Geochemistry and Origin of Middle Miocene Volcanic Rocks from Santa Cruz and Anacapa Islands, Southern California Borderland

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Abstract – Major-oxide and trace-element compositions of middle Miocene volcanic rocks from north Santa Cruz and Anacapa Islands are very similar. In contrast, they are geochemically distinct from the volcanic clasts from the Blanca Formation, of similar age but located south of the Santa Cruz Island fault, which implies significant strike-slip movement on this fault. The island lavas are also compositionally distinct from the Conejo Volcanics located onshore in the Santa Monica Mountains. The island lavas are part of a larger group of about 12 similar-aged volcanic suites from the California Borderland and onshore southern California that all belong to the calc-alkaline magma series. This group is interpreted to have originated in a subduction environment in one of two possible scenarios: 1) their magmas were produced from the subduction of the Cocos plate south of the Rivera triple junction, which would imply that the Baja-Borderland allochthon onto which they were emplaced experienced northwestward translation subsequent to eruption or 2) their magmas were produced from warm, young subducted slab located north of the Rivera triple junction, which would imply that slab persisted in the Los Angeles area after the triple junction had migrated to the south.

Introduction

The volcanic rocks on Santa Cruz and Anacapa Islands (Fig. 1) are part of a larger group of volcanic centers that erupted in the Los Angeles and California Borderland areas about 13-18 m.y. ago. These areas represent the culmination in southern California of Cenozoic volcanism that began in the eastern Mojave Desert about 30 m.y. ago and swept irregularly west and north. This extensive extrusive activity was related closely to complex tectonic activity that included subduction of the Farallon plate whose subduction angle was steepening, and interaction of the Pacific and North American plates along a lengthening transform boundary; this activity additionally involved rotation and possible northward translation of crustal blocks.

The origin of the volcanic rocks in this area has been variously ascribed to subduction of the Farallon plate (Weigand 1982; Crowe *et al.* 1976; Higgins 1976), subduction of the Pacific-Farallon spreading center (Dixon & Ferrar 1980), mantle diapirism into a slab-free window (Dickinson & Snyder 1980), extensional melting at a migrating triple junction (Hurst 1982), upper mantle and crustal dilation related to the East Pacific Rise (Hawkins 1970) and extension related to the formation of coastal California Cenozoic basins (*i.e.*, Crowell 1987). A knowledge of the chemical composition of the volcanic rocks may provide a better understanding of the specific tectonic environment of their magma genesis. The chemical characterization of these lavas will aid also in the correlation between different volcanic areas. This information would be useful in placing constraints on amounts of northward translation, strike-slip offset and rotation experienced by adjacent crustal blocks. A better knowledge of the correlation between volcanic units also might be useful in helping to direct exploration efforts for oil and gas in offshore southern California.

For this project, I determined the major-oxide and trace-element concentrations in samples from north Santa Cruz and Anacapa

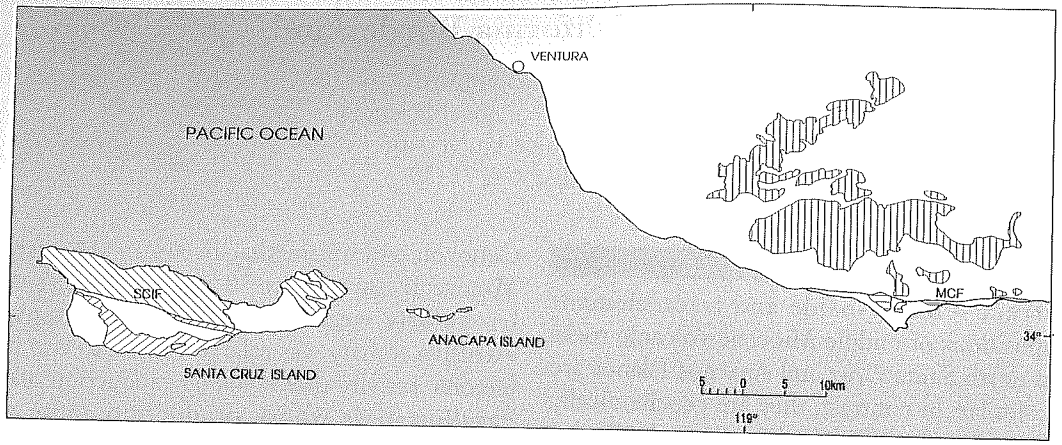

Figure 1. Sketch map showing some of the Miocene volcanic areas (lined) mentioned in the text. The Santa Cruz Island Volcanics and Blanca Formation crop out respectively north and south of the Santa Cruz Island fault (SCIF), volcanic rocks comprise all of Anacapa Island, and the Conejo Volcanics and Zuma Volcanics crop out respectively north and south of the Malibu Coast fault (MCF).

Islands in order to 1) evaluate possible correlations between the two lava sequences and other nearby volcanic units of similar age and 2) evaluate the origin of the lavas and the tectonic setting of their emplacement.

Previous Work

Santa Cruz Island: The volcanic sequence exposed north of the Santa Cruz Island fault was first correlated with the Conejo Formation (now the Conejo Volcanics) of the western Santa Monica Mountains on the basis of lithologic similarities and stratigraphic position (Kleinpell 1938). The volcanic section was renamed the Santa Cruz Island (SCI) Volcanics and subdivided into four members by Nolf & Nolf (1969). It forms a north-dipping homocline composed of interbedded flows, flow breccias and volcaniclastic rocks that have a cumulative thickness of 2,400 m and that are cut by numerous shallow intrusions at an inferred eruptive center near Devil's Peak. The formation overlies inferred San Onofre Breccia in the subsurface and is overlain by the Monterey Formation.

The following brief summary of stratigraphy and petrography is from Nolf & Nolf (1969), with additional information from Crowe & co-authors (1976). The lowermost Griffith Canyon Member consists of flows and epiclastic volcanic breccias of basaltic and andesitic composition that were deposited in a subaerial environment. The overlying Stanton Ranch Member is composed of andesite flows, flow breccias and subordinate tuff breccias erupted on the flanks of a volcanic edifice. Next younger is the Devil's Peak Member containing a variety of scoriaceous andesitic and dacitic flows, flow breccias, and reworked pyroclastic rocks. These rocks were apparently emplaced on the slopes of, and adjacent to, a volcanic center. The uppermost Prisoner's Harbor Member is composed of andesitic and dacitic flows, flow breccias and tuffaceous volcaniclastic beds, probably deposited in a submarine environment. Basalt, andesite and dacite are most commonly porphyritic and all contain phenocrysts of plagioclase, opaque oxides and variable amounts of augite, hypersthene and pigeonite. An-contents of plagioclase decrease from An_{65} to An_{28} in the three rock types. Basalt contains areas of alteration (iddingsite) presumed to be pseudomorphic after olivine, and dacite contains variable amounts of highly altered hornblende. The sequence is mafic near the base (basalt and andesite), intermediate in composition in the middle members (largely andesite) and more felsic near the top (andesite and dacite).

Crowe & co-authors (1976) studied the petrology and chemical composition of the SCI Volcanics. They noted a slight iron-enrichment trend and a similarity in major-oxide composition to island-arc tholeiites, and suggested that they may have formed part of an island-arc sequence that recorded Miocene subduction off southern California. They speculated that the East Pacific Rise played a significant but unknown role in the generation of these magmas. Higgins (1976) included the SCI Volcanics in his study of Miocene volcanism in the greater Los Angeles Basin area and supported the conclusion that this volcanism was probably related to active subduction. Higgins also noted that the SCI Volcanics 1) lack a distinctive iron-enrichment trend on an AFM diagram, 2) are generally higher in K_2O than are the Conejo Volcanics SCI Volcanics and 3) are both calc-alkaline and tholeiitic on the basis of SiO_2-K_2O relationships.

Hurst & co-authors (1982) and Hurst (1983) included the SCI Volcanics in their studies of Miocene volcanism in the Southern California Borderland. They reviewed the available geochemical data and presented Sr-isotopic data for 10 samples of SCI Volcanics. Initial $^{87}Sr/^{86}Sr$ ratios range from 0.70253 to 0.70318, overlap the range of Leg 63 DSDP samples from the California Borderland (Pal Verma 1981), and are generally lower than those from Conejo or Santa Catalina Island volcanic rocks. Hurst & co-authors (1982) concluded on the basis of a variety of petrographic, chemical and isotopic evidence that the SCI Volcanics exhibit a mixture of tholeiitic and calc-alkaline characteristics, and resulted from mantle-ridge melting due to complex ridge-trench-transform interactions in the vicinity of the Rivera triple junction.

Johnson & O'Neil (1984) measured trace-element abundances and isotopic ratios of Sr and O in numerous Neogene volcanic centers in western California. They concluded that differences in the stress regime at a triple junction largely control the petrologic processes that operate. Locally variable and mild extension and compression at the Mendocino triple junction resulted in magmas dominated by crustal anatexis, whereas substantial extension at the Rivera triple junction produced rocks derived primarily by crystal fractionation of mantle-derived basalt with only limited crustal contamination. For samples of SCI volcanics, they reported $\delta^{18}O$(magma) values of 6.7 to 7.3‰ and $^{87}Sr/^{86}Sr$(initial) ratios of 0.70253 to 0.70361.

The SCI Volcanics are classified subalkaline on a SiO_2-alkalis plot and calc-alkaline on the basis of AFM ratios (Crowe *et al.* 1976, Fig.2; Higgins 1976, Fig. 3). They also are classified as calc-alkaline according to the SiO_2-FeO/MgO criterion of Miyashiro (1974) and the Al_2O_3-normative plagioclase criterion of Irvine & Baragar (1979). Silica-K_2O relationships show that these rocks are predominantly medium-potassium andesite using the scheme of Gill (1981, Fig. 1.2), which is in agreement with petrographic estimates (Nolf & Nolf 1969; Crowe *et al.* 1976).

Turner (1970) reported K/Ar age dates of 16.1 ± 0.9 Ma on a sample probably from the upper part of the Devil's Peak Member, and 16.5 ± 0.8 Ma on a sample probably from the middle of the Prisoner's Harbor Member (these and subsequent dates have been corrected to new IUGS constants). Crowe & co-authors (1976) reported dates of 16.0 ± 0.7 Ma and 19.9 ± 0.9 Ma on the same sample from a dike cutting the lower part of the Devil's Peak Member. The lower part of the sequence has not been dated. San Onofre Breccia of probable Saucesian age was encountered beneath the volcanics in the Union Oil Gherini No. 1 well drilled at the east end of the island (Weaver & Meyer 1969), which probably limits the onset of volcanism to less than 23-25 Ma (Crouch & Bukry 1979).

Anacapa: Being nearly entirely volcanic, the geology of Anacapa Island is much simpler than that of Santa Cruz Island and has

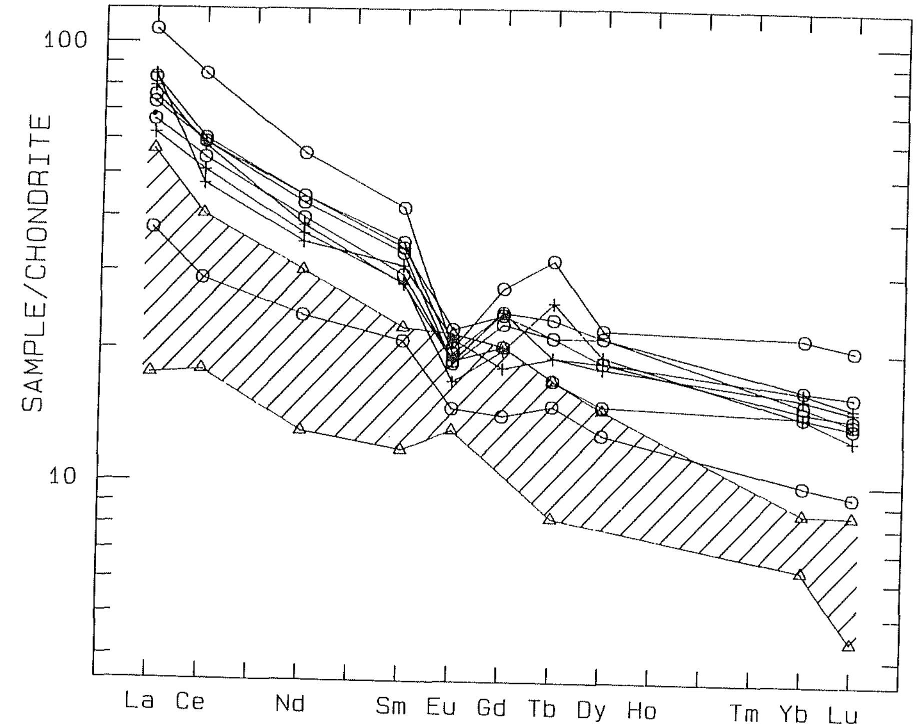

Figure 2. Rare-earth element patterns normalized to chondritic values. Circles are SCI Volcanics, crosses are Anacapa samples. Lined area represents field of available Conejo data (Weigand 1982, unpubl.).

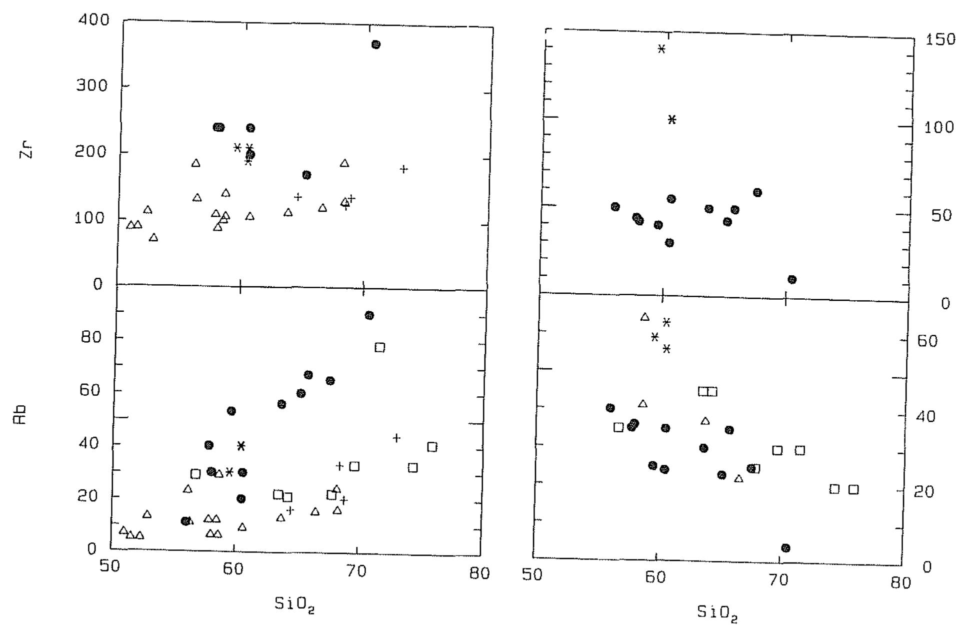

Figure 3. Silica-variation diagrams for selected trace elements. Filled circles are SCI Volcanics, stars are Anacapa samples, triangles and crosses are respectively Conejo and Zuma samples (Weigand 1982, unpubl.), and boxes are Blanca samples (Savage & Despard 1990; H. McLean & D. Howell unpubl.).

correspondingly received less attention. Scholl (1960) correlated the lava flows and various volcanic and volcaniclastic breccias with the Conejo Volcanics. As on Santa Cruz, the volcanic sequence forms a north-dipping homocline. A maximum of 1,700 m is exposed although neither the base nor top are seen. Two strata of San Onofre Breccia are interbedded with the volcanic rocks near their exposed base. The rock type is vesicular and porphyritic andesite containing phenocrysts of plagioclase, augite, hypersthene and opaque oxides. No previous geochemical or isotopic analyses or age determinations have been published.

Methods

Six samples of SCI Volcanics were chosen from numerous cores available from a paleomagnetic study by Kamerling & Luyendyk (1985) on the basis of freshness and representative geographic and stratigraphic location. Sites SB and SF are located in the Griffin Canyon Member, SCVA and SCFA in the Devil's Peak Member, and SP in the Prisoner's Harbor Member. Site SS is located in rocks mapped as undifferentiated Santa Cruz Island Volcanics (Weaver 1969). The Stanton Ranch Member is not represented. The three Anacapa samples were chosen from a collection of cores drilled at the east end of the island as part of an earlier paleomagnetic study by Kamerling & Luyendyk (1979).

The Channel Islands samples and a geochemical standard were analyzed by X-Ray Assay Laboratories (XRAL) for 10 major oxides, 44 trace elements and loss on ignition (LOI). Methods included x-ray fluorescence (XRF), direct coupled plasma (DC), atomic absorption (AA), neutron activation (NA) and delayed neutron count (DNC). Methods and detection limits are included in Table 1. Precision is estimated to be ± 100% at detection limit (DL), ± 20% at 20 x DL, and ± 5% at 100 x DL.

To assess the accuracy of these analyses, U.S. Geological Survey geochemical reference

Table 1. Methods, detection limit (DL) and comparison of values reported by XRAL (plus errors estimated for trace elements) with values from Flanagan (1973) for reference basalt BCR 1; Flanagan's data are **recommended**, averages or magnitudes

			BCR 1	
	Method	DL	XRAL	Flanagan
SiO_2	XRF	0.01	54.60	54.50
TiO_2	XRF	0.01	2.20	2.20
Al_2O_3	XRF	0.01	13.50	13.61
FeO_T	XRF	0.01	12.06	12.06
MnO	XRF	0.01	0.19	0.18
MgO	XRF	0.01	3.38	3.46
CaO	XRF	0.01	6.94	6.92
Na_2O	XRF	0.01	3.18	3.27
K_2O	XRF	0.01	1.80	1.70
P_2O_5	XRF	0.01	0.36	0.36
V	DCP	2	nd	—
Cr	NA	0.1	22±1	17.6
Ni	DCP	1	nd	—
Co	NA	0.1	44±2	38
Cu	DCP	0.5	nd	—
Zn	DCP	0.5	nd	—
Ge	DCP	10	nd	—
As	NA	1	1±1	0.7
Se	NA	0.5	<.5	0.1
Br	NA	0.5	0.8±.6	0.15
Mo	NA	2	3_2	1.1
Ag	DCP	0.5	nd	—
Cd	DCP	0.2	nd	—
W	NA	1	<2	0.4
Au (ppb)	NA	5	<5	0.7
Pb	DCP	2	nd	—
Bi	DCP	0.1	0.1±.1	0.05
Li	AA	1	nd	—
Be	DCP	1	nd	—
B	DCP	10	nd	—
Sc	NA	0.01	42.9±2	33
Rb	XRF	10	50±17	46.6
Sr	XRF	10	310±25	330
Cs	NA	0.2	1.0±.4	0.95
Ba	XRF	10	670±34	675
Y	XRF	10	20±3	37.1
Zr	XRF	10	200±24	190
Nb	XRF	10	20±6	13.5
Sb	NA	0.1	0.9±.2	0.69
Hf	NA	0.2	5.2±.5	4.7
Ta	NA	0.5	1.1±.7	0.91
Th	NA	0.2	7.2±.5	6.0
U	NA	0.1	4.8±.3	1.74
La	NA	0.1	33.1±1.6	26
Ce	NA	1	66±4	53.9
Nd	NA	3	32±6	29
Sm	NA	0.01	7.52±.4	6.6
Eu	NA	0.05	1.95±1.4	1.94
Gd	NA	0.5	7.6±1.1	6.6
Tb	NA	0.1	1.1±.2	1.0
Dy	NA	0.5	7.0±1.1	6.3
Yb	NA	0.05	4.31±.31	3.36
Lu	NA	0.01	0.63±.03	0.55

Major oxides in wt. %, trace elements in ppm except Au, total iron expressed as FeO_T, nd not determined; see text for methods.

standard basalt BCR-1 was included as an unidentified sample in the set sent to XRAL. Table 1 compares values reported by XRAL with those reported by Flanagan (1973). Eleven elements were not determined due to insufficient sample. Major oxides show excellent agreement, as do the majority of the trace elements. Four elements (Ce, Lu, Nb and Th) are about 20% higher than the values reported to have the highest reliability by Flanagan (1973). Only U shows a gross dissimilarity. None of these elements forms the main basis of the conclusions in this study. Because many of the comparisons are made between samples analyzed by XRAL, precision is a more important parameter than accuracy. Nevertheless, accurate results give confidence in the analytical procedures, and for the comparison of these analyses with those from other labs.

Results

The petrography of the analyzed samples, including those from Anacapa, agrees closely with the descriptions of Crowe & co-authors (1976). Plagioclase, the most abundant phenocryst, occurs as small to large, euhedral to subhedral crystals, many of which are concentrically zoned and many of which enclose numerous rounded inclusions of glass. The other phenocryst, less abundant, smaller and less well formed than the plagioclase phenocrysts, is pyroxene, both augite and hypersthene. A few grains exhibit compositional zoning, and others enclose rounded glass inclusions. The SCI basaltic-andesite samples have a fine-grained groundmass of plagioclase, pyroxene, opaque oxides and minor glass. The SCI andesite and dacite samples exhibit a dark, very fine-grained matrix; the dacite matrix is cut by thin quartz veins. The andesite samples from Anacapa are variably vesicular and exhibit a merocrystalline groundmass with plagioclase and pyroxene set in dark glass.

Major-oxide analyses of the nine samples are listed in Table 2, trace-element analyses are listed in Table 3, and previously unpublished analyses of an additional 5 samples (H. McLean & D. Howell, priv. comm.) are listed in Table 4. The classification of Le Bas & co-authors (1986) can be used to identify the rock type of the samples; these are indicated in Tables 2 and 4). The observation by Nolf & Nolf (1969) and Crowe & co-authors (1976) that the SCI Volcanics become less mafic upsection is reflected in the major-oxide analyses (Tables 2 and 4); Griffin Canyon

Table 2. Major-oxide analyses of lavas from north Santa Cruz and Anacapa Islands; SCI samples listed in ascending stratigraphic order.

Sample	SB 15	SF 24	SCFA 2	SCVA 11	SP 82	SS 68B	AC 18A	AE 32A	AJ 45A
Member	GC	GC	DP	DP	PH	?	—	—	—
Rock Type	BA/A	BA/A	A	A/D	D/R	A	A	A	A
SiO_2	56.60	56.20	59.20	62.80	68.80	58.90	59.10	57.30	59.00
TiO_2	1.70	1.68	1.45	1.19	1.00	1.60	1.40	1.40	1.42
Al_2O_3	15.60	15.70	15.80	16.20	13.70	15.10	16.40	15.90	16.40
FeO_T	7.86	7.47	6.72	4.74	4.12	7.29	5.51	6.09	5.01
MnO	0.11	0.12	0.10	0.05	0.04	0.13	0.08	0.09	0.08
MgO	3.90	3.94	3.11	0.91	0.15	3.08	3.61	3.72	3.53
CaO	6.80	6.79	5.83	4.33	2.50	6.21	6.39	6.24	6.67
Na_2O	3.79	3.96	4.01	4.55	4.59	3.99	4.14	4.08	4.21
K_2O	0.95	1.12	1.34	1.48	2.40	0.81	1.04	1.01	1.10
P_2O_5	0.30	0.30	0.27	0.18	0.28	0.31	0.24	0.56	0.21
LOI	1.39	1.16	1.47	2.77	2.23	1.54	1.70	2.16	1.70
SUM	99.00	98.44	99.30	99.20	99.81	98.96	99.61	98.55	99.33

Major oxides in wt. %, total iron expressed as FeO_T, LOI is loss on ignition.

samples are basaltic-andesite and andesite, those from the Stanton Ranch and Devil's Peak members are andesite and andesite transitional to dacite and the Prisoner's Harbor samples are dacite transitional to rhyolite. Unfortunately, the stratigraphic position of the 24 samples analyzed by Crowe & co-authors (1976) are unknown.

The Santa Cruz samples fall within the range of previous analyses (Crowe *et al.* 1976) and are valid representative samples from the island. The Anacapa samples fall within the range defined by available analyses of SCI Volcanics (Table 2; Crowe *et al.* 1976) for every major oxide, and agree in all cases with the calc-alkaline classification of SCI Volcanics on the basis of major-oxide abundances.

On the basis of trace-element abundances, the Channel Islands rocks are classified as calc-alkaline according to the MgO-Ni criterion of Gill (1981) and to the Ti-Zr-Y-Sr criteria of Pearce & Cann (1973). On the other hand, principal component values derived by the recalculation of these latter trace elements (Butler & Woronow 1986) suggest that these rocks are more similar to within-plate basalts than to calc-alkaline basalts. However, evaluating these andesites using criteria derived from basalts is probably not appropriate. It is primarily the relatively high Zr contents that

Table 3. Trace-element analyses in ppm; grouped approximately according to geochemical behavior. Elements below detection in all samples include Ag, Au, Cd, Se and W.

Sample	SB 15	SF 24	SP 82	SCFA 2	SCVA 11	SS 68B	AC 18A	AE 32A	AJ 45A
V	160	160	58	130	86	120	140	130	130
Cr	42	44	11	55	43	30	100	140	100
Ni	36	35	4	35	23	24	63	59	56
Co	35	48	45	29	21	38	34	35	33
Cu	29	31	14	30	31	29	22	29	25
Zn	100	110	99	110	39	110	96	180	76
Ge	<10	10	<10	10	10	10	10	<10	10
As	1	2	7	2	1	1	3	3	2
Br	1.1	2.8	1.5	2.7	1.4	1.1	4.1	3.3	4.7
Mo	2	2	2	3	<2	<2	2	2	<2
Pb	4	<2	4	<2	4	<2	<2	190	8
Bi	0.1	0.1	0.1	0.2	0.1	0.1	0.1	0.1	0.1
Li	14	19	13	16	8	23	11	13	11
Be	2	2	3	2	2	3	2	2	3
B	10	20	80	30	20	<10	30	20	20
Sc	22.7	23.9	13.0	21.9	17.2	21.2	21.5	24.5	23.7
Rb	30	40	90	30	60	20	40	30	40
Sr	380	400	250	410	490	400	420	400	460
Cs	1.6	1.2	4.5	2.3	1.8	4.4	2.4	1.5	2.0
Ba	360	360	610	330	470	430	630	380	520
Y	34	36	42	30	24	32	42	28	42
Zr	240	240	370	200	170	240	190	210	210
Nb	16	16	18	14	10	16	14	14	12
Sb	0.4	0.1	1.2	0.2	0.2	0.2	0.3	0.6	0.4
Hf	5.4	6.0	9.0	5.5	4.2	5.7	5.6	5.0	5.9
Ta	1.0	1.3	0.9	1.0	1.0	1.1	0.7	0.7	0.8
Th	4.0	4.5	8.5	4.2	4.3	4.2	3.7	3.8	3.9
U	1.3	1.8	24.8	1.6	1.6	2.8	1.5	2.0	1.6
La	27.4	24.9	35.3	21.9	12.4	24.0	27.8	20.4	26.1
Ce	52	51	73	47	25	51	41	44	50
Nd	28	28	35	25	15	27	22	23	24
Sm	7.09	6.90	8.50	5.99	4.24	6.71	6.27	5.74	5.69
Eu	1.51	1.71	1.55	1.45	1.13	1.43	1.62	1.30	1.45
Gd	6.7	6.6	7.6	5.6	3.9	6.3	5.0	5.5	6.7
Tb	1.1	1.0	1.5	0.8	0.7	1.0	0.9	1.2	0.9
Dy	7.3	7.3	7.6	5.1	4.4	6.4	6.2	6.6	6.4
Yb	3.33	3.61	4.73	3.14	2.19	3.23	3.45	3.13	3.57
Lu	0.47	0.54	0.69	0.46	0.32	0.48	0.50	0.43	0.51

Table 4. Additional chemical analyses of SCI Volcanics from H. McLean & D. Howell (priv. comm.); listed in ascending stratigraphic order.

Sample	104	105	102	101	103
Member	GC	GC	SR	PH	Ti
Rock type	BA	A	A	D	D
SiO_2	52.80	61.30	56.90	64.90	63.40
TiO_2	1.60	1.30	1.30	1.40	1.00
Al_2O_3	15.90	14.80	16.00	15.40	15.20
Fe_2O_3	4.20	3.10	6.40	4.80	4.30
FeO	3.80	2.70	0.76	0.60	0.40
MnO	0.12	0.07	0.05	0.04	0.03
MgO	4.60	2.60	2.70	0.01	2.10
CaO	6.40	4.50	5.20	2.80	3.30
Na_2O	4.10	4.10	4.20	3.90	4.40
K_2O	0.39	1.60	1.80	1.90	2.10
P_2O_5	0.37	0.34	0.30	0.41	0.29
H_2O^+	1.50	1.30	1.40	1.70	0.99
H_2O^-	3.30	1.90	1.50	0.85	1.40
SUM	99.08	99.61	98.51	98.71	98.91
V	110	110	120	140	50
Cr	50	50	40	60	50
Ni	40	30	25	25	35
Co	40	35	40	30	30
Cu	30	27	56	30	26
Zn	110	110	110	50	120
Rb	11	56	53	65	67
Sr	350	280	325	325	360
Ba	300	460	380	470	460

Major oxides in wt. %, trace elements in ppm; Ti is Tertiary intrusion.

cause the similarity to within-plate basalts. These high Zr contents are likely caused not by tectonic setting, but rather by crystal fractionation, since Zr generally increases during this process.

Although the trace-element averages reported in Jakes & White's (1971) comparison of calc-alkaline and tholeiitic rock series in orogenic areas are somewhat obsolete, a comparison of these averages with the results of this study is instructive. Abundances of nine trace elements in the Channel Islands andesites compare more closely with the average calc-alkaline andesite - Rb, Ba, Sr, La, Th, U, Cr, Zr and Hf. Only Yb contents compare more closely with the average tholeiitic andesite.

Rare-earth element (REE) patterns (Fig. 2) are similar for the nine analyzed samples, especially for the seven samples with SiO_2 <60%. The rocks as a whole exhibit moderate light REE enrichment (La ~74 x chondrite), moderate light REE fractionation (La_N/Lu_N averages 5.2) and a relatively flat heavy REE enrichment (Tb_N/Yb_N averages 1.3). All of the samples exhibit small Eu-anomalies; Eu*/Eu averages 1.4.

The Ni contents of the samples are relatively low (<63 ppm for Anacapa, <37 for Santa Cruz). In addition, the Mg-numbers [100 x molar ratio $Mg/(Mg+Fe^{2+})$] also are relatively low (<62); none of the samples from Crowe & co-authors (1976) exceed 56. Both of these parameters preclude any of the samples so far analyzed from Santa Cruz or Anacapa Islands from being direct melts from the mantle (Gill 1981). Although the basaltic andesite and andesite samples exhibit only a small compositional range, parabolic relationships exhibited between Ni and Rb are consistent with these rocks being the result of 10-15% partial melting of a primitive basalt or eclogite (Gill 1981). The higher contents of Ni in Anacapa samples imply a source with a higher initial abundance of this element. The Anacapa samples have Ba/Ta ratios (542-900) that exceed 450, satisfying the single most diagnostic geochemical characteristic of arc magmas (Gill 1981); SCI andesite samples range from 277 to 391. Ratios of La/Th between 7.5 and 5.1, and of La/Ba between 13.1 and 22.7 for the seven basaltic andesites and andesites are within the ranges shown by most orogenic andesites (Gill 1981). Conversely, La/Nb ratios of 1.5 to 2.2 for these samples compare most closely to normal-type mid-ocean ridge basalt (Gill 1981).

Comparison: The three samples from Anacapa fall within the range exhibited by available analyses of SCI Volcanics (Crowe *et al.* 1976; this report) for every major oxide, and for many trace elements (Tables 2, 3 and 4). Abundances of several trace elements differ, however, between the two sets of samples. Anacapa samples are generally higher in Y, Ba, Ni, Cr and Br, and are generally lower in Co and Ta compared to the SCI andesites (Fig. 3). These differences are minor and probably

Table 5. Summary of modelling calculations.

Parent	B	BA	A	D
Offspring	GA	A	D	RD
% mineral subtracted				
Olivine	0	0	0	0
Augite(cpx)	10.5	4.6	5.0	0
Hypersthene(opx)	0	0	6.8	4.0
Plagioclase(%An)	8.9(67)	3.7(67)	14.6(55)	19.3(50)
Ilmenite	4.4	1.5	3.1	1.6
Apatite	.3	.1	.2	0
% liquid left	75.8	90.1	70.2	75.0
sosor	.51	.08	.03	.12

B = basalt, BA = basaltic andesite, A = andesite, D = dacite and RD = rhyodacite. Sosor is sum of squares of residuals, a measure of the goodness of fit of the calculations.

reflect inadequate sampling. Petrographic and geochemical similarities suggest that the lavas on Anacapa Island are genetically similar to, and stratigraphically correlative with the SCI Volcanics.

With respect to major oxides, northern Channel Islands lavas are similar to those from the Conejo Volcanics located in the Santa Monica Mountains. Previous studies have noted that SCI Volcanics have higher abundances of TiO_2 and K_2O relative to the Conejo Volcanics (Crowe *et al.* 1976; Higgins 1976; Hurst *et al.* 1982). These comparisons persist (Fig. 4) when a larger Conejo data set is used (Weigand 1982; Blackerby 1965, unpubl. data). Anacapa samples mimic those from SCI. Isotopic ratios of Sr and O overlap between the SCI and Conejo volcanics (Hurst 1983; Johnson & O'Neil 1984). These general similarities do not extend to trace-element comparisons. Unfortunately, data available for the Conejo Volcanics (Weigand 1982, unpubl. data) are somewhat restricted. For the great majority of trace elements, abundances are significantly lower in Conejo rocks than they are in SCI and Anacapa rocks (Rb, Zr, Nb, REE, Y Hf, Th, Sc and Co; Figs. 2 and 3). The two exceptions are Ni, for which Conejo rocks are intermediate between those from Anacapa (higher) and SCI (lower), and Cr, for which SCI abundances are lower than those of Conejo or Anacapa.

Available analyses of volcanic rocks from the Blanca Formation located south of the SCI fault (Shelton 1988; Savage & Despard 1990; H. McLean & D. Howell unpubl. data) confirm the high proportion of dacite and rhyolite suggested by petrography (Weaver *et al.* 1969). Of the 42 available samples, about 2/3 are higher in SiO_2 than any sample of SCI Volcanics so far analyzed. Compared to SCI volcanic rocks, the silicic Blanca samples as a whole are generally lower in TiO_2, FeO_T, K_2O, P_2O_5, Rb, Ba and Cu, and higher in MgO and Ni (Figs. 3 and 4). These differences in chemical composition agree with the conclusion of McLean & co-authors (1976) that the Blanca Formation was not derived by erosion of the SCI volcanics. This conclusion is consistant with the ~30 km separation of the island along the Santa Cruz Island fault required by the restoration of ~80° of Neogene clockwise rotation evidenced by paleomagnetic data (Hornafius *et al.* 1986).

Fractionation modelling: Crystal fractionation models were calculated using methods described by Bryan & co-workers (1969). Five major-oxide compositions were chosen that span the range of available analyses (Crowe *et al.* 1976; this study). Because no mineral analyses are available from SCI volcanic rocks, selected mineral analyses were compiled from the Conejo Volcanics (Weigand 1982, unpubl. data) and Central American volcanic rocks (M. J. Carr, pers. comm. 1985), as well as from Deer & co-authors (1961, 1963). Pigeonite, which is a minor phase in all SCI Volcanic rocks and hornblende, which is

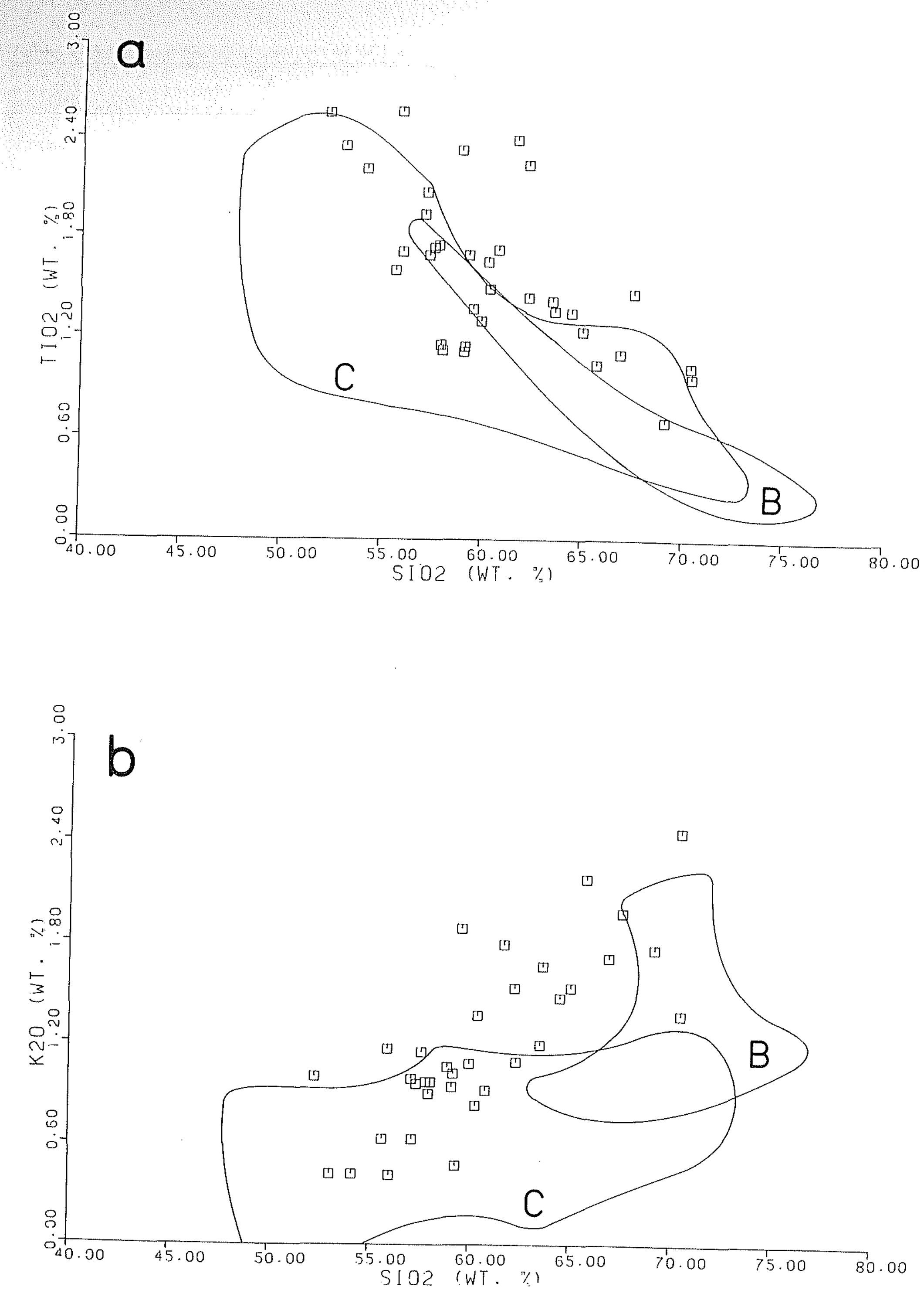

Figure 4. Silica-variation diagrams comparing SCI Volcanics (boxes) and fields of the Conejo Volcanics (C) and Blanca Formation (B). Data for fields from Weigand (1982, unpubl.), Crowe & co-authors (1976), Higgins (1976), Shelton (1988), Savage & Despard (1990), B. Blackerby (unpubl.) and H. McLean & D. Howell (unpubl.).

abundant in some dacites (Crowe *et al.* 1976), were not considered in the models.

Results of the calculations are summarized in Table 5. The low sums of squares of residuals (sosor) indicate a relatively good fit for each case. The calculations infer that olivine was not an important fractionating phase in the differentiation of basalt to basaltic andesite. Fresh olivine has not been observed in SCI basalts, although its presence was inferred by Crowe & co-authors (1976) by the shape of pseudomorphic iddingsite and by jackets of altered pyroxene around these alteration masses in most basalt samples. The calculations indicate that augite (WoEnFs = 42:46:12) was more important in the earlier stages of fractionation and hypersthene (WoEnFs = 4:77:19) was more important in later stages. This is consistent with the observation by Hurst & co-authors (1982) that augite predominates over hypersthene in mafic rocks; however, it is inconsistent with the observed predominance of augite in the intermediate rocks as well. The range in plagioclase compostions falls within the ranges measured by Crowe & co-authors (1976). The small amounts of Fe-Ti oxides suggested by these calculations are supported by the report of minor or sparse Fe-Ti oxide microphenocrysts in rocks of all composition (Crowe *et al.* 1976).

Discussion

An understanding of the origin of the SCI and Anacapa lavas cannot be attempted without also considering the other mid-Miocene volcanic rocks found throughout coastal southern California. Gross geochemical and age similarities led the author to recognize these as a group of volcanic rocks distinct from those generally located to the north and adjacent to the San Andreas fault (Weigand 1982). Besides Santa Cruz and Anacapa, this group includes the following volcanic centers: Santa Catalina, San Clemente and Santa Barbara Islands, Conejo, Zuma, Glendora, El Modeno, Palos Verdes, Laguna Beach and Rosarito Beach. In addition, presumably similar mid-Miocene volcanic rocks floor the center of the Los Angeles basin (Yerkes *et al.* 1965) and are present throughout much of the Southern California Borderland (Vedder *et al.* 1981). As a group, these rocks are characterized by being calc-alkaline, low- to medium-K basalt and andesite that erupted primarily around 15±1 Ma (Weigand & Savage 1991). Available isotopic ratios of Sr and O are low, that of Nd relatively high (Weigand 1982; Hurst 1983; Johnson & O'Neil 1984).

The bulk of the major-oxide and trace-element evidence, presented in detail for SCI and Anacapa volcanic rocks above, demonstrates that all of these volcanic centers are predominantly calc-alkaline and were erupted in an orogenic environment. Thus, according to the preponderance of data, the SCI Volcanics are calc-alkaline in spite of relatively high TiO_2 contents similar to some tholeiites; similarly, the Conejo Volcanics are calc-alkaline in spite of relatively low K_2O contents similar to some tholeiitic rocks (Fig. 5). To my knowledge, all modern calc-alkaline volcanic rocks are being erupted in subduction settings. Available Sr, O and Nd isotopic data for these lavas from coastal southern California are all consistent with generation from a mantle source in a subduction environment.

Several theories of origin for the coastal volcanic rocks involve dilation or extension. Volcanic rocks in modern and ancient rifted areas, whether oceanic or continental, almost invariably belong to the tholeiitic or alkalic rock series; with two known exceptions, calc-alkaline rocks are non-existent. "Triple-junction" magmatism described by Johnson & O'Neil (1985) produced a string of calc-alkaline volcanic centers adjacent to the San Andreas fault that were associated with the northward-migrating Mendocino triple junction during the Neogene. There is no similar geochemical or age-location evidence to suggest that the coastal California volcanic rocks were associated with a non-stable migrating triple junction. Calc-alkaline volcanic rocks of middle Cenozoic age

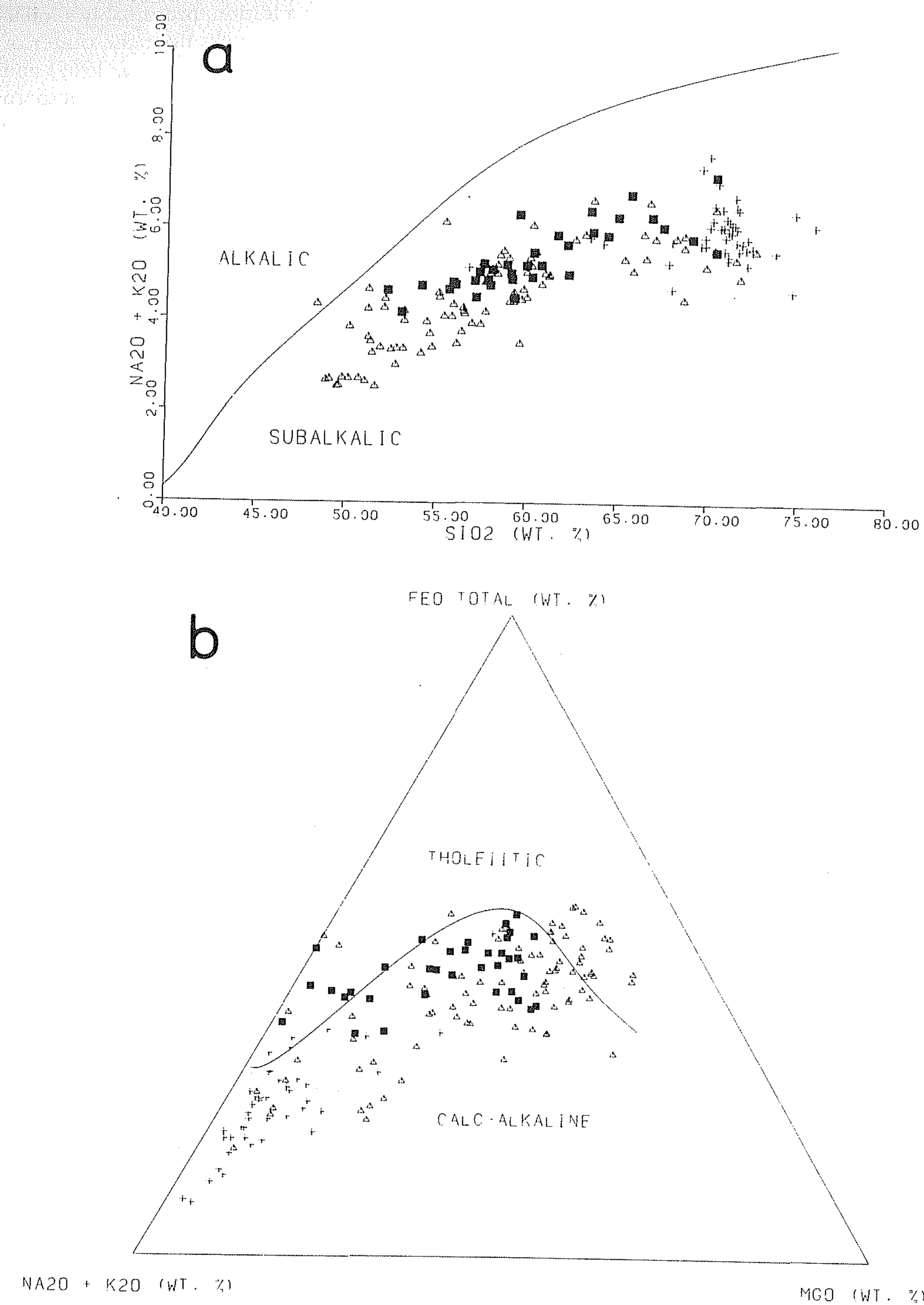

Figure 5. Alkalis-silica (a) and AFM (b) diagrams for SCI Volcanics (squares), Conejo Volcanics (triangles) and Blanca Formation (crosses). Data sources as for Fig. 4.

also have been reported from the Rio Grande rift in New Mexico by Thompson & co-authors (1986). The origin of these volcanic rocks, however, actually may be related to the subducted Farallon plate. Until the igneous processes that gave rise to these types of volcanic rocks are better described and understood, the more conventional interpretation that the generation of calc-alkaline rocks is related in some manner to subduction environments seems the more prudent explanation.

The fundamental plate-tectonic framework of California during the Cenozoic has been understood since the work of Atwater (1970). A critical question that must be addressed concerns whether or not southern California was the site of active subduction during the volcanism that occurred in the middle Miocene. Relevant aspects include: 1) the Farallon plate was being subducted under the North American plate until middle to late Oligocene time; 2) when the Pacific plate impinged on the North American plate, the Farallon split into the northern Juan de Fuca and the southern Cocos plates; 3) a transform boundary (the proto-San Andreas) was established between the Pacific and North American plates; 4) two triple junctions formed the ends of this transform boundary - the northern transform-transform-trench Mendocino triple junction and the southern spreading-transform-trench Rivera triple junction; and 5) inboard of this lengthening transform boundary, a no-slab window incapable of generating calc-alkaline magmas began enlarging beneath the North American plate.

The coastal volcanics could not have been produced by subduction of the Juan de Fuca plate because the Mendocino triple junction was in the Los Angeles area about 25 m.y. ago and had migrated 400-500 km to the northwest by the time most coastal volcanism was occurring (Atwater & Molnar 1973; Engebretson *et al.* 1985). The origin of the Vasquez Volcanics, dated at 25 Ma and located <20 km northeast of the Conejo Volcanics, has been tied to the passage of the Mendocino triple junction (Weigand & Frizzell 1986).

The alternative is that the coastal volcanics were produced by subduction of the Cocos plate, yet this interpretation is not without difficulties. Primarily, it seems geometrically impossible to produce the Vasquez Volcanics at the site of the northward-migrating Mendocino triple junction 25 m.y. ago, and subsequently produce Conejo Volcanics less than 20 km away 10 m.y. later at a site that was south of the Rivera triple junction. Furthermore, several reconstruction models place the location of the Rivera triple junction far south of the Los Angeles area by 16-14 m.y. ago (Atwater & Molnar 1973; Engebretson *et al.* 1985). Restoration of offset of the Los Angeles area produced by movement on the southern San Andreas fault and shear in the southern Sierran orocline and the Basin And Range province only moves these volcanic centers 450 ± 85 km nearer to the Rivera triple junction (Atwater 1989).

There are four considerations that may yield a solution to this dilemma. 1) Uncertainties in plate reconstructions are large, leaving both the timing of onset of interaction between the North American and Pacific plates, and its position of incidence, only modestly constrained (Stock & Molnar 1983). Thus, the Rivera triple junction may have been farther north than some models postulate (see for example Crowell 1987). 2) Subduction of the Cocos plate was not normal to the subduction zone, but was oblique. For instance, Engebretson & co-authors (1985) suggest that its motion was oriented about N30°E3) Movement of the Rivera triple junction did not mirror the motion of its sibling and migrate constantly southward; its position was more or less stationary until the middle Miocene (see Crowell 1987). 4) All of the coastal volcanic rocks are located on the Baja-Borderland allochthon (Blake *et al.* 1982). Although the uncertainties are large, this allochthon may have been about 2.5° farther south relative to the North American craton and the Santa Lucia-Orocopia allochthon (Howell *et al.* 1987); the latter is the site of the Vasquez

Volcanics. Paleomagnetic evidence from the coastal volcanic rocks is consistent with the interpretation that since their eruption, the Conejo and northern Channel Island volcanic rocks experienced northward translation relative to the North American craton, perhaps up to 8° or ~860 km (Kamerling & Luyendyk 1985; see also Champion *et al.* 1986). Movement may have been fairly rapid because correlations of middle to late Miocene sedimentary rocks across the Gulf of California suggest little movement since the middle Miocene (Hausback 1984).

On the other hand, recent quantitative plate reconstructions based on plate circuit or hot-spot circuit methods offer little support for this amount of translation of the Baja-Borderland allochthon since the Pacific plate first impinged on the North American plate about 25 m.y. ago (Atwater 1989). It seems significant that volcanism in the Los Angeles area post-dated the initial formation of the Los Angeles and Ventura basins (*ca.* 22 Ma; Crowell 1986) and was largely coincident with the onset of crustal rotation (*ca.* 16 Ma; Kamerling & Luyendyk 1985). Perhaps some sort of warm, young slab persisted in the Los Angeles area after the Rivera triple junction moved to the south and the extension attendent with crustal rotation initiated the melting event. The area of volcanism would have been positioned within the no-slab window of Dickenson & Snyder (1980) or the slab-free region of Severinghaus & Atwater (1990). However, the latter authors noted that exactly where and when subduction ceased at the Rivera triple junction is poorly constrained. Thus calc-alkaline volcanism in the Los Angeles area, if indeed it was associated with a subducted slab, may provide important constraints on the middle Miocene tectonic history of this area.

Summary

With minor-exceptions, lavas from Santa Cruz and Anacapa Islands are compositionally similar and are probably stratigraphically correlative. In contrast, these rocks differ considerably in trace-element contents from the Conejo Volcanics, implying differences in source area or petrologic process, or both. Significant dissimilarities in petrography and major-oxide and trace-element abundances between the SCI Volcanics and the Blanca Formation imply strike-slip movement along the Santa Cruz Island fault.

Lavas on Santa Cruz and Anacapa are part of a larger group of volcanic centers located on the Baja-Borderland allochthon that share gross age and geochemical characteristics. Several lines of compositional evidence indicate that these rocks were produced from a mantle source in a subduction environment. Volcanism may have occurred above the subducting Cocos plate south of the Rivera triple junction; the Baja-Borderland allochthon may then have undergone northwestward translation subsequent to the wind-down of volcanic activity about 14 m.y. ago. Alternatively, volcanism may have occurred north of the Rivera triple junction above warm, young subducted slab which was encouraged to melt by extension related to crustal rotation.

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