SUMMARY OF THE MIOCENE IGNEOUS ROCKS OF THE CHANNEL ISLANDS, SOUTHERN CALIFORNIA

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ABSTRACT

Middle Miocene igneous rocks, mainly volcanic, are found on all eight of southern California's Channel Islands. Activity began about 19 million years ago (Ma), became widespread by 17 Ma, and waned about 13 Ma. Andesite lava flows predominate on Anacapa Island. Santa Cruz Island has widespread lavas of basaltic-andesite to dacite in composition north of the cross-island fault and a thick sedimentary unit dominated by rhyodacitic debris south of the fault. Santa Rosa Island has a thick unit of basaltic debris and associated intrusions as well as a sedimentary unit containing conglomerates of volcanic debris. San Miguel Island has two volcanic units: an older unit of basaltic flows and sediments, and a younger unit of a felsic intrusion and associated flows and sediments. Santa Barbara Island is nearly entirely composed of basaltic to andesitic flows. On Santa Catalina Island is a diorite pluton and a volcanic sequence that ranges from basalt to rhyolite in composition. Volcanic rocks on San Clemente Island are dominated by andesite flows with minor rhyolite-dacite units. Igneous activity on San Nicolas Island is limited to several thin dikes of probable mafic composition. Widespread Miocene magmas in southern California were generated by decompression melting in response to extension related to the tectonic rotation of the Western Transverse Ranges block.

Keywords: Channel Islands, volcanics, Miocene.

INTRODUCTION

A burst of volcanic activity erupted throughout southern California during the middle of the Miocene Epoch mainly between about 17 and 13 Ma, resulting in about two dozen volcanic areas ranging from Point Arguello south to Rosarito Beach, Baja California (Weigand 1982; Dickenson 1998). Included in this igneous episode was activity on all eight of southern California's Channel Islands (Figure 1); coverage ranges from a maximum of 100% on Santa Barbara Island to a few dikes on San Nicolas Island. Forms of igneous rocks include lava flows, flow breccias, sedimentary units composed exclusively of volcanic material, dikes, and one plutonic intrusion (on Santa Catalina Island). The composition of the volcanic rocks ranges from basalt to rhyolite, with the most common being the intermediate

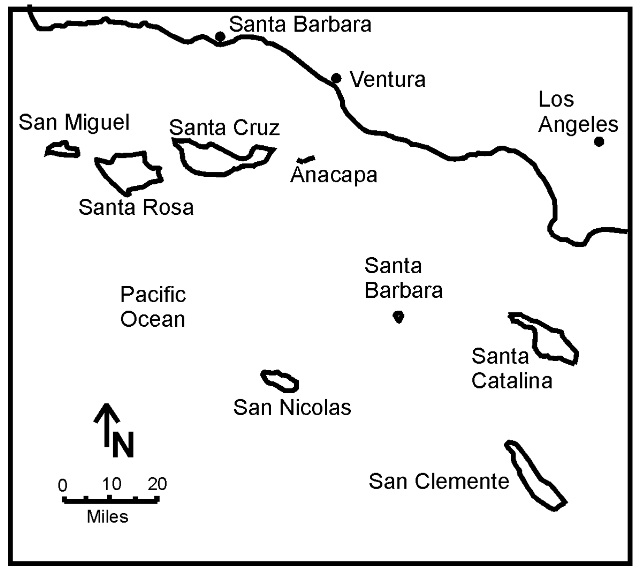

Figure 1. Map of the Channel Islands of southern California.

compositions basaltic-andesite and andesite. A summary of the age and petrology of the igneous suites on the islands is presented in Table 1. The suites on seven of the eight Channel Islands are summarized below.

This middle Miocene volcanism occurred during a period in which southern California experienced large amounts of rifting, clockwise rotation, and extension in and around the area of the Inner Borderland of Southern California (Crouch and Suppe 1993; Nicholson et al. 1994). Generation of magmas within this extensional environment has been interpreted as being the result of decompression melting of the mantle (Weigand et al. 1998; Dickinson 1998).

ANACAPA ISLAND

The geology of Anacapa Island has been summarized by Scholl (1960) and Norris (1995). The island is composed of a volcanic sequence that forms a gently north-dipping homocline. About 300 m of vesicular and porphyritic lava flows, breccia, agglomerate, and tuff are exposed, although neither the base nor top of the sequence are seen. Strata of San Onofre Breccia are interbedded with the volcanic rocks near their exposed base, implying a submarine origin for at least some of the volcanic rocks. Weigand (1993) found three

Table 1. Summary of Miocene Igneous Centers on the Channel Islands.

VOLCANIC CENTER	FORM	AGE RANGE (Ma)	ROCK TYPES	PETROLOGIC AFFINITY	$K_{57.5}$	$^{87}Sr/^{86}Sr$	ϵ_{Nd}	$\delta^{18}O$	REFS.
Anacapa Island	Ext	15.8-16.28(3)A	And 100%	Low-K CA	1.02 (3)	nd	nd	nd	1, 2
Santa Cruz Island Volcanics	Ext	16.1-16.5(2)K 16.33-17.12(5)A	BA 24% And 49% Dac 24% Rhy 3%	Low-K CA	0.98 (37)	0.7025- 0.7032 (10)	nd	nd	3, 1, 2, 4, 5
Blanca Formation	Clasts	14.9-13.3(2)K	And 5% Dac 55% Rhy 40%	Low-K CA	0.98 (61)	0.7030- 0.7040 (11)	nd	8.1 (2)	3, 6, 7
Santa Rosa Island Volcanics	Ext + Int	18.1-19.3(2)A	Bas 88% BA 12%	Low- to med-K CA	0.85 (8)	nd	nd	nd	1, 8
Beecher's Bay Formation	Clasts	15.8(1)	And 36% Dac 36% Rhy 27%	Low- to med-K CA	1.40 (11)	0.7029- 0.7045(7)	3.4-6.1 (4)	nd	9
San Miguel Island Volcanics	Ext + Int	17.0-18.5(2)A	Bas 50% BA 8% Dac 17% Rhy 25%	Low- to med-K CA	na	nd	nd	nd	1, 8
Santa Barbara Island Volcanics	Ext	14.8-16.8(2)K 15.5(1)A	Bas 10% BA 30% And 60%	Low- to med-K CA	1.30 (10)	nd	nd	nd	10, 1, 8
Santa Catalina Island Volcanics	Ext	12.7-15.4(13)K 17.2(1)A	Bas 9% BA 26% And 46% Dac 14% Rhy 6%	Low- to med-K CA	0.94 (36)	0.7029- 0.7034(2)	9.4 (1) 4.1- 6.1(2)	nd	11, 1, 12, 13, 14
	Pluton	19.0(2)K	Diorite	nd	na	nd	nd	nd	11
San Clemente Island Volcanics	Ext	13.6-16.1(5)K	And 85% Dac 12% Rhy 3%	Med-K CA	1.23 (17)	0.7037- 0.7045(3)	nd	6.8 (3)	3, 15, 16, 12, 17, 18
San Nicolas Island	Dikes	nd	nd	nd	nd	nd	nd	nd	19

Notes: Number in parentheses indicate number of samples for which data are available; Ext = extrusives; Int = intrusives, K = K-Ar dating, A = Ar-Ar dating, Bas = basalt, BA = basaltic andesite, And = andesite, Dac = dacite, Rhy = rhyolite, CA = calc-alkaline, $K_{57.5}$ = K_2O content of the suite at a value of 57.5% SiO_2; nd = not determined; na = not applicable.

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1. Luyendyk et al. (1998)
2. Weigand (1993)
3. Turner (1970)
4. Higgins (1976)
5. Hurst (1983)
6. Savage and Weigand (1994)
7. Weigand, unpub. data
8. Weigand et al. (1998)
9. Chinn and Weigand (1994)
10. Howell (1976)
11. Vedder et al. (1979)
12. Weigand (1994)
13. Wood (1981)
14. Stewart et al. (1992)
15. Merrifield et al. (1971)
16. Olmstead (1958)
17. Johnson and O'Neil (1984)
18. Hawkins and Divis (1975)
19. Vedder and Norris (1963)

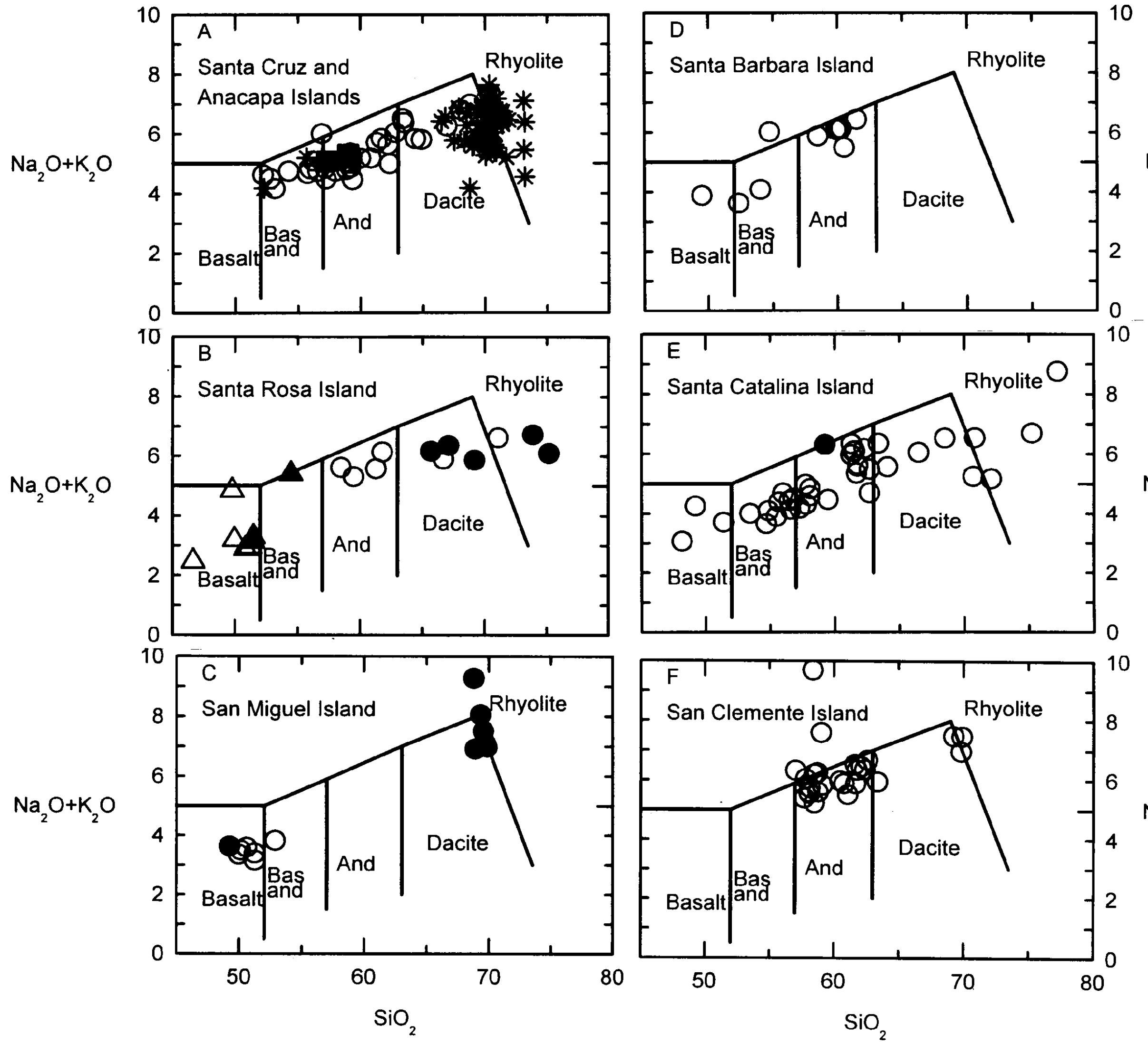

Figure 2. Classification diagram showing rock names (Le Bas et al. 1986). A. Santa Cruz and Anacapa Islands. Solid squares = Anacapa lavas, open circles = Santa Cruz Island Volcanics, stars = Blanca Formation clasts. B. Santa Rosa Island. Open triangles = Santa Rosa Island Volcanics intrusions, solid triangles = Santa Rosa Island Volcanics flows, open circles = clasts from the San Onofre breccia member, solid circles = clasts from members D and E of the Beecher's Bay Formation. C. San Miguel Island. Open circles = lower mafic unit, solid circles = upper felsic member. D. Santa Barbara Island. E. Santa Catalina Island. Open circles = Santa Catalina Island Volcanics, solid circle = diorite pluton. F. San Clemente Island.

analyzed samples to be andesitic, virtually identical in composition to andesites from the Santa Cruz Island Volcanics (Figure 2A). Luyendyk et al. (1998) obtained Ar-Ar dates on plagioclase separates from Anacapa lavas of 16.2±0.2 and 16.3±0.2 Ma.

SANTA CRUZ ISLAND

Santa Cruz Island, the largest of the northern Channel Islands, is cut by the east-west trending Santa Cruz Island fault. The northern half of the island is underlain mostly by Santa Cruz Island Volcanics and Monterey Formation, while the southern half consists of Jurassic metamorphic and plutonic rocks covered by a Tertiary sedimentary and volcaniclastic section.

Santa Cruz Island Volcanics

The Santa Cruz Island Volcanics exposed north of the Santa Cruz Island fault were named and subdivided into four members by Nolf and Nolf (1969). They form a north-dipping homocline composed of interbedded lava 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.

Nolf and Nolf (1969) and Crowe et al. (1976) summarized the stratigraphy and petrography of these volcanic rocks. 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. The next younger Devil's Peak Member contains a variety of scoriaceous andesitic and dacitic flows, flow breccias, and reworked pyroclastic rocks apparently emplaced on the slopes of, and adjacent to, a volcanic center. The uppermost Prisoners Harbor Member is composed of andesitic and dacitic flows, flow breccias, and tuffaceous volcaniclastic beds, probably deposited in a submarine environment.

Chemical analyses by Crowe et al. (1976) and Weigand (1993) show that the volcanic rocks are polygenetic and range in composition from basaltic andesite to dacite (Figure 2A). These data largely confirm petrographic evidence showing the overall volcanic sequence to be 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).

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 Prisoners Harbor Member (these and subsequent dates have been corrected to new IUGS constants). Crowe et al. (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 three younger dates are largely compatible with more recent Ar-Ar dates of 17.0 to 16.3 Ma (Luyendyk et al. 1998).

Volcanic Clasts from the Blanca Formation

The medial Miocene Blanca Formation crops out on the southern half of Santa Cruz Island. Exposures cover 20 km^2 and reach a maximum thickness of 1,400 m (Fisher and Charlton 1976). The Blanca locally overlies the Willows Plutonic Complex, the San Onofre Breccia, or the Rincon Formation. The top of the formation is nowhere exposed on land; it may continue offshore to the south (Vedder et al. 1986). The Blanca Formation consists of volcaniclastic conglomerates and breccias, epiclastic tuffaceous sandstone and siltstone interbedded with primary pyroclastic layers, and minor basaltic-andesite flows (McLean et al. 1976a). Weaver et al. (1969) divided the formation into three members — lower, middle, and upper — based on color, texture, and percentage of volcanic clasts. Deposition of the Blanca Formation is believed to have occurred in a nearshore marine environment, adjacent to an active volcanic source (Fisher and Charlton 1976).

Based on geochemical criteria, Savage and Weigand (1994) have shown that the majority of the clasts are classified as dacite and rhyolite (Figure 2A). In agreement with McLean et al. (1976b), Savage and Weigand (1994) concluded that the outcrop of volcaniclastic rocks overlying the San Onofre Breccia on the southwest side of the island is correlative with the Blanca Formation. Weaver et al. (1969) concluded that the source of the volcanic clasts of the Blanca Formation was the Santa Cruz Island Volcanics located north of the Santa Cruz Island fault, whereas Howell and McLean (1976) and Savage and Weigand (1994) presented petrographic and geochemical evidence strongly suggesting that the Santa Cruz Island Volcanics were not the source; the volcanic center that served as the provenance for the clasts is currently unidentified. An andesite flow from the upper member of the Blanca Formation has been dated at 14.9 ± 0.8 Ma, and a dacite clast from the upper member has been dated at 13.3 ± 1.2 Ma, both by the K-Ar method (McLean et al. 1976a).

SANTA ROSA ISLAND

With an area of 218 km^2, Santa Rosa Island is the second largest of the Northern Channel Islands. The island is cut by the east-west trending Santa Rosa Island fault. North of the fault, well-developed Pleistocene terrace deposits overlie low-dipping, mid-Tertiary marine clastic and volcaniclastic units. South of the fault, the more rugged terrain is cut by deep canyons which expose older Tertiary sandstone and shale and middle Tertiary volcaniclastic strata cut by volcanic intrusions (Weaver and Nolf 1969).

Santa Rosa Island Volcanics

Volcanic rocks on Santa Rosa Island were first mapped by Kew (1927) as upper Miocene intrusions. Avila and Weaver (1969) recognized that the volcanic rocks consisted of intrusive, extrusive, and clastic components and named them the San Miguel Volcanics on the supposition that these volcanic rocks had their volcanic origin from nearby San Miguel Island to the west. Dibblee and Ehrenspeck (1998) proposed the name Santa Rosa Island Volcanics for this volcanic formation, which crops out in the central part of the island south of the Santa Rosa Island fault and on the central and western coasts north of this fault (Dibblee et al. 1998).

Chemical analyses from both lava flows and intrusions show that most are composed of basalt (Weigand et al. 1998; Figure 2B). Samples of flows are somewhat higher in SiO_2 than are samples of intrusions. A sample from an intrusion south of the fault has been dated at 18.1 ± 0.3 Ma by the Ar-Ar method on whole-rock material (Luyendyk et al. 1998). Intrusive activity persisted for some time because some of the bodies intrude the lower Monterey Shale of late Saucesian-Relizian age (ca. 16.5 to 15.5 Ma; Dibblee and Ehrenspeck 1998).

Volcanic Clasts from the Beecher's Bay Formation

Pebbles and cobbles of volcanic origin occur in three conglomeratic units which crop out along the northeastern and eastern coast of Santa Rosa Island. These conglomerates have been included in a variety of formations (see Chinn and Weigand 1994); we will follow the assignment of Dibblee et al. (1998). Nuccio and Wooley (1998) recommended that the unit be named the Beecher's Bay Formation and divided the formation into five informal units, designated A through E in ascending order. The lowermost blueschist-bearing unit A, exposed along the northwest shore of Carrington Point, has been named the San Onofre breccia facies of the Beecher's Bay Formation by Dibblee et al. (1998). These five units have been interpreted to represent various parts of a submarine fan complex (Nuccio and Wooley 1998).

Based on geochemical criteria, Chinn and Weigand (1994) showed the clasts from the San Onofre breccia facies to range in composition from andesite to dacite and the clasts from upper members D and E to range in composition from dacite to rhyolite (Figure 2B). Although only the San Onofre breccia member yielded andesite clasts, clasts from all three units sampled are very similar to each other with respect to trace elements (Chinn and Weigand 1994).

Although the formation as a whole is generally devoid of fossils, middle member C contains well-developed foraminiferal assemblages. Based on these assemblages and its stratigraphic position, the Beecher's Bay Formation is assigned a Relizian to middle-Luisian age (17 to 15 Ma; Avila 1968). A date of 15.80 ± 0.08 Ma was determined by the Ar-Ar method on plagioclase grains from a San Onofre andesite clast (Chinn and Weigand 1994). The same sample yielded two plagioclase grains that were significantly older (avg. = 24.4 Ma); these grains were presumably picked up from crustal rocks traversed by the ascending magma.

SAN MIGUEL ISLAND

San Miguel Island, the westernmost Channel Island, is composed of a sequence of sedimentary and volcanic strata that range in age from Upper Cretaceous to Miocene. These units are largely covered by Quaternary sands. Weaver and Doerner (1969) distinguished two members in the San Miguel Volcanics: 1) a lower member of basaltic flows and volcaniclastic strata which crop out on the southeastern third of the island, and 2) an upper member of massive dacite intrusions, flows, and clastic strata which crop out on the northern tip of the island around and south of Harris Point. The bimodality of the San Miguel Volcanics is largely confirmed by chemical composition. The lower member is primarily classified as basalt, while samples from the upper member straddle the dacite/rhyolite boundary; a single clast from the upper member is compositionally basalt (Weigand et al. 1998; Figure 2C). Several K-Ar dates have suggested that the San Miguel Volcanics are Oligocene in age (e.g. Crowe et al. 1976; Kamerling and Luyendyk 1985), in apparent conflict with paleontological evidence. However, a new Ar-Ar date of 17.7 ± 0.3 Ma on plagioclase from a basalt flow in the lower member (Luyendyk et al. 1998) is more geologically reasonable.

SANTA BARBARA ISLAND

Santa Barbara Island, the smallest of the Channel Islands, has had the least amount of geological study. Kemnitzer (1933) first mapped the island and showed it to consist nearly entirely of volcanic rocks whose Miocene age was established by a typical Luisian foraminiferal assemblage from intercalated shales (Kleinpell 1938). Vedder and Howell (1976) described a volcanic section more than 325 m in thickness that they divided into three general units. The lower and thickest unit is composed of basalt or andesite flows, local flow breccia, and minor layered pyroclastic(?) material. Abundant pillow structures and vesicles suggest submarine eruption at shallow depth (Norris 1991). This unit is overlain by a thin, discontinuous unit of mudstone intercalated with lava flows, which in turn is overlain by a volcanic breccia that may in part be a hyaloclastite.

Weigand et al. (1998) sampled flows and volcanic clasts and found them to range in composition from basalt to andesite (Figure 2D); samples collected from the western side were uniformly andesite in composition. Howell (1976) reported K-Ar dates of 14.8 ± 1.8 and 16.8 ± 2.0 Ma on plagioclase separate from two andesite flows along the southeast part of the island. The average of these two dates is similar to the whole-rock Ar-Ar date of 15.5 ± 1.0 Ma reported by Luyendyk et al. (1998) on a basalt.

SANTA CATALINA ISLAND

Santa Catalina Island, the second largest Channel Island, is characterized by the widespread occurrence of Catalina Schist, a Mesozoic unit of exhumed oceanic crust. These rocks are cut by a Miocene intrusion and unconformably overlain in places by Miocene volcanic and sedimentary strata. Miocene igneous activity on Santa Catalina Island took two forms. A hornblende quartz diorite pluton intruded into Catalina Schist basement 19.5 ± 0.6 Ma (K-Ar; Vedder et al. 1979). This pluton covers an area of about 39 km^2 on the island and also crops out offshore over an additional area of about 7 km^2.

Unconformably overlying the schistose basement and diorite pluton is a formerly extensive sequence of volcanic and sedimentary rocks now limited to one broad area midway between Avalon and the Isthmus and several other small areas. Volcanic rocks now crop out over an area of about 32 km^2 on the island (Vedder et al. 1986). Surrounding much of the island is a unit of undifferentiated terrace deposits of late Miocene and Quaternary age; underlying this are additional exposures of Miocene volcanic rocks that cover about 190 km^2 (Vedder et al. 1986). Vedder et al. (1979) mapped in detail the volcanic and sedimentary sequence in the Fisherman's Cove, Cactus Peak-Cottonwood Canyon, and East End Quarry areas. The Fisherman's Cove sequence exceeds 150 m in thickness and is composed of a wide variety of fine-grained sedimentary rocks, volcanic and sedimentary breccias, extrusive flows and domes, and tabular intrusions. Wood (1981) showed the volcanic section in the Black Jack Peak-Whitley's Peak area to be composed of subaerially deposited lava flows, laharic breccias, and tabular and dome intrusions that exceed 400 m in thickness.

Chemical analyses (Vedder et al. 1979; Wood 1981; Weigand 1994) show the Black Jack Peak-Whitley's Peak volcanic section to be composed of a polygenetic suite that ranges from basalt to rhyolite in composition (Figure 2E). A single analyzed sample of the pluton plots near the andesite samples on this diagram. Based on 12 K-Ar measurements, Vedder et al. (1979) determined that volcanism on Santa

Catalina Island began about 14.7 Ma and extended until some time after 12.4 Ma. A single whole-rock Ar-Ar determination by Luyendyk et al. (1998) of 17.2 ± 0.6 Ma suggests that volcanism may have begun somewhat earlier.

SAN CLEMENTE ISLAND

San Clemente Island is the emerged portion of a structural block bounded on the northeast by the San Clemente fault that has a vertical displacement of at least 500 m (Junger 1976). The island consists of interbedded Miocene volcanic and sedimentary rocks, and is partly blanketed by Quaternary sedimentary rocks and unconsolidated sediments (Smith 1898; Olmsted 1958). Excluding the Quaternary cover, volcanic rocks crop out over an area of about 160 km^2 (Olmsted 1958). An additional 172 km^2 of volcanic rocks surround the island (Vedder et al. 1986).

Andesite flows and minor pyroclastic units that exceed 600 m in thickness dominate the bulk of San Clemente Is1and (Olmsted 1958). Dacite occurs as two or more distinct flows that overlie the andesite and that reach 70 m in thickness. Flows and minor tuffs of rhyolite up to 45 m in thickness also overlie the andesite flows; the rhyolite and dacite units are not in contact with each other. Merrifield et al. (1971) described the petrology of a core drilled at Eel Point, which is located about mid-island on the southwest coast. About 364 m of andesite were encountered, which are largely not exposed on the island.

Chemical analyses (Weigand 1994) confirm that the main volcanic unit is compositionally andesite, whereas samples from the upper dacite and rhyolite units are indistinguishable and plot on the dacite-rhyolite boundary (Figure 2F). Merrifield et al. (1971) reported a whole-rock K-Ar date determined from near the bottom of the Eel Point core of 16.1 ± 0.8 Ma and one from near the top of the core of 15.9 ± 0.7 Ma. They reported additional K-Ar ages on plagioclase separates of 15.4 ± 1 Ma from a subaerial andesite flow and 13.6 ± 0.4 Ma from a rhyolite collected near the top of the volcanic sequence. These dates are compatible with Luyendyk et al.'s (1998) whole-rock Ar-Ar dates which range from 16.0 to 14.5 Ma.

SAN NICOLAS ISLAND

San Nicholas Island consists of about 3,000 ft of Eocene sedimentary strata covered in places by Pleistocene marine terraces and wind-blown sand (Vedder and Norris 1963). Igneous activity on San Nicolas Island is limited to several dikes of possible basalt to andesite composition assumed to be middle Miocene in age (Vedder and Norris 1963).

DISCUSSION

The Miocene igneous suites on the Channel Islands exhibit geochemical characteristics that have traditionally been associated with igneous rocks produced above an active subduction zone (e.g., Thompson et al. 1984). However, it is now well established that subduction of the Farallon plate had ceased by the time and in the area that these igneous centers on the Channel Islands were active (Atwater 1989; Lonsdale 1991). Savage and Weigand (1997) have interpreted the generation of the middle Miocene Conejo Volcanics of the nearby Santa Monica Mountains, for which considerable major-oxide, trace-element, and isotopic data are available, in light of recent extensional tectonic models for southern California that involve large components of rifting, rotation, and extension in and around the areas currently occupied by the western Transverse Ranges and inner California Continental Borderland (Crouch and Suppe 1993; Nicholson et al. 1994). This model can explain the generation of all the Miocene igneous centers of coastal and offshore southern California, including the occurrences on the Channel Islands.

In short, Savage and Weigand (1997) proposed that generation of the Conejo magmas involved a two-stage process presented in a slightly modified form here. The first stage involved emplacement of oceanic lithosphere, including the subduction of accretionary sediments that became metamorphosed into Catalina Schist, beneath Western North America during subduction of the Farallon plate in Cretaceous and Paleogene time. The second stage involved the rifting and clockwise rotation of the western Transverse Ranges block caused by the capture of the partially subducted Monterey microplate by the Pacific plate at about 20 Ma. Continued rifting and rotation of the overlying continental crust in response to newly initiated transtensional Pacific plate motion of the captured microplate led to unroofing and exposure of the underlying Catalina Schist and to the attenuation and uplift of the underlying oceanic lithospheric and asthenospheric mantle. Decompression melting of this depleted mantle source produced primitive basaltic magmas that repeatedly intruded the overlying crust where they underwent fractional crystallization and assimilated Catalina Schist or isotopically similar material. Thus, the distinctive geochemical signatures in this suite were developed during magma evolution and interaction with previously subducted oceanic crust and were not derived from their primary source. These more evolved magmas erupted throughout what is now coastal and offshore southern California starting about 19 Ma and lasting until about 13 Ma in Channel Islands volcanic centers.

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