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Petrology and Geochemistry of the Volcanic Clasts from the Miocene Blanca Formation, Santa Cruz Island, California

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Abstract. The Blanca Formation of medial Miocene age consists of primary and reworked fragments of volcanic origin. It crops out south of the Santa Cruz Island fault on Santa Cruz Island and has been divided into 3 members. Major-oxide, trace-element, and Sr-isotopic analyses were made of volcanic pebbles and cobbles from the conglomeratic units. About 95% of these clasts are dacite and rhyolite and belong to the low- to medium-K calc-alkaline magma series. Relative to typical calc-alkaline rhyolites, the Blanca clasts have a high Sr abundance and low abundances of incompatible trace elements such as Rb, Ba, Zr, Hf, Th, and U. Niobium, characteristically depleted in subduction-related calc-alkaline suites, is not depleted in Blanca clasts. The light rare-earth elements are moderately enriched (La = 40–60 x chondrite) and moderately fractionated (La_N/Lu_N = ~7) in the felsic clasts. Initial $^{87}Sr/^{86}Sr$ values of 5 felsic clasts average 0.70366 and indicate a mantle origin for the parental magma. Crystal fractionation calculations adequately model the major-oxide variation from basaltic-andesite to rhyolite, assuming assemblages of plagioclase + augite + magnetite ± hypersthene ± olivine, but are less successful in reproducing trends exhibited by several incompatible trace elements. Clasts from 3 members of the Blanca Formation are chemically identical with one exception: TiO_2 content in clasts from the upper unit exceed those in clasts from the lower 2 units (0.49 ± 0.08 wt% vs 0.29 ± 0.04 wt%, respectively). The Blanca clasts share geochemical, isotopic, and age similarities with the Conejo, Zuma, and Glendora Volcanics and clasts from the Beecher's Bay Formation. In spite of the calc-alkaline character of this group of suites, evidence suggests that extensional melting in the mantle produced the magmas parental to these volcanic suites, combined with subsequent low-pressure fractional crystallization, produced the felsic end members including the Blanca clasts.

Keywords: California; Channel Islands; Miocene; volcanic rocks; geochemistry.

Introduction and Previous Work

Santa Cruz Island, the largest of the northern Channel Islands off the coast of southern California, is located approximately 40 km due south of Santa Barbara. The island is cut by the east-west trending Santa Cruz Island fault; the northern half of the island is underlain mostly by Santa Cruz Island Volcanics and Monterey Formation, while the southern half consists of Jurassic metamorphic and plutonic rocks and a Tertiary sedimentary and volcaniclastic section. The medial Miocene Blanca Formation crops out on the southern half the island and extends from Valley Anchorage west to Christi Ranch (Fig. 1). Exposures cover 20 km^2 and reach a maximum thickness of 1,400 m (Fisher and Charlton, 1976). The Blanca locally overlies the Willows Plutonic Complex, the San Onofre Breccia, or the Rincon Formation. The top of the formation is nowhere exposed on land, but it may continue offshore to the south (Vedder et al. 1986). The Blanca Formation consists of volcaniclastic conglomerates and breccias, epiclastic tuffaceous sandstone, and siltstone interbedded with primary pyroclastic layers and minor basaltic-andesite flows (McLean et al. 1976a). Weaver et al. (1969) divided the formation into 3 members—lower, middle, and upper—based on color, texture, and percentage of volcanic clasts. Deposition of the Blanca Formation is believed to have occurred in a near-shore environment, adjacent to an active volcanic source (Fisher and Charlton 1976).

McLean et al. (1976a) reported that 40% of a sample set of 91 clasts are andesite. Fisher and Charlton (1976) concluded that 15 to 90% of the clasts in the upper member are composed of andesite. However, Shelton (1988) has shown that the majority of the clasts are classified as rhyolite based on SiO_2 contents.

Weaver and Nolf (1969) mapped the outcrop of volcaniclastic rocks overlying the San Onofre Breccia at Near Point as the Beecher's Bay Member of the Monterey Formation. Using stratigraphic and petrographic evidence, McLean et al. (1976b) concluded that this exposure was correlative with the Blanca Formation. McLean

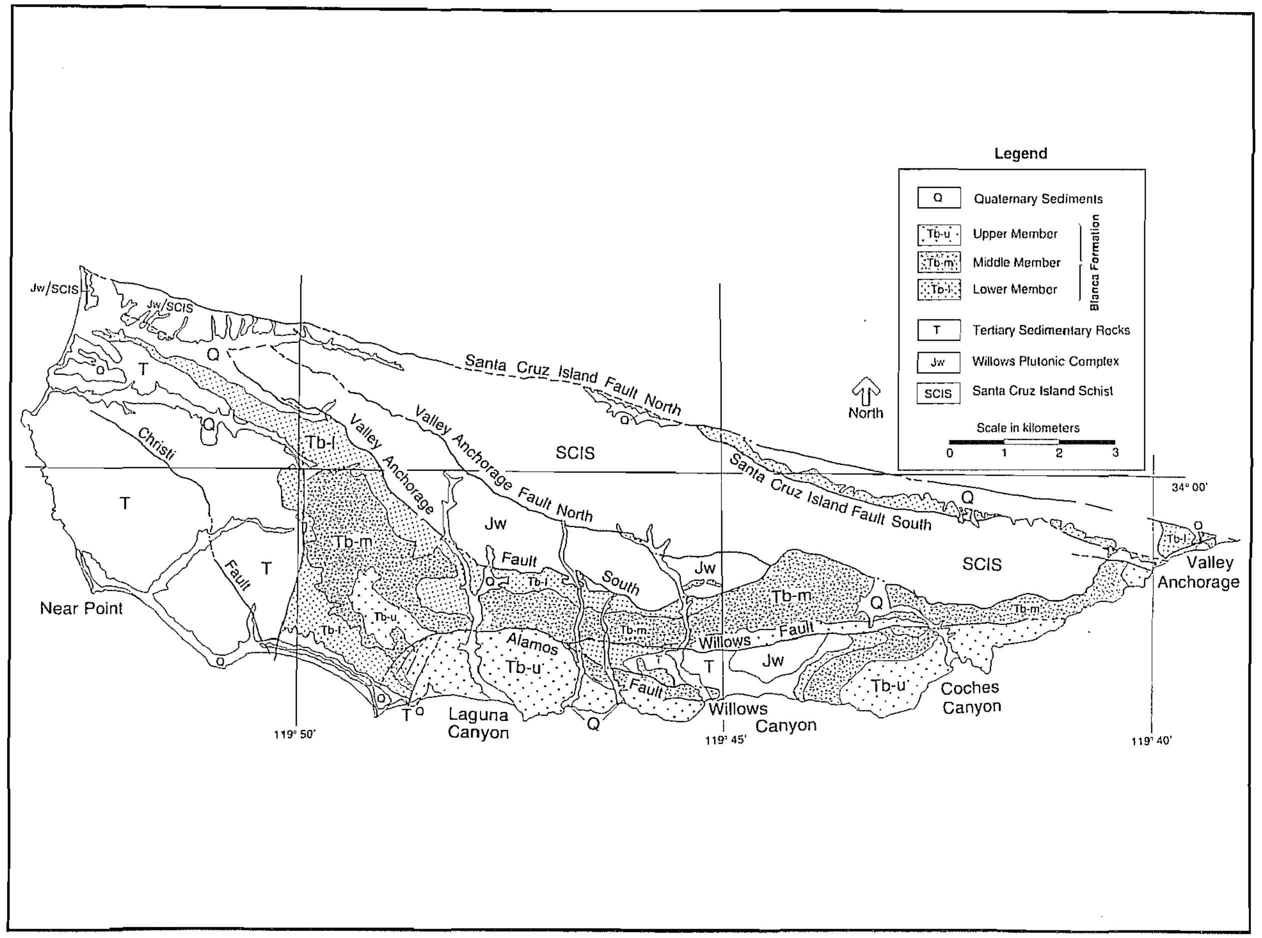

Figure 1. Geological map of the southern portion of Santa Cruz Island modified from Weaver and Nolf (1969).

and Howell (1985) proposed that the Blanca Formation, including both the exposure at Near Point on Santa Cruz Island and the correlative Beecher's Bay Member exposed on Santa Rosa Island 10 km to the west, was deposited as various parts of a submarine fan. They 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.

Weaver et al. (1969) reported a Relizian foraminiferal assemblage in the volcaniclastic strata at Near Point. A basaltic-andesite flow from the upper member of the Blanca Formation has been dated at 14.9 ± 0.8 Ma, and a dacite clast from the upper member has been dated at 13.3 ± 1.2 Ma, both by the K-Ar method (McLean et al. 1976a).

Weaver et al. (1969) concluded that the source of the volcanic clasts of the Blanca Formation was the Santa Cruz Island Volcanics located north of the Santa Cruz Island fault, whereas Howell and McLean (1976), Shelton (1988), and Weigand (1993) presented petrographic and geochemical evidence strongly suggesting that the Santa Cruz Island Volcanics was not the source. The volcanic center that served as the provenance for the clasts is currently unidentified.

The purpose of this study was multifold. We sought to (1) define the intra- and intermember geochemical variation within the Blanca Formation to determine whether 1 or more magma types are represented; (2) to reassess at the correlation between the clasts and the Santa Cruz Island Volcanics utilizing trace-element and isotopic data; (3) to determine if fractional crystallization could account for the geochemical variation shown by the clasts; (4) to compare and contrast the geochemical composition of the Blanca clasts with other nearby Miocene volcanic suites; (5) to elucidate the petrogenesis of the source magma, including the tectonic environment of magma genesis.

A variety of analytical techniques was utilized during the course of this study. Mineral analyses of the basaltic-andesite clast were made with an ARL-EMX microprobe at University of California, Los Angeles. X-

Table 1. Major-oxide and trace-element analyses of selected samples from the Blanca Formation.

Sample	BF 34	BF 43	BF44	BF58	BF 22	BF 4	BF 2	BF 54	Mbb 2	Mbb 10	Mbb 12	D.L.	Method
Member	Upper	Upper	Upper	Upper	Middle	Lower	Lower	Flow					
SiO_2	70.9	70.0	73.2	66.8	71.4	70.3	52.3	55.7	73.1	71.2	70.2	0.01	XRF
TiO_2	0.45	0.63	0.34	0.49	0.35	0.31	1.53	1.87	0.28	0.28	0.31	0.01	XRF
Al_2O_3	16.3	15.5	14.1	15.6	14.6	16.9	15.9	15.2	15.2	16.0	17.2	0.01	XRF
Fe_2O_{3T}	0.83	2.09	1.65	2.95	2.13	0.65	9.89	9.54	0.55	0.80	0.45	0.01	XRF
MnO	0.01	0.02	0.02	0.01	0.01	0.01	0.14	0.18	BD	BD	BD	0.01	XRF
MgO	0.14	0.53	0.48	1.26	0.12	0.36	5.58	3.87	0.37	0.31	0.31	0.01	XRF
CaO	3.53	3.76	2.83	3.62	3.05	3.75	8.75	6.48	3.02	3.69	3.97	0.01	XRF
Na_2O	5.95	4.67	5.12	5.38	4.99	5.54	3.41	4.11	5.78	5.70	6.06	0.01	XRF
K_2O	1.23	1.36	1.27	1.18	1.33	1.09	0.77	1.08	1.33	1.08	1.25	0.01	XRF
P_2O_5	0.02	0.09	0.07	0.01	0.07	0.03	0.23	0.34	0.01	0.01	0.01	0.01	XRF
LOI	0.85	1.23	0.70	3.00	2.00	0.77	0.70	1.62	0.54	0.85	0.62		
Sum	100.21	99.97	99.78	100.30	100.05	99.71	99.20	99.99	100.18	99.92	100.38		
V	38	90	40	60	42	38	210	160	28	30	30	2	DCP
Cr	16	48	26	38	28	36	140	54	45	40	43	2	NA
Ni	5	18	16	27	25	14	58	23	18	12	20	1	ICP
Co	4	8	7	8	8	4	35	29	3	BD	3	1	ICP
Cu	4	20	10	28	18	9	41	31	11	9	9	0.5	ICP
Zn	7	42	32	51	24	13	93	108	14	8	26	0.5	ICP
Ga	20.5	18.8	18.3	21	17.8	17.7	25	26	16	18	18	0.1	ICP
Li	10	24	16	17	20	14	6	11	18	18	22	1	ICP
Sc	5	10	6	7.7	6	4	24	19.1	3.7	4.3	4.4	0.05	ICP
Rb	40	52	42	15	58	46	22	35	31	25	32	2	XRF
Sr	597	434	481	377	456	579	309	335	423	406	456	1	ICP
Cs	0.5	0.5	0.5	BD	BD	1.3	1.3	1	1	BD	1	0.5	NA
Ba	375	460	402	389	425	293	164	315	441	301	281	10	XRF
Y	4	10	8	9	7	3	25	29	4	4	1	1	ICP
Zr	94	91	75	133	75	61	117	218	103	101	107	1	XRF
Nb	10	12	8	12	6	12	14	23	12	12	10	2	XRF
Sb	0.2	0.2	0.2	0.2	0.2	0.1	0.2	BD	BD	0.2	BD	0.2	NA
Hf	3	3	3	3.4	BD	3	3	6.5	3	2.8	3.2	0.5	NA
Ta	BD	BD	BD	BD	BD	BD	1	BD	BD	BD	BD	1	NA
Th	1.8	2.4	2.4	2.3	BD	2.5	1.8	3.5	2.1	1.9	2.0	0.5	NA
U	1.1	1.5	1.1	1.1	BD	0.8	0.5	1.5	0.9	1.2	0.9	0.5	NA
La	6.6	8.0	8.9	11.7	10.4	7.4	12.0	20.8	7.7	8.0	7.2	0.1	ICPMS
Ce	12.6	16.7	18.2	23.9	20.9	14.2	28.8	46.4	15.7	16.0	14.7	0.1	ICPMS
Pr	1.5	2.2	2.3	2.9	2.6	1.7	4.0	6.1	1.9	2.1	1.8	0.1	ICPMS
Nd	5.8	10.2	9.9	12.4	11.0	6.4	18.4	28.7	8.3	9.0	8.5	0.1	ICPMS
Sm	1.2	2.0	2.0	2.5	2.0	1.2	4.5	6.0	1.7	1.5	1.4	0.1	ICPMS
Eu	0.95	0.95	0.77	0.75	0.74	0.70	1.51	1.85	0.49	0.51	0.52	0.1	ICPMS
Gd	1.1	1.9	2.1	2.4	1.9	1.0	5.2	6.1	1.1	1.4	1.4	0.1	ICPMS
Tb	0.1	0.3	0.2	0.4	0.2	BD	0.8	1.0	0.2	0.2	0.2	0.1	ICPMS
Dy	1.1	2.0	1.7	1.9	1.5	0.8	5.5	5.9	1.0	0.9	1.1	0.1	ICPMS
Ho	0.19	0.37	0.33	0.36	0.023	0.09	1.01	1.15	0.17	0.16	0.23	0.05	ICPMS
Er	0.5	1.1	1.0	1.0	0.5	0.2	2.9	3.5	0.4	0.4	0.6	0.1	ICPMS
Tm	BD	BD	BD	0.1	BD	BD	0.2	0.4	BD	BD	BD	0.1	ICPMS
Yb	0.6	1.2	1.0	0.9	0.6	0.4	3.1	3.2	0.4	0.3	0.6	0.1	ICPMS
Lu	BD	0.15	0.11	0.13	BD	BD	0.43	0.46	0.06	0.05	0.08	0.05	ICPMS

BD = below detection. Mbb samples from Near Point, D.L., is detection unit. Major oxides in wt %. Trace elements in ppm. Total iron expressed as Fe_2O_3.

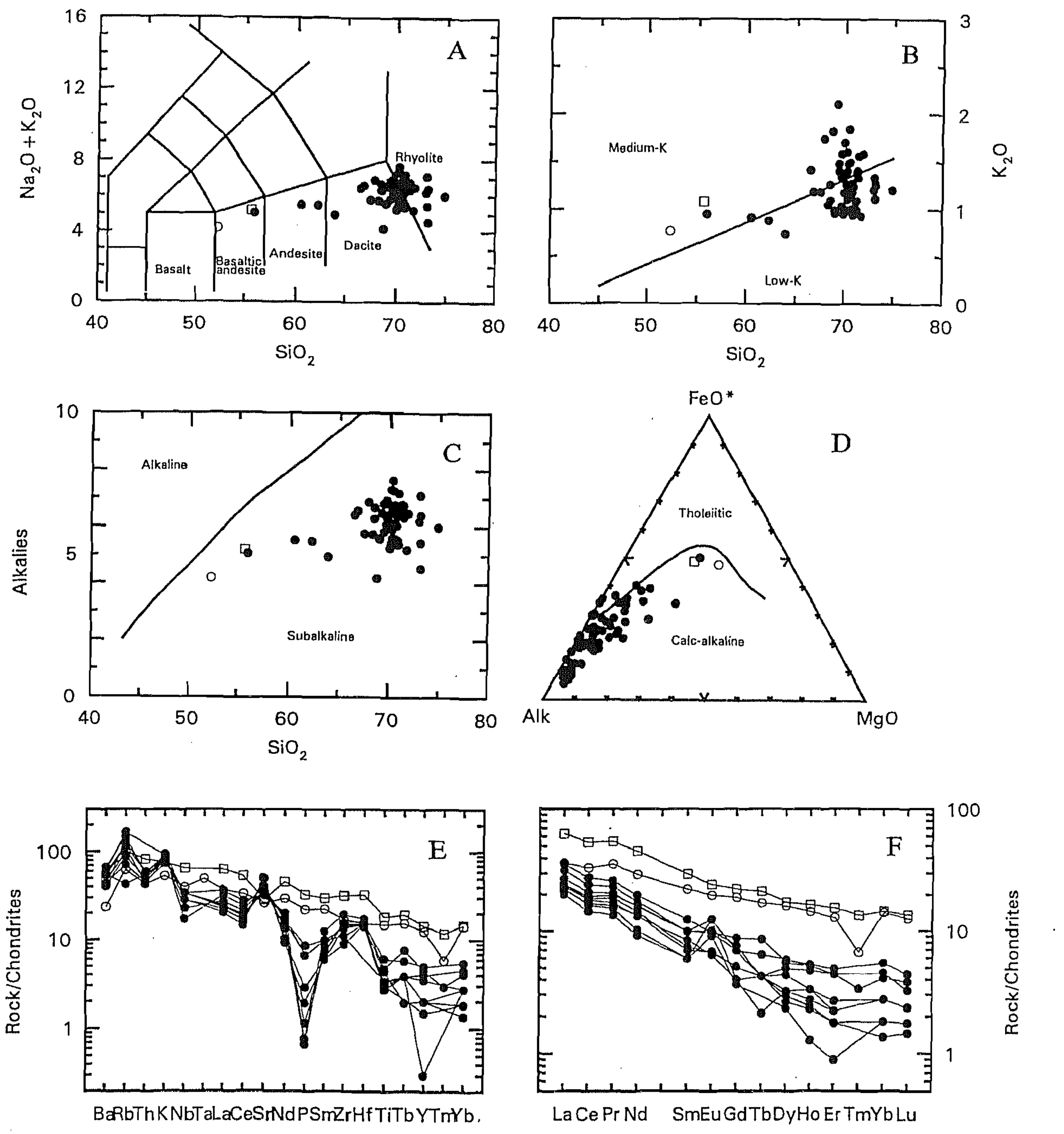

Figure 2. Geochemical diagrams. Basaltic-andesite clast BF 2 plotted as an open circle, basaltic-andesite flow BF 54 plotted as a square. **2A.** Rock names of individual samples; boundaries from Le Bas et al. (1986). **2B.** K_2O series; boundaries from Gill (1981, p. 6). **2C** and **2D.** Alkalies-silica and AFM diagrams for magma series; boundaries from Irvine and Baragar (1971). Alk = $Na_2O + K_2O$. **2E.** Spider diagram; normalizing data from Thompson et al. (1984). **2F.** Rare-earth element diagram; normalizing data from Nakamura (1974).

ray fluorescence spectrometry was used to determine the major-oxide composition of 43 clasts following procedures detailed in Shelton (1988); analyses are listed in Shelton (1988) and Savage and Despard (1990). Analyses of an additional 8 samples (D. Howell and H. McLean 1984, pers. comm.) are listed in Shelton (1988). The 11 samples (10 clasts and 1 flow) listed in Table 1 were analyzed by X-ray Assay Laboratories by X-ray fluorescence (XRF), direct coupled plasma (DCP), neutron activation (NA), induction coupled plasma (ICP), and plasma mass spectrometry (ICPMS). Isotopic analyses of powdered whole-rock samples were made on an AVCO 90°, thermal ionization source mass spectrometer at California State University, Los Angeles.

Results

Virtually all of the samples examined in this study are porphyritic. Subhedral to anhedral plagioclase phenocrysts occur in all samples and range from 25 to 40% in abundance. It is the solitary phenocrystic phase in about 15% of the samples. The crystals are complexly zoned and twinned and commonly exhibit alteration and resorption characteristics. The plagioclase phenocrysts in some samples have a coarse sieve-like texture in which areas of fine-grained and glassy areas are enclosed by the mineral. Medium-grained, euhedral to subhedral hornblende phenocrysts occur in about one half of the samples and range from 5 to 10% in abundance. Hornblende exhibits all stages of alteration to fine-grained aggregates of opaque oxides and unidentified silicates. Pyroxene phenocrysts occur in about one third of the samples and range from 5 to 10% in abundance. Both augite and hypersthene are present in variable amounts. Quartz phenocrysts occur in small amounts (< 4%) in about one third of the samples, most commonly in association with hornblende. Small amounts of iron-titanium oxides occur as phenocrysts in a few samples. Small, thin brown areas of an altered mineral characterize some samples and may represent former biotite crystals; no unaltered biotite was observed. The groundmass of these porphyritic rocks is composed of the same phases listed above plus variable amounts of glass and cryptocrystalline material. Groundmass plagioclase laths are randomly oriented. Vesicles are present in only a few samples. Six samples from the Near Point exposure contained significant amounts of secondary calcite; analyses of these rocks were excluded from the geochemical plots. Based on phenocryst mineralogy and geochemical criteria presented below, the predominant rock types represented in our sample set, listed in decreasing order of abundance, are quartz hornblende rhyodacite, pyroxene rhyodacite, hornblende rhyodacite, and rhyodacite. Rhyodacite containing hornblende and/or quartz phenocrysts is most common in the lower 2 members and in the exposure at Near Point, whereas rhyodacite and pyroxene rhyodacite are most common in the upper member.

The only mafic clast in our sample set (BF 2), composed of basaltic-andesite, was collected from the lower member in Laguna Canyon. It has a porphyritic texture with phenocrysts of plagioclase (~75%), pyroxene (augite and hypersthene, ~12%), olivine (~12%), and opaque oxides (~1%). Some of the pyroxene is altered. The fine-grained groundmass is partially glassy. Samples collected from a basaltic-andesite flow just south of Valley Anchorage (i.e., BF 54) are petrographically identical. Microprobe analyses of clast BF 2 show that the olivine crystals have an average composition of Fo_{75} and are unzoned. The plagioclase grains analyzed range from An_{46} to An_{61}; the crystals are reversely zoned, with cores ranging from An_{46} to An_{58} and edges ranging from An_{56} to An_{61}. Augite crystals average $Wo_{35}En_{51}Fs_{14}$, and the single hypersthene crystal analyzed has a composition of $Wo_5En_{72}Fs_{24}$.

The total alkalis vs silica plot (Fig. 2a) for major-element analyses of 63 volcanic clasts from the Blanca Formation assigns rock names to the samples according to the chemical classification of Le Bas et al. (1986). These clasts vary from basaltic-andesite to rhyolite, with the majority straddling the dacite-rhyolite boundary. The Blanca samples have low to medium contents of K_2O (Fig. 2b), and K_{70} (the wt% of K_2O at 70 wt% SiO_2) is 1.26. On the alkaline/subalkaline classification diagram (Fig. 2c), all samples plot within the subalkaline field, and the samples are predominantly calc-alkaline rather than tholeiitic (Fig. 2d).

Samples were collected from the upper member of the Blanca Formation in Coches, Willows, and Laguna Canyons, allowing the assessment of lateral variation of that member. The major-oxide and trace-element data show no significant differences in the upper member between these 3 sampling areas. In addition, all major oxides and trace elements with 1 exception are virtually identical in samples collected from the 3 different members. That exception, as shown previously by Shelton (1988), is titania, which is higher in the upper member (TiO_2 = 0.49 ± 0.08 wt%, n = 22) than in the underlying two members (TiO_2 = 0.29 ± 0.04 wt%, n = 22). Titania concentrations in the Near Point samples (TiO_2 = 0.28 ±0.02 wt%, n = 9) are comparable to those in the lower 2 Blanca members. These relationships are reflected in the phenocryst mineralogy of the clasts. Samples from the lower 2 members and from Near Point are virtually free of pyroxene phenocrysts, whereas they are common in samples from the upper member.

Trace-element analyses of Blanca samples were compared with analyses of samples from other middle to late Tertiary volcanic suites from California by Savage and Despard (1990). First-row transition elements (V, Cr, Ni, Sc, Co, Cu, and Zn) are depleted in the felsic Blanca clasts, similar to the low contents of these elements in most of the dacites and rhyolites chosen for comparison. Incompatible trace-elements such as Rb, Ba, Zr, Hf, Th, and U are also depleted in the Blanca samples, in marked contrast to the high contents of these elements in most of the comparison of dacites and rhyolites. For example, felsic Blanca clasts have an average Rb abundance of 38 ppm compared to an average concentration of 122 ppm for 16 samples from other California Tertiary volcanic areas that have between 65 and 75 wt% SiO_2. Strontium, an element that is low in most other evolved rocks, is relatively high in the Blanca samples (446 ppm compared to 186 ppm for other California volcanic rocks of comparable SiO_2 content).

The 6 Blanca rhyolite samples show similar patterns on a spider diagram (Fig. 2e). Relative to chondritic meteorites, a large negative spike for P is present as well as slight negative spikes for Ba, Th, and Ti; Sr exhibits a small positive spike. The basaltic-andesite flow and clast samples exhibit similar patterns with small negative spikes for Sr and Ti. Niobium, characteristically depleted along with Ta in subduction-related calc-alkaline rocks, does not exhibit a negative spike in these patterns.

The rare-earth element (REE) data normalized to chondrites are plotted in Figure 2f. The rhyolite clasts have a moderate light-REE enrichment (La = 40–60 x chondrite) and moderate light-REE fractionation (La_N/Lu_N = ~7). Six of the rhyolite clasts have no or small positive Eu anomalies (Eu/Eu* ≤ 1.5, where Eu* is the concentration of Eu interpolated from its neighbor elements in the REE pattern). The 2 samples that have larger positive Eu anomalies (Eu/Eu* for BF 4 = 1.9, for BF 34 = 2.5) also have the highest contents of Sr (579 and 597 ppm, respectively), suggesting that these 2 samples show the effects of plagioclase accumulation. The basaltic-andesite samples show a typical calc-alkaline REE trend (Wilson 1989). They have a moderate light-REE enrichment (La = 20–40 x chondrite) and less heavy REE depletion than the rhyolites (La_N/Lu_N = ~4).

Wilson (1989) notes that unmodified mantle melts possess the following geochemical characteristics: Ni > 400 ppm, Cr > 1,000 ppm, and Mg# > 76 [where Mg# = 100 molar MgO/(MgO+FeO)]. The basaltic-andesite samples have Ni < 58 ppm, Cr, 140 ppm, and Mg# < 53. Thus, although these 2 basaltic-andesite samples are the most mafic samples found in this study, they probably have undergone some fractional crystallization if they are derived from the mantle as argued below.

Strontium isotopic ratios and concentrations of Rb and Sr were measured on 5 rhyolite clasts (Table 2). The initial $^{87}Sr/^{86}Sr$ ratio for these 5 samples averages 0.70366. This low value suggests that the parental magmas were generated in the mantle and were not contaminated to any significant degree by continental crust. Weigand and Savage (1993) compared Blanca data with data from other Miocene volcanic centers located in the Transverse Ranges. Although the lowest ratios are found in basalt and andesite and the highest ratios are found in dacite and rhyolite, no significant correlation exists between $^{87}Sr/^{86}Sr$ and SiO_2 content either within individual volcanic centers or in the data set as a whole. Samples from the volcanic centers from the Transverse Ranges range from 0.7029 to 0.7045 and cluster around 0.7036 (n = 40, 5 areas).

Table 2. Strontium isotopic data.

Sample	Sr ppm	Rb ppm	$\frac{^{87}Sr}{^{86}Sr_m}$	$\frac{^{87}Sr}{^{86}Sr_i}$
BF 4	447	30.0	0.70378 ± 4	0.70374
BF 44	372	12.6	0.70372 ± 6	0.70370
BF 58	374	23.9	0.70375 ± 7	0.70371
Mbb 2	445	28.2	0.70358 ± 5	0.70354
Mbb 10	400	22	0.70362 ± 6	0.70359

m = measured; i = initial; initial ratios calculated using an age of 15 Ma. Analytical methods summarized in Savage and Despard (1990).

Discussion

When the Blanca Formation was first defined by Weaver et al. (1969), it was postulated that the source of the volcanic clasts within the Blanca Formation was erosional debris from the Santa Cruz Island Volcanics. They based this hypothesis on the following information: (1) age similarities between the 2 formations, (2) up-section changes in the Blanca Formation that appear equivalent to erosion through the stratigraphic sequence on the Santa Cruz Island Volcanics, (3) dacite clasts within the Blanca Formation that appear similar in composition to dacite of the Santa Cruz Island Volcanics, and (4) thickening of the Blanca Formation in the direction of the source for the Santa Cruz Island Volcanics. Later studies by McLean et al. (1976a), Shelton (1988), and Weigand (1993) revealed distinct compositional differences between the Blanca Formation volcanic clasts and the Santa Cruz Island Volcanics. For instance, the majority of samples from the Santa Cruz Island Volcanics have SiO_2 values less than 65 wt%, whereas most of the Blanca clasts have SiO_2 values greater than 65 wt%. Furthermore, most of the Santa Cruz Island Volcanics samples are medium-K (K_{70} = 1.97) while the Blanca samples are low- to medium-K (K_{70} = 1.26). Trace-element data collected during this study (Table 1) further support this compositional difference. Concentrations of Rb, Zr, and Ba are generally higher in Santa Cruz Island Volcanics specimens than they are in Blanca clasts at comparable SiO_2 values. In addition, up-section changes in the composition of Blanca clasts presumed by Weaver et al. (1969) are not supported by our data.

Our results also confirm the findings of Shelton (1988), who showed that the great majority of the Blanca clasts are classified as rhyolite based on SiO_2 content. Using the alkalis-silica classification of Le Bas et al. (1986), the felsic clasts straddle the dacite-rhyolite boundary (Fig. 2a). The large amounts of petrographically defined pyroxene andesite reported by McLean et al. (1976a) are probably pyroxene rhyodacite that contains no quartz.

Crystal fractionation models were calculated in order to make a first-order assessment whether either basaltic-andesite clast BF 2 or sample BF 54 from the basaltic-andesite flow near Valley Anchorage could represent parental compositions from which the rhyolite clasts were derived by Rayleigh fractional crystallization. Although these types of modelling calculations have limitations, they nevertheless provide first-order evidence whether a fractional crystallization relationship is *possible* within the compositions used and as such is 1 line of evidence that can be considered along with others.

Table 3. Summary of modelling calculations.

Parent	clast BF 2	flow BF 54
Daughter	AVCLAST	AVCLAST
% Mineral subtracted		
Olivine	0	2.4
Hypersthene	8.6	0
Augite	17.2	14.2
Plagioclase (% An)	40.2 (57)	28.6 (46)
Magnetite	7.4	8.6
% Liquid left	25.8	45.2
SOSOR	0.20	0.37

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

The calculations show that the composition of an average felsic clast can be produced by removing a substantial amount of plagioclase plus lesser amounts of augite, hypersthene, and magnetite from a liquid having the composition of either the basaltic-andesite clast or flow. These calculations yield low sums of squares of residuals (sosor), which indicate a good fit for both cases (Table 3). The importance of plagioclase as a fractionating phase is consistent with its predominance in the phenocryst assemblage observed in the clasts. The amount of augite removed in both scenarios exceeds that of hypersthene, which is consistent with its predominance over hypersthene in the mafic samples. The proportion of crystals required to be removed from the basaltic-andesite BF 2 is greater than that from the flow BF 54 (71 wt% vs 66 wt%), consistent with the less evolved composition of BF 2. For the same reason, the An content of the plagioclase removed from BF 2 exceeds that of the plagioclase removed from BF 54 (An_{50} vs An_{41}).

These models based on major oxides were tested using a set of trace elements. Similar to the limitation noted above, these tests are not unique—wide ranges in the partition coefficient (or distribution coefficient, K_D) for all trace elements can be found in the literature. Nevertheless, permissive models and useful constraints can result. The compatible trace elements V, Cr, and Ni and the incompatible trace elements Rb, Sr, and Ba can be successfully modelled. These are important results for the latter elements because, as emphasized previously, Rb and Ba in these volcanic clasts are anomalously low, and Sr anomalously high, when compared to other suites of calc-alkaline volcanic rocks. Thus, fractional crystallization of a reasonable mineral assemblage can alone account for the observed concentrations of these 3 elements. However, the elements Zr and La (the latter being representative of the rare-earth elements) present severe problems. The K_Ds for the model mineral assemblage are all low, meaning that Zr should increase with fractionation as illustrated by other volcanic suites. Yet the concentration of Zr in the rhyolite clasts (mean = 88 ppm) is lower than either of the 2 putative parents (BF 2 = 117 ppm, BF 54 = 218 ppm). The removal of small amounts of a minor phase such as allanite or zircon may have been involved to produce these relationships. Removal of small amounts of 1 or both of these minerals also may have contributed to the lower concentrations of the REE in the daughter (mean La = 8.4 ppm) than in the parents (12–20 ppm).

Recent research suggests that volcanic clasts from the Beecher's Bay Formation (Chinn and Weigand 1994), the Conejo and Zuma Volcanics (Weigand and Savage 1993), and the Glendora Volcanics (Weigand 1982 and unpub. data) share distinctive characteristics with the clasts from the Blanca Formation and the 5 volcanic areas could be considered as a petrographic suite. In other words, volcanic rocks from these 5 areas, though not comagmatic in the sense that all were derived from the same magma, are geochemically similar, were derived from similar sources by similar degree of partial melting, and underwent similar petrologic processes before erupting in their respective areas. These areas are collectively referred to as TRASC (*T*ransverse *Ra*nges of *s*outhern *C*alifornia) suites. Attributes shared by the five suites include (1) all belong to the low- to medium-K calc-alkaline magma series, (2) all are low in incompatible trace elements and are relatively high in Sr, (3) all have low initial $^{87}Sr/^{86}Sr$ values where measured, (4) all erupted virtually simultaneously, and (5) all erupted along the southern boundary of the Transverse Ranges marked by a major fault system composed of the Santa Cruz Island, Malibu Coast, Santa Monica, Hollywood, and Raymond Hills faults. Clasts from the Blanca and Beecher's Bay Formations consist of greater amounts of dacite and rhyolite than does the Conejo suite, which is interpreted to mean that greater amounts of crystal fractionation affected these clasts.

Conclusions

The analyses of additional clasts from the upper member of the Blanca Formation reproduce the higher TiO_2 contents found by Shelton (1988) and confirm that the unit exhibits no observable lateral variation in composition. Clasts from the Near Point outcrop are identical to those from the Blanca Formation with respect to petrography and geochemistry and probably correlate specifically with the lower or middle member. Low initial Sr-isotopic values and distinct concentrations of incompatible elements suggest a common mantle source for the Blanca, Beecher's Bay, Conejo, Zuma and Glendora volcanic rocks; observed compositional variations in this suite can be explained by fractional crystallization without the addition of any continental crust. These geochemical characteristics suggest that this is a unique calc-alkaline volcanic suite.

Howell and McLean (1976) proposed that the Blanca Formation on Santa Cruz Island, including the outcrop at Near Point, and the Beecher's Bay Formation on Santa Rosa Island constitute different portions of a single submarine fan. This study, by confirming the correlation of the 2 units, strongly supports this scenario.

The cause of volcanism is unclear and numerous tectonic scenarios have been proposed to explain the Miocene igneous activity in southwestern California. Weigand and Savage (1993) summarized 4 general theories — subduction of the Farallon plate, migration of the Rivera triple junction, overriding of the East Pacific Rise, and rifting of the lithosphere—and concluded that extension caused by dextral shear between the North American and Pacific plates initiated decompression melting in the mantle. Although extension commonly produces volcanic rocks that belong to the alkalic and/or tholeiitic magma series, some calc-alkalic volcanics associated with extensional regimes have been reported (Robyn 1979; Hooper et al. 1993).

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