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Petrology and Geochemistry of Volcanic Clasts from the Miocene Beecher's Bay Formation, Santa Rosa Island, California

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Abstract. Petrographic, geochemical, and geochronologic analyses were made on volcanic pebbles and cobbles collected from 3 of the 5 members of the middle Miocene Beecher's Bay Formation, which crops out on the eastern portion of Santa Rosa Island, California. These clasts belong to the low- to medium-K, calc-alkaline magma series and include pyroxene andesite, pyroxene dacite, and hornblende ± pyroxene rhyolite. A $^{40}Ar/^{39}Ar$ date of 15.80 ± 0.08 Ma, measured on 5 plagioclase grains in an andesite clast from the lowermost member, is consistent with a Relizian foraminiferal assemblage found in the middle member. Rare-earth element patterns are moderately enriched in the light REE (La = 25 to 60 times chondrite) and are moderately fractionated (La_N/Lu_N = 5 to 18). Spider-diagram patterns show small negative spikes for Ba, Th, Nb, P, and Ti and slight positive spikes for Sr and Zr-Hf. These samples lack the characteristic depletion in Ta and Nb shown by subduction-related igneous rocks. Initial $^{87}Sr/^{86}Sr$ values range from 0.7037 to 0.7045, and initialε_{Nd} values range from 3.4 to 6.1. These isotopic data suggest a mantle origin for the parent magmas of the clasts. These new data support previous studies that suggested the Beecher's Bay Formation and the Blanca Formation on nearby Santa Cruz Island have the same provenance. The stratigraphic positions and radiometric ages of the 2 formations are similar. Beecher's Bay clasts vary regularly in composition from andesite to rhyolite, whereas the majority of Blanca clasts are composed of dacite and rhyolite. Chemical data of clasts from the 2 formations show similar patterns on SiO_2-variation diagrams, spider diagrams, and rare-earth element plots. The similarity in stratigraphic position of the 2 formations and in the ages and geochemistry of the clasts within the formations indicate that the clasts were derived from a single volcanic complex. This places an important constraint on the overall tectonic history of the area by demonstrating that the geographic areas of exposure have remained in proximity to each other and have not been significantly displaced from each other since deposition.

Keywords: California; Channel Islands; Miocene; volcanics; geochemistry.

Introduction

Santa Rosa Island is located about 55 km southwest of Santa Barbara, California. With an area of 218 km², it is the second largest of the northern Channel Islands that lie at the northernmost extension of the Southern California Continental Borderland. The island is cut by the east-west trending Santa Rosa Island fault (Fig. 1). North of the fault, well-developed Pleistocene terrace deposits overlie low-dipping, mid-Tertiary marine clastic and volcaniclastic units. South of the fault the more rugged terrain is cut by deep canyons which expose older Tertiary sandstone and shale and mid-Tertiary volcaniclastic strata cut by volcanic intrusions (Weaver and Nolf 1969).

The middle Miocene Beecher's Bay Formation crops out on the northeastern and eastern sides of Santa Rosa Island. Kew (1927) mapped the unit as the Santa Margarita Formation whereas Bremner (1932) included it in the Monterey Formation. Avila (1968) redefined the Beecher's Bay unit and elevated it to formation status, but Weaver and Doerner (1969) defined it as the coarse clastic Beecher's Bay Member of the Monterey Formation. Avila and Weaver (1969) described the blueschist-bearing volcaniclastic unit exposed along the northwest shore of Carrington Point as being similar to the San Onofre Breccia, but because of the abundance of dacitic volcanic clasts, McLean et al. (1976b) suggested that this sequence correlates with the Blanca Formation.

Nuccio (1977) concluded that these strata bear little resemblance to the Monterey Formation and recommended that they be renamed the Beecher's Bay Formation; this paper will adopt his nomenclature. He divided the formation into 5 informal units, designated A through E in ascending order (Fig. 1). The following discussion of stratigraphy and depositional environment is from Nuccio

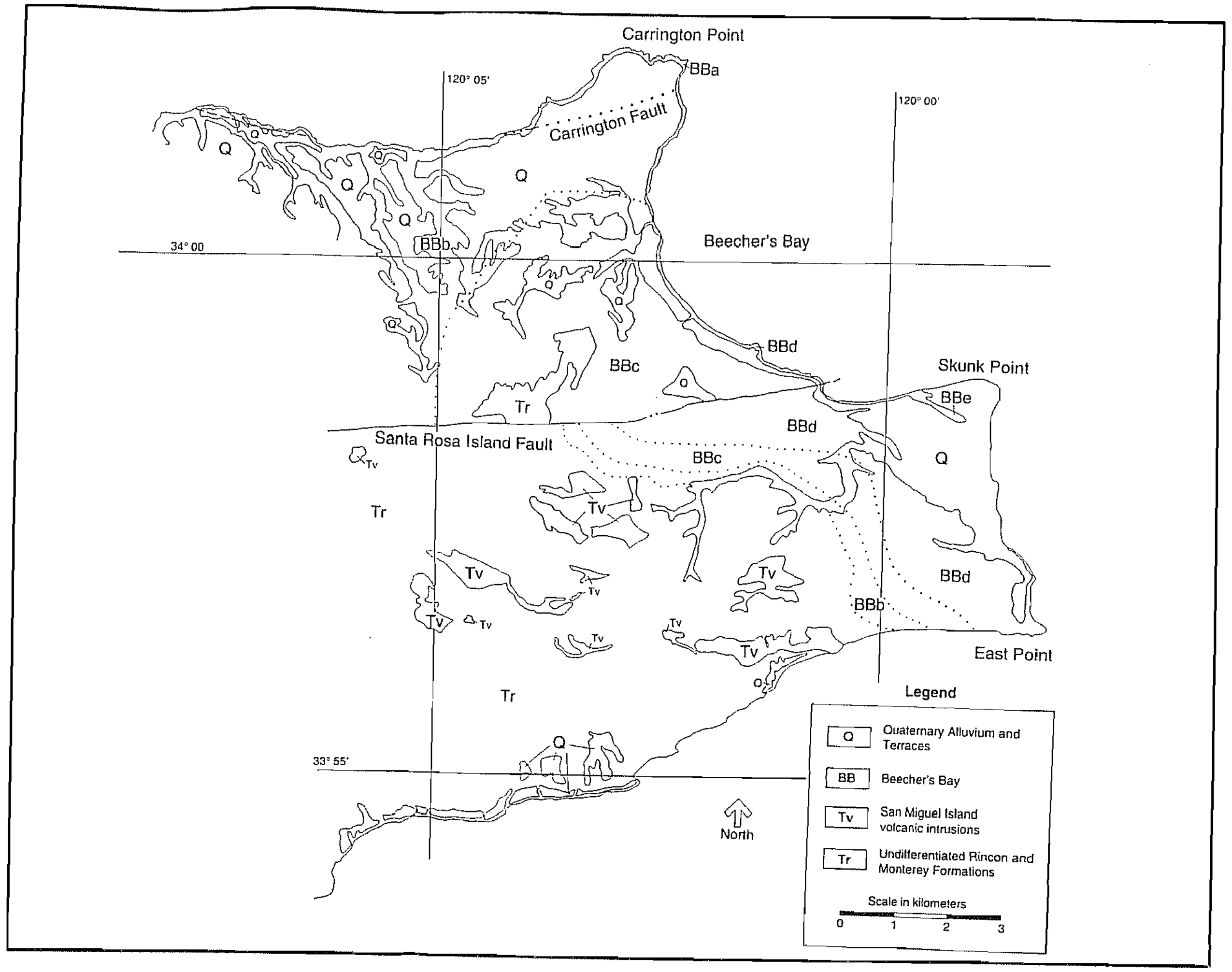

Figure 1. Geologic sketch map of eastern Santa Rosa Island modified from Nuccio (1977).

(1977). The lowest unit, member A, consists of interbedded sandstones and conglomerates. This member crops out only at Carrington Point, where it conformably overlies the Rincon Formation. Member B is primarily massive sandstone with a few interbedded siltstones. To the northeast, member B overlies member A, but where member A pinches out to the west and south, member B overlies the Rincon Formation. Member C is composed of rhythmically bedded sandstones and muddy siltstones with intermittent conglomerate deposits and thick channel sands. Its contact with member B is gradational laterally as well as vertically. Member D is primarily thick, homogeneous sandstone with interbedded siltstones. Uppermost, member E is composed of massive conglomerates with interbedded sandstones. It is similar to member A except that the sandstone beds are much less abundant.

These 5 units have been interpreted to represent various parts of a submarine fan complex (Nuccio 1977). Member A probably represents channel fill deposits in the upper fan. Members B and D signify the channelized portion of the middle fan. Member C contains deposits that represent proximal turbidites and channel lag conglomerates and represents the interchannel deposits of the middle fan channel. Disorganized conglomerates and pebbly sandstones of member E indicate channel fill deposits of the upper fan.

Though the formation as a whole is generally devoid of fossils, the middle section (member C of Nuccio 1977) contains well-developed foraminiferal assemblages. Based on these assemblages and its stratigraphic position, the Beecher's Bay Formation is assigned a Relizian to middle-Luisian age, 17 to 15 Ma (Avila 1968).

McLean et al. (1976b) used lithologic similarities and stratigraphic position to suggest stratigraphic correlation of the Beecher's Bay Formation and the Blanca Formation on adjacent Santa Cruz Island. Using petrographic similarities and paleocurrent directions, McLean and Howell (1985) concluded that these 2 formations are part of the same submarine fan complex. If both units

Table 1. $^{40}Ar/^{39}Ar$ data for individual plagioclase grains from sample BBF 12.

$^{37}Ar/^{39}Ar$	$^{36}Ar/^{39}Ar$	$^{40*}Ar/^{39}Ar$	% Rad.	Age	SD	2 SEM
20.44568	0.00698	76.33545	99.3	25.007	3.134	
13.27181	0.02423	72.36768	112.9	23.716	6.356	
Average of older grains				24.361	0.913	1.292
13.68914	0.09707	48.28064	63.4	15.857	2.247	
15.59350	0.07102	48.35963	70.7	15.883	4.905	
15.99145	0.07418	48.18100	69.7	15.824	2.000	
12.62708	0.09566	47.63596	63.4	15.646	1.757	
14.67452	0.08567	48.02068	66.3	15.772	1.235	
Average of younger grains				15.796	0.094	0.084

SD = *S*tandard *D*eviation. SEM = *S*tandard *E*rror of the *M*ean. Age of the irradiation monitor mineral, Fish Canyon sanidine (FC-2), is 27.84 Ma. Correction values for dating plagioclase: $^{36}Ca/^{37}Ca = 0.0002557$, $^{39}Ca/^{37}Ca = 0.0006608$, and $^{40}K/^{39}K = 0.0024$.

were indeed deposited as parts of a single fan, then there has been no significant horizontal displacement between the 2 formations since deposition (Chinn 1990; Savage et al. 1991).

The purpose of this study is (1) to characterize the petrography and geochemistry of the volcanic clasts contained within the Beecher's Bay Formation on Santa Rosa Island, and (2) to compare these clasts to those from the Blanca Formation on Santa Cruz Island using geochemical methods in order to test the ideas of McLean et al. (1976b) and McLean and Howell (1985) on the correlation between the 2 units.

Results

Thirty-two specimens of volcanic pebbles and cobbles were collected from conglomerate units in the Beecher's Bay Formation. Samples were collected to the west and south of Carrington Point from Member A, west of Skunk Point from member D, and at East Point from member E (sample locations are shown in Chinn 1990). Members B and C were not sampled because both are predominantly sandstone and siltstone with few volcanic clasts. Eleven representative samples were chosen on the basis of thin-section petrography and freshness for major-oxide and trace-element analyses. Seven samples were further analyzed for Sr isotopes and four for Nd isotopes.

Two whole-rock samples were dated by the K-Ar method (Chinn 1990); andesite BBF 12 (Member A) yielded an age of 21.0 ± 1.3 Ma and rhyolite sample BBF 18 (Member D) yielded an age of 25.5 ± 1.8 Ma. These dates are stratigraphically inconsistent and too old in view of the Relizian to middle-Luisian age suggested by the foraminiferal assemblage. Sample BBF 12 was redated using the $^{40}Ar/^{39}Ar$ method yielding a date of 15.80 ± 0.08 Ma based on data from 5 single plagioclase grains (Table 1). This date is consistent with the foraminiferal assemblages from member C. Two older plagioclase grains yielded a significantly older date of 24.4 ± 1.3 Ma and may have been derived from older volcanic units. The San Miguel Volcanics on San Miguel Island have K-Ar dates that range from 25 to 32 Ma (Crowe et al. 1976; Kamerling and Luyendyk 1985), and equivalent units have been mapped on Santa Rosa Island. Although the source of these grains is unknown, their presence has undoubtedly contributed to the apparently old K-Ar ages.

Petrographic descriptions of the Beecher's Bay clasts led Chinn (1991) to divide them into 3 main petrographic groups (Table 2): (1) clasts containing pyroxene phenocrysts (no hornblende), (2) clasts containing hornblende phenocrysts (no pyroxene), and (3) clasts containing both pyroxene and hornblende phenocrysts. Pyroxene-only clasts can be further subdivided on the basis of groundmass crystallinity. All samples containing hornblende but no pyroxene phenocrysts were collected from Member D and all holohyaline, pyroxene-only samples are from Member A. Clasts that belong to the merocrystalline, pyroxene-only group were collected from members A and E, and clasts that belong to the pyroxene-hornblende group were found in all 3 members. Most clasts have merocrystalline, fine-grained hypidiomorphic, porphyritic textures. Seven clasts have a holohyaline groundmass that results in a vitrophyric texture. The hornblende-bearing clasts have a merocrystalline groundmass with a felty texture consisting of very fine-grained,

Table 2. Summary of clast mineralogy.

Groups	Pyroxene only		Pyroxene and hornblende	Hornblende only
	Merocrystalline	Holohyaline		
Groundmass	(25-69) 46	(10-35) 18	(35-50) 42	(40-50) 45
Plagioclase	(20-50) 39	(45-80) 67	(30-55) 43	(35-55) 47
Augite	(2-20) 7	(5-10) 6	(3-10) 6	0
Hypersthene	(0-20) 5	(2-10) 4	(5-15) 3	0
Hornblende	0	0	(1-10) 3	(3-5) 4
Quartz	0	0	0	(1-4)2
Alteration products	(2-2) 2	(0-15) 4	(1-5) 1	(0-7) 2
Opaque minerals	(1-2) 1	0	0	0
Number of samples	12	7	8	5
Member(s)	A, E	A	A, D, E	D

Range of percent of minerals in parentheses followed by average. All abundances based on visual estimates.

tabular plagioclase, glass, and a small amount of pyroxene. Plagioclase phenocrysts are lath-shaped, subhedral to anhedral, and strongly zoned. Augite phenocrysts are euhedral to anhedral and show twinning and some zonation. Hypersthene is distinguished from augite by lower birefringence, anhedral shape, and faint green-to-pink pleochroism. Hornblende crystals are euhedral to subhedral; some are zoned and many are altered. Of the 8 samples in the hornblende and pyroxene group, only 2 contain hypersthene. All 5 samples in the hornblende-only group contain quartz.

Eleven representative samples were chosen for major-oxide and trace-element analyses (Table 3). Analytical methods used were X-ray fluorescence (XRF), direct coupled plasma (DCP), neutron activation (NA), induction coupled plasma (ICP), and plasma mass spectrometry (ICPMS). According to the classification of Le Bas et al. (1986), the Beecher's Bay clasts are classified as andesite, dacite, and rhyolite on a total alkalis-silica plot (Fig. 2a). Samples that belong to the pyroxene-only petrographic group are andesite and dacite, whereas those that contain hornblende are rhyolite. Beecher's Bay clasts plot in the low- to medium-K_2O fields on a potash-silica plot (Fig. 2b), in the subalkalic field on an alkalis-silica diagram (Fig. 2c), and are calc-alkaline on an AFM diagram (Fig. 2d). Harker diagrams for major oxides show fairly smooth trends for TiO_2, Al_2O_3, CaO, MgO, FeO_T, and P_2O_5 but exhibit more scatter for MnO, Na_2O, and K_2O (Chinn 1990). Clasts for this study were collected from Nuccio's (1977) members A, D, and E. There appears to be limited variation in the chemical composition of the clasts within these units. Harker diagrams of major elements vs SiO_2 (Chinn 1990) show that the pattern for samples from members A and E overlaps with SiO_2 concentrations of about 60 to 70 wt%. Titania concentrations are highest in member A and lowest in member D.

Plots of rare-earth elements (REE) normalized to chondrites show moderate overall enrichment and enrichment in the light REE (Fig. 2e), typical of calc-alkaline rocks (Wilson 1989). Values of La_N range from 25 to 60 and average 42, and those of La_N/Lu_N range from 5 to 18 and average 9. The heavy REE show more scatter and minor irregularities than the light REE. Two samples have small positive Eu anomalies and the rest have slight to moderate negative anomalies; Eu/Eu* ranges from 1.2 to 0.6 (Eu* is the concentration of Eu interpolated from its neighbor elements in the REE pattern). Patterns of selected Blanca samples demonstrate that the 2 sets of clasts have overlapping REE contents (Fig. 2e). Concentrations of the REE decrease in both sets of clasts with decreasing SiO_2 contents.

Table 3. Major-oxide and trace-element analyses of selected samples from the Beecher's Bay Formation.

Sample	BBI 4	BBF 10	BBF 11	BBF 12	BBF 14	BBF 17	BBF 18	BBF 24	BBF 26	BBF 29	BBF 34	DL	Method
Member	A	A	A	A	A	A	D	E	E	E	E		
Group	P(h)	P(m)	P+H	P(m)	P(h)	P(h)	P+H	H	P(m)	P(m)	P(m)		
SiO_2	61.8	66.7	71.1	59.5	58.5	61.3	73.9	75.2	69.2	65.7	67.1	0.01	XRF
TiO_2	0.91	0.91	0.29	1.09	1.14	0.98	0.27	0.30	0.55	0.74	0.67	0.01	XRF
Al_2O_3	16.2	17.0	14.9	16.5	16.9	15.7	14.9	13.6	15.8	15.9	15.0	0.01	XRF
Fe_2O_{3T}	5.01	2.03	1.79	6.02	6.14	5.65	0.40	0.58	1.26	3.23	3.31	0.01	XRF
MnO	0.09	0.02	0.03	0.10	0.10	0.10	< 0.01	0.01	0.01	0.07	0.07	0.01	XRF
MgO	2.63	0.71	1.44	3.71	2.78	3.31	0.23	0.33	0.80	1.67	1.85	0.01	XRF
CaO	5.21	5.58	2.79	6.61	5.91	5.59	2.77	2.74	4.70	4.32	3.93	0.01	XRF
Na_2O	4.18	4.86	5.15	4.29	4.26	4.26	5.35	5.00	4.70	4.67	4.90	0.01	XRF
K_2O	1.95	1.04	1.47	1.01	1.35	1.31	1.37	1.09	1.16	1.49	1.46	0.01	XRF
P_2O_5	0.21	0.18	0.08	0.19	0.21	0.19	0.06	0.07	0.10	0.15	0.14	0.01	XRF
LOI	1.54	1.00	0.77	0.93	0.85	0.93	0.77	1.08	0.54	1.16	0.93		
Sum	99.73	100.03	99.99	99.95	98.14	99.32	100.02	100.00	98.82	99.10	99.36		
S	BD	5,410	1,920	100	BD	BD	485	668	BD	BD	BD	50	XRF
V	93	107	52	120	87	96	32	30	66	62	64	2	DCP
Cr	41	77	35	78	20	83	25	19	110	27	28	2	NA
Ni	25	23	38	29	16	38	15	13	22	20	20	1	ICP
Co	23	21	8	28	26	25	3	5	9	15	14	1	ICP
Cu	14.1	19.5	14.0	29.5	19.4	24.0	12.0	12.3	18.2	10.0	14.0	0.5	ICP
Zn	64.6	28.0	35.8	75.7	74.4	74.8	15.1	18.3	37.6	50.0	55.4	0.5	ICP
Ga	20.9	17.6	17.0	20.3	22.9	20.6	16.5	14.9	16.6	20.4	18.4	0.1	ICP
Li	13	24	26	18	32	29	29	29	29	18	23	1	ICP
Sc	11.1	12.6	4.98	15.1	12.9	12.7	2.88	2.76	7.14	9.56	8.06	0.5	ICP
Rb	29	20	38	42	35	39	26	23	30	61	56	2	XRF
Sr	466	453	531	384	404	377	575	426	431	384	349	1	XRF
Cs	2	1	3	2	3	1	1	1	1	3	3	0.5	NA
Ba	449	384	513	326	445	347	494	454	394	496	534	10	XRF
Y	17	12	8	19	21	17	4	7	10	16	15	1	ICP
Zr	135	140	105	156	174	154	92	86	114	176	164	1	XRF
Nb	15	18	11	18	22	18	14	10	18	17	17	2	XRF
Sb	0.2	< 0.2	0.6	0.5	0.2	0.2	0.2	< 0.2	0.2	0.2	0.4	0.2	NA
Hf	3.6	3.9	2.9	4.2	4.3	4.5	2.5	2.4	2.9	3.7	4.3	0.5	NA
Ta	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	BD	1	NA
Th	2.8	2.0	2.8	2.6	3.8	3.0	2.3	1.9	2.6	3.5	4.2	0.5	NA
U	1.4	1.1	1.5	1.2	1.7	1.5	1.2	1.1	1.4	1.7	2.0	0.5	NA
La	15.1	14.1	10.9	15.5	20.0	16.4	8.5	9.4	11.5	15.1	16.3	0.1	ICPMS
Ce	31.5	28.4	21.0	30.1	39.2	34.1	16.8	19.3	23.1	31.3	32.8	0.1	ICPMS
Pr	4.0	3.2	2.2	4.3	5.4	4.4	2.3	2.2	2.6	3.5	3.7	0.1	ICPMS
Nd	3.7	3.1	1.4	4.0	3.7	3.3	2.0	2.0	2.3	3.3	3.9	0.1	ICPMS
Sm	3.7	3.1	1.4	4.0	3.7	3.3	2.0	2.0	2.3	3.3	3.9	0.1	ICPMS
Eu	0.79	0.70	0.31	1.27	1.25	1.07	0.62	0.50	0.47	0.91	1.12	0.1	ICPMS
Gd	2.7	2.7	1.8	3.2	4.9	5.4	1.0	1.6	2.0	2.8	3.4	0.1	ICPMS
Tb	0.6	0.5	0.3	0.7	0.7	0.6	0.2	0.3	0.3	0.5	0.5	0.1	ICPMS
Dy	3.2	2.7	1.2	3.4	4.6	3.7	0.7	1.2	1.9	2.9	3.7	0.1	ICPMS
Ho	0.86	0.50	0.26	0.87	0.82	0.75	0.16	0.18	0.39	0.52	0.51	0.05	ICPMS
Er	1.5	1.5	0.6	2.1	2.7	2.0	0.3	0.5	1.5	1.7	1.8	0.1	ICPMS
Tm	0.3	0.1	BD	0.4	0.4	0.4	BD	BD	0.1	0.2	0.3	0.1	ICPMS
Yb	1.7	1.3	0.9	1.9	2.1	2.2	0.3	0.6	1.1	1.7	1.7	0.1	ICPMS
Lu	0.30	0.19	0.07	0.30	0.31	0.24	BD	0.14	0.10	0.27	0.16	0.05	ICPMS

DL = *D*etection *L*imit. Major oxides in wt %, trace elements in ppm. Total iron expressed as Fe_2O_{3T}. LOI = *L*oss *O*n *I*gnition. BD = *B*elow *D*etection. Group refers to petrographic group: P(h) = *P*yroxene-only *h*olohyaline, P(m) = *P*yroxene-only *m*erocrystalline, P+H = *P*yroxene + *H*ornblende, and H = *H*ornblende only.

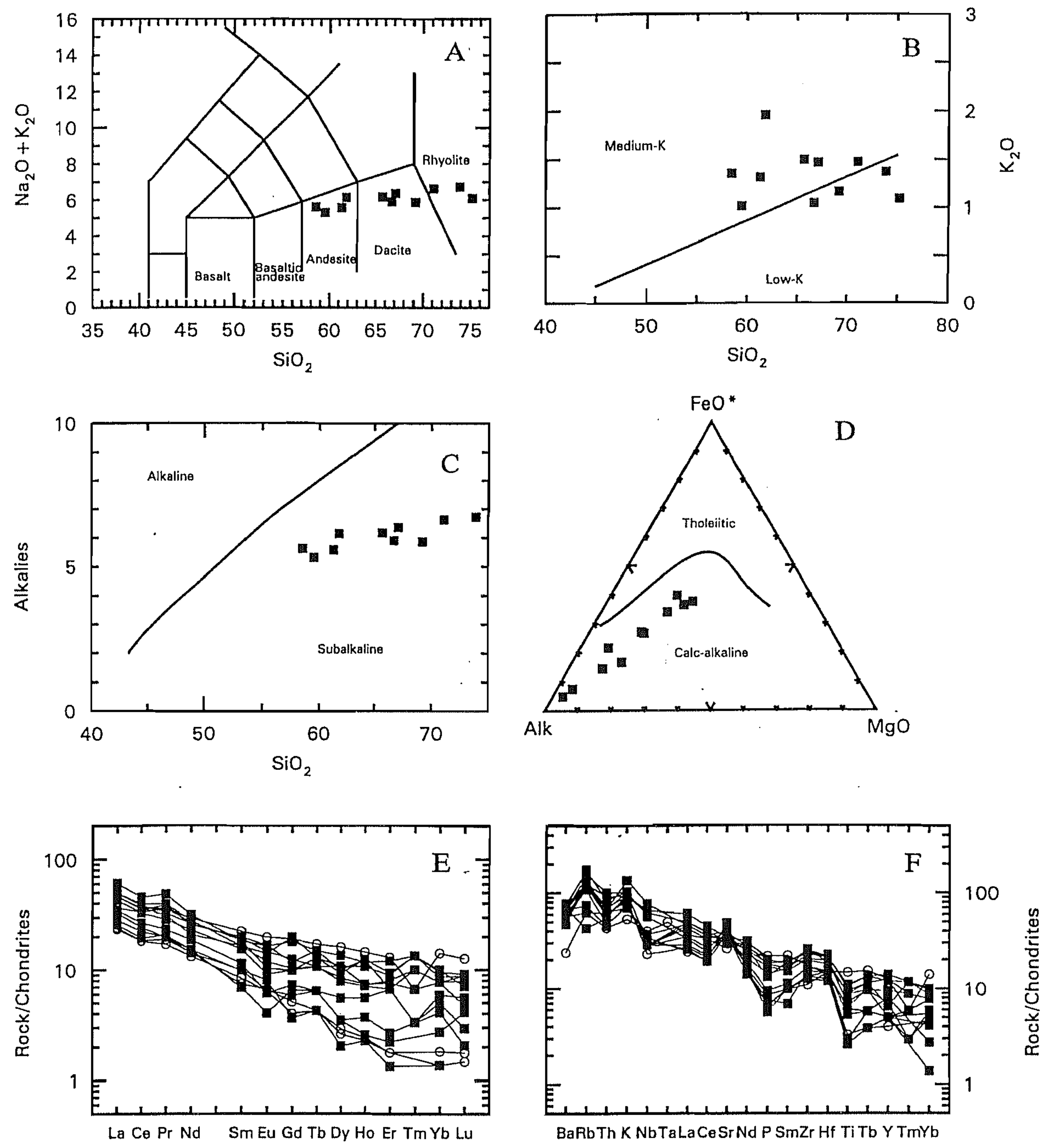

Figure 2. Geochemical diagrams for volcanic clasts from the Beecher's Bay Formation. **2A.** Rock names of individual samples; boundaries from Le Bas et al. (1986). **2B.** K_2O series; boundaries from Gill (1981). **2C** and **2D.** Alkalis-silica and AFM diagrams for magma series; boundaries from Irvine and Barager (1971). **2E.** Rare-earth element diagram; normalizing data from Nakamura (1974). Data from selected Blanca clasts plotted as open circles. **2F.** Spider diagram; normalizing data from Thompson et al. (1984).

Spider-diagram patterns normalized to chondritic meteorites are shown in Figure 2f. The Beecher's samples show slight negative spikes for Ba, Th, Nb, P, and Ti and slight positive spikes for Sr and Zr-Hf. These clasts do not exhibit a distinct Ta-Nb trough typical of subduction-related igneous rocks. Also shown are patterns of selected Blanca clasts. Patterns from both sets of clasts are strikingly similar.

None of the Beecher's clasts are very mafic. The most mafic samples are classified as andesite based on SiO_2 contents (Fig. 2a). In addition, MgO, Ni, and Cr contents and Mg# are all low; for instance, the highest Mg# is 41. These data demonstrate that none of these samples represent mantle melts unmodified by differentiation processes.

Crystal fractionation models were calculated by least-squares methods, which start with the known major-

Table 4. Summary of modelling calculations.

Parent	andesite BBF 12	dacite BBF 29
Daughter	dacite BBF 29	rhyolite BBF 18
% Mineral subtracted		
Olivine	0	0
Augite	8.8	3.9
Hypersthene	3.6	2.9
Plagioclase (% An)	28.5 (46)	20.7 (41)
Magnetite	3.1	2.4
% Liquid left	55.5	69.4
SOSOR	0.03	0.37

SOSOR = *S*um *O*f *S*quares *O*f *R*esiduals (see text).

oxide composition of 2 samples and calculate the abundance of various minerals which could be removed from the parent to form the daughter. Goodness of fit of the model is determined from the sum of the squares of the residuals (sosor), or differences between the observed and calculated major-oxide abundances. The smaller the sosor the better the model is in explaining compositional differences between less evolved and more evolved samples.

Three samples were chosen which span the compositional range from andesite to rhyolite. A 2-step model was used in which andesite BBF 12 was used as parent to dacite BBF 29 and BBF 29 was then considered to be parent to rhyolite BBF 18. Since no analyses of minerals from Beecher's Bay clasts are available, analyses from a variety of sources were used: Blanca clasts (Savage and Weigand 1994), Central American volcanics (M. J. Carr 1985, pers. comm.), and a general compilation (Deer et al. 1963). Neither apatite nor ilmenite were considered in these calculations.

The results are presented in Table 4. The low magnitudes of the sosor indicate a good fit in both cases. The large amounts of plagioclase and lack of olivine are consistent with the high modal percentage of plagioclase and lack of modal olivine in the samples examined (Table 2). A better fit for the derivation of the rhyolite from the dacite is possible if plagioclase of higher An content is used, but an An content of 41 for plagioclase in dacite seems more reasonable. A further test of these models can be made by using the best-fit mineral assemblages to predict variations of geochemically diverse trace elements. Trends of compatible transition elements such as Ni, Cr, and V are adequately predicted. However, the decreasing trends of incompatible elements such as Rb, Ba, Zr, and La with increasing SiO_2 content are not predicted, nor is the increasing trend of Sr. The reason for failure of the best-fit mineral assemblages to model these trace-elements is not clear, although trends of these elements in the Conejo Volcanics and the Blanca clasts could not be modeled either (Weigand and Savage 1993; Savage and Weigand 1994).

Trace-element abundances can be used to statistically compare clasts from the Beecher's Bay and Blanca Formations. We used 8 trace elements whose concentrations in igneous rocks are the result of magmatic processes and are relatively unaffected by postmagmatic alteration processes (Abbott and Smith 1989). The 2 data sets are considered comparable if the standard error of the difference is less than 3 times the difference between the means (Reichmann 1961). Using this criterion, the 2 sets of clasts are statistically identical with respect to these 8 trace elements (Table 5).

Table 5. Comparison of standard error of the difference between clasts from the Beecher's Bay and Blanca Formations using selected trace elements.

Trace	Beecher's Bay [1,2]		Blanca [1,2]			Standard	Significant
element	$\bar{X}_1$	1σ	$\bar{X}_2$	1σ	$\lvert\bar{X}_1-\bar{X}_2\rvert$	difference[3]	difference
Ni	23.55	8.08	17.22	6.27	6.32	3.21	None
Cr	49.36	30.15	35.56	9.75	13.81	9.66	None
V	73.55	28.14	44.00	18.60	29.55	10.51	None
Rb	34.45	12.34	37.89	12.75	3.43	5.65	None
Sr	434.55	65.45	467.6	70.49	33.12	30.68	None
Zr	136.00	30.82	93.33	20.10	42.67	11.46	None
Nb	16.18	3.30	10.44	2.06	5.74	1.21	None
Ba	439.64	65.65	374.1	63.28	65.53	28.93	None

Abundances expressed as ppm. Sample size (n) for Beecher's Bay = 11 and for Blanca = 9.

[1] Mean = $\frac{1}{n}\sum_{i=1}^{n}$

[2] Standard deviation = $\sqrt{(\Sigma x^2 - n\bar{x}^2)/n}$

[3] Standard error of the difference = $\sqrt{(\sigma_1^2/n_1)+(\sigma_2^2/n_2)}$

Table 6. Strontium and neodymium isotope data.

Sample number	Rock type	Rb	Sr	$^{87}Sr/^{86}Sr_m$	$^{87}Sr/^{86}Sr_i$	$^{143}Nd/^{144}Nd_m$	ε_{Nd} i
BBF 11	Rhyolite	44	531	0.704103 ± 13	0.70405		
BBF 12	Andesite	42	384	0.704092 ± 13	0.70402		
BBF 14	Andesite	44	404	0.703998 ± 15	0.70393	0.512809 ± 10	3.4
BBF 18	Rhyolite	39	575	0.704530 ± 70	0.70449		
BBF 24	Rhyolite	26	426	0.703873 ± 12	0.70383	0.512925 ± 8	6.0
BBF 29	Dacite	61	384	0.703859 ± 14	0.70376	0.512931 ± 8	6.1
BBF 34	Dacite	56	349	0.703752 ± 12	0.70365	0.512908 ± 8	5.7

Rb and Sr in ppm; m = measured; i = initial. Initial ratios calculated using an age of 15 Ma. $^{143}Nd/^{144}Nd$ ratio of CHUR, normalized to $^{146}Nd/^{144}Nd$ = 0.7219, is 0.512638.

Strontium and neodymium isotopic ratios are listed in Table 6. Initial $^{87}Sr/^{86}Sr$ values are relatively low and range from 0.70365 to 0.70449. Initial ε_{Nd} values range from 3.4 to 6.1. These data are plotted on a Nd-Sr correlation diagram in Figure 3. The orthogonal lines represent estimates of the isotopic composition of the bulk earth, and data from oceanic-ridge and oceanic-island basalts, thought to represent mantle melts, define a "mantle array" (Faure 1986). Beecher's Bay samples plot on the mantle array in upper left quadrant of the diagram. Samples that plot in this quadrant are interpreted to have originated from the depleted zone of the mantle and to have experienced very little crustal contamination (Faure 1986).

Discussion

Howell and McLean (1976) proposed that the Blanca Formation on Santa Cruz Island, including the exposure at Near Point, and the Beecher's Bay Formation on Santa Rosa Island constitute different portions of a single submarine fan. McLean and Howell (1985) described what they called the Blanca submarine fan and suggested that the volcanic source was located on the northern side of a transcurrent fault, one of many that existed in early and middle Miocene time. The source continued to move to the southeast along this fault, which formed deep basins and uplifted linear ridges; these ridges, in turn, provided the sediment source of the Blanca Fan.

Combined with the results of other studies, the data from this study can be used to elucidate these theories. Information from the following areas can be examined: (1) stratigraphic position and age, (2) trace-element abundances, and (3) isotopic ratios.

Weaver et al. (1969) showed that the Blanca Formation on Santa Cruz overlies the San Onofre Breccia and is younger than the Monterey Formation. McLean et al. (1976a) reported a foraminiferal assemblage in the Blanca that ranges in age from Relizian to Luisian (17–14 Ma). A basaltic-andesite flow from the upper member has a K-Ar date of 19.9 ± 0.8 Ma and a clast from the middle member has a K-Ar date of 13.3 ± 1.2 Ma. Avila (1977) showed that the Beecher's Bay Formation overlies the Rincon Formation and underlies the Monterey Formation on Santa Rosa Island. Fossils suggest a Relizian to middle-Luisian age (17 to 15 Ma). This study reports an Ar-Ar age of a clast from member A of 15.8 ± 0.09 Ma. Thus, fossil and radiometric ages of the two overlap and are indistinguishable.

There are several ways that the trace-element composition of the 2 sets of clasts can be compared. A statistical comparison shows that the 2 clast populations are identical with respect to 8 trace elements whose concentrations are thought to be the result of magmatic, not alteration, processes (Table 6). Silica-variation diagrams for all trace elements show overlapping trends for both clast suites (Chinn 1991). These similarities are also shown on REE and spider diagrams (Figs. 2e and 2f), in which patterns for both Beecher's Bay and Blanca clasts overlap and are very similar. Savage and Despard (1990) compared abundances of trace elements in Blanca clasts with abundances in selected other middle to late Tertiary volcanic suites in California. They found that with the exception of Sr, incompatible elements like Rb, Zr, Ba, Hf, Th, and La are depleted in Blanca clasts relative to other evolved volcanic rocks. Strontium, which is generally low in evolved rocks, has a relatively high abundance in Blanca clasts. This study has shown that Beecher's Bay clasts are similar in trace-element characteristics to Blanca clasts. Thus, not only are Beecher's Bay and Blanca clasts similar in trace-element abundances, but as a group are different from other nearby volcanic centers.

Similarities in trace-element characteristics in the Beecher's Bay and Blanca clasts extend to fractional crystallization models. Calculations in Savage and Weigand (1994) showed that the mineral assemblage that can best explain the variation in major oxides shown by Blanca clasts cannot successfully model the variations shown by several incompatible trace elements. Similar calculations for the Beecher's Bay clasts discussed above also show that the best-fit mineral assemblage calculated from major-oxide concentrations cannot reproduce the variations shown by numerous incompatible trace elements.

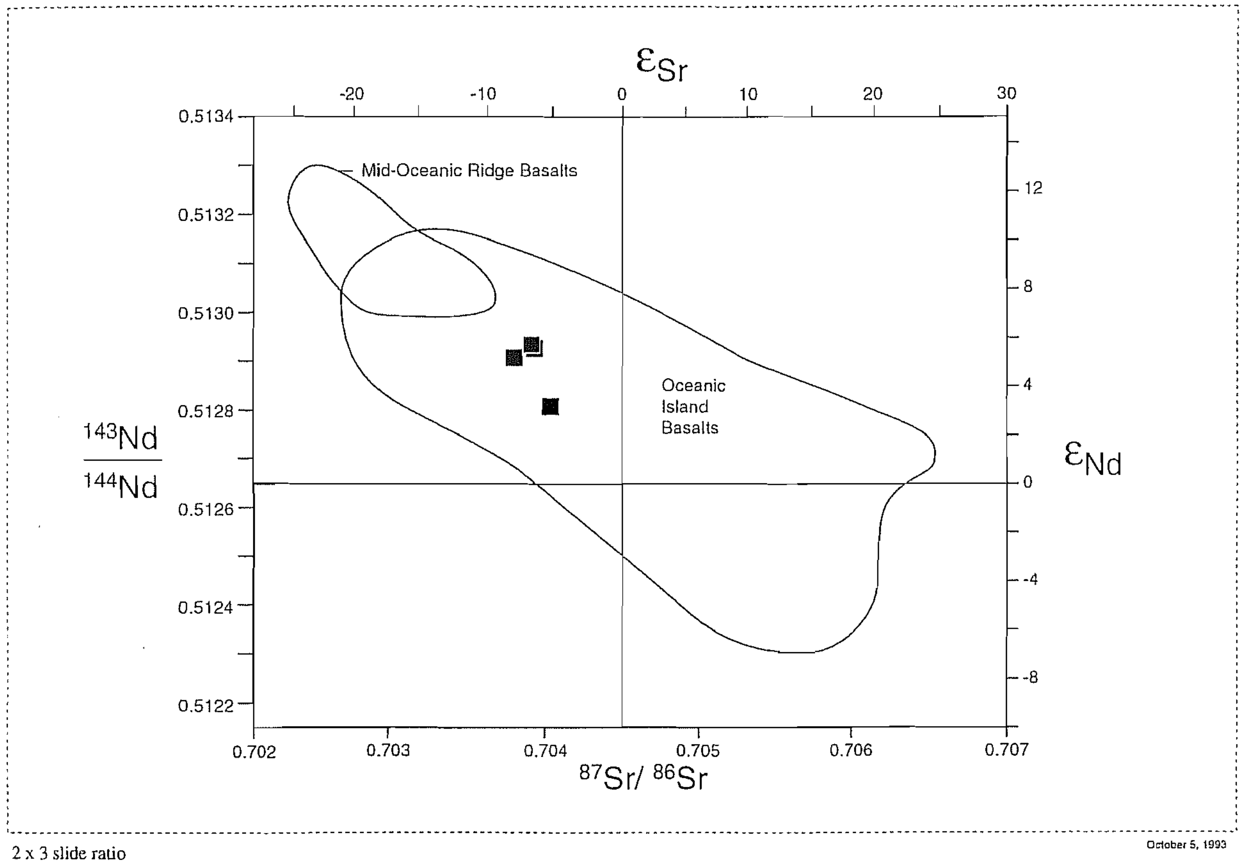

Figure 3. Neodymium-strontium isotope correlation diagram.

Finally, isotopic values of $^{87}Sr/^{86}Sr$ for both Beecher's Bay clasts and Blanca clasts are low and similar. Beecher's Bay values average 0.70403 ± 0.00020 (±2 SEM, n=7) and Blanca values average 0.70374 ± 0.00024 (±2 SEM, n=10); these averages statistically overlap.

The only geochemical parameter that exhibits a difference between the 2 sets of clasts is major-oxide concentrations. The limited number of Beecher's Bay clasts that have been analyzed suggests that compositions vary regularly from andesite to rhyolite. Blanca clasts, on the other hand, predominantly fall on the dacite-rhyolite boundary, and andesite clasts are uncommon. Nevertheless, the preponderance of evidence suggests that the volcano(es) that were the source of the Beecher's Bay and Blanca clasts are consanguineous, that is they were probably derived from the same parent magma. Thus, we conclude that the 2 sets of clasts had the same provenance. This confirms a key aspect of the submarine-fan models of Howell and McLean (1976) and McLean and Howell (1985).

Conclusions

Both the Beecher's Bay Formation and the Blanca Formation occupy the same stratigraphic position and contain volcanic clasts that had the same provenance. Radiometric dates for the 2 formations are similar, and fossil evidence shows them to have a similar age. Major-oxide and trace-element Harker diagrams for clasts from both formations show very similar patterns. Spider diagrams and rare-earth element patterns for both sets of clasts overlap, and both sets have anomalously low concentrations of the incompatible trace elements when compared to other Tertiary California volcanic rocks (Savage and Despard 1990). These various lines of evidence lead us to conclude that both sets of clasts were derived from a single volcanic complex and were deposited as different parts of a single submarine fan. This implies that their geographic areas of exposure have remained in proximity to each other and thus have not been significantly displaced from each other since deposition.

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