Al_2O_3 and CaO contents, suggesting different amounts of plagioclase fractionation.

Adam Seamount

Five glass samples were analyzed from Adam seamount. Four glass samples are shards from volcaniclastic breccias which consist of angular shards in a brown, sandy matrix. One analysis is of the glassy rind of a large pillow basalt. The four breccia glasses are of the same fractionated (Mg# 50), strongly alkalic flow unit (Ne 5-6%), whereas the glassy rind of the large pillow is less fractionated (Mg# 61) and tholeiitic (Hy ~7%). Both flow units are undegassed with S contents of 1000 ppm for the tholeiitic and 800-900 ppm for the alkalic flow unit. Dredge 9 recovered additional volcanic rocks from this edifice that represent yet another lithology, but no fresh glass was recovered

Hoss Seamount

Three glass fragments were analyzed from volcaniclastic breccia samples recovered in dredge 10. The breccia has a sandy matrix similar to that described for the other sites, but glass fragments are typically more rounded. The analysis from dredge 11 is the rind of a large pillow. The three breccia glass fragments are assigned to a single flow unit. Both flow units are relatively unfractionated (Mg#s 62-63), low-K_2O basalt that resembles N-MORB. Sulfur content is high (~1000 ppm), indicating undegassed compositions.

Little Joe Seamount

The two dredges from Little Joe seamount each recovered one lithology with fresh glass. Dredge 13 recovered fresh glass in a volcaniclastic breccia that is similar to that described for the other edifices, and dredge 14 is the glassy rind on a large pillow fragment. Both are strongly alkalic basalt. Sulfur content is as low as 600 ppm in glass from dredge 13 and greater than 1000 ppm in glass from dredge 14. Both lithologies were dredged from about the same water depth. The lower S content occurs in the more alkalic sample (K_2O ~ 2.3%) which has a low FeO^* content (6.8%), whereas the high S content occurs in the less alkalic sample (~1.5% K_2O) which has a higher FeO^* content (10.3%).

Ben Seamount

Fresh glass is abundant in the single large dredge haul from Ben seamount. Fifteen glasses were analyzed from dredge 17. Ten of these are from glassy rinds of pillow fragments. Four glass analyses are from volcaniclastic breccia and one glass sample from a cross-bedded sandstone. The breccia from which glass shards were analyzed has a brown sandy matrix and some fragments show graded bedding. One unusual breccia sample was recovered that consists of angular to concave, imbricated, glass shards in a white to beige calcareous matrix. All of the glass shards in this sample are altered to reddish-golden palagonite and hence no glass was analyzed. All of the fifteen analyses are low-K_2O normal MORB, although four flow units appear to be present. Three flow units are very similar, unfractionated compositions (Mg#s 68-69.5), whereas one flow unit is more fractionated (Mg# ~59). Differences between the three unfractionated flow units consist of small variations in MgO and FeO contents, suggesting that variations resulted from minor olivine fractionation. Most of the glass samples are higher in MgO (>9%) and lower in TiO_2 (<1%) than MORB-like samples from Hoss Seamount and resemble primitive MORB. Sulfur contents are uniformly high (800-1000 ppm), indicating that these glasses did not degass.

Flint Seamount

Two dredges from Flint seamount recovered a few cobble- and boulder-sized pillow fragments with glassy rinds. No glass-bearing breccias were recovered. Each dredge sampled a different flow unit of highly differentiated, mildly alkalic basalt of similar composition. Due to the large degree of differentiation, these samples have higher normative Hy contents (~6-9%) than other samples that plot mildly alkalic on the alkali vs. silica plot (Fig. 2). With Mg-numbers as low as 45, these are the most differentiated compositions recovered from any of the seven seamounts sampled. Sulfur contents range from about 900 to 1300 ppm, for dredge 21 and 23, respectively. Since both flow units are differentiated to a similar degree the large difference in S contents may be due to partial degassing of the sample from dredge 21 since it was recovered from lower depth (~1450 m) than samples from dredge 23 (~ 2860 m).

Petrologic Summary

The glass samples recovered from the seven volcanic edifices offshore southern California are compositionally highly diverse. Tholeiitic compositions include strongly depleted N-MORB that are more primitive than lavas typically erupted on mid-ocean ridges in the Pacific Ocean (e.g. Cousens and others, 1984; Davis and Clague, 1987; Eaby and others, 1984, Perfit and Fornari, 1983). Except for the extensively fractionated basalt from Flint seamount, alkalic lavas are moderately fractionated (Figs. 2,3). Most of the lavas are high in Al_2O_3 (>17%). Selected oxides plotted against MgO (Fig. 3) show a large amount of scatter, especially for SiO_2, Al_2O_3 and FeO. Less compatible elements, like K, Ti, and P, show less scatter. Like the other incompatible elements, P increases with differentiation and shows the most linear trend. The range in K_2O/P_2O_5 ratios from <1 for MORB-like samples to about 3 for strongly alkalic compositions (Fig. 4), suggests large variations in degrees of partial melting and/or source composition. Sulfur content is also highly variable. MORB-like compositions range from 800 to 1100 ppm, increasing with fractionation as is commonly observed for MORB over this fractionation range (Fig. 5). Sulfur content in alkalic lavas shows large scatter at comparable levels of fractionation, which is in part related to partial degassing. Sulfur versus average dredging depth (Fig. 6), shows the shallowest dredges, from Rodriguez and Flint, have the lowest S contents. However, no correlation between depth and S contents exists for the other dredges.

COMPARISON WITH SEAMOUNTS NEAR THE EPR

Small volcanic edifices are abundant near the EPR (e.g. Batiza, 1980; Batiza and others, 1984; Lonsdale and Batiza, 1980). The bulk of these edifices appears to consist of depleted N-MORB, but minor amounts of transitional and alkalic basalt are also present. The lavas from these small volcanoes near the flanks of a spreading center are petrologically diverse (Fig. 2; Batiza and Vanko, 1984; Allen and Batiza, 1987). The bulk of each edifice appears to consist of low-K_2O MORB more depleted and less fractionated than tholeiites erupted on the adjacent ridge (Batiza and Vanko, 1984; Allen and Batiza, 1987). N-MORB was the only lithology recovered from many of the young edifices, whereas edifices on somewhat older crust yielded volcanic rocks with transitional, alkalic and strongly alkalic compositions as well.

The seamounts near the EPR are morphologically and chemically similar to those in the Bonanza group. All of the glasses from Ben seamount are N-MORB, although some compositions are more primitive (MgO >9%) than many of the lavas from the EPR seamounts. Compositions from Hoss are also tholeiitic and MORB-like but they are less depleted and more fractionated than those from Ben. The tholeiitic flow unit from Adam seamount falls well within the range of compositions observed on seamounts near the EPR (Fig. 2). However, the stongly alkalic compositions from Adam and Little Joe appear more silica-undersaturated than alkalic compositions from seamounts near the EPR.

The other three edifices yielded only alkalic compositions, but at least two of these seamounts are morphologically distinct. Instead of small, circular to slightly elliptical cones, Rodriguz guyot and San Marcos seamount are elongated ridges with a distinct NE-SW orientation similar to that observed for other edifices near or on the continental margin. Although the two flow units from San Marcos are both alkalic, the one recovered in a deep water dredge (>3000 m) is only mildly alkalic (Fig. 2), suggesting that the strongly alkalic lavas mantle a less alkalic shield. The alkalic compositions from

Rodriguez and San Marcos appear more undersaturated in SiO_2 (Fig. 2) and higher in TiO_2 and Al_2O_3 than alkalic compositions from the EPR seamounts. Flint seamount does not have the ridge-like morphology and NE-SW orientation of the edifices nearer to the continental margin, but it is larger than most of the small conical volcanoes near the EPR. However, the mildly alkalic, differentiated compositions recovered from Flint fall within the range of compositions encountered on the EPR seamounts.

COMPARISON WITH SEAMOUNTS FROM THE NE PACIFIC

Abundant seamounts and guyots exist close to the continental margin in the north-east Pacific Ocean, especially in the Gulf of Alaska. Some of these are aligned in chains and show NW-orientation sub-parallel to that of the Hawaiian or other age-progressive chains, generated as the Pacific plate moved over hot spots. Recent $^{40}Ar/^{39}Ar$ age data (Dalrymple and others, 1987) suggest that alignment of at least some chains in the Gulf of Alaska is largely fortuitous and that edifices formed by multiple, intermittent episodes of mid-plate volcanism, while others formed at or near spreading centers. Basalts from seamounts in the Gulf of Alaska range from low-K_2O, MORB-like compositions to mildly and strongly alkalic (Fig. 2; Dalrymple and others, 1987). Many of the alkalic basalts are more extensively fractionated than any recovered from the seamounts offshore California and include hawaiite, mugearite, benmoreite and trachyte. Since these differentiated alkalic lavas are best suited for age dating, they may represent a biased sample. Many of the rocks from the seamounts in the Gulf of Alaska, that were considered too altered for dating (Dalrymple and others, 1987) were not chemically analyzed and may have included tholeiitic basalts. Seamounts near spreading centers, such as the Dellwood seamounts near the Explorer Ridge and Cobb seamount near the Juan de Fuca Ridge are low-K_2O tholeiite (Cousens and others, 1984). Sixty-nine analyses of glass samples from the President Jackson seamounts, a short seamount chain west of the northern Gorda Ridge, consist entirely of N-MORB, as depleted as that from Ben seamount (Figs. 2,5; Davis and Clague, unpublished data).

DISCUSSION AND CONCLUSIONS

Basaltic glasses from seamounts offshore southern California are petrologically diverse, ranging from primitive, MORB-like compositions to moderately fractionated, strongly alkalic basalt. Three of the Bonanza seamounts yielded MORB-like compositions similar to those comprising the bulk of small volcanoes generated at the EPR. Although dredges on Little Joe, the easternmost edifice of the Bonanza seamount group, recovered only strongly alkalic lava, it is possible that tholeiitic lava comprises some or even most of the edifice but was not sampled by the two shallow dredges. Numerous EPR seamounts also erupted alkalic basalt, but the strongly alkalic compositions from Little Joe and Adam are more silica-undersaturated and K_2O/P_2O_5 ratios are more similar to those of samples from Rodriguez and San Marcos seamounts. Alkalic basalt on the EPR seamounts appears to occur only on older edifices (Batiza and Vanko, 1984; Allen and Batiza, 1987). The MORB-like compositions of some of the Bonanza seamounts suggest that some or all of Bonanza group originated at, or close to, a spreading center. Young seamounts located close to spreading centers in the northeast Pacific, such as Dellwood, Cobb and the President Jackson seamount chain, yielded only N-MORB compositions. Dredging at the EPR seamounts and President Jackson seamount chain was extensive, and compositions of basalts recovered are probably representative of the bulk of the edifices. It is possible that the tholeiitic shield-building and alkalic stages are separated by long periods of time and due to totally different mechanisms. If this is true, establishing an age progression among seamounts would have to be done using only samples from the shield stage. Unfortunately, these tholeiitic or mildly alkalic rocks are typically too altered for K-Ar dating.

The great range of (La/Sm_N) and isotopic ratios (Batiza and Vanko, 1984; Allen and Batiza, 1987) for seamount samples from the flanks of the EPR indicate that diverse sources are being tapped by these small volcanoes. No isotopic or rare earth data are yet available for the seven edifices offshore southern California. However, variation in K_2O/P_2O_5 and K_2O/TiO_2 ratios also suggest diverse source compositions, although the range in K_2O/P_2O_5 ratios from MORB to strongly alkalic compositions may be due in part to a decrease in percentage of partial melting.

Rodriguez and San Marcos seamounts, with different geomorphology and pronounced NE-SW orientation, are compositionally distinct from the Bonanza seamounts and undoubtedly originated by different mechanisms. Their higher K_2O/P_2O_5 ratios and more silica-undersaturated composition suggests a more enriched source and/or smaller percentage of melting. The mildly alkalic samples recovered in the deep-water dredge from San Marcos seamount may represent the shield-stage of this edifice.

The elongated NE-SW oriented volcanic ridges may have originated in response to extension related to faulting along the continental margin (Lonsdale, 1989). Two other prominent volcanic ridges, Davidson seamount to the north and Guadalupe Island to the south of the study area, have been interpreted as fossil spreading centers, based on geomorphology and magnetic anomalies (Lonsdale, 1989). However, lava compositions from Davidson seamount (Clague, unpublished data) and Guadalupe Island (Batiza, 1977) do not include MORB-like compositions but instead are moderately to strongly alkalic. Lonsdale (1989) suggested that seamounts on the continental slope, such as Rodriguez, Guide and Pioneer, formed when segments of the EPR intersected the continental margin. However, Northeast Bank, a guyot about 25 km landward from the Patton escarpment was built 14 million years after the ridge-margin collision occurred (Lonsdale, 1989). Alkalic basalt from Northeast Bank (Hawkins, 1970) is chemically similar to that from Rodriguez and San Marcos seamount, the latter being located more than 100 km seaward from the continental margin. The region seaward of the continental borderland is tectonically highly complex and volcanic edifices may have originated by several different processes. Some may be fossil spreading centers whereas others may be small off-ridge volcanoes that formed near the flanks of spreading centers. Still others may have formed by mid-plate volcanism of short-lived hot spots. The only seamounts identified as belonging to an age-progressive hot spot are the edifices of the Fieberling seamount chain (Lonsdale, 1989). In addition, edifices may have originated, or existing ones may have been modified, during collision of EPR segments with the continental margin or in response to extensional tectonics related to faulting along the continental margin. Additional complexity is introduced by rotation of microplates (Lonsdale, 1989), and edifices that are age-progressive may not now be aligned, while alignment for others may be fortuitous. Clearly, very detailed sampling and precise dating will be required before the volcanic history of this region can be more fully understood.

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Table 1: Dredge locations

Dredge	Start of Dredge			End of Dredge		
	Lat.(N)	Long.(W)	Depth (m)	Lat. (N)	Long. (W)	Depth(m)
<u>Rodriguez guyot</u>						
D3	34° 00.3'	121° 01.7'	1580	34°00.9'	121°02.3'	1045
D4	34°01.4'	121°02.7'	900	34°01.6'	121°02.7'	820
<u>San Marcos seamount</u>						
D5	32°33.2'	121°30.4'	4080	32°32.9'	121°30.2'	3045
D6	32°34.3'	121°31.8'	2305	32°34.7'	121°32.2'	2170
<u>Adam seamount</u>						
D7	32°02.7'	121°13.7'	3880	32°02.9'	121°14.0'	3310
D8	32°03.4'	121°14.4'	3250	32°03.3'	121°15.0'	3170
D9	32°05.1'	121°16.7'	2300	32°16.1'	121°16.1'	2235
<u>Hoss seamount</u>						
D10	31°59.1'	121°28.8'	2850	31°58.8'	121°28.7'	2700
D11	31°59.4'	121°28.5'	2560	31°59.4'	121°28.6'	2540
<u>Little Joe seamount</u>						
D13	31°54.4'	120°01.7'	2840	31°54.3'	120°01.5'	2155
D14	31°54.6'	120°02.2'	2530	31°54.5'	120°01.9'	2175
<u>Ben seamount</u>						
D17	31°44.2'	120°44.1'	2925	31°44.5'	120°44.2'	2875
<u>Flint seamount</u>						
D21	30°36.6'	123°13.1'	1470	30°36.5'	123°13.1'	1455
D23	30°33.6'	123°11.3'	2890	30°33.7'	123°10.2'	2855

Table 2. Glass Compositions

Sample	F.U.	SiO_2	Al_2O_3	FeO*	MnO	MgO	CaO	Na_2O	K_2O	P_2O_5	Ti_2O	S	Sum	Mg#	Ne	Hy
Rodriguez guyot																
D3-6a	1(B)	46.55	17.22	9.56	0.17	6.49	11.62	3.60	1.20	0.45	2.38	0.06	99.3	57.4	7.6	-
D3-9a	1(B)	47.21	17.08	9.56	0.17	6.68	11.59	3.68	1.21	0.46	2.49	0.06	100.2	58.1	7.3	-
D3-13c	1(B)	46.64	17.01	9.56	0.16	6.52	11.38	3.48	1.22	0.40	2.49	0.06	98.9	57.5	6.4	-
D3-16b	1(B)	46.36	17.04	9.47	0.15	6.57	11.57	3.50	1.20	0.46	2.44	0.06	98.8	57.9	7.1	-
D3-20	1(F)	46.94	17.08	9.53	0.15	6.52	11.45	3.62	1.22	0.48	2.47	0.07	99.5	57.6	6.7	-
San Marcos seamount																
D5-3d	1(B)	47.83	15.76	12.39	0.20	6.50	10.31	3.35	0.52	0.35	1.87	0.12	99.2	51.0	-	1.4
D5-17	2(F)	49.12	17.59	9.49	0.15	5.09	8.65	4.61	1.84	0.81	2.91	0.11	100.4	51.6	5.0	-
D5-20	2(F)	49.08	17.62	9.59	0.16	5.15	8.63	4.61	1.82	0.83	2.86	0.10	100.5	51.6	5.2	-
D5-21	1(F)	48.37	15.91	12.27	0.17	6.69	10.38	3.43	0.51	0.34	1.77	0.13	99.9	52.0	-	1.2
D5-23	2(F)	48.90	18.06	9.56	0.16	5.08	8.55	4.37	1.87	0.84	2.93	0.10	100.4	51.3	3.9	-
D6-5j	3(B)	47.63	17.19	9.70	0.17	4.95	9.07	4.23	1.85	0.75	2.90	0.09	98.5	50.3	5.5	-
D6-8a	3(B)	48.28	17.33	9.73	0.16	5.07	9.09	4.37	1.81	0.80	2.87	0.08	99.6	50.8	5.6	-
D6-8b	3(B)	47.86	17.29	9.78	0.16	4.98	8.87	4.27	1.90	0.71	2.86	0.08	98.8	50.3	5.7	-
D6-9a	2(F)	48.42	17.71	9.54	0.15	5.04	8.41	4.35	1.83	0.82	2.83	0.09	99.2	51.2	4.0	-
D6-22	2(B)	48.67	17.55	9.50	0.15	5.06	8.50	4.48	1.81	0.83	2.91	0.09	99.6	51.4	4.5	-
D6-23a	3(B)	47.89	17.05	9.72	0.18	5.07	9.10	4.43	1.82	0.78	2.89	0.08	99.0	50.9	6.5	-
D6-50	2(B)	48.73	17.69	9.75	0.17	5.11	9.17	4.10	1.90	0.74	2.87	0.08	100.3	51.0	4.2	-
D6-51	3(B)	47.85	17.22	9.75	0.15	5.03	8.87	4.31	1.87	0.72	2.90	0.08	98.8	50.6	5.7	-
Adam seamount																
D7-3a	1(B)	47.91	17.33	9.72	0.15	5.01	8.81	4.31	1.87	0.78	2.83	0.08	98.8	50.6	5.5	-
D7-3b	1(B)	48.36	16.77	9.89	0.17	5.08	8.99	4.45	1.91	0.77	2.90	0.09	99.4	50.5	6.1	-
D7-3c	1(B)	47.73	16.94	9.71	0.16	4.93	8.97	4.19	1.86	0.77	2.78	0.09	98.2	50.2	4.9	-
D7-3c	1(B)	47.61	17.15	9.78	0.16	5.00	8.74	4.13	1.86	0.74	2.85	0.08	98.1	50.4	4.6	-
D8-1c	2(F)	51.03	14.95	9.32	0.18	7.28	11.79	3.38	0.34	0.23	1.76	0.10	100.4	60.8	-	7.0
Hoss seamount																
D10-4e	1(B)	49.11	16.13	9.19	0.18	7.84	12.01	3.29	0.06	0.13	1.43	0.10	99.5	62.9	-	0.1
D10-4c	1(B)	49.28	16.22	9.22	0.16	7.88	11.96	3.23	0.05	0.17	1.51	0.10	99.8	62.9	-	2.6
D10-4d	1(B)	50.13	15.63	9.30	0.19	8.01	11.96	3.47	0.05	0.17	1.48	0.11	100.5	63.1	-	1.4
D11-2a	2(F)	49.30	15.45	9.63	0.17	7.87	11.52	3.28	0.05	0.14	1.43	0.11	99.0	61.9	-	4.7
Little Joe seamount																
D13-1e	1(B)	49.93	18.02	6.84	0.13	5.54	8.50	4.63	2.31	0.98	2.36	0.06	99.5	61.6	5.7	-
D14-1d	2(F)	48.61	16.64	10.25	0.17	5.46	9.08	4.18	1.46	0.64	2.84	0.12	100.9	51.4	2.8	-
Ben seamount																
D17-26a	1(F)	49.24	17.30	8.56	0.17	9.69	12.64	2.29	0.05	0.06	0.87	0.08	101.3	69.2	-	8.8
D17-27b	1(B)	49.68	17.03	8.61	0.15	9.79	12.61	2.36	0.06	0.08	0.85	0.08	100.7	69.3	-	9.1
D17-27d	1(B)	49.05	17.15	8.52	0.15	9.71	12.72	2.29	0.06	0.08	0.85	0.08	99.6	69.3	-	7.8
D17-28b	2(F)	50.14	14.62	10.17	0.19	7.55	12.47	2.80	0.08	0.11	1.34	0.11	100.7	59.6	-	11.9
D17-29b	1(F)	49.30	17.21	8.53	0.17	9.75	12.46	2.28	0.06	0.10	0.83	0.09	101.1	69.4	-	10.6
D17-29a	3(B)	49.63	16.75	8.89	0.18	9.45	12.67	2.38	0.06	0.08	0.98	0.09	100.4	67.8	-	9.6
D17-29D	4(F)	49.59	16.62	8.85	0.18	9.25	12.49	2.36	0.06	0.06	0.86	0.08	100.8	67.5	-	11.0
D17-29c	1(F)	49.34	17.18	8.50	0.16	9.75	12.56	2.25	0.06	0.06	0.85	0.09	100.9	69.5	-	10.5
D17-29e	4(B)	49.82	16.69	9.02	0.16	9.19	12.49	2.36	0.06	0.09	0.90	0.09	100.8	66.9	-	12.2
D17-29g	1(B)	49.41	17.00	8.60	0.14	9.70	12.60	2.28	0.05	0.07	0.91	0.08	101.4	69.1	-	10.3
D17-27c	1(B)	49.62	17.41	8.55	0.16	9.69	12.56	2.33	0.07	0.07	0.83	0.08	100.9	69.2	-	9.6
D17-28a	4(F)	49.82	16.64	8.92	0.16	9.05	12.48	2.47	0.08	0.09	1.03	0.10	100.6	66.8	-	11.1
D17-29f	4(B)	49.44	16.77	8.78	0.15	9.07	12.59	2.49	0.08	0.09	1.01	0.09	100.3	67.2	-	8.4
D17-27a	4(B)	49.00	16.73	8.97	0.18	9.19	12.71	2.36	0.06	0.10	0.88	0.09	99.7	67.0	-	8.3
D17-31a	3(S)	48.82	16.84	8.64	0.17	9.32	12.56	2.29	0.07	0.09	0.89	0.08	99.9	68.2	-	9.0
Flint seamount																
D21-3	1(F)	49.82	15.85	11.38	0.18	5.68	9.07	3.37	1.23	0.60	2.61	0.09	99.9	49.8	-	9.1
D23-2a	2(F)	48.93	15.85	12.69	0.21	5.23	9.00	3.40	1.11	0.64	3.48	0.13	100.7	45.0	-	9.6
D23-3a	2(F)	48.07	15.56	13.02	0.20	5.35	8.64	3.47	1.11	0.63	3.40	0.12	99.6	44.9	-	6.1

F.U., flow unit; (B), breccia; (F), flow; (S), sandstone, Ne, normative nepheline, Hy, normative hypersthene. FeO* is total iron as FeO. Mg# is 100*Mg/(Mg+Fe^{2+}), where Fe^{2+}=0.9 FeO*.

FIGURE CAPTIONS

Figure 1. Bathymetric map of study area. Sample sites are labeled.

Figure 2. Alkali versus silica plot for glasses dredged from seven sites offshore southern California. Fields of tholeiitic and alkalic compositions after Macdonald and Katsura (1964). Fields for seamounts from the flanks of the EPR, from the Gulf of Alaska and the President Jackson seamount chain include only glass compositions; whole rock analyses were excluded. Glass compositions from the Gulf of Alaska include only relatively unfractionated compositions; mugearites, benmoreites and trachytes fall outside the plot. Data for EPR seamounts from Batiza and Vanko (1984), Gulf of Alaska seamounts from Dalrymple and others (1987), and President Jackson seamounts from Davis and Clague (unpublished data).

Figure 3. Plots showing selected oxides versus MgO. (A) SiO_2, (B) Al_2O_3 and (C) FeO^*.show a large amount of scatter. (D) K_2O, (E) TiO_2 and (F) P_2O_5 increase with differentiation and show much less scatter. Symbols as in Figure 2.

Figure 4. Plots of K_2O/P_2O_5 ratios versus (A) MgO and (B) TiO_2 show low ratios (<1) for depleted MORB-like samples, and higher ratios for transitional and mildly alkalic (>1) and for strongly alkalic compositions (>2). High ratios suggest smaller percentage of partial melting and/or more enriched source compositions. Symbols as in Figure 2.

Figure 5. Plots of sulfur versus (A) MGO and (B) FeO^* show S increasing with differentiation in the MORB-like samples (open and filled circles). Such a trend is commonly observed for MORB over this fractionation range. Sulfur in the alkalic samples is highly variable, with variation at comparably fractionated samples probably at least in part due to partial degassing. Symbols as in Figure 2.

Figure 6. A plot of sulfur versus average dredging depth shows that samples from the two shallowest dredges have the lowest sulfur contents, as might be expected from eruptions with lower hydrostatic pressure. For other samples, no simple trend is apparent, and a large range of sulfur contents is observed

for samples recovered from a similar depth. Symbols as in Figure 2.

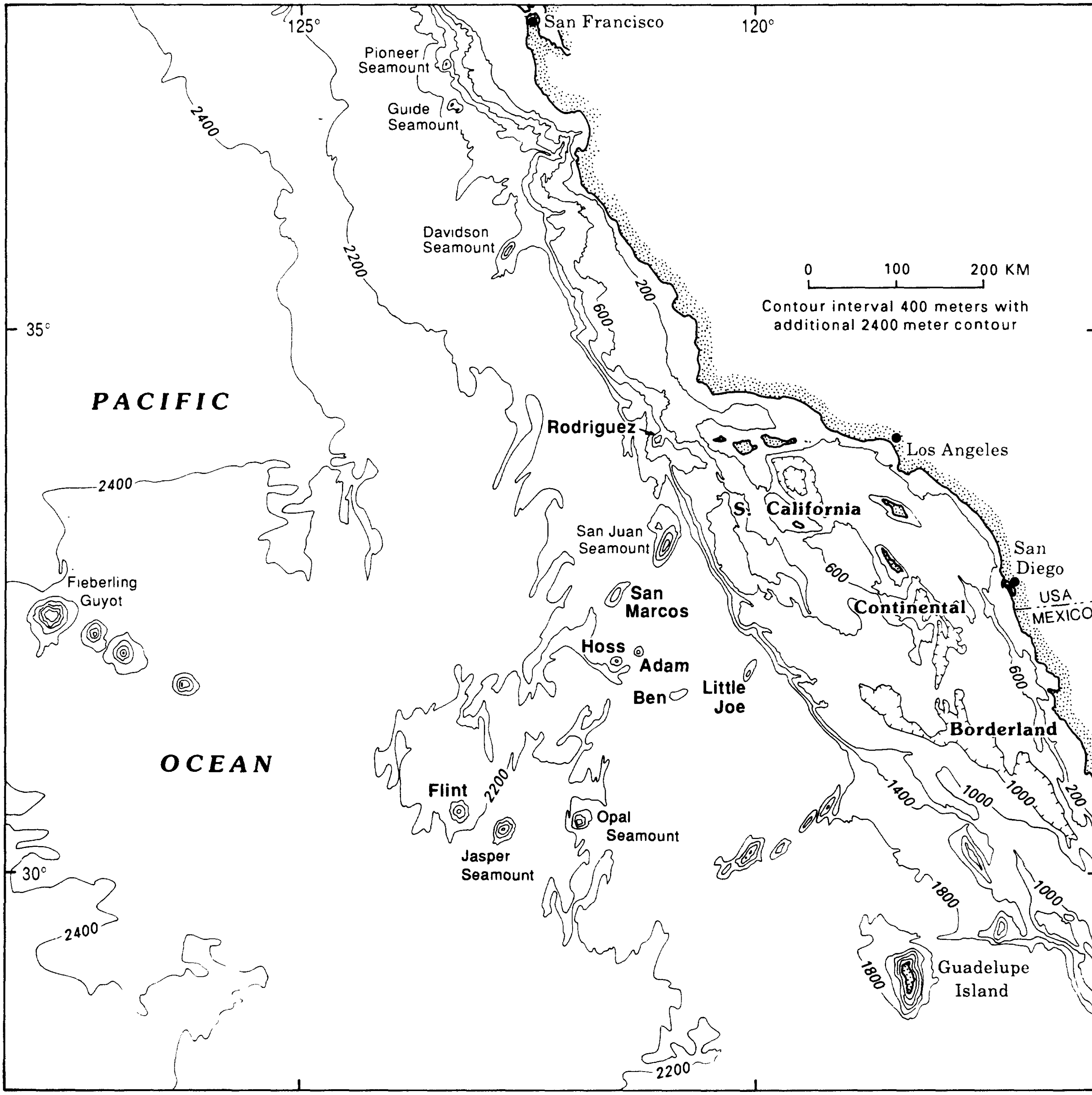
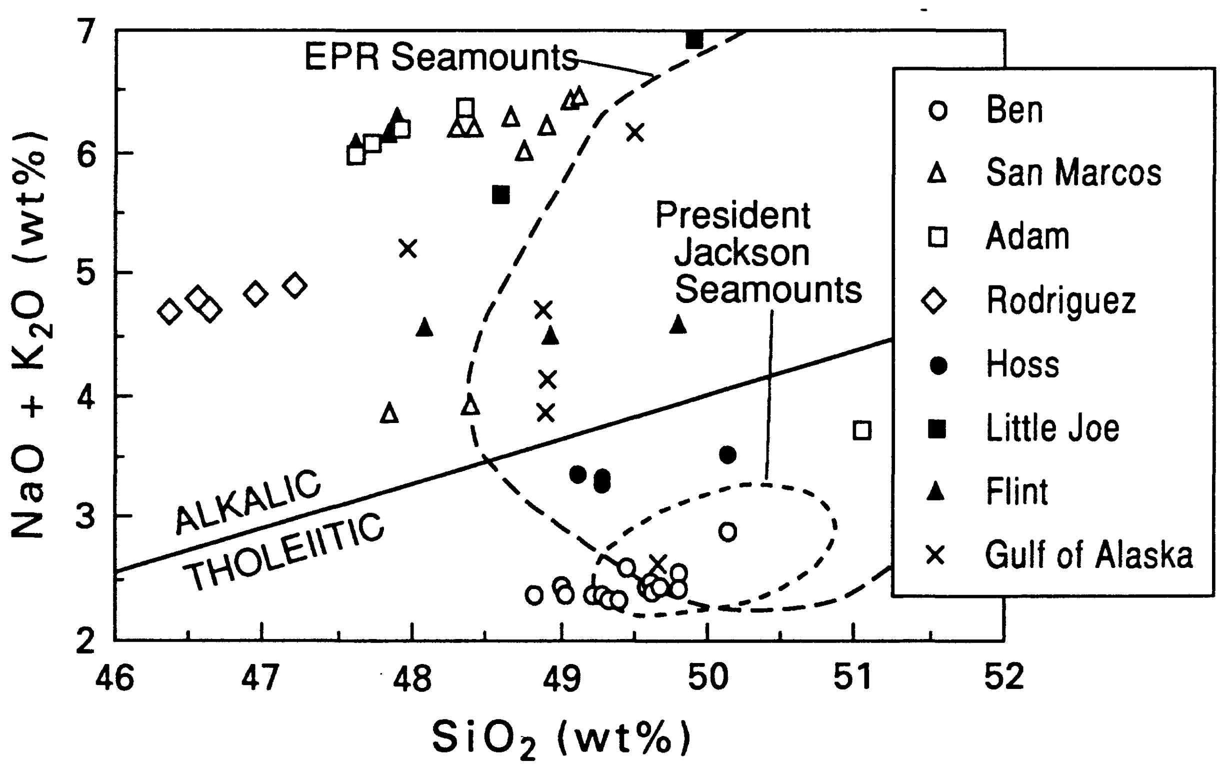
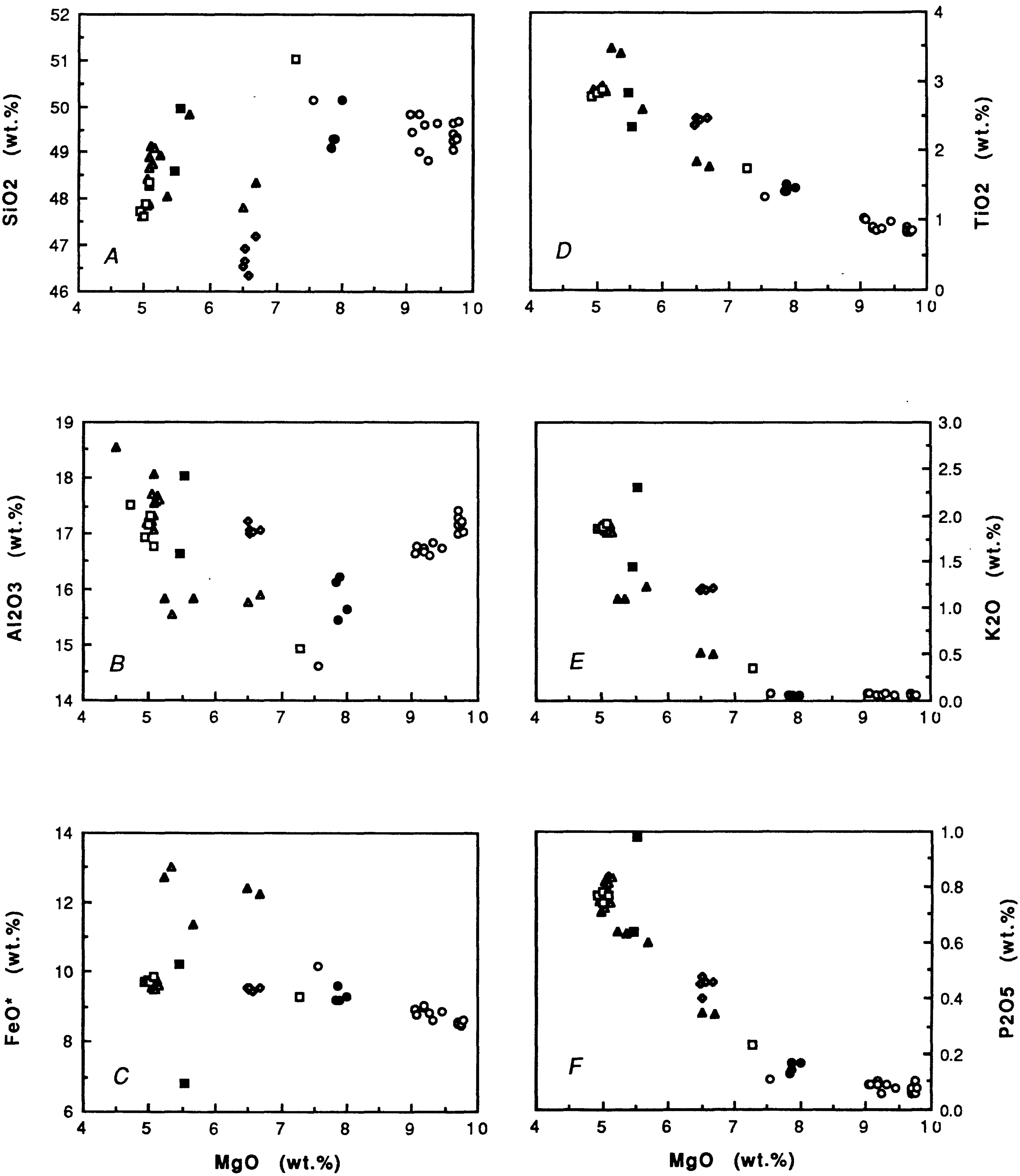

San Francisco
125°
120°
Pioneer Seamount
Guide Seamount
Davidson Seamount
2400
2200
200
600
0 100 200 KM
Contour interval 400 meters with additional 2400 meter contour
35°
PACIFIC
Rodriguez
Los Angeles
S. California
San Juan Seamount
San Diego
USA
MEXICO
Fieberling Guyot
San Marcos
Continental
Hoss
Adam
Ben
Little Joe
Borderland
OCEAN
Flint
Opal Seamount
Jasper Seamount
1400
1000
1800
30°
Guadelupe Island

Figure 1.



EPR Seamounts
President Jackson Seamounts
ALKALIC
THOLEIITIC
Ben
San Marcos
Adam
Rodriguez
Hoss
Little Joe
Flint
Gulf of Alaska
NaO + K2O (wt%)
SiO2 (wt%)
2
3
4
5
6
7
46
47
48
49
50
51
52

Figure 2.



SiO2 (wt.%)
A
TiO2 (wt.%)
D
Al2O3 (wt.%)
B
K2O (wt.%)
E
FeO* (wt.%)
C
P2O5 (wt.%)
F
MgO (wt.%)
MgO (wt.%)

Figure 3.

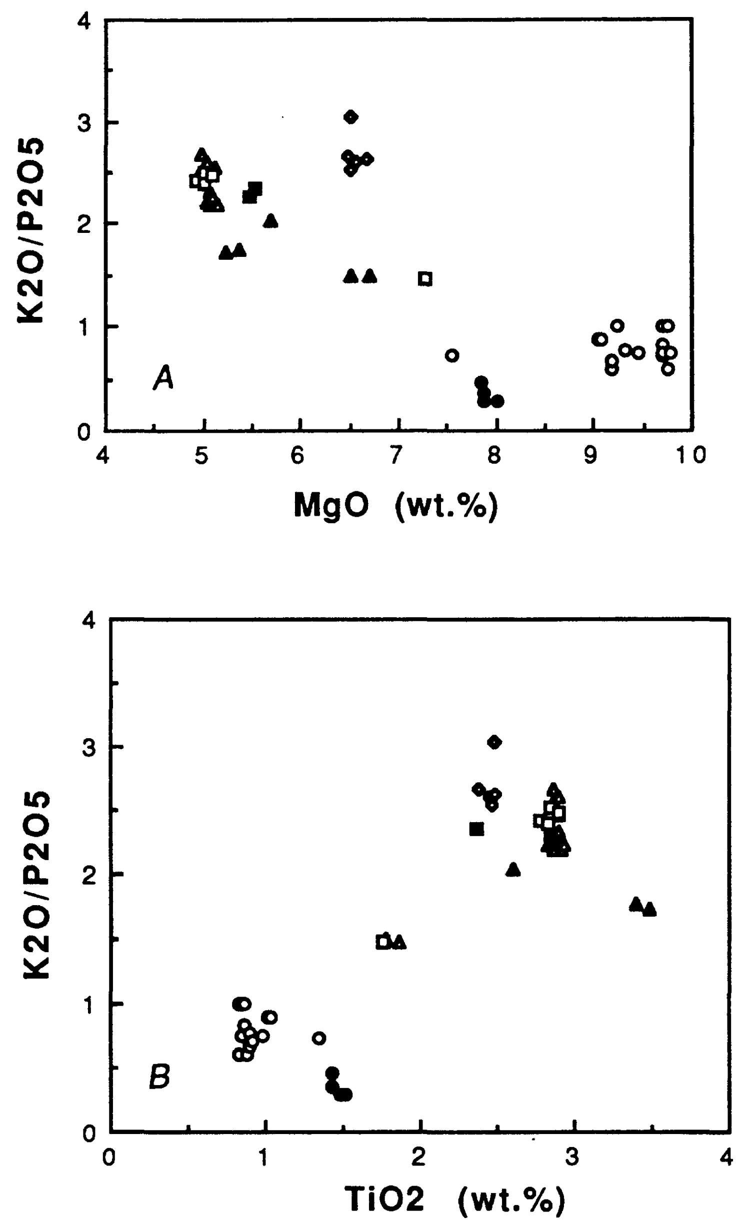
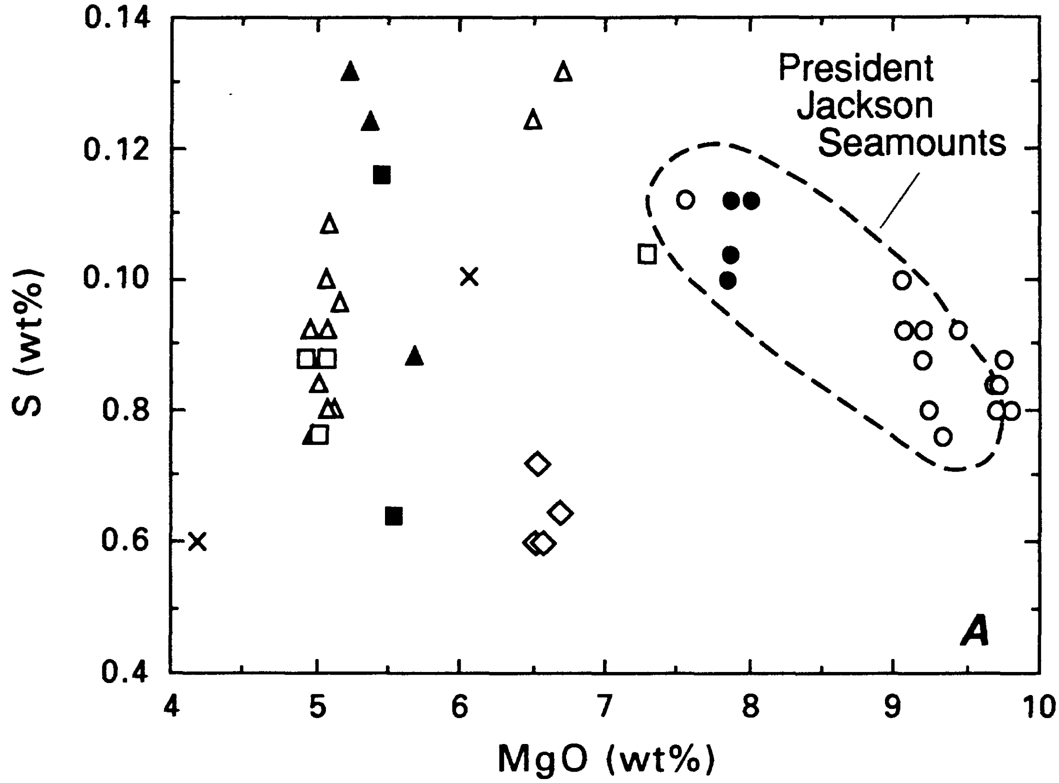

4
3
2
1
0
K2O/P2O5
A
4
5
6
7
8
9
10
MgO (wt.%)
4
3
2
1
0
K2O/P2O5
B
0
1
2
3
4
TiO2 (wt.%)

Figure 4.


0.14
0.12
0.10
0.8
0.6
0.4
S (wt%)
4
5
6
7
8
9
10
MgO (wt%)
President
Jackson
Seamounts
A

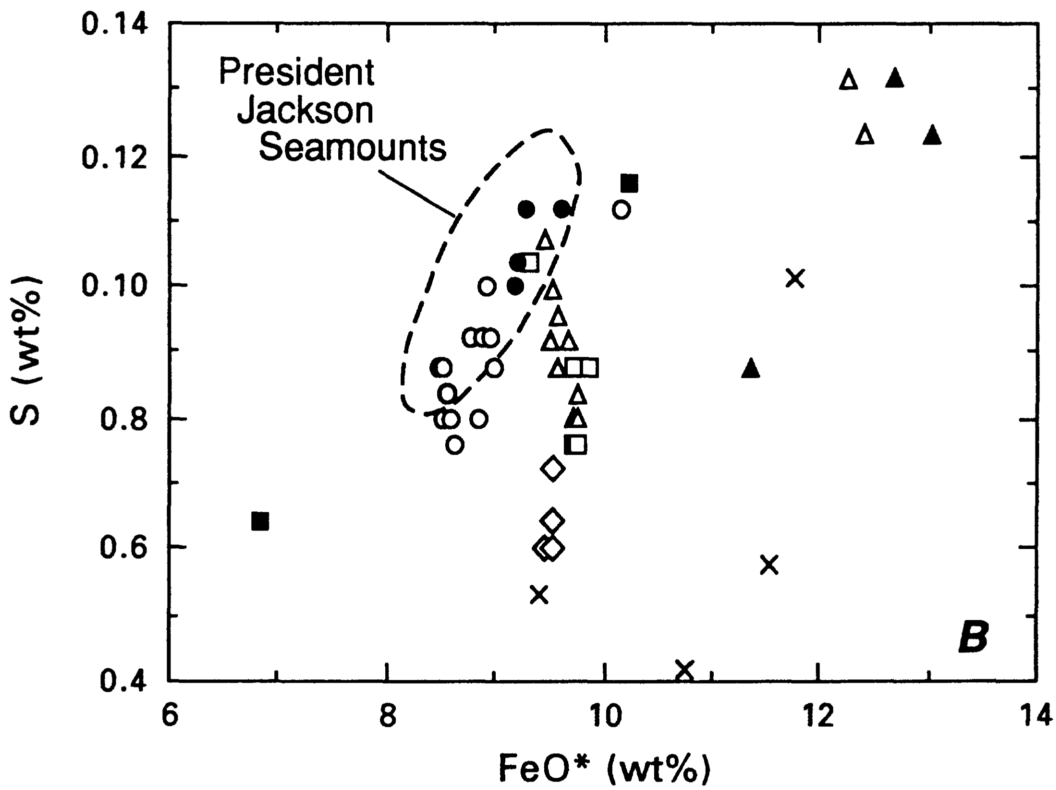

0.14
0.12
0.10
0.8
0.6
0.4
S (wt%)
6
8
10
12
14
FeO* (wt%)
President
Jackson
Seamounts
B

Figure 5.

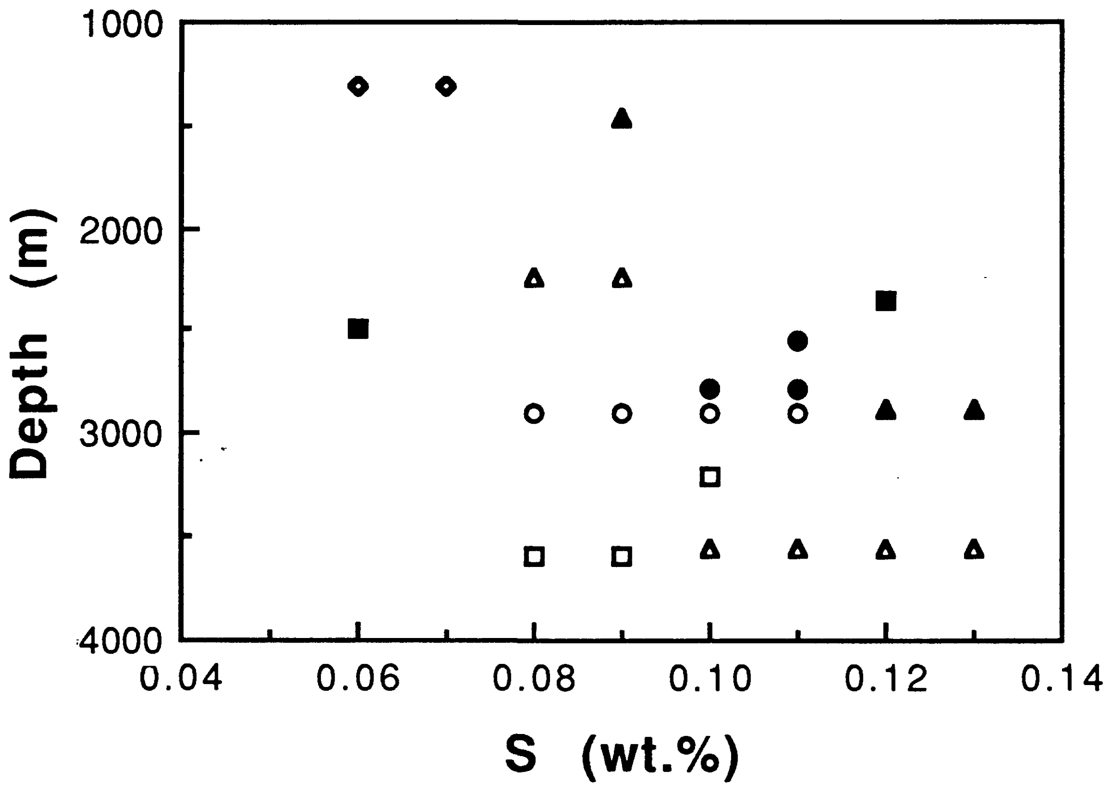


Figure 6.