Nd-Sr isotopic geochemistry and tectonics of ridge subduction and middle Cenozoic volcanism in western California

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ABSTRACT

Episodes of middle Cenozoic near-trench volcanism in California occurred during the transition from convergent to transform plate boundaries as segments of the East Pacific Rise intersected a subduction zone along western North America. Geochemical features of volcanic rocks from the Coast Range Province and Santa Maria Province, which represent two near-trench volcanic episodes, indicate that magmas from each province were derived from depleted mantle and evolved by assimilation-fractional crystallization processes to form predominantly bimodal suites. Basalt and basaltic andesite from both provinces yielded $\varepsilon_{Nd}(t)$ values between +9.3 and +2.4 and $^{87}Sr/^{86}Sr(t)$ ratios of 0.702 58–0.706 72. The observed $\varepsilon_{Nd}(t)$ values that cluster around +9 and the $^{87}Sr/^{86}Sr(t)$ ratios <0.7029 imply a source of depleted mantle, analogous to mid-ocean-ridge basalt (MORB) sources, for these rocks. Th/Ta and Ba/Ta ratios as low as 0.49 and 35.78, respectively, for the basalt are similar to those of MORB and also suggest a magma source from depleted mantle. Acidic rocks, including rhyolite, dacite, and trachyte samples have $\varepsilon_{Nd}(t)$ values between +6.3 and −3.2 and $^{87}Sr/^{86}Sr(t)$ ratios of 0.703 93 to 0.711 31. The variation among the Coast Range and Santa Maria Provinces volcanic rocks in Nd-Sr isotope ratio space suggests that mixing occurred between the depleted mantle-derived basaltic end-member and an incompatible-element–enriched crustal reservoir through which these rocks erupted. The observed negative correlation of $\varepsilon_{Nd}(t)$ and positive correlation of $^{87}Sr/^{86}Sr(t)$ ratios with SiO_2, respectively, also suggest assimilation of an isotopically distinct crustal component by depleted mantle-derived melts. The ages and paleogeographic distributions of these volcanic rocks indicate that they were erupted during episodes when segments of the East Pacific Rise intersected southern California. Depleted mantle that was emplaced beneath the continental margin during ridge subduction became a source of magma for the episodes of near-trench volcanism as a new strike-slip regime evolved along the continental margin.

INTRODUCTION

The nature of volcanism in California changed markedly during the middle Cenozoic Era when segments of the East Pacific Rise approached and intersected a subduction zone along western North America (Fig. 1) (Atwater, 1970, 1989; Lipman et al., 1972; Christiansen and Lipman, 1972). Prior to early Tertiary time, a belt of calc-alkalic Andean-type magmatism characterized eastern California along the Sierra-Nevada arc during subduction of the Farallon plate beneath North America (Lipman et al., 1972; Christiansen and Lipman, 1972; Snyder et al., 1976). As parts of the Farallon plate were consumed at the subduction zone and the East Pacific Rise approached western North America, increasingly younger oceanic lithosphere was subducted (Atwater, 1970; Dickinson and Snyder, 1979a; Severinghaus and Atwater, 1990). Subduction of young, buoyant oceanic crust and the ridge-trench interactions that ensued resulted in the termination of subduction, development of a no-slab region beneath the continental margin, cessation of Sierran arc magmatism, and the transition from a convergent to a transform plate boundary along western North America (Atwater, 1970, 1989; Dickinson and Snyder, 1979a, 1979b; Severinghaus and Atwater, 1990). Magmatism in California during this tectonic tran-

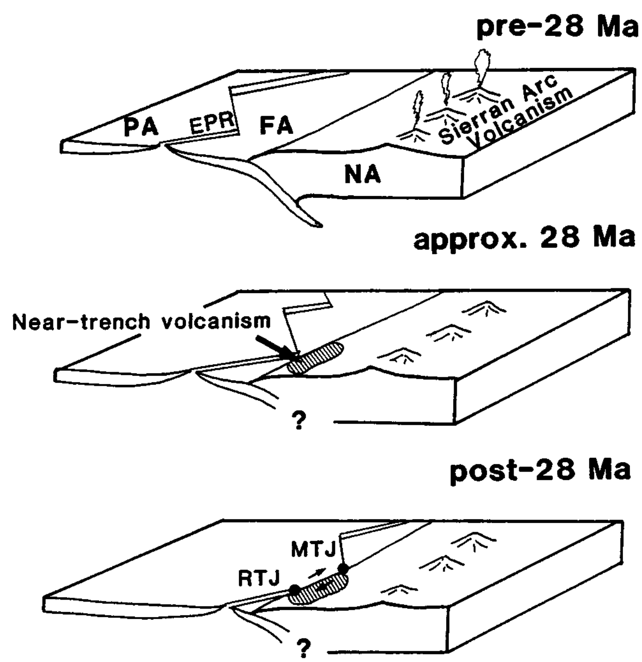

Figure 1. Model for middle Tertiary North American (NA)–Pacific (PA)–Farallon (FA) plate interactions. From Atwater (1970, 1989) and Severinghaus and Atwater (1990). Arrows show relative motion between Pacific and North American plates along the San Andreas transform boundary. EPR = East Pacific Rise; MTJ = Mendocino triple junction; RTJ = Rivera triple junction.

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TABLE 1. AGES OF SOME OLIGOCENE-MIOCENE VOLCANIC UNITS IN WESTERN CALIFORNIA

Volcanic unit	Age (Ma)*	References
Coast Range Province (CRP) volcanic centers		
Halfmoon Bay basalt HMB*	Lower Miocene	Stanley (1987)
Pescadero Beach basalt PB*	22.0 ± 0.7	Taylor (1990)
Mindego basalt and related volcanic rocks M[†]	20.2 ± 1.2 to 23.7 ± 0.7	Turner (1970)
Carmel basalt CM[†]	27.0 ± 0.8 to 27.1 ± 0.8	Clark and others (1984)
San Juan Bautista volcanics SJB[†]	21.3 ± 1.3 to 23.5 ± 1.4	Turner (1968), Weigand and Thomas (1990)
Pinnacles volcanics P[†]	22.1 ± 3.2 to 24.5 ± 1.2	Turner (1968), Weigand and Swisher (1991)
Morro Rock MR[†]	22.6 ± 0.9 to 27.2 ± 0.8	Turner and others (1970), Buckley (1986)
Cambria felsite CF	Upper Oligocene to early Miocene	Ernst and Hall (1974)
Simmler Fm. basalt S[†]	22.9 ± 0.7 to 23.4 ± 0.8	Ballance and others (1983)
Pine Creek basalt PC[†]	26.6 ± 0.5	Vedder and others (1991)
Plush Ranch Fm. basalt PR[†]	20.4 ± 0.9 to 26.5 ± 0.5	Frizzell and Weigand (1993)
Tecuya Fm. volcanics T	22.1 ± 0.6 to 25.2 ± 2.9	Turner (1970)
Neenach volcanics N[†]	21.30 + 0.22 to 23.55 + 0.06	Weigand and Swisher (1991)
Parkfield volcanic rocks PK[†]	>22.3 to 23.8 ± 0.7	Turner (1968), Weigand and Thomas (1990)
Vasquez Fm. basalt VQ[†]	23.6 ± 0.4 to 25.6 ± 2.1	Frizzell and Weigand (1993)
Diligencia Fm. basalt DI	22.0 ± 0.5 to 23.6 ± 0.5	Frizzell and Weigand (1993)
Iversen basalt IB	22.6 ± 1.2 to 24.3 ± 1.3	Turner (1970)
Point Ano Nuevo basalt AN	Lower Miocene	Clark (1981), Brabb and others (1977)
Point Reyes basalt PY	Lower Miocene	Clark and others (1984)
Santa Maria Province (SMP) volcanic centers		
Obispo Fm. OB[†]	15.7 ± 0.9 to 16.9 ± 1.2	Turner (1970)
Lospe Fm. tuffs LO[†]	17.39 ± 0.12 to 17.70 ± 0.3	Stanley and others (1991)
Point Sal diabase PS[†]	Lower Miocene	Dibblee (1989)
Tranquillon volcanics type section TQ†	16.5 ± 0.6 to 18.6 ± 1.2	Turner (1970), Stanley and others (1991)
Tranquillon "basalt" TB†	17.4 ± 1.2	Turner (1970)
Summerland tuff SU	16.5 ± 0.6 to 17.2 ± 0.5	Turner (1970)
Catway basalt CB†	18.8 ± 1.5	J. Vedder (1991, personal commun.)
Lopez Mountain basalt LM†	Lower Miocene	H. McLean (1990, personal commun.)
Triple basalts TP	14.6 ± 0.6 to 16.5 ± 1.3	Turner (1970)
Northwestward "younging" volcanic centers		
Clear Lake volcanics CL	0.26 ± 0.04 to 2.24 ± 0.29	Donnelly-Nolan et al. (1981)
Sonoma-Tolay volcanics ST	2.6 ± 0.3 to 13.62 ± 2.39	Fox and others (1985)
Berkeley Hills volcanics BH	7.9 to 12.0	Evernden and others (1964), G. Curtis (1991, personal commun.)
Page Mill basalt PM	14.8 ± 2.4	Turner (1970)
Quien Sabe volcanics QS	9.1 ± 0.10 to 11.6 ± 0.15	Drinkwater and others (1992)
Southern California (borderland) volcanic centers[§]		
Conejo volcanics CO	13.4 ± 0.9 to 16.6 ± 2.4	Turner (1970)
Glendora volcanics G	Lower Miocene	Higgins (1976)
Los Angeles basin basalts LA	12.0 to 15.0	Turner and others (1970)
El Modeno volcanics EM	14.1 ± 1.6	Turner (1970)

[*]K/Ar ages from Turner (1968; 1970) and Turner et al. (1970) corrected using methods described in Dalrymple (1979).
[†]Volcanic units analysed in this study. See Table 2 for sample numbers and Figure 2 for locations.
[§]Table does not include channel island volcanic units or all of the onshore borderland volcanic units.

sition is characterized by localized bimodal volcanic assemblages that erupted in western California ~200 km west of the preexisting Sierran magmatic arc (Christiansen and Lipman, 1972; Pilger and Henyey, 1979; Snyder et al., 1976; Dickinson and Snyder, 1979a). These near-trench volcanic rocks did not erupt in a "typical" tectonic setting (i.e., magmatic arc or continental rift zone) and, therefore, represent a distinct style of continental margin volcanism during a transition from a convergent to a transform plate boundary.

This study addresses the origin and petrogenesis of some of these middle Tertiary volcanic rocks and tests the existing tectonic models for their emplacement by using Nd and Sr isotopes, their spatial and temporal distributions, and trace and major element chemistry. We conclude that magmas for middle Tertiary near-trench volcanism in California were derived from a more widespread depleted suboceanic mantle component than previously recognized for this region. These results are consistent with tectonic models, which show that segments of the East Pacific Rise had intersected the continental margin before and during these volcanic episodes. Our model suggests that depleted mantle, which was emplaced beneath the continental margin during ridge subduction, became a source of magma for episodes of near-trench volcanism.

GEOLOGIC BACKGROUND AND STUDY AREA

The transform boundary between the Pacific and North American plates, represented today by the San Andreas fault system, joins two triple junctions (Fig. 1). The Mendocino triple junction is a transform-transform-trench triple junction that is migrating to the northwest, and the Rivera triple junction is a ridge-transform-trench triple junction that is migrating to the southeast. Judging from recent plate reconstruction models and refinements of earlier models (Engebretson et al., 1985; Stock and Molnar, 1988; Atwater, 1989; Severinghaus and Atwater, 1990), small segments of the East Pacific Rise interacted complexly with the western margin of California during the initial stages of the convergent-to-transform transition.

Previous studies revealed a relationship between the distribution and ages of some Miocene volcanic units in western California and the northwestward migration path of the Mendocino triple junction (Snyder et al., 1976; Dickinson and Snyder, 1979a, 1979b; Johnson and O'Neil, 1984; Fox et al., 1985). These studies suggest that the progressive northwestward cessation of Sierran arc volcanism and the eruption of a series of Miocene volcanic centers that become younger to the northwest in western California were a direct response to Mendocino triple junction migration. Whereas some Miocene volcanic centers east of the San Andreas fault do become younger to the northwest (Table 1, Fig. 2), two coeval groups of volcanic rocks, primarily on the west side of the San Andreas fault, do not fit this trend. These two groups of volcanic rocks were emplaced during the initial phases of the convergent-to-transform transition and are the focus of this paper. The two groups are distinguished from each other primarily on the basis of age and partly by their geographic distributions (Table 1, Fig. 2). One of these groups has an age range between ca. 22 and 26 Ma and is found mostly in the Coast Ranges of western California. These rocks are referred to in this paper as the Coast Range Province volcanic rocks. A second group of volcanic rocks, which has an age range between ca. 16 and 19 Ma, is primarily located within the Santa Maria Province of west-central California.

EXPERIMENTAL PROCEDURES AND SAMPLES

A set of 37 samples from 19 late Oligocene–early Miocene volcanic units in western California was analyzed for Nd- and Sr-isotopic compositions and major and trace element chemistry (Tables 2–4). About 50 g of each sample was crushed in a zirconia mill. Most trace element concentrations were determined by inductively coupled plasma–mass spectroscopy (ICP-MS) at Batelle Pacific Northwest Laboratories. The ICP-MS data for the trace elements were checked against the BCR-1 (U.S. Geological Survey, Columbia River basalt) rock

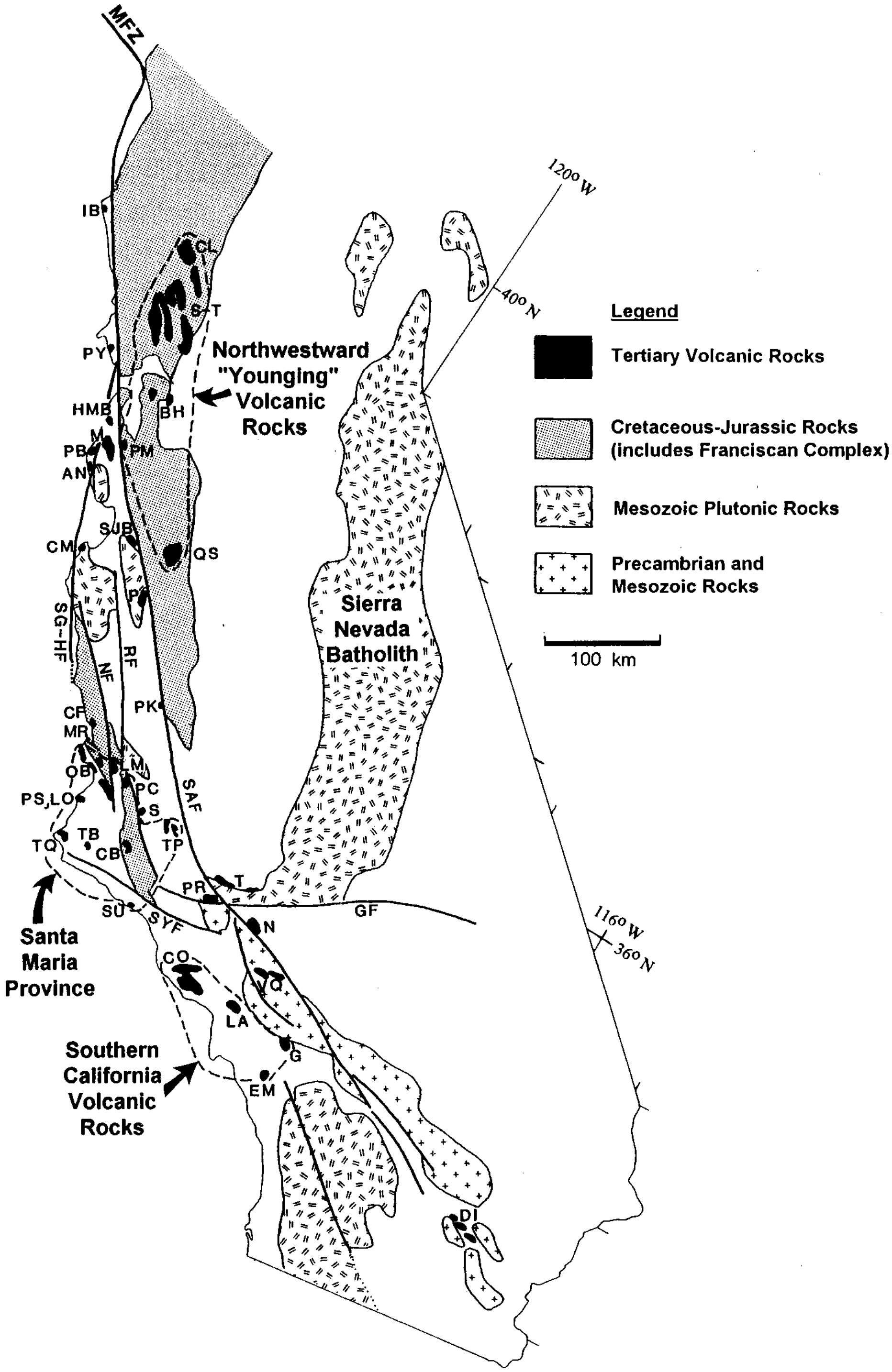

Figure 2. Study area map of Tertiary volcanic units in western California. Dashed lines define groups of volcanic units as labeled except for the Coast Range Province volcanic units, which are not outlined. Abbreviations for volcanic units are given in Table 1. SAF = San Andreas fault, SG-HF = San Gregorio–Hosgri fault, RF = Rinconada fault, NF = Nacimiento fault, GF = Garlock fault, SYF = Santa Ynez fault, MFZ = Mendocino fracture zone.

standard, which was also analyzed by the same method. Results for the BCR-1 rock standard were within 2%–5% for the rare earth elements and usually <10% for the other trace elements of their recommended values for this standard. Eight samples were analyzed with the instrumental neutron activation analysis method by the Oregon State University Radiation Center. Analyses by this method usually have errors between 5% and 12% for the rare earth elements and between 6% and 15% for the other trace elements. Major element determinations were made by X-ray fluoresence spectrometry by Chemex Labs Inc., Sparks, Nevada. We attribute the high loss on ignition (LOI) values for some samples to zeolite minerals among the pore spaces in some tuff and vesicular basalt units. Samples 21 and 23 are the same as samples NV31 and PV17, respectively, from Weigand and Thomas (1990), who presented trace and major element data for these two rocks. Sr and Nd isotopic data were collected for all samples with a VG Sector thermal ionization mass spectrometer at the University of Rochester using the procedures outlined by Basu et al. (1990).

MAJOR AND TRACE ELEMENT GEOCHEMISTRY

Volcanic rocks from the Coast Range and Santa Maria Provinces are generally bimodal in composition, including a basalt end-member and an acidic end-member of mostly rhyolite and dacite with minor trachyte (Fig. 3) (classification is after Le Bas et al., 1986). Few samples exhibit intermediate SiO_2 concentrations and include basaltic andesite, andesite, and trachyandesite (Fig. 3). In both suites MgO and Al_2O_3 correlate negatively, whereas Na_2O and K_2O correlate positively with SiO_2. The basalts of each group are transitional between subalkalic and alkalic types on the basis of weight percent of total alkalis versus SiO_2.

All of the samples from each province exhibit variable degrees of light rare earth element (LREE) enrichment (Figs. 4 and 5). Overall, rock samples from the Coast Range Province show greater LREE enrichment than samples from the Santa Maria Province among all rock types. For example, La/Sm ratios for Santa Maria Province acidic, intermediate, and basic rocks are 1.8–6.0, 2.4–4.2, and 1.7–2.8, respectively. La/Sm ratios for Coast Range Province acidic, intermediate, and basic rocks are 2.9–7.6, 4.3–5.1, and 2.1–5.5, respectively. Rhyolite and

TABLE 2. MAJOR ELEMENT COMPOSITION OF SAMPLES FROM THE SMP AND CRP VOLCANIC ROCKS*

Sample	Unit†	SiO_2	Na_2O	K_2O	MgO	Fe_2O_3	Al_2O_3	CaO	MnO	P_2O_5	TiO_2	LOI	Total
						Santa Maria Province							
1	LO	74.06	3.81	1.76	0.97	1.01	11.76	0.48	0.01	0.03	0.17	6.39	100.45
2	LO	76.15	5.07	1.23	0.51	0.42	10.82	0.32	0.01	0.05	0.11	4.99	99.69
3	LO	68.89	1.33	0.80	1.65	0.60	11.32	2.37	0.01	0.07	0.13	12.17	99.35
4	TQ	77.10	3.11	5.06	0.04	1.20	11.13	0.50	0.01	0.06	0.14	1.38	99.73
5	TQ	77.28	3.09	5.34	0.05	1.17	11.41	0.53	0.01	0.09	0.15	1.27	100.40
6	TQ	78.32	2.57	6.25	0.01	0.68	11.22	0.32	0.01	0.08	0.14	1.04	100.65
7	OB	66.29	4.15	2.41	0.80	2.54	11.45	1.06	0.02	0.11	0.30	10.21	99.33
8	OB	55.45	2.12	1.27	4.71	2.10	13.11	3.97	0.02	0.12	0.21	17.25	100.30
9	OB	68.15	2.78	2.67	1.24	1.85	12.89	1.19	0.01	0.16	0.56	6.30	99.43
10	TQ	53.92	3.72	1.27	3.17	12.97	14.58	6.99	0.20	0.45	2.41	0.01	99.69
11	TQ	52.78	3.84	1.28	2.94	11.89	11.41	4.58	0.18	0.48	2.15	1.05	99.65
12	PS	47.64	3.46	1.02	5.36	7.91	17.37	9.25	0.13	0.26	1.55	3.62	99.56
13	LM	43.56	1.46	0.60	14.95	11.56	12.40	5.52	0.13	0.20	1.09	8.21	98.60
14	CB	46.70	3.47	0.75	5.69	11.28	16.43	9.79	0.12	0.38	2.33	2.98	99.92
15	CB	47.16	3.31	0.82	5.78	10.72	15.44	8.12	0.08	0.34	2.52	5.47	99.75
16	CB	46.24	3.44	0.64	5.83	11.37	16.63	8.68	0.09	0.37	2.50	4.98	99.85
17	OB	48.13	3.78	0.87	4.14	13.60	14.40	8.75	0.18	0.46	3.34	1.29	98.95
18	OB	47.68	3.84	0.72	3.83	13.20	13.89	7.96	0.12	0.41	3.21	1.58	99.25
						Coast Range Province							
19	MR	67.49	4.10	3.10	1.11	3.29	15.79	2.72	0.04	0.22	0.48	1.36	99.69
20	N	70.20	4.38	3.63	0.20	3.08	15.06	2.22	0.01	0.13	0.22	1.37	101.80
21	N	68.30	4.03	4.91	0.25	3.21	15.50	1.66	0.01	0.11	0.19	1.16	99.33
22	P	68.02	4.71	3.97	0.23	4.25	16.14	2.02	0.03	0.20	0.23	0.66	100.45
23	P	74.00	3.98	5.47	0.13	1.02	13.70	0.51	0.01	0.02	0.05	0.54	99.43
24	PK	75.96	3.44	4.85	0.10	0.77	13.88	0.69	0.01	0.08	0.04	1.45	101.25
25	SJB	65.55	4.22	2.73	0.16	4.41	15.51	3.17	0.01	0.48	0.89	1.38	98.51
26	SJB	71.96	4.46	3.32	0.08	1.27	13.66	1.14	0.02	0.10	0.02	3.29	99.32
27	SJB	57.84	4.35	1.82	0.84	7.71	16.05	4.38	0.10	0.55	1.00	3.61	98.25
28	CM	61.48	4.48	3.05	0.60	5.71	17.47	4.44	0.04	0.51	1.31	1.93	101.01
29	VQ	58.24	3.57	2.41	3.34	6.80	16.37	6.61	0.07	0.34	2.45	2.02	101.20
30	HMB	45.54	2.44	0.50	5.18	11.21	17.39	11.12	0.13	0.20	1.49	4.57	99.75
31	PB	46.57	3.47	2.39	4.17	8.37	15.19	9.86	0.12	0.50	1.69	14.79	99.11
32	M	48.22	3.20	1.11	4.95	8.79	16.64	9.48	0.19	0.45	2.16	3.42	98.61
33	M	48.74	3.19	0.35	4.57	8.67	17.24	10.26	0.12	0.40	2.10	3.21	98.84
34	PR	48.00	2.93	1.16	6.82	9.95	15.86	8.49	0.13	0.29	1.60	5.30	99.62
35	PR	47.09	3.35	1.31	5.54	9.20	16.08	8.45	0.15	0.28	1.56	4.18	100.20
36	S	50.50	3.03	0.96	4.75	8.42	17.05	9.46	0.11	0.27	1.55	3.19	99.28
37	PC	51.06	3.32	1.42	5.01	8.51	16.79	8.73	0.10	0.25	1.52	2.33	100.60

*Samples 21, 23, and 24 from P. Weigand. Data for 21 and 23 from Weigand and Thomas (1990); for these samples total iron is expressed as FeO.
†See Table 1 for unit abbreviations and Figure 2 for unit locations.

dacite from both provinces also have strong negative Eu anomalies. Between the two provinces, the Coast Range Province basalts exhibit, in general, greater enrichment of incompatible elements than the Santa Maria Province basalts (e.g., higher Rb/Sr, Th/Sc, and La/Sc ratios) (Figs. 4 and 5, Table 3).

PETROGENESIS OF THE COAST RANGE AND SANTA MARIA PROVINCES VOLCANIC ROCKS

The combined major and trace element and Nd- and Sr-isotopic trends in the Coast Range and Santa Maria Provinces volcanic rocks indicate that depleted magmas of each province evolved by combinations of fractional crystallization and assimilation of low $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$ crust (Fig 6). Evidence that each province consists of a related suite of rocks includes the correlations of radiogenic isotopic ratios with SiO_2 (Fig. 7), the coherent variations among major and trace elements (Figs. 3–5) (Cole, 1993), and the coeval ages of eruptions in each province (Table 1). Comagmatic relationships for some of these volcanic units have also been inferred by Weigand (1982), Johnson and O'Neil (1984), Weigand and Thomas (1990), and Frizzell and Weigand (1993). Although the Coast Range and Santa Maria Provinces volcanic units represent separate age suites, our major and trace element and isotopic data, together with the common tectonic setting, suggest that volcanic rocks of each province may share a common petrogenetic history.

The Nd- and Sr-isotopic data for these rocks may be interpreted to indicate that ba-

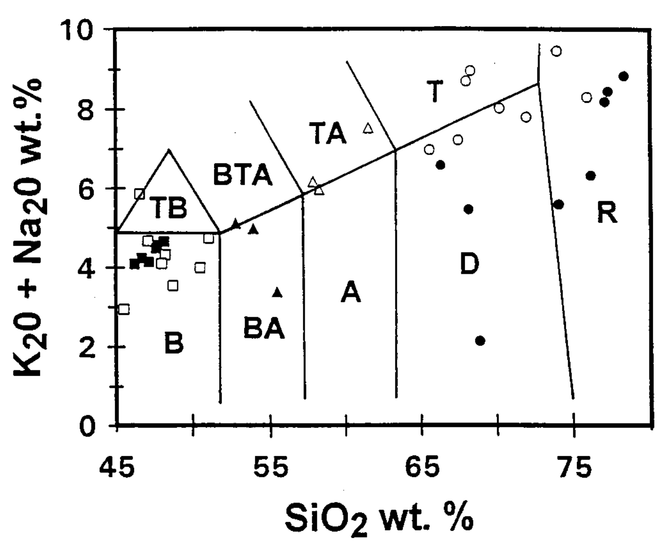

Figure 3. SiO_2 versus $Na_2O + K_2O$ (total alkalis) for samples from the Coast Range Province (CRP) and Santa Maria Province (SMP) volcanic rocks. Rock fields are from Le Bas et al. (1986). B = basalt, BA = basaltic andesite, TB = trachybasalt, BTA = basaltic trachyandesite, A = andesite, TA = trachyandesite, T = trachyte, D = dacite, and R = rhyolite. Filled symbols represent samples from the SMP, and open symbols represent samples from the CRP.

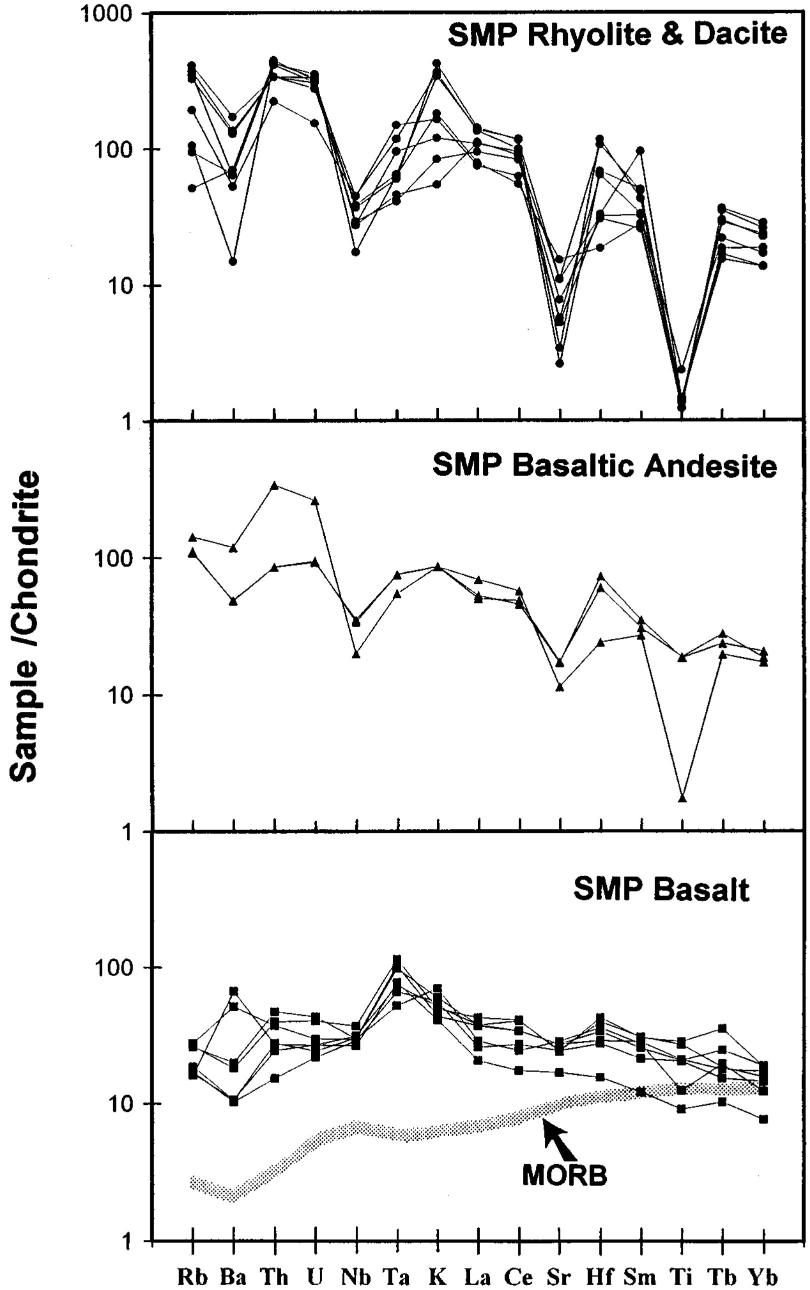

Figure 4. Trace element concentration diagrams for the Santa Maria Province (SMP) volcanic rocks. Data are normalized to chondrites according to Thompson et al. (1984), except for K and Rb, which are normalized to primitive mantle after Sun (1980).

salts of each province were derived from depleted magmas similar to those of mid-ocean-ridge basalts (MORB) (Fig. 6) (e.g., Sun and McDonough, 1989). Of the two provinces, basalts in the Santa Maria Province are isotopically similar to MORB with $\varepsilon_{Nd}(t)$ values reaching +9.3 and $^{87}Sr/^{86}Sr(t)$ ratios as low as 0.702 58. Basalts of the Coast Range Province have lower $\varepsilon_{Nd}(t)$ and higher $^{87}Sr/^{86}Sr(t)$ values than MORB, but form a trend toward the MORB field in the Nd-Sr isotopic correlation diagram (Fig. 6), reaching $\varepsilon_{Nd}(t)$ values of +7.9 and $^{87}Sr/^{86}Sr(t)$ values of 0.702 94.

The coherent variation among the Coast Range and Santa Maria Provinces volcanic rocks as seen in Nd-Sr isotopic space (Fig. 6) suggests mixing between the depleted end-member and a low $^{143}Nd/^{144}Nd$ and high $^{87}Sr/^{86}Sr$ enriched end-member. The predominant crustal rocks that the Coast Range and Santa Maria Provinces volcanic rocks were erupted through include (1) Jurassic-Cretaceous rocks of the Franciscan complex (San Simeon and Stanley Mountain terranes), which include thick graywacke and metagraywacke sequences that petrographically are similar to Great Valley Group fore-arc basin deposits (Dickinson et al., 1982; McLean, 1991) along with blueschist and ultramafic rocks; (2) Mesozoic granitic and metamorphic rocks of the Salinian terrane; and (3) small areas of the Tujunga terrane, which includes Precambrian metamorphic, Paleozoic metasedimentary, and Mesozoic intrusive rocks. Each of these crustal terranes includes components with low $\varepsilon_{Nd}(t)$ values and high $^{87}Sr/^{86}Sr(t)$ isotopic ratios (general range is −4 to <−12 and 0.706 to >0.712, respectively; Kistler and Peterman, 1978; Mattinson, 1990; DePaolo et al., 1991; Linn et al., 1991) (Fig. 6). The Nd and Sr isotopic trends of the Coast Range and Santa Maria Provinces volcanic rocks could have resulted from mixing between depleted basaltic magma and melts of these crustal components. Assimilation of crustal rocks by depleted magmas to form the Coast Range and Santa Maria Provinces acidic rocks also is demonstrated by the coherent variations between Nd and Sr isotopic ratios and SiO_2 (Fig. 7). These variations would not result from closed system fractionation of a mantle-derived magma, but require mixing with, or assimilation of, isotopically distinctive crustal components (Leeman and Hawkesworth, 1986; DePaolo, 1988).

The effects of crustal contamination of mantle-derived magmas may also be ascertained from trace element concentrations (Leeman and Hawkesworth, 1986; Sun and McDonough, 1989). In upper crustal rocks, trace elements such as Rb, Th, U, K, and the LREE tend to be enriched, whereas Ba, Nb, and Ta are typically more depleted. The progressive enrichment in Rb, Th, U, K, and the LREE with increasing SiO_2 contents among the Coast Range and Santa Maria Provinces volcanic rocks, from basalt through rhyolite, dacite, and trachyte (Figs. 4 and 5), strongly suggests assimilation of crustal components by mantle-derived basaltic magmas. Even the basalts of this study with high initial εNd and low initial $^{87}Sr/^{86}Sr$ values show variable incompatible trace element enrichment. We suggest here that these basalts, despite their origin from depleted mantle, have undergone some assimilation of crustal material

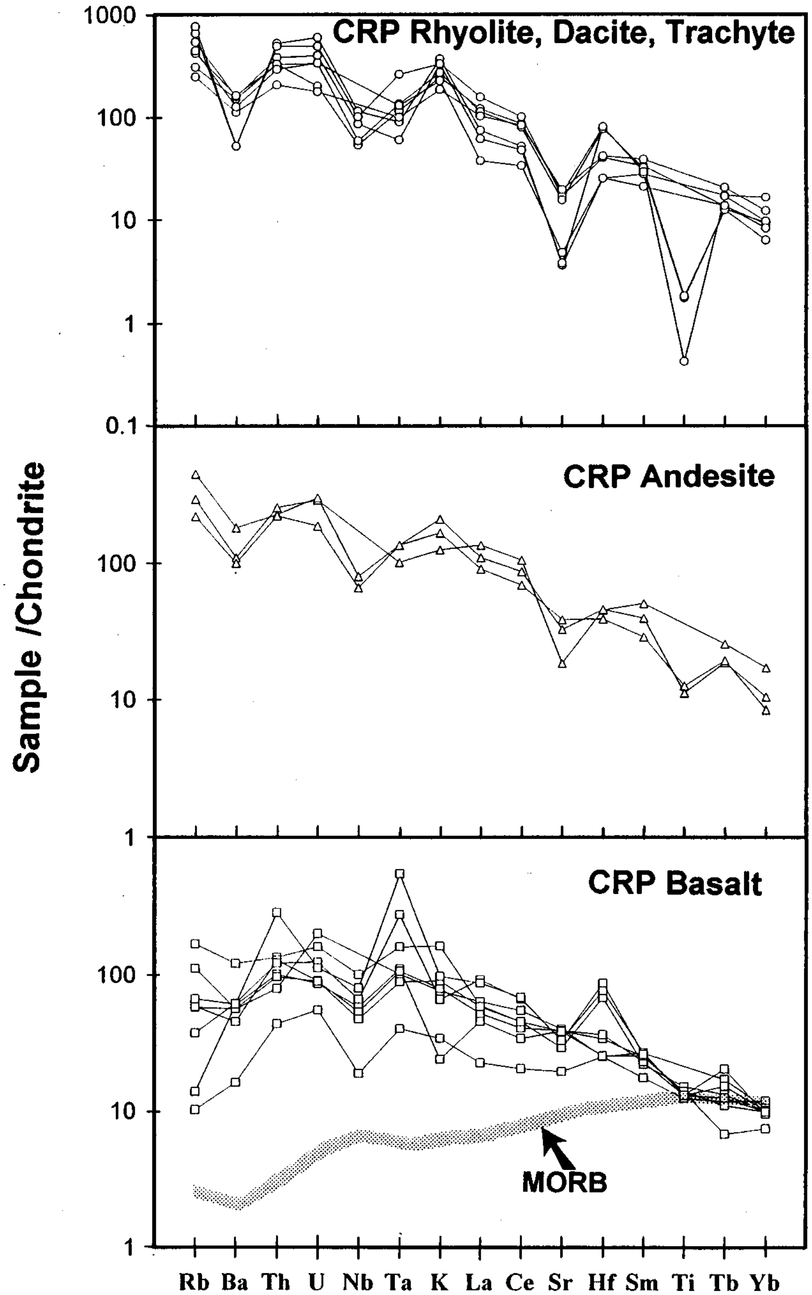

Figure 5. Trace element concentration diagrams for the Coast Range Province (CRP) volcanic rocks. Data are normalized to chondrite according to Thompson et al. (1984), except for K and Rb, which are normalized to primitive mantle after Sun (1980).

with accompanying fractional crystallization. This resulted in their enrichment with incompatible elements as compared to MORB (Figs. 4 and 5). In addition, the marked depletions of Ba, Nb-Ta, Sr, and Ti in the Coast Range and Santa Maria Provinces acidic rocks resemble the characteristics exhibited by upper continental crustal rocks (Taylor and McLennan, 1985). The depletion of these elements relative to chondrite is characteristically absent in the Coast Range and Santa Maria Provinces basalt (Figs. 4 and 5).

The concentration ratios between highly incompatible trace elements are another useful means to evaluate mixing between mantle and crustal sources. Such ratios should be constant during fractional crystallization processes but will vary if two source components of different compositions are mixed (e.g., Loubet et al., 1988). Basalt samples from both the Coast Range and Santa Maria Provinces have low Th/Ta and Ba/Ta ratios of 0.49–2.59 and 35.78–338.46, respectively (Table 3), which are similar to those of MORB (Loubet et al., 1988). These ratios are typically much higher in the lower and upper continental crust (Taylor and McLennan, 1985). The Coast Range and Santa Maria Provinces acidic rocks exhibit high Th/Ta and Ba/Ta ratios of 2.36–21.22 and 53.93–908.33, respectively (Table 3). Thus mixing of MORB-like magmas and enriched crustal components is suggested by the observed variations of Th/Ta and Ba/Ta among the Coast Range and Santa Maria Provinces volcanic suites.

In addition to crustal assimilation, the trace element variations among Coast Range and Santa Maria Provinces volcanic rocks also suggest that fractional crystallization had occurred. The decrease of Sr and Ti in the acidic rocks of each province may be attributed to fractionation of plagioclase and Fe-Ti oxides (e.g., magnetite), respectively. In addition, fractionation of olivine and clinopyroxene from the basalts is suggested by the progressive decrease of Sc and MgO from basalts to more silica-rich rocks (Tables 2 and 3).

In summary, our evaluation of the isotopic and geochemical data for the Coast Range and Santa Maria Provinces volcanic rocks suggests open-system differentiation of a depleted-mantle derived magma by combined assimilation of enriched crust and fractional crystallization processes. The greater concentration of the incompatible trace elements, including the LREE, in the Coast Range Province samples suggests that its magmatic source may have undergone a greater degree of assimilation-fractionation and/or assimilated a more enriched crustal component than the Santa Maria Province magmas. Several basalt samples of each province retain a depleted mantle Nd and Sr isotopic signature, which provides control on the mantle end-member composition (Fig. 6). Based on the observed LREE-enrichment in these end-member basalts as compared to MORB, we suggest that these basalts underwent a small degree of crustal assimilation and/or fractional crystallization and represent a slightly enriched and modified depleted-mantle end-member component. Available isotopic data for basement rocks in the Coast Range and Santa Maria Provinces provide a crustal end-member compositional field (Fig. 6) (Kistler and Peterman, 1978; Mattinson, 1990; DePaolo et

TABLE 3. TRACE ELEMENT COMPOSITION OF SAMPLES FROM THE SMP AND CRP VOLCANIC ROCKS

Sample	Ba	Rb	Sr	Th	Nb	Ta	La	Ce	Nd	Sm	Eu	Tb	Yb	Lu	Hf	Ti	Tb	Sc	U
Santa Maria Province																			
1	103	37.00	61.7	18.10	9.72	1.91	35.60	81.90	32.20	5.98	0.29	0.87	3.00	0.38	6.58	899	0.87	21.10	4.34
2	453	33.00	91.0	17.40	10.20	0.82	31.10	71.70	33.20	5.21	0.22	0.80	2.97	0.42	6.10	875	0.80	2.30	4.00
3	486	18.00	129.0	18.90	9.57	0.92	36.50	77.20	31.70	6.53	0.25	0.96	4.09	0.52	6.40	905	0.96	2.60	4.20
4	892	115.00	40.2	14.30	13.50	1.30	45.20	101.70	46.30	8.70	0.63	1.50	5.18	0.70	23.40	848	1.50	1.70	3.60
5	1190	144.00	30.6	14.20	15.80	2.36	44.10	85.70	42.50	10.20	0.88	1.81	5.69	0.74	13.70	838	1.81	3.90	3.98
6	938	132.00	130.0	14.30	12.90	1.20	46.90	99.50	50.70	9.97	0.70	1.55	4.96	0.69	21.40	860	1.55	2.40	4.30
7	365	67.50	66.7	9.39	15.60	2.97	24.50	54.20	28.90	6.74	1.45	1.14	3.72	0.68	12.80	1450	1.14	9.18	2.01
8	818	49.70	135.0	14.10	6.99	1.10	22.80	49.50	23.60	5.49	0.90	1.02	3.78	0.44	4.84	1080	1.02	5.83	3.37
9	443	123.00	180.0	17.80	6.12	1.27	25.80	47.50	22.10	5.70	1.43	1.89	4.27	0.45	3.71	759	1.89	15.30	4.62
10	338	38.00	206.0	3.60	11.90	1.51	16.50	42.00	26.10	6.24	2.56	1.45	4.08	0.72	12.10	11700	1.45	31.20	1.23
11	332	39.10	202.0	3.59	12.40	1.52	17.40	39.50	27.50	7.15	2.25	1.23	4.55	0.61	14.80	11500	1.23	26.70	1.20
12	352	9.64	334.0	1.56	10.40	1.04	9.35	21.00	14.10	5.50	1.74	1.01	2.67	0.65	7.11	7630	1.01	40.10	0.39
13	459	5.61	197.0	1.14	9.24	1.53	6.72	15.00	9.02	2.44	0.81	0.53	1.88	0.29	3.07	5600	0.53	19.10	0.35
14	73	5.75	318.0	1.02	10.90	1.47	12.30	29.30	21.90	5.67	1.88	0.92	3.76	0.68	5.71	12900	0.92	37.80	0.35
15	70	5.92	285.0	0.64	10.10	1.31	8.46	23.40	14.20	4.29	1.77	0.79	3.16	0.52	5.43	12500	0.79	36.20	0.28
16	73	6.48	320.0	1.16	10.60	2.04	12.10	29.30	18.00	5.12	1.95	1.27	4.16	0.84	6.68	12700	1.27	44.50	0.32
17	137	9.05	289.0	1.97	10.40	1.95	12.30	34.80	21.00	6.19	2.13	0.95	3.42	0.48	7.85	16600	0.95	45.20	0.56
18	125	9.20	281.0	1.67	12.90	2.27	13.90	35.20	25.70	6.11	2.50	1.53	4.06	0.85	8.43	17500	1.83	60.00	0.52
Coast Range Province																			
19	775	136.00	182.0	15.10	N.D.	1.10	32.90	65.20	28.10	6.30	1.09	0.81	2.83	0.43	6.90	N.D.	0.81	6.10	5.00
20	1040	107.00	216.0	13.80	18.70	2.30	39.70	74.90	30.60	6.22	1.48	0.66	2.06	0.26	16.00	1090	0.66	11.00	2.61
21	1090	190.00	200.0	16.00	30.00	1.20	51.50	87.00	32.00	6.79	0.76	0.70	1.99	0.38	8.10	N.D.	0.70	2.32	5.20
22	1120	146.00	184.0	13.80	20.60	2.69	37.10	68.80	31.80	6.53	1.36	0.64	2.40	0.50	15.40	1130	0.64	8.92	4.35
23	360	230.00	43.0	22.00	40.00	1.80	24.40	45.00	18.00	5.65	0.35	0.90	3.64	0.61	5.10	N.D.	0.90	2.49	7.80
24	364	269.00	44.9	20.60	35.40	5.21	20.20	41.40	18.90	5.96	0.43	0.88	2.12	0.34	16.10	262	0.88	4.36	6.39
25	774	86.00	232.0	8.70	N.D.	2.00	33.70	71.80	38.60	7.92	1.86	1.07	2.68	0.36	8.40	N.D.	1.07	11.20	2.30
26	869	155.00	57.0	12.30	N.D.	2.60	12.40	29.20	15.30	4.26	0.67	0.71	1.81	0.26	5.10	N.D.	0.71	0.35	4.40
27	752	102.00	215.0	10.60	N.D.	2.00	43.80	89.80	45.50	10.20	2.55	1.31	3.71	0.54	9.00	N.D.	1.31	10.90	3.70
28	1240	156.00	382.0	9.43	27.80	2.68	35.40	74.00	41.50	7.90	2.40	0.96	2.28	0.24	9.09	6820	0.96	20.50	3.87
29	684	76.50	450.0	9.22	22.90	2.67	29.30	59.00	31.80	5.78	1.94	0.98	1.83	0.47	7.69	7680	0.98	15.70	2.40
30	111	3.55	228.0	1.83	6.55	0.80	7.36	17.60	13.60	3.55	1.21	0.60	2.59	0.46	4.98	7620	0.60	32.90	0.71
31	829	58.80	342.0	5.61	34.70	3.20	19.40	38.80	19.90	4.44	2.05	0.68	2.19	0.31	13.60	9320	0.68	15.60	2.08
32	387	20.00	472.0	3.30	N.D.	2.00	20.80	47.00	29.00	5.37	1.88	0.88	2.30	0.29	5.00	N.D.	0.88	25.80	2.60
33	412	4.83	453.0	4.21	20.20	2.20	14.90	29.30	18.70	5.04	1.78	0.35	1.63	0.25	6.74	8520	0.35	26.50	1.11
34	310	20.30	457.0	5.35	18.60	2.11	17.00	35.00	18.30	4.63	1.72	0.79	2.21	0.36	7.22	8040	0.79	23.30	1.16
35	388	38.70	451.0	4.04	16.40	1.76	19.10	38.90	21.90	5.11	1.43	0.57	2.16	0.42	5.05	8630	0.57	28.60	1.15
36	425	13.00	393.0	5.10	22.90	5.51	30.00	57.20	25.00	5.43	1.66	1.05	2.09	0.36	15.20	8080	1.05	25.70	1.60
37	417	23.10	386.0	12.00	27.70	10.90	28.30	58.50	27.10	5.28	1.13	0.65	2.16	0.35	17.20	8030	0.65	26.70	1.45

Note: See text for methods of trace element determinations. Volcanic units for each sample are shown in Table 2. N.D. = not detected.

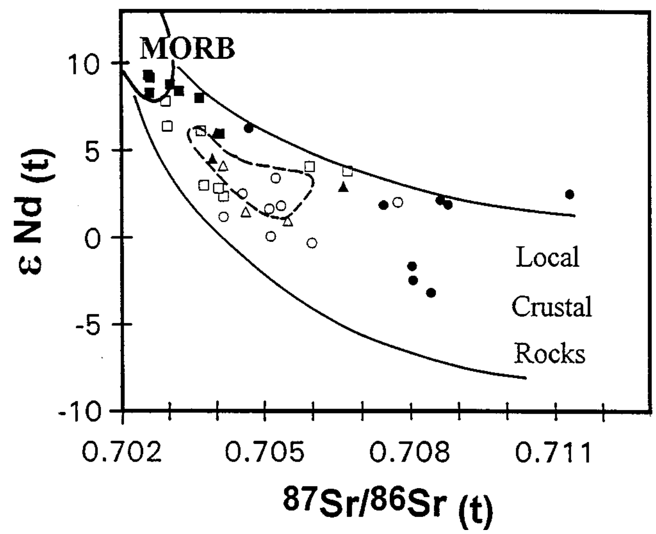

Figure 6. Plot of initial εNd versus initial $^{87}Sr/^{86}Sr$ for samples from the Coast Range Province (CRP) and Santa Maria Province (SMP) volcanic units. Filled symbols represent samples from the SMP, and open symbols represent samples from the CRP. Squares = basic rocks (basalt and trachybasalt), triangles = intermediate rocks (andesite, trachyandesite, and basaltic andesite), and circles = acidic rocks (dacite, rhyolite, and trachyte). Also shown are data from the Tecuya volcanic rocks (Sharma et al., 1991), which constitute one of the CRP volcanic units (dashed outline). Field of mid-ocean-ridge basalt (MORB) is from Sun and McDonough (1989) and references therein. The Nd- and Sr-isotopic compositions for local crustal rocks in the Coast Range and Santa Maria Provinces are generally strongly enriched (Kistler and Peterman, 1978; Mattinson, 1990; DePaolo et al., 1991; Linn et al., 1991), resulting in distinctive Nd and Sr-isotopic signatures falling in the lower right hand corner of the diagram.

al., 1991; Linn et al., 1991). Mixing among these end-member components resulted in the observed isotopic compositions of the Coast Range and Santa Maria Provinces volcanic rocks.

TECTONIC MODELS FOR VOLCANISM

The predominantly bimodal nature, localized eruption centers, depleted isotopic signatures, and proximity of volcanism to the paleo-subduction zone suggest a unique setting for the Coast Range and Santa Maria Provinces volcanic rocks. Several hypotheses have been proposed to relate late Oligocene–early Miocene volcanism in western California (including the Coast Range and Santa Maria Provinces volcanic rocks) to processes associated with different plate interactions. These hypotheses include volcanism in relation to the migration of the Mendocino triple junction, subduction-related processes, and regional extension or transtension along pre–San Andreas strike-slip faults during East Pacific Rise–trench interactions. In this section we discuss these hypotheses with regard to the spatial, temporal, geochemical, and isotopic data for the Coast Range and Santa Maria Provinces volcanic rocks.

Mendocino Triple Junction Migration

One hypothesis for late Oligocene–early Miocene volcanism in western California involves the northwestward migration of the Mendocino triple junction. This hypothesis is based on spatial and temporal correlations between the northwestward migration of volcanism in California and the passage of the triple junction (Christiansen and Lipman, 1972; Snyder et al., 1976; Dickinson and Snyder, 1979a; Glazner and Supplee, 1982; Johnson and O'Neil, 1984; Fox et al., 1985). In this hypothesis, a potential magma source for volcanism may have been subcontinental mantle that upwelled into a slab-window beneath western California during passage of the triple junction (Dickinson and Snyder 1979b; Johnson and O'Neil, 1984; Fox et al., 1985).

Whereas the migrating Mendocino triple junction model is tenable for some Tertiary volcanic units in California, inconsistencies in this model for the Coast Range and Santa Maria Provinces volcanic units are based on their temporal and spatial relations (Fig. 8). Stanley (1987) demonstrated that many middle Tertiary volcanic units, including the Coast Range Province and Santa Maria Province, do not define a trend of decreasing age to the northwest. The relatively widespread paleogeographic distribution of Coast Range and Santa Maria Provinces volcanic rocks invokes spatial problems when attempting to relate particular volcanic centers to a particular position of the Mendocino triple junction at a given time. For example, based on paleogeographic reconstruction of volcanic units analysed in this study, the Mindego Basalt and Plush Ranch Formation basalt erupted coevally, but were several hundred kilometers apart (Fig. 8). This is true for many of the late Oligocene–early Miocene volcanic units in western California which, in the past, have individually been attributed to the passage of the Mendocino triple junction. Realistically, the Mendocino triple junction could not have been located in two, or more, different places at the same time; therefore some other model is required to account for the widespread coeval distribution of Coast Range and Santa Maria Provinces volcanism. Dickinson and Snyder (1979a) and Hall (1981) also recognized that volcanic rocks in the Santa Maria Province were younger than would be expected if they were related to the passage of the Mendocino triple junction and attributed these rocks to later strike-slip faulting.

Subduction-Related Processes

As an alternative to the Mendocino triple junction model, Weigand (1982) attributed parts of early Miocene volcanism in southern California (including parts of the Coast Range Province and Santa Maria Province) to Farallon plate subduction, which according to the reconstructions by Engebretson et al. (1985) continued beneath southern California until ca. 16 Ma. Other studies also have suggested subduction as a model for early Miocene near-trench volcanism in southern California (Christiansen and Lipman, 1972; Pilger and Henyey, 1979). According to some of these models, subduction of young, hot oceanic lithosphere beneath southern California with the approach of the East Pacific Rise could have induced melting of overlying subcontinental lithosphere farther to the west than expected for

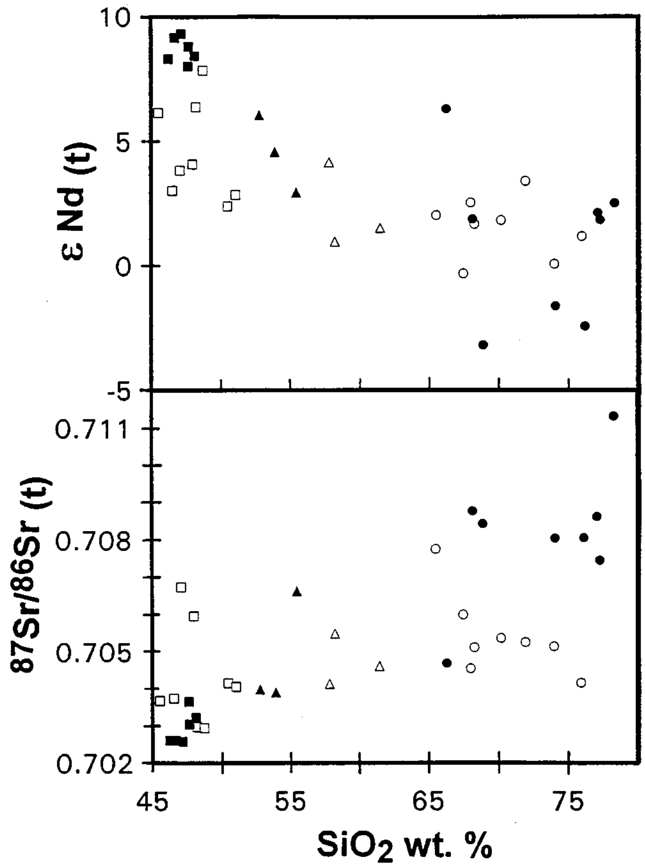

Figure 7. Variation of initial εNd and initial $^{87}Sr/^{86}Sr$ with SiO_2 in the Santa Maria Province (SMP) and Coast Range Province (CRP) volcanic rocks. Filled symbols represent samples from the SMP, and open symbols represent samples from the CRP. Squares = basic rocks (basalt and trachybasalt), triangles = intermediate rocks (andesite, trachyandesite, and basaltic andesite), and circles = acidic rocks (dacite, rhyolite, and trachyte).

cold-slab subduction. This would have resulted in a westward shift in the locus of volcanic activity and narrowing of the arc-trench gap (Christiansen and Lipman, 1972; Pilger and Henyey, 1979). While we agree that there are spatial and temporal inconsistencies in correlating Coast Range and Santa Maria Provinces volcanic rocks with Mendocino triple junction migration, we disagree with the subcontinental lithospheric source of magma for these rocks implied by the subduction models.

Ridge-Trench Interactions

As an alternative to previous tectonomagmatic models for these rocks, we suggest that Coast Range and Santa Maria Provinces volcanism was a response to interactions between segments of the East Pacific Rise and the continental margin prior to development of the Mendocino triple junction. Our results, here and in Cole and Basu (1992), indicate a more prevalent depleted mantle source of magma than previously recognized for volcanism in the Coast Range and Santa Maria Provinces. We suggest that melts of this depleted source erupted to form basalt and also assimilated and melted enriched crustal rocks to form acidic magmas. This is generally consistent with models of earlier studies, which suggested that mantle material welled up into a space (slab-window) beneath the continental margin (e.g., Dickinson and Snyder, 1979a, 1979b; Johnson and O'Neil, 1984). We contribute to this model by more clearly defining a depleted MORB-like end-member composition, which can be attributed to sub*oceanic* lithospheric mantle or upper asthenospheric sources as opposed to sub*continental* lithospheric mantle sources within the initial slab window (Fig. 9). Based on our data we suggest that the Coast Range and Santa Maria Provinces volcanic rocks were derived from a more depleted source than typically attributed to enriched subcontinental lithospheric mantle melts (Menzies, 1983; Perry et al., 1987). Subcontinental lithospheric mantle may have been a more important magma source farther to the east (e.g., along the east side of the modern San Andreas fault), where North American continental crust and remnant subcontinental lithosphere may have been present beneath parts of the Sierran fore-arc basin (DePaolo, 1988). In our model, suboceanic mantle welled up beneath parts of southern California along segments of the East Pacific Rise that intersected the North American subduction zone and that possibly continued to diverge to form a slab-window (e.g., Dickinson and Snyder, 1979b; Severinghaus and Atwater, 1990).

Our model is consistent with the restored spatial and temporal distributions of the Coast Range and Santa Maria Provinces volcanic units and recently revised plate reconstruction models, which show that before the Mendocino triple junction was formed along western North America, several short East Pacific Rise segments existed along the western margin of southern California south of the Mendocino fracture zone (Fig. 8) (Stock and Molnar, 1988; Atwater, 1989; Severinghaus and Atwater, 1990). The positions of these short East Pacific Rise segments coincide with the restored distributions of Coast Range and Santa Maria Provinces volcanic rocks (Fig. 8). According to these reconstructions, the Mendocino triple junction would have formed after several of these East Pacific Rise segments reached the subduction zone, north of the paleogeographic positions of the Santa Maria Province and many of the Coast Range Province volcanic rocks (Fig. 8). If this is true, then asthenospheric upwelling associated with the passage of the Mendocino triple junction would not have been responsible for Coast Range and Santa Maria Provinces volcanism. Instead, the source of depleted magma for Coast Range and Santa Maria Provinces volcanism would have existed when segments of the East Pacific Rise intersected the continental subduction zone and suboceanic mantle was emplaced beneath southern California (Figs. 8 and 9). Magmas then reached the surface during two successive episodes of crustal extension or transtension and basin development.

A regional episode of late Oligocene–early Miocene extension and basin formation in southern California that coincided with the episode of Coast Range Province volcanism of this study may be defined by compiling the results of several studies, which are summarized in Stanley (1987), Crowell (1987), Atwater (1989), and Cole (1993). Many of these studies document the presence of Coast Range Province volcanic units within extensional or transtensional basins; this links Coast Range Province volcanism with widespread crustal extension, which may have been associated with pre–

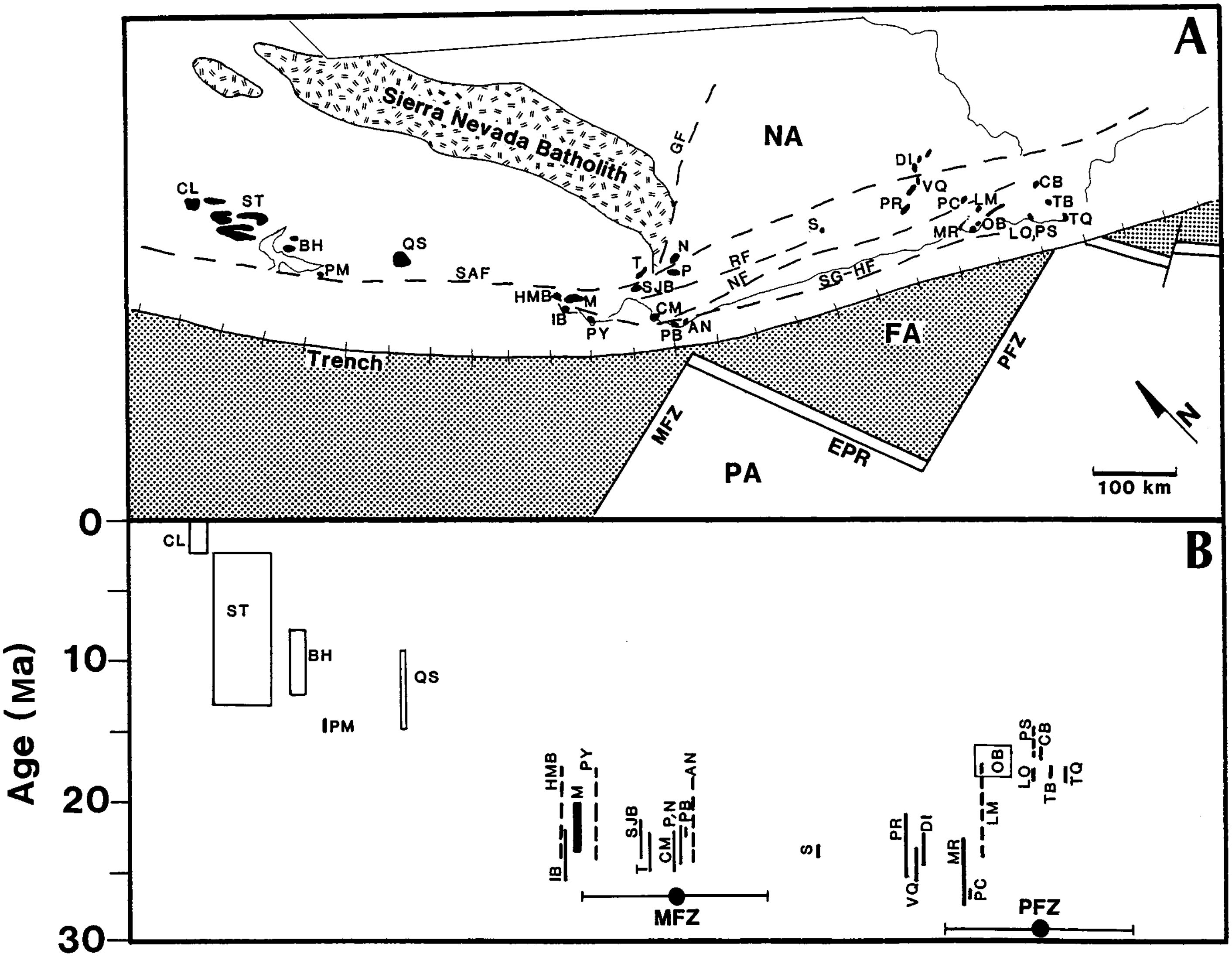

Figure 8. (A) Early Miocene restoration of the Coast Range Province (CRP) and Santa Maria Province (SMP) volcanic centers. Restoration is schematic and was constructed by removing the right-lateral displacements of major strike-slip faults as summarized in Atwater (1989) (including 314 km along the San Andreas fault, 115 km along the San Gregorio–Hosgri fault, 55 km along the Rinconada fault, and 15 km along the Nacimiento fault) and by removing 90° of clockwise rotation of the SMP (Hornafius et al., 1986; Luyendyk, 1991). The restored modern coastline and modern position of the Sierra Nevada batholith are shown for reference. The positions of the Mendocino and Pioneer fracture zones (MFZ and PFZ, respectively), where they initially intersected the continental margin, are from Atwater (1989) and Severinghaus and Atwater (1990). Uncertainties on this diagram include up to ±115 km for combined fault offsets (Atwater, 1989) and ~100 km of north-south uncertainty in the positions of the Mendocino and Pioneer fracture zones (Atwater, 1989; Severinghaus and Atwater, 1990). In addition, this reconstruction does not account for rotation of the southern Sierran orocline or Basin and Range extension. Dashed lines are the future traces of strike-slip faults. Fault abbreviations are given in Figure 2.

(B) Time-space diagram for the CRP and SMP volcanic rocks as well as a series of volcanic centers, located along the east side of the San Andreas fault, that become younger towards the northwest. Constructed by plotting positions of palinspastically restored volcanic centers from A by their ages. Abbreviations for volcanic units are given in Table 1. Vertical bars represent ranges in ages (Table 1); dashed vertical lines indicate only biostratigraphic age control. Errors for palinspastic restorations are not plotted, but average ~70 km. The positions of the MFZ and PFZ are shown with the approximate spatial error bars as determined by Atwater (1989) and Severinghaus and Atwater (1990).

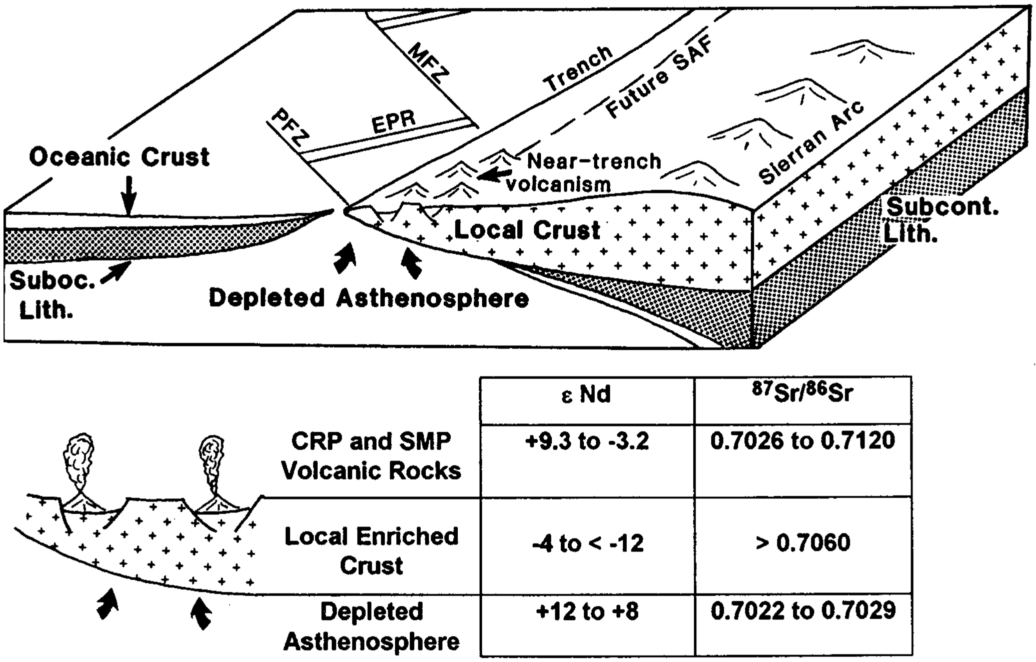

Figure 9. Schematic illustration of the tectonomagmatic model for Coast Range Province (CRP) and Santa Maria Province (SMP) volcanism. These near-trench volcanic rocks were erupted in response to interactions between spreading-ridge segments of the East Pacific Rise (EPR) and the continental margin. MFZ = Mendocino fracture zone, and PFZ = Pioneer fracture zone.

TABLE 4. Sr- AND Nd-ISOTOPIC DATA FOR SAMPLES FROM THE SMP AND CRP VOLCANIC ROCKS

Sample	Rock type*	$^{87}Sr/^{86}Sr_{(m)}$†	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr_{(t)}$§	$^{143}Nd/^{144}Nd_{(m)}$#	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd_{(t)}$§	$\varepsilon_{Nd}(t)$**
				Santa Maria Province				
1	R	0.708452 ± 35	1.735	0.708033	0.512561 ± 25	0.259	0.512532	−1.63
2	R	0.708301 ± 40	1.049	0.708048	0.512501 ± 14	0.095	0.512491	−2.45
3	D	0.708525 ± 41	0.404	0.708428	0.512466 ± 12	0.125	0.512452	−3.19
4	R	0.710617 ± 38	8.279	0.708619	0.512738 ± 20	0.114	0.512726	2.14
5	R	0.710729 ± 47	13.619	0.707441	0.512727 ± 20	0.145	0.512711	1.85
6	R	0.712017 ± 48	2.938	0.711308	0.512759 ± 19	0.119	0.512746	2.53
7	D	0.705386 ± 40	2.929	0.704675	0.512954 ± 12	0.141	0.512938	6.29
8	BA	0.706884 ± 45	1.065	0.706627	0.512783 ± 15	0.141	0.512768	2.96
9	D	0.709247 ± 47	1.978	0.708770	0.512729 ± 26	0.156	0.512712	1.87
10	BA	0.704033 ± 46	0.534	0.703904	0.512867 ± 16	0.146	0.512851	4.59
11	BA	0.704125 ± 40	0.560	0.703990	0.512943 ± 19	0.157	0.512926	6.04
12	B	0.703659 ± 38	0.084	0.703639	0.513053 ± 23	0.236	0.513027	8.02
13	B	0.704096 ± 39	0.082	0.704076	0.512940 ± 20	0.164	0.512922	5.97
14	B	0.702620 ± 39	0.052	0.702607	0.513103 ± 12	0.157	0.513086	9.16
15	B	0.702590 ± 38	0.060	0.702575	0.513114 ± 14	0.183	0.513094	9.32
16	B	0.702615 ± 40	0.059	0.702601	0.513061 ± 12	0.172	0.513042	8.31
17	B	0.703236 ± 38	0.091	0.703214	0.513068 ± 14	0.178	0.513048	8.44
18	B	0.703059 ± 37	0.095	0.703036	0.513083 ± 14	0.144	0.513067	8.80
				Coast Range Province				
19	D	0.706695 ± 38	2.163	0.705989	0.512612 ± 24	0.136	0.512592	−0.32
20	D	0.705818 ± 40	1.434	0.705350	0.512720 ± 11	0.123	0.512702	1.82
21	T	0.706003 ± 35	2.735	0.705071	0.512712 ± 28	0.128	0.512693	1.65
22	T	0.705293 ± 36	2.284	0.704514	0.512762 ± 16	0.124	0.512743	2.64
23	R	0.710187 ± 37	15.405	0.704936	0.512640 ± 12	0.189	0.512611	0.07
24	R	0.709810 ± 38	17.254	0.703929	0.512697 ± 15	0.191	0.512668	1.18
25	D	0.708090 ± 45	1.073	0.707740	0.512730 ± 26	0.124	0.512711	2.02
26	D	0.707808 ± 40	7.830	0.705139	0.512808 ± 26	0.168	0.512783	3.41
27	TA	0.704579 ± 38	1.366	0.704114	0.512842 ± 17	0.136	0.512822	4.17
28	TA	0.704997 ± 35	1.176	0.704596	0.512703 ± 18	0.115	0.512686	1.52
29	A	0.705640 ± 35	0.492	0.705479	0.512675 ± 24	0.110	0.512658	0.98
30	B	0.703689 ± 43	0.045	0.703674	0.512947 ± 16	0.158	0.512923	6.15
31	TB	0.703892 ± 39	0.498	0.703729	0.512783 ± 17	0.135	0.512763	3.02
32	B	0.703011 ± 35	0.123	0.702971	0.512952 ± 15	0.112	0.512935	6.38
33	B	0.702952 ± 37	0.031	0.702942	0.513035 ± 23	0.163	0.513011	7.85
34	B	0.705987 ± 39	0.129	0.705945	0.512840 ± 25	0.153	0.512817	4.08
35	B	0.706802 ± 38	0.248	0.706721	0.512825 ± 19	0.141	0.512804	3.82
36	B	0.704179 ± 35	0.096	0.704148	0.512750 ± 20	0.131	0.512730	2.38
37	B	0.704099 ± 43	0.173	0.704042	0.512771 ± 15	0.118	0.512753	2.83

*Rock types: R = rhyolite, D = dacite, T = trachyte, TA = trachyandesite, A = andesite, BA = basaltic andesite, B = basalt.

†Measured isotopic ratios normalized to $^{86}Sr/^{88}Sr = 0.1194$. NBS987 Sr Standard yielded $^{87}Sr/^{86}Sr$ ratio of 0.710 230 ± 30. Reported uncertainties are ~2 σ of the mean.

§Isotopic ratios corrected for t = 17 Ma for SMP samples and t = 24 Ma for CRP samples.

#Measured isotopic ratios corrected for mass fractionation effects using $^{146}Nd/^{144}Nd = 0.7219$. La Jolla Nd Standard yielded $^{143}Nd/^{144}Nd$ = 0.511 850 ± 17. Reported uncertainties are ~2 σ of the mean.

**Refers to 0.1 mil deviations of $^{143}Nd/^{144}Nd_{(m)}$ from Bulk Earth calculated at t = 17 Ma for SMP samples and t = 24 Ma for CRP samples assuming present-day Bulk Earth $^{147}Sm/^{144}Nd = 0.1967$ and $^{143}Nd/^{144}Nd$ = 0.512 638.

San Andreas oblique-slip along the continental margin.

At ca. 18 Ma, coincident with the episode of Santa Maria Province volcanism, crustal blocks rotated within the western Transverse Ranges in the southern part of the Santa Maria Province (Hornafius et al., 1986; Luyendyk, 1991), and local areas of extension formed along the mismatches between rotating blocks in an overall releasing geometry of a strike-slip system. Thickness and facies trends of some of the Santa Maria Province volcanic rocks suggest that they probably erupted into some of these local zones of extension (Cole et al., 1991; Cole, 1993).

After the East Pacific Rise segments intersected the continental margin, and the Pacific plate reorganized south of the Mendocino fracture zone (Severinghaus and Atwater, 1990), the Mendocino triple junction was established *north* of where the Santa Maria Province and most of the Coast Range Province volcanic rocks erupted (Fig. 8). Subsequent northwestward migration of the Mendocino triple junction may then have been responsible for the volcanic centers, which were erupted along the east side of the modern San Andreas fault and which are younger to the northwest (Table 1, Fig. 2) (Dickinson and Snyder, 1979a; Johnson and O'Neil, 1984; Fox et al., 1985). Accompanying the migration of the Mendocino triple junction was expansion of the slab-window beneath the continental margin (Dickinson and Snyder, 1979b; Severinghaus and Atwater, 1990). Our study demonstrates that this slab-window filled initially with depleted suboceanic mantle, which was a source for the Santa Maria and Coast Range Provinces volcanic rocks. Low initial $^{87}Sr/^{86}Sr$ ratios and high initial εNd values for basalt in the Sonoma-Tolay volcanic center (Fig. 2, Table 1) (Johnson and O'Neil, 1984; C. Johnson, 1994, personal commun.) indicate that depleted mantle continued to fill the slab-window as it expanded towards the northwest and was also a source for younger volcanism.

CONCLUSIONS

The results of this study suggest that mid-ocean ridge and trench interactions were important for volcanism during middle Tertiary time in western and southern California. These types of interactions have been documented for other plate boundaries throughout the geologic past and, as suggested by Cox and Hart (1986), must have occurred whenever an ocean basin has closed. Other examples of near-trench volcanism attributed to ridge-trench interactions have been described for Japan (Uyeda and Miyashiro, 1974; Hibbard and Karig, 1990), the Aleutian arc (Marshak and Karig, 1977; Moore et al., 1983), southern Chile (Forsythe et al., 1986) and the Pacific northwest (Wells et al., 1984). Aside from our studies, this model has not previously been entertained for rocks of the Coast Range and Santa Maria Provinces. Johnson and O'Neil (1984) and Hurst (1982), however, described other middle Tertiary volcanic rocks in southern California and Baja that they attribute to ridge-trench interactions related to the Rivera triple junction. The combined results of all these studies suggest that ridge-trench interactions may result in unique and important tectonomagmatic events. In particular, we conclude that subduction of the East Pacific Rise and the juxtaposition of suboceanic mantle beneath the continental margin were a more widespread mechanism of middle Tertiary volcanism in southern and western California than previously recognized. In this model, Santa Maria and Coast Range Provinces volcanism was a result of processes closely associated with short-lived ridge-trench-transform triple junctions where small ridge segments were overriden by the leading edge of the continental margin.

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