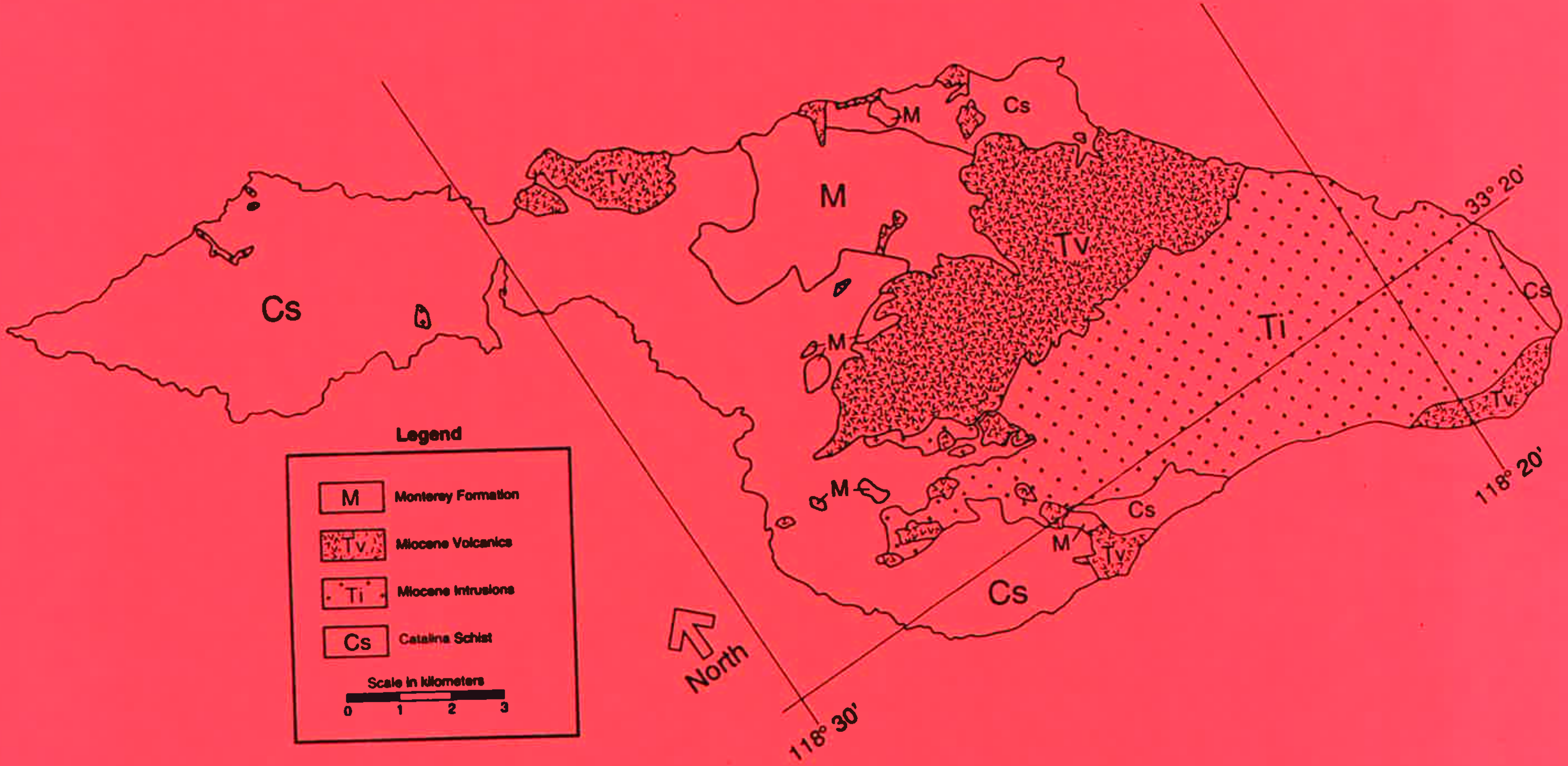
# SANTA CATALINA ISLAND



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# INTRODUCTION TO SANTA CATALINA ISLAND

Eldon Gath

The story of man on Santa Catalina Island begins at least 4,000 years ago with the earliest known Indian occupation. They were known locally as the Pimugnans but more regionally as Chumash. The island was highly valued by its natives for the rock, steatite, a fine grained talc that made excellent boiling pots. Steatite had the uniqueness of being soft and easily carved, the advantages of being highly resistant to heat and cracking, and the decency to occur in several easily accessible surface exposures. The natives on Catalina Island lived well on abalone and fish, trading their bowls and shellfish with the more agrarian mainlanders. The population of Catalina Island is estimated to have been around 2,500 when the white man arrived on the scene.

On September 28, 1542, Juan Rodriquez Cabrillo, a Portuguese sailing for the Spanish, discoverd San Diego Bay. Ten days later, on October 8, he arrived at the future Avalon Harbor, thereby becoming the discoverer but not the namer of the island. Looking across the channel at the future San Pedro/Los Angeles Harbor, Cabrillo showed remarkable foresight by calling it "the Bay of Smokes". Cabrillo left Catalina soon afterwards for continuing ventures northwards, where, on San Miguel Island, he broke either his arm or leg. Not one to allow trifles to deter him, he continued to push northwards, only to be rebuffed by deteriorating weather. Returning to San Miguel Island, Cabrillo died of complications (probably gangrene) from his injury which proved fatal. On January 3, 1543, Juan Rodriquez Cabrillo, the white man's discoverer of Catalina Island, was buried in an unmarked grave on the island that ended his discovery journey, San Miguel. Sebastian Vizcaino, a Spanish missionary-explorer traveled the coast of California in 1602. He was quite into assigning names and to him we owe the name Santa Catalina Island. The Indian population of the island was eventually moved, in its entirety, to the San Gabriel Mission by the Jesuit missionaries. There they became known as "Gabrielinos", and there they all died.

Boston fur hunters began visiting the area in 1796, gathering fur seal and sea otter pelts. Avalon Bay was highly favored because it was local to Los Angeles yet remote enough to avoid the pitfalls (taxes) of dealing with the Spanish and Mexican authorities of the mainland. The bay was also a favorite local for stripping the barnacles from their ships before beginning the long return voyage to Canton or Boston. By the 1920's, however, the fur seals were essentially extinct, and the fur traders turned to exporting abalone to the Orient. By the 1830's the abalone was running very low; laws were passed restricting its harvest and export, and Catalina Island faded away for awhile.

In 1846, a Mr. Thomas Robbins was land-granted the entire island of Catalina by the Mexican appointed governor, Don Pio Pico. In early 1863, the mining boom began with the discovery of galena containing some gold and silver. On New Years Day, 1864, soldiers of the Union Army under the command of Lt. Colonel James F. Cutis, occupied Avalon to prevent its

Facing page: Fishermans Cove, Santa Catalina Island (mid 60's) falling into Confederate hands. A company of men was stationed in barracks at the isthmus of the island until September 14, 1864, when they suddenly departed for the mainland. The island had apparently been saved.

Mining began to flourish after the military occupation ended, however, the inaccessability of many of the mines, and the lack of an adequate water supply proved economically prohibitive to many of the smaller operations. By the time the Banning family acquired Catalina Island in 1891, mining activity had nearly ceased, and in 1893 the last known ore shipment was dispatched. In 1912, pioneer aviator Glenn Martin made the first flight to Catalina Island in an improvised hydroplane. The Bannings made their residence at Two Harbors and in 1910 completed the magnificent Banning House Lodge that served as their summer home until 1919 when they sold out to William Wrigley, Jr.

William Wrigley, Jr., the chewing gum magnate and founder of the Chicago Cubs, purchased Catalina in 1919 for around $3,000,000, determined to mine lead and zinc on the island. Wrigley and his wife established their home at Avalon Harbor, the name originated by Mrs. Wrigley. By 1927, however, the world wide collapse of the lead market put an end to Wrigley's mining empire aspirations.

Modern usage of the island is principally directed towards the get-away tourist. The bulk of the island remains as it was at the close of the mining period due to the Wrigley's establishment of the Santa Catalina Nature Conservancy. A herd of bison graze peacefully in the interior, brought there by a movie company. Cars are virtually unknown except in the town of Avalon, and petrologists are free to hammer on the famous Catalina Schist, while geomorphologists bemoan the invisible marine terraces. Hope you, too, can enjoy beautiful, unspoiled Santa Catalina Island.

Catalina Harbor, Isthmus area, Santa Catalina Ialand (1869) (from Davidson,1869, Pacific Coast-Coast Pilot of California, Oregon, and Washington Territory).

# GEOLOGY OF THE SAN PEDRO BASIN
# LOS ANGELES HARBOR TO SANTA CATALINA ISLAND

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## LOS ANGELES HARBOR

The Los Angeles-Long Beach Harbor is a man-made facility produced by construction of three rock breakwaters across San Pedro Bay. These breakwaters have a combined length of 8.1 miles creating the largest artificial harbor in the world. About 1200 acres of marshland were dredged to create the inner harbor north and east of the Catalina Island boat terminal at the Vincent Thomas Bridge. Extensive oil production from the Wilmington Oil Field has caused deep subsidence in the harbor area. Since production began in 1928 the eastern end of Terminal Island has subsided 29 feet; whereas general subsidence of 2 feet or more extends across a bowl-shaped depression 6 miles long and 3 miles wide. Some of the bottom areas in the inner harbor have deepened as much as 28 feet, requiring a dike system to prevent flooding of adjacent lands on Terminal Island and Wilmington.

The harbor is used for a variety of purposes ranging from commerical activities associated with shipping to significant recreational activities. Several industrial uses, including discharges of heat and organic wastes, have resulted in a concern of possible degradation of environmental conditions within the harbor. As a result of this concern, numerous studies have been completed recently or are presently underway to assess the effects of the discharges.

Studies of the effects of thermal effluent indicate that the majority of waste heat is dissipated into the upper layers of the harbor water column and is subsequently transferred to the atmosphere or is flushed out of the harbor to the open ocean. Concommitant faunal analyses of benthic organisms appear to substantiate this conclusion because the benthic faunas do not show significant detrimental effects resulting from thermal discharges.

In order to accommodate larger bulk cargo and container vessels, the Corps of Engineers has dredged the main entrance channel and much of the inner Los Angeles Harbor to a depth of -45 feet MLLW. Dredged maerials were so toxic that they were retained behind dikes and 307 acres of new harbor land were created. The total volume excavated was about 10 million cubic yards at a cost of 7.5 million dollars.

Due to years of uncontrolled waste discharges a thick layer of toxic sludge has accumulated on the floor of the inner harbor. Decaying organic matter depleted the dissolved oxygen in the interstitial and overlying waters and substantial quantities of hydrogen sulfide are produced by anaerobic

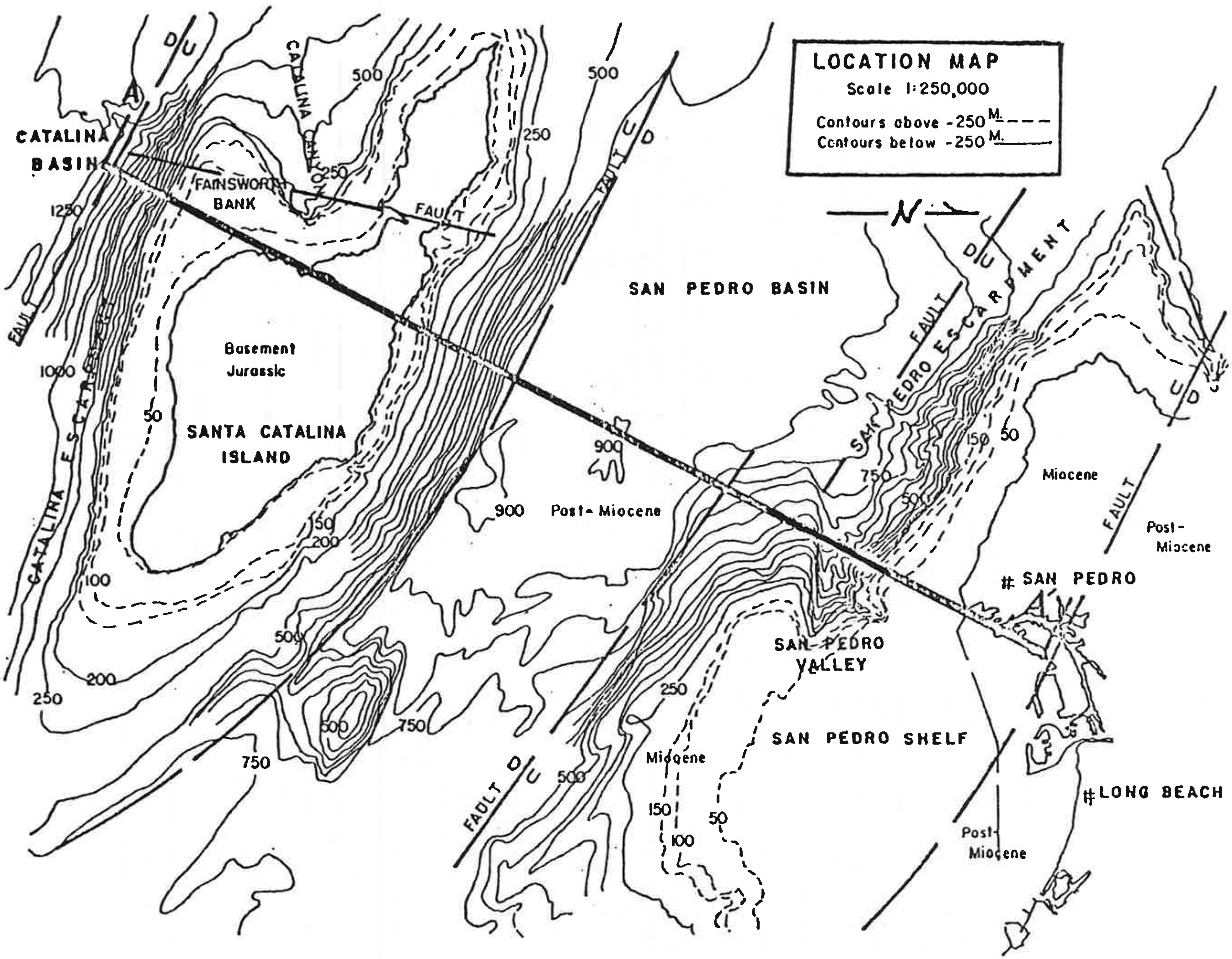
LOCATION MAP
Scale 1:250,000
Contours above -250 M.
Contours below -250 M.
N
A
A'
CATALINA BASIN
FAINSWORTH BANK
CATALINA CANYON
FAULT
D U
SAN PEDRO BASIN
SAN PEDRO ESCARPMENT
CATALINA ESCARPMENT
Basement Jurassic
SANTA CATALINA ISLAND
Post-Miocene
Miocene
SAN PEDRO
SAN PEDRO VALLEY
SAN PEDRO SHELF
LONG BEACH
1250
1000
900
750
500
250
200
150
100
50

Figure 1

bacteria. Consequently, most forms of marine life were eliminated in the affected areas. In recent years reduced waste discharges into the harbor has greatly improved the water quality and many life forms are returning, much to the chagrin of pleasure-boat owners.

Five cores ranging in length from 2.5 to 9.0 feet were anlyzed by the Corps of Engineers for chlorinated hydrocarbon pesticides, and heavy metals. All samples contained zinc in excess of EPA limits, and EPA standards were exceeded in at least two core samples for Kjeldahl nitrogen, B.O.D., oil and grease, and volatile solids. For this reason the Corps opted a special two-step design for containment of dredge spoil. A stone dike from the harbor floor to highest tide level was constructed to contain coarser, less polluted spoil from the outer harbor. The second step dike was built upon dredged material and finer, more polluted sediment from the inner harbor was placed over the first-step fill. Final grading requires a blanket seal of clean material over all dredge spoil above sea level.

Because of the success of the deep-dredge channel and spoil containment the Corps of Engineers has undertaken review studies for further expansion of deep-dredge dockage and new landfills.

## SAN PEDRO CHANNEL

The borderland off southern California consists of a series of fault-controlled basins and ridges analogous to basin-range topography in eastern California and Nevada. On the passage to Avalon we will pass over the mainland (San Pedro) shelf and slope, the San Pedro Basin (900 meters deep), and the insular slope and shelf of Catalina Island (Figs. 1 & 2). Should we continue on a southerly course we would traverse the Catalina Basin (1250 meters deep) to San Clemente Island, and then over a series of deep basins and shallow banks to the true continental slope known as the Patton Escarpment.

San Pedro Shelf. The oceanographic current regime on the shelf is not well known at present, but, tidal, wind-driven, and wave generated long-shore drift all appear to influence the water circulation and distribution of bottom sediments. The surface sediment trends are generally aligned in a northwest-southeast direction, with the present sources of sediment supply located primarily at the northwest and southeast extremities of the shelf. The central shelf is dominated by outcrops of Miocene rocks and relict sediments.

High resolution profiles indicate that the unconsolidated sediment cover on the shelf is very thin. However, the thickness of unconsolidated sediment increases rapidly from the shelf break toward the center of the Channel. Seismic records also indicate that considerable tectonic activity has taken place and the sediment structure is modified by numerous faults and slumps.

The oxygen content of the bottom water in the northern part of the San Pedro Channel is very low, and this results in an impoverished fauna or lack of benthic organisms in some areas. However, to the south, the benthic fauna is extremely abundant. Both areas were selected as sites for solid waste disposal in the past, and an evaluation of the effects of this material is continually monitored.

San Pedro Basin. This 900-meter deep graben forms a very flat-floored valley between San Pedro and Catalina. The deepest part of the basin is displaced toward the island from its geometric axis because of higher sedimentation rates closer to the mainland. Much of the sediment in the basin owes its origin to slumping on the basin slopes and turbidity currents and sand flows in submarine canyons. Pelagic sediment in the basin is characteristically blue-green mud high in organic matter and $H_2S$. The muds contain silt and sand layers of turbidity current origin.

This basin, and the Santa Monica Basin to the north, are characterized by oxygen rich (aerobic) to anoxic (anaerobic) gradients with depth. Oxygen profiles shown the anaerobic-dysaerobic boundary occurs at about 300 m (1.0 ml/l d.o.), and the dysaerobic-anaerobic boundary at about 900 m (0.1 ml/l d.o.). The importance of these zones is their impact on sedimentary structures such as bedding. In general, aerobic facies are characterized by thoroughly churned, bioturbated sediments and a diverse fauna. Dysaerobic facies are bioturbated with a less diverse fauna dominated by smaller soft-bodied organisms. Anaerobic facies are characterized by laminated, undisturbed sediments and a lack of significant macrofauna. These findings are significant in the search for oil and are also of importance in offshore slope stability. Areas of rapid sedimentation that are highly churned by benthic organisms are more prone to mass movement than slowly deposited sediments in an oxygen starved environment.

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# CROSS SECTION A-A'

Scale: Horizontal = 1:250,000
Vertical = 1: 24,000
(or x 10½)

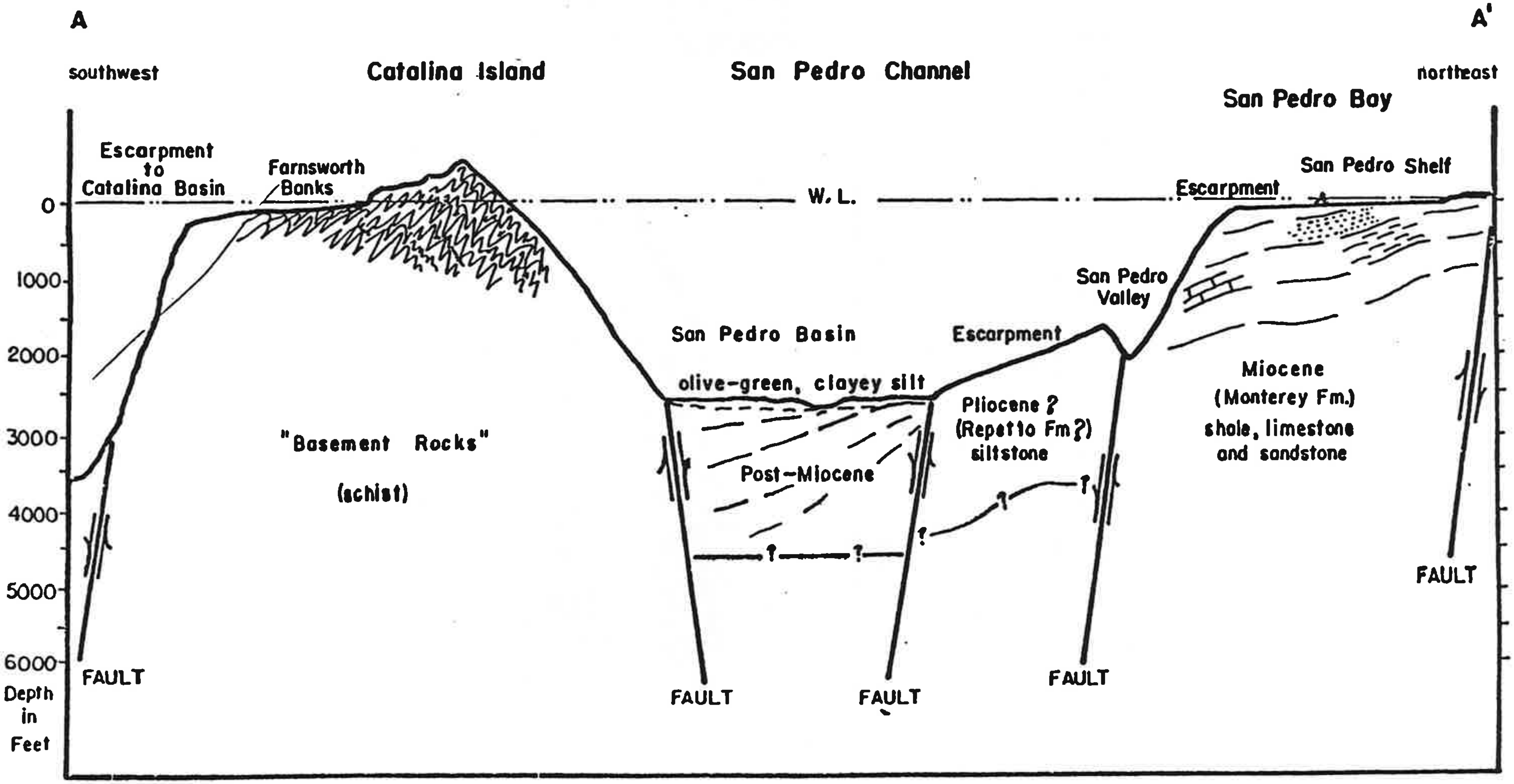

Figure 2

# BRIEF OVERVIEW OF THE TECTONIC ORIGIN OF THE SOUTHERN CALIFORNIA CONTINENTAL BORDERLAND

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The California Continental Borderland, extending north-south from Point Conception to Cedros Island off the Vizcaino Peninsula in central Baja, California, and east-west from the Peninsular Ranges to the Patton Escarpment (Figure 1) is typified by elongated northwest and west trending seafloor ridges and basins. The Capistrano Embayment (Ehlig, 1979) and the Los Angeles Basin represent landward extensions of the borderland, basins which are now filled with thick clastic sediments reflecting initial subsidence followed by eventual uplift and sea regression. The borderland style of deformation initiated 20-24 m.y.a. as large-scale transform tectonism and volcanism began assuming dominance over the continental margin, following its intersection with the East Pacific Rise, approximately 30 m.y.a. (Howell and Vedder, 1981). Prior to 30 m.y.a., the "Andean type" lithologic belts were continuous along the continental margin (Crouch, 1979); the rifting, transportation and rotation of the borderland tectonic blocks is treated in this review.

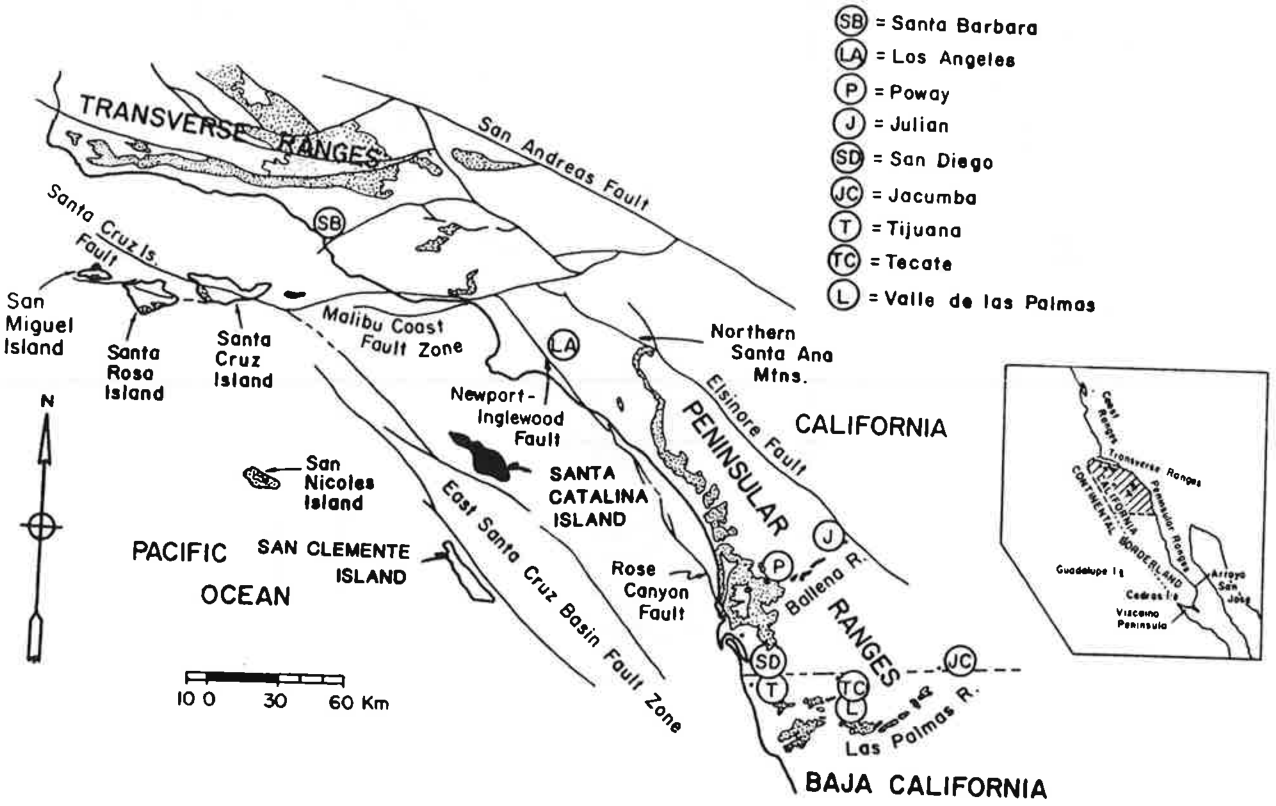

Figure 1. Index map of the northern part of the California Continental borderland. Modified from Kies and Abbott, 1982.

Rocks present within the borderland province reflect the dynamic history subjected upon this very active continental margin (Figure 2). Mid-Jurassic crystalline rocks of the batholith, Franciscan blueschist facies rocks of the subduction complex, and ophiolitic rocks of the Coast Ranges were all stratigraphically overlain by Cretaceous through Oligocene Great Valley type sediments rocks deposited within a forearc basin. Wrench tectonics splintered the borderland into deep basins in early Miocene time resulting in thick Neogene sedimentary sequences. Since the mid-Pliocene, uplift within the province has elevated portions of the borderland 2,000 meters at rates of 0.5-0.7 m/1000 years (Howell and Vedder, 1981). Late Pleistocene-Holocene uplift rates near Ventura, estimated as high as 10m/1000 years (Sarna-Wojcicki, et al, 1981), appear to indicate a local acceleration of that older, average rate. Uplift rates along the coast south of Ventura, however, range from a high of about 0.5 m/1000 years at Malibu (Sarna-Wojcicki, et al, 1981) to an apparent low of 0.05 m/1000 years at San Onofre (Shleman, 1979).

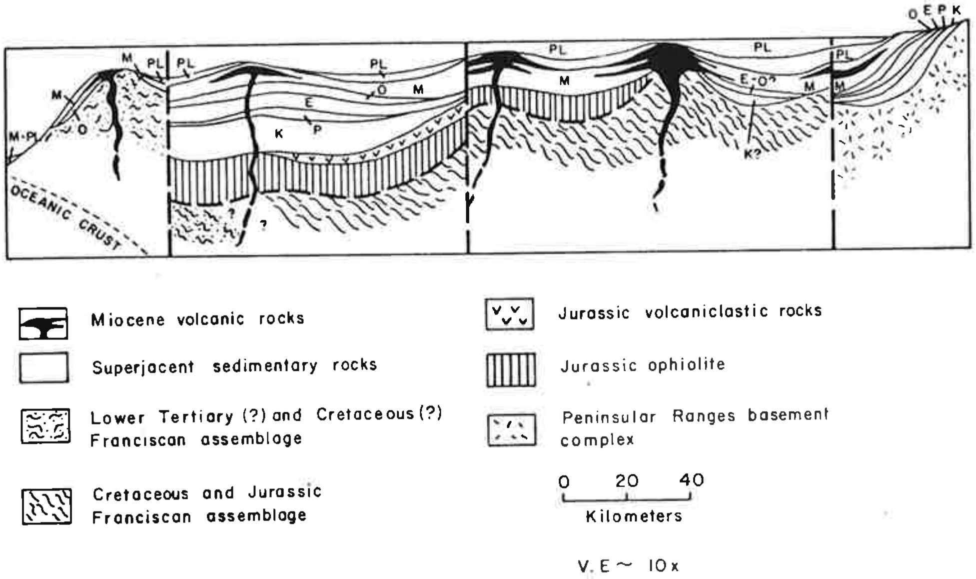

Figure 2. Schematic east-west cross section of the southern California borderland. The relations shown in this figure are diagrammatic and largely speculative. Letter symbols indicate sedimentary rock sequences as follows: K, Upper Jurassic (?) and Cretaceous; K? , Cretaceous or Paleocene; P, Paleocene; E, Eocene; O, Oligocene; M, Miocene; Pl, Pliocene and younger. From Howell and Vedder, 1981.

Studies within the northern borderland reveal lithologic and paleomagnetic inconsistencies with their present locations. Sedimentologic comparisons of Eocene conglomerates and sandstones by several investigators (Minch, et al, 1976; Kies and Abbott, 1982), relate them to Poway type conglomerates of the San Diego area, (Figure 3). They are interpreted to be submarine fan sediments deposited off the continental slope by

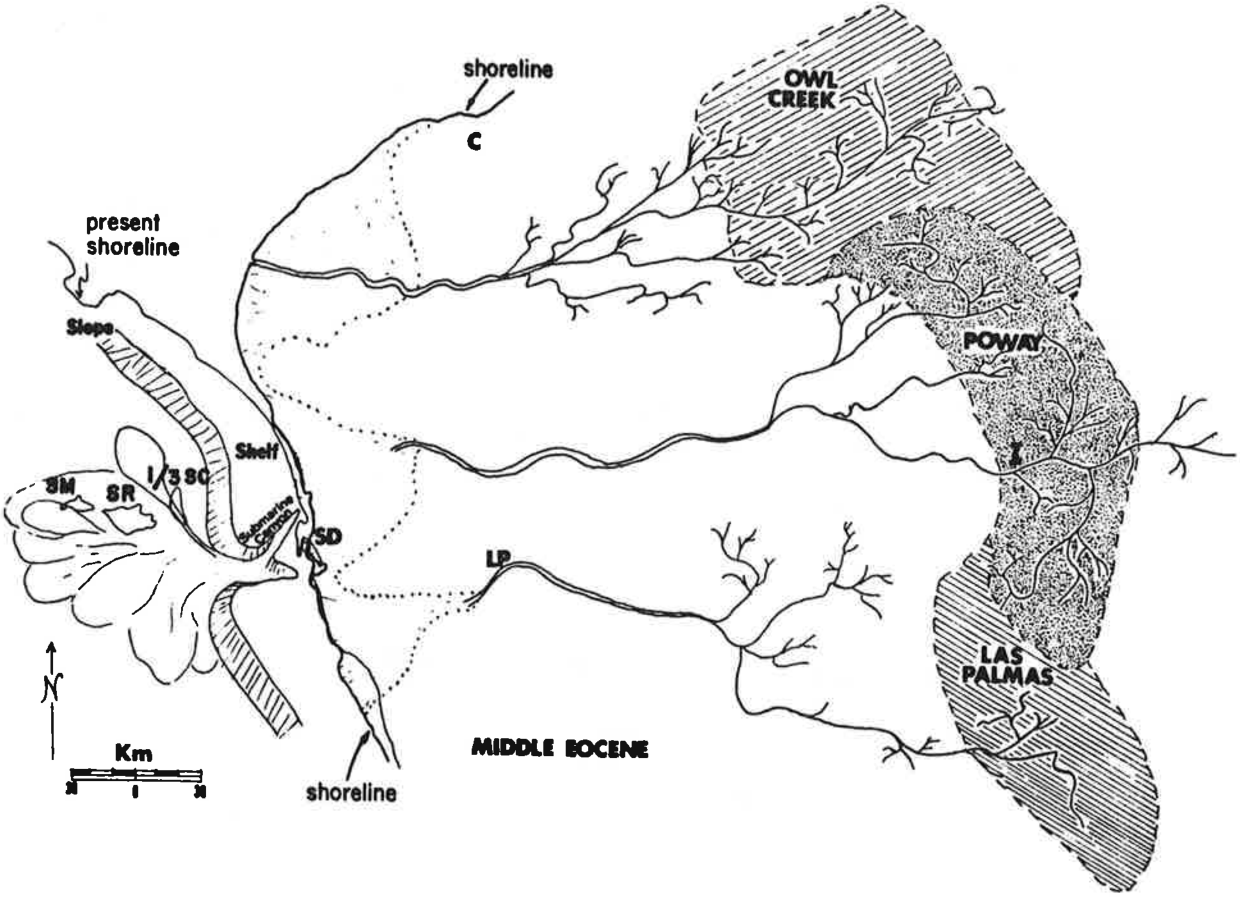

Figure 3. Middle Eocene paleogeography. Rivers delivered abundant gravels with unique rhyolitic textures to the paralic and deep marine environments. From Kies and Abbott, 1982.

headwardly erroding streams (Kies and Abbott, 1982), before being transported 120 to 160 km northward (Howell, et al, 1974). Howell and others (1974) proposed the name "East Santa Cruz Fault System" for this right lateral fault located just west of Santa Catalina Island (Figure 1). Sedimentologic flow directions on the northern Channel Islands indicate that the islands have been rotated away from any likely source areas. Paleomagnetic vectors confirm a 70° rotation clockwise (Figure 4) of a large tectonic block bounded by the Malibu Coast and Santa Monica fault systems on the south (Komerling and Luyendyk, 1979), possibly along the model postulated by Dibblee (1982, Figure 5), which would fit the sedimentary data to an eastern source. Progressive lessening of rotation with younger ages of emplacement demonstrate that rotation of the borderland blocks was occurring throughout the Miocene volcanic episode. Volcanism apparently ceased within the borderland around 14 m.y.a. (Wiegand, 1982). Pliocene beds reportedly overlap the Malibu Coast Fault without offset indicating movement, and therefore, rotation had mostly ceased by then (Truex, 1976).

Komerling and Luyendyk's paleomagnetic data also suggest that the borderland area has a paleolatitude of 24± 9 degrees or roughly 10 degrees to the south. They postulate that the borderland block originated near

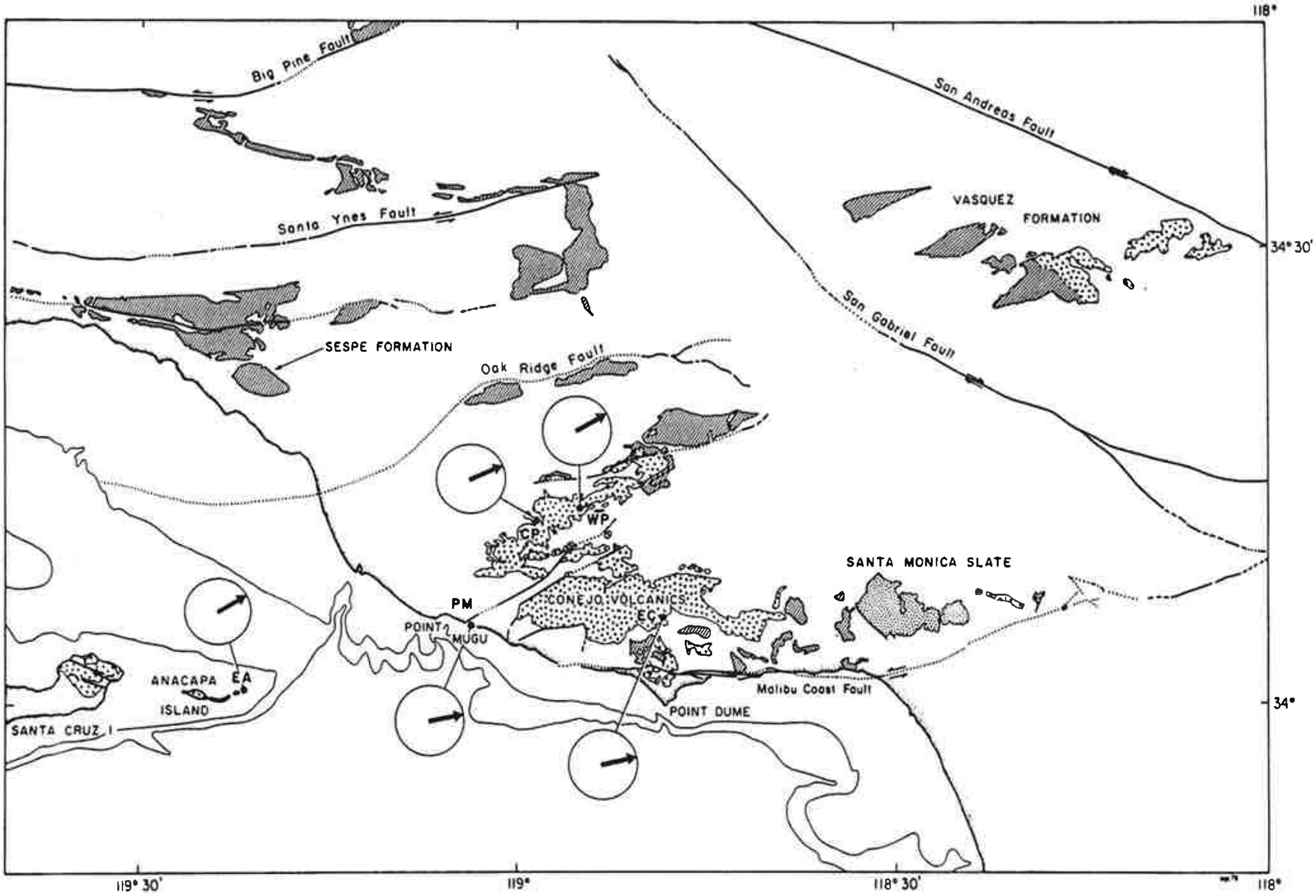

Figure 4. The arrows in the open circles show the paleomagnetic declinations in Miocene rocks determined. All sites are reversely magnetized except PM (Point Mugu), EA (East Anacapa), EC (Encinal Canyon, CP (Camarillo Park), and WP (Wildwood Park). From Kamerling and Luyendyk, 1979.

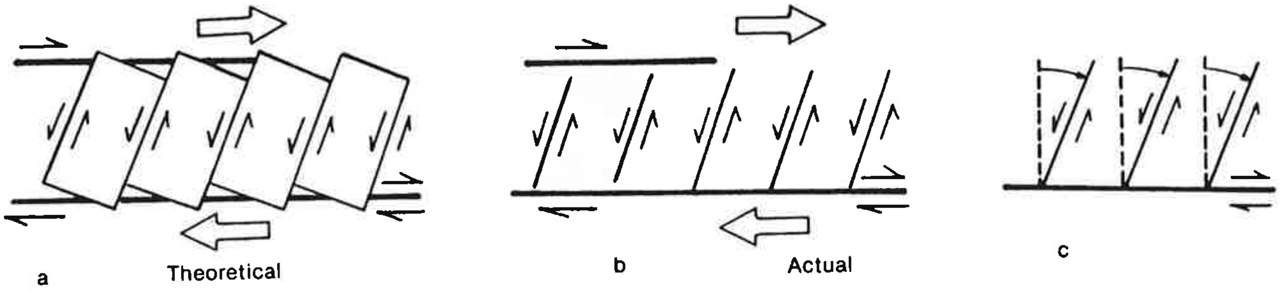

Figure 5. Transverse fault blocks partly rotated by strike-slip movement on or between major strike-slip faults: (a) theoretical model; (b) actual conditions in field; (c) development of strike-slip movement on transverse faults by rotation from initial positions normal to major strike-slip fault. From Dibblee, 1982.

Cedros Island in early Miocene time, became detached and transported northward, finally being rotated 70-120 degrees clockwise into its present location. Minch, et al (1976) report significant lithologic and paleontologic correlation between Vizcaino Peninsula strata and rocks from the Channel Islands and Great Valley. Figure 6 illustrates those possible palinspastic restorations for the borderland terrane. Position A restores the Eocene fan deposits to their probable on-shore sources. Position B by Crouch (1979) attempts to correlate major lithologic belts (Franciscan type metamorphics and Great Valley type sediments) with similar Borderland and Baja California lithologies. Position C restores the paleomagnetic vectors to their calculated original location off the Vizcaino Peninsula.

At present, the large discrepancy between the sedimentologic and paleomagnetic restorations cannot be reconciled. If the miocene paleomagnetic data is accurate, and the similar rock types of Cedros Island further suggest that it is, and if the strong Eocene correlations are valid, which seems to be the case, then speculatively, the on-shore Eocene conglomerates have also been transported northward since Eocene times. I am unfamiliar with any paleomagnetic data for the Santiago Peak Volcanics or the San Joaquin volcanic intrusives. If these show northward relocation as well, a major pre-Pliocene strike-slip fault may be unrecognized somewhere in the Peninsula Ranges. Paleocene lateritic paleosols present in the Santa Ana Mountains are indicators of tropical environments (Peterson, et al, 1975), suggesting a more southerly origin. If the Paleocene/Eocene sediments can be clearly defined eastward, that suspected fault may be revealed.

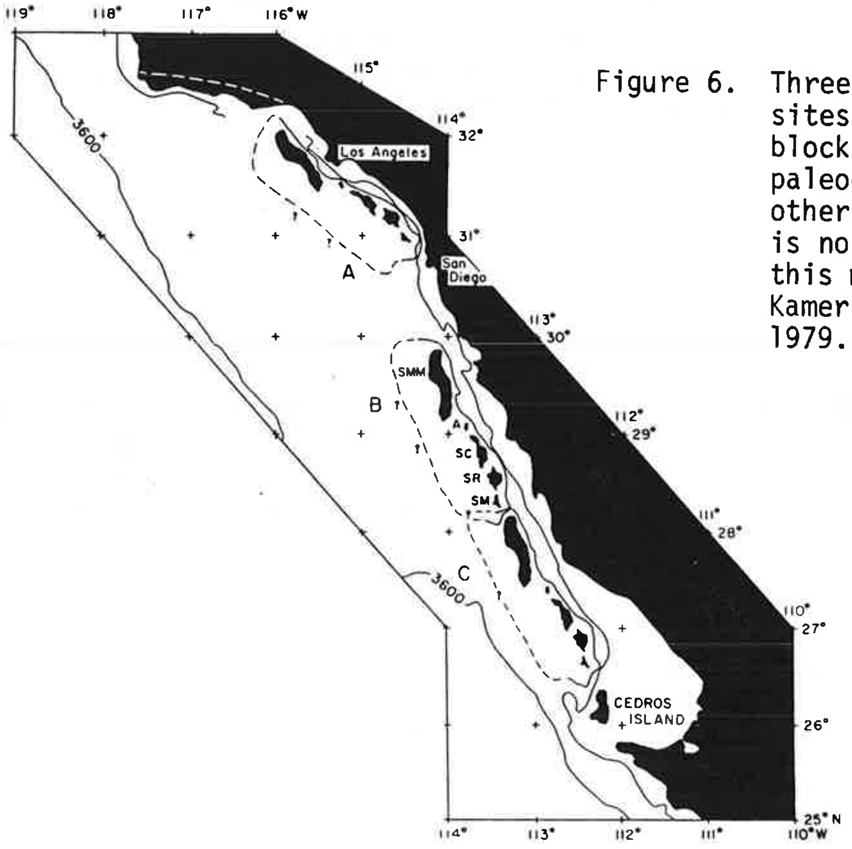

Figure 6. Three possible origin sites for the rotated blocks (A, B, C). The paleogeography of the other channel islands is not considered in this model. From Kamerling and Luyendyk, 1979.

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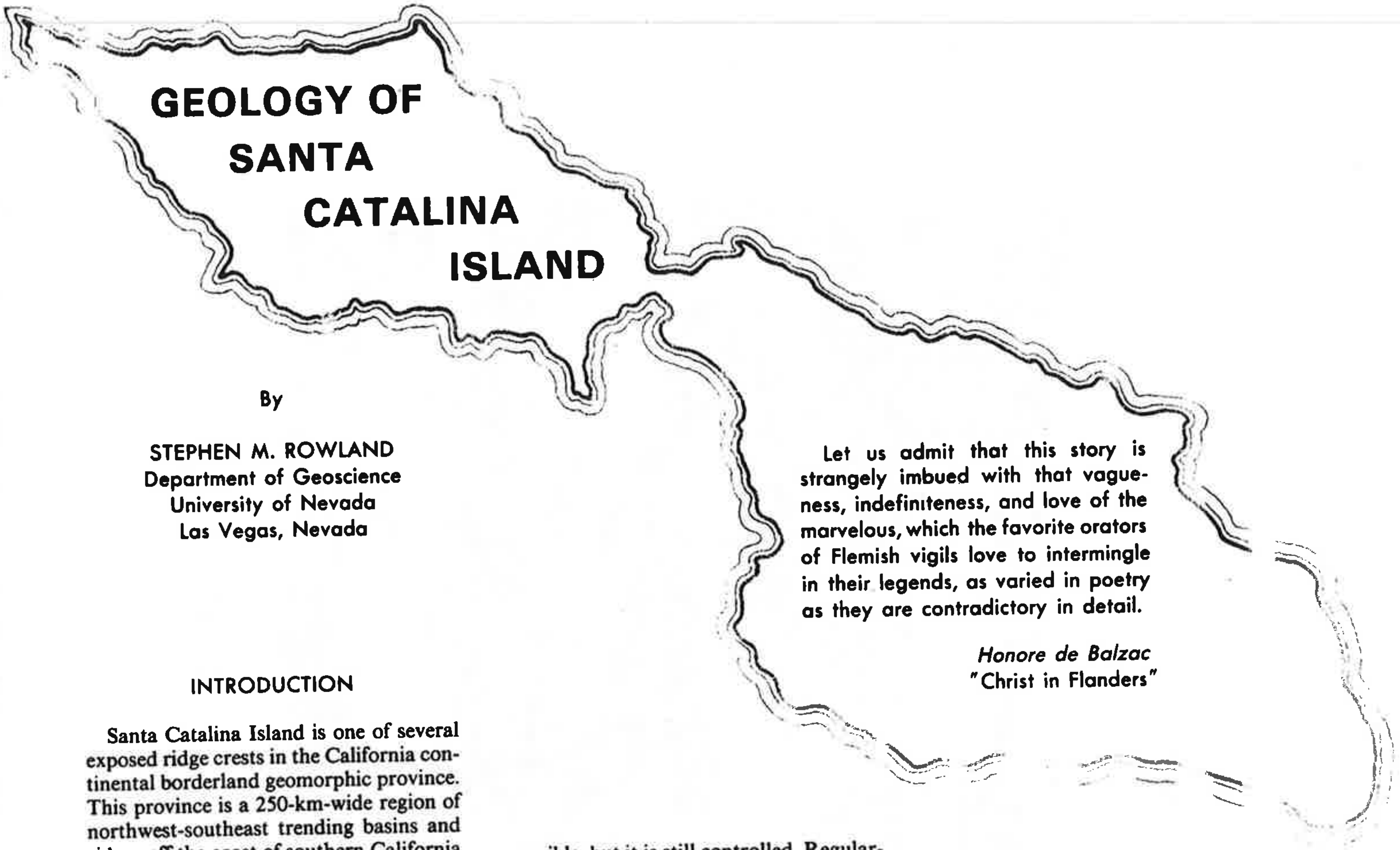

# GEOLOGY OF SANTA CATALINA ISLAND

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> Let us admit that this story is strangely imbued with that vagueness, indefiniteness, and love of the marvelous, which the favorite orators of Flemish vigils love to intermingle in their legends, as varied in poetry as they are contradictory in detail.
>
> *Honore de Balzac*
> "Christ in Flanders"

## INTRODUCTION

Santa Catalina Island is one of several exposed ridge crests in the California continental borderland geomorphic province. This province is a 250-km-wide region of northwest-southeast trending basins and ridges off the coast of southern California and Baja California. The geology of the continental borderland is complex, and because it is mostly under water, it has been the last major province in California to receive detailed study. Recent work on Santa Catalina and throughout the continental borderland has resulted in a much improved picture of this region's geologic history.

Simply stated, the geology of Santa Catalina consists of a Mesozoic metamorphic basement complex intruded and overlain by Miocene igneous rocks. A few scattered deposits of Tertiary sedimentary rocks are also present (Figure 1). The basic geologic relationships, if not the exact ages, have been known since 1897 when the first geologic map of the island was published (Smith, 1897). Until very recently, however, it was not known how these rocks fit into the geologic evolution of western North America.

Prior to 1975, it was difficult to casually examine the rocks on Santa Catalina because most of the island was privately owned by the Wrigley (chewing-gum) family. In 1975, however, 86 percent of the island was transferred to a non-profit foundation called the Santa Catalina Island Conservancy. Los Angeles County has a 50-year easement on most of this land. Access to the island's interior is now possible, but it is still controlled. Regularly scheduled bus tours depart from Avalon, and arrangements for geologic field trips or research can be made through the Santa Catalina Island Conservancy, P.O. Box 2739, Avalon, California 90704.

## CATALINA SCHIST AND THE FARALLON-NORTH AMERICAN SUBDUCTION ZONE

### Distribution

The Catalina Schist, a Mesozoic metamorphic complex, occupies most of the northwestern half of the island (Figure 1). Catalina Schist crops out on land in only two places—Santa Catalina Island and in a small area on the Palos Verdes Peninsula. Samples of Catalina Schist have been dredged from several localities within the continental borderland (Howell and Vedder, 1981), however, and it is thought to form the basement complex of much of the inner borderland (see Crouch, 1979, Figure 1).

### Relationship with the Franciscan Complex

Catalina Schist lithologies are similar to those of the Franciscan Complex, and the Catalina Schist has generally been considered to be a southward extension of the Franciscan (Woodford, 1924). Potassium-argon dating of Catalina amphibolite and blueschist has yielded ages of 95-109 million years (uppermost Lower Cretaceous) (Suppe and Armstrong, 1972), which falls within the Upper Jurassic through Eocene age for the Franciscan of the Coast Ranges. The Catalina Schist is not "typical" Franciscan, however, because the blueschists of the Catalina Schist terrane are more thoroughly recrystallized than most Franciscan blueschists (Platt, 1975). Also, it has been shown that Catalina blueschists probably experienced relatively higher temperatures and/or relatively lower pressures (that is, a lower P/T ratio) than those of Coast Range Franciscan (Sorenson, 1984a, b).

### Lithology

The Catalina Schist comprises three metamorphic grades (Table 1).These are blueschist, greenschist, and amphibolite, all of which are derived from mafic igneous rocks and sedimentary rocks (Platt, 1975; Sorensen, 1984a, 1984b). The greenschist and amphibolite facies rocks

View of Little Harbor embayment on the west side of Santa Catalina Island, site of many "south sea island" movies. Photo from Santa Catalina Island Company.

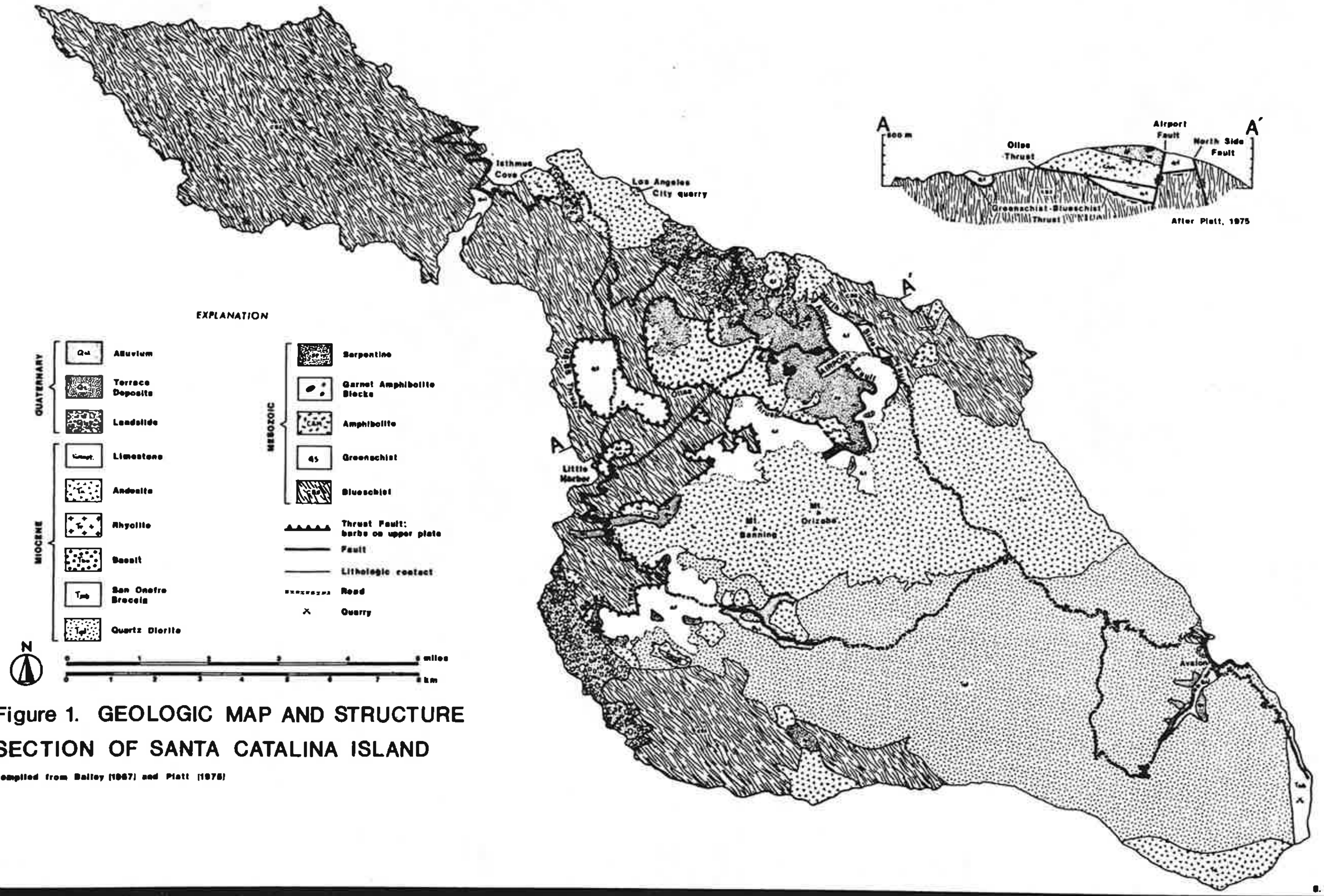


Figure 1. GEOLOGIC MAP AND STRUCTURE SECTION OF SANTA CATALINA ISLAND

Compiled from Bailey (1967) and Platt (1976)

S. Rowland 1982

*Photos by Stephen M. Rowland.*

**Photo 1. Blueschist mélange at Little Harbor. The geology here is confused due to landsliding. An enlargement of the right-hand-central portion of this photo is shown in Photo 2.**

occur as relatively coherent tectonic blocks (Platt, 1975), while the blueschist is a mélange (Photos 1, 2, 3) (Sorensen, 1984a, 1984b).

All three metamorphic facies of the Catalina Schist are stable at a pressure of around 9 kilobars (kb), but each has a unique range of stable temperatures (Table 1). The Catalina blueschists formed under relatively low-temperature conditions (approximately 300°C), while the greenschists formed under intermediate-temperature conditions (450°C), and the amphibolites formed under much hotter conditions (580-620°C). The surprising thing is that the three facies are structurally arranged with the low-temperature blueschists on the bottom and the high-temperature amphibolites on top (Figure 1, cross section A-A')—an inverted thermal gradient. Although the three facies lie in fault contact with one another, the similar parent-rock assemblages, the common high-pressure metamorphic history, and the present structural relationships suggest that they formed in a single, zoned metamorphic complex (Platt, 1975).

## Structure

Two thrust faults have been mapped in the central part of Santa Catalina (Figure 1) (Platt, 1975). The structurally lower of the two is the Greenschist-Blueschist thrust, which consistently separates blueschists below from greenschists above. Structurally above and truncating the Greenschist-Blueschist thrust is the younger Ollas thrust, which separates the amphibolites from the underlying units (Figure 1, Structure Section A-A'). Both of these thrusts are poorly exposed zones of variable width.

The Ollas thrust is a zone of sheared serpentinite, talc, and chlorite that is several meters thick (Smith, 1897; Bailey, 1941, 1967; and Platt, 1975, 1976). It is exposed in only two localities, Buffalo Springs Canyon and the west fork of Big Springs Canyon, but elsewhere it can usually be located within about 20 m (Platt, 1976, p. 76). This fault crosscuts schistosity as well as minor folds in both the lower and upper plate.

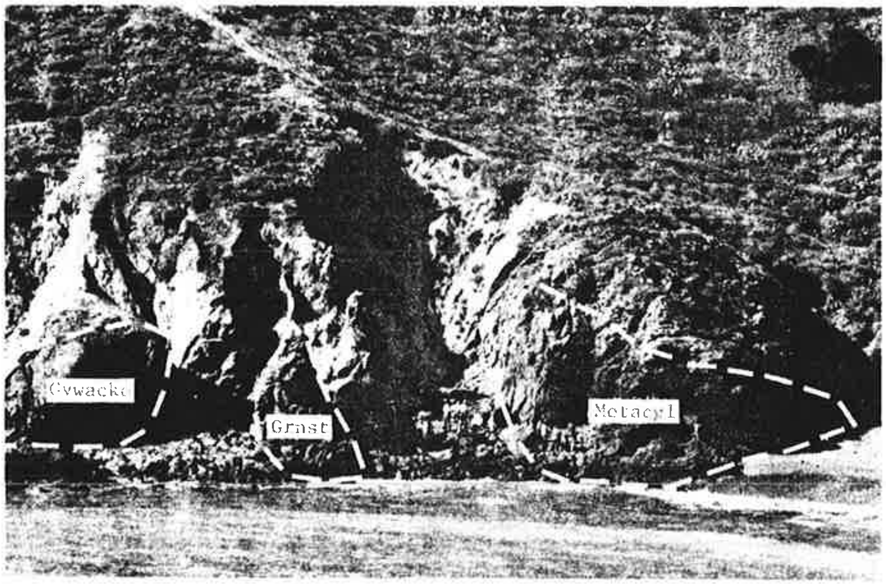


**Photo 2. North shore of Little Harbor showing three discrete blocks in a mélange matrix. Note people between greenstone and metaconglomerate blocks for scale. Gywacke = graywacke, grnst = greenstone, metacgl = metaconglomerate.**

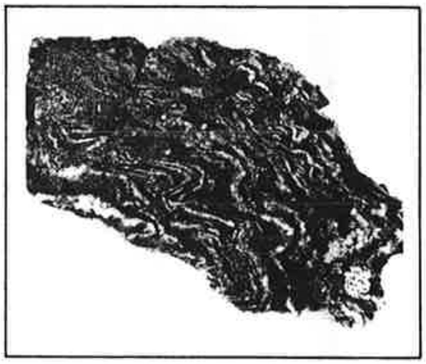


**Photo 3. Blueschist-grade metachert from the Little Harbor area. Rock is approximately one foot long.**

**Table 1. Characteristics of the Catalina Schist on Santa Catalina Island. Compiled from Platt (1975 and 1976) and Sorensen (1984a).**

| METAMORPHIC GRADE<br>TEMPERATURE & PRESSURE | TEXTURE | LITHOLOGIES (Temperature- and pressure-diagnostic minerals in parentheses) | INFERRED PARENT ROCKS |
|---|---|---|---|
| Blueschist<br>300° C<br>9 kb | Melange with blocks of various lithologies in a fine-grained schistose matrix; primary textures are preserved in individual blocks | Metagraywacke (lawsonite) | Graywacke (75%) |
| | | Metachert | Chert |
| | | Schist and phyllite (glaucophane, lawsonite) | Well-bedded basaltic sand and conglomerate |
| | | Greenstone (omphacite, lawsonite) | Diabase, flow breccia, pillow lava |
| | | Eclogite blocks | Basalt |
| Greenschist<br>450° C<br>7-10 kb | Pervasive schistosity; primary textures largely destroyed; contains garnet-amphibolite blocks | Mafic schist (clinozoisite, epidote, ± glaucophane & crossite) | Basalt (50%) |
| | | Gray schist (albite ± almandine garnet and biotite) | Graywacke (40%) |
| | | FE- & Mn-rich quartz schist (± crossite & glaucophane) | Chert (10%) |
| Amphibolite<br>580-620° C<br>8.5-12.5 kb | Coarse-grained metamorphic texture; no primary textures preserved; contains serpentinite masses and chlorite/actinolite/talc melange and tectonic blocks of various lithologies | Green hornblende schist (zoisite) | Mafic igneous rock (dominant lithology) |
| | | Semipelitic schist (garnet, biotite, muscovite, kyanite, zoisite) | Mudrock (volumetrically minor) |
| | | Garnet quartzite | Chert (minor) |
| | | Serpentinite, chlorite/actinolite/talc melange, & tectonic blocks of various lithologies | Hanging-wall peridotite with tectonically incorporated basalt and metasediment from the subducting oceanic plate |

The Greenschist-Blueschist thrust is more obscure and complex than the Ollas thrust. It is a zone that is "locally up to 200 m thick, filled with tectonic blocks of amphibolite-facies rocks and serpentinite in a matrix of talc-chlorite-actinolite schist" (Platt, 1975, p. 1338). This is the same lithologic assemblage that forms the serpentinite portion of the amphibolite unit in the vicinity of the airport.

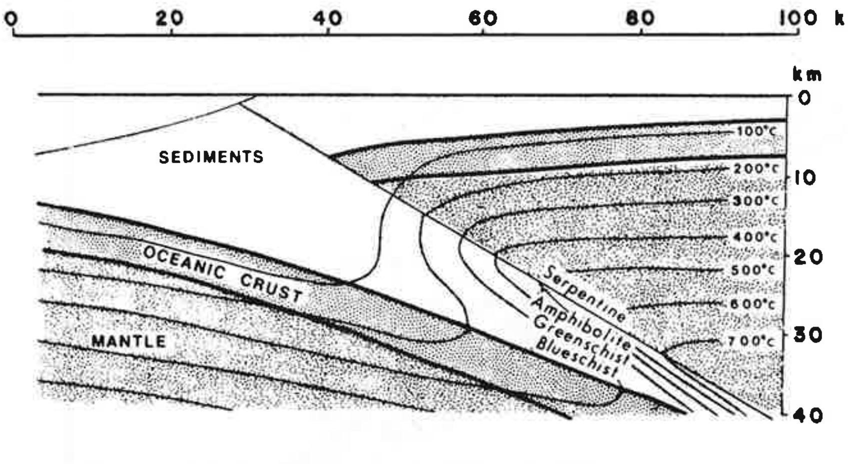
### Newly Formed Subduction Complex

If the three metamorphic facies of the Catalina Schist represent separate tectonic units that formed as parts of a single, high-pressure metamorphic complex with an inverted thermal gradient, then they probably formed in a subduction zone with an overthrusting heat source (Platt, 1976) (Figure 2a). The inverted thermal gradient (see isotherms in Figure 2a) develops as the cold slab of oceanic crust slides beneath the hot, mantle peridotite of the subduction zone's hanging wall.

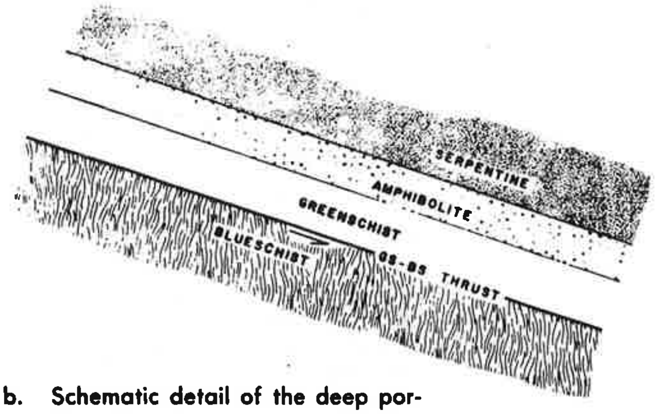
Several lines of evidence suggest that the subduction zone in which these rocks were metamorphosed was newly formed. The first is the inferred inverted thermal gradient. This phenomenon only exists during the early stages of subduction (Platt, 1975). As a subduction zone matures, insulating material accretes to the cooling hanging wall, and the inverted thermal gradient disappears. Another reason to infer a nascent subduction zone is the parent-rock composition of the three units. The amphibolite unit is mostly derived from mafic igneous rocks and lacks any graywacke-like protolith (Sorensen, 1984a, b). Graywacke, which comprises about 40 percent of the greenschist and 75 percent of the blueschist (Table 1) (Sorensen, 1984a, b), becomes an increasingly important component in each successively lower unit. Graywacke is the most common trench-fill sediment and would be expected to increase in importance as a subduction zone develops.

Detailed petrologic studies of eclogite (garnet + clinopyroxene) blocks within the Catalina amphibolite unit further support the interpretation of a newly formed subduction zone (Sorensen, 1984a, b). The eclogite blocks are interpreted to represent metamorphosed tholeiitic basalt that was transported to a depth of 35-40 km (pressure of 12 kb). The mineralogy of these blocks indicates a high temperature/pressure ratio that is diagnostic of the early stages of subduction. Many of these blocks were tectonically incorporated into the peridotite of the hanging wall of the subduction zone (Photo 4).

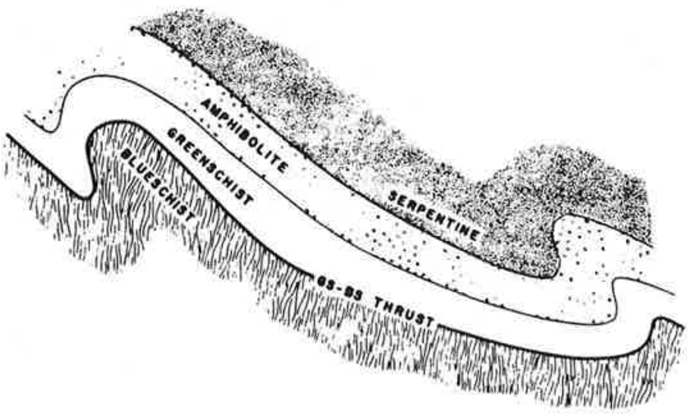
**Figure 2.** Structural scenario for the structural relationships observed in the Catalina Schist, central Santa Catalina Island. *Adapted from Platt, 1975.*



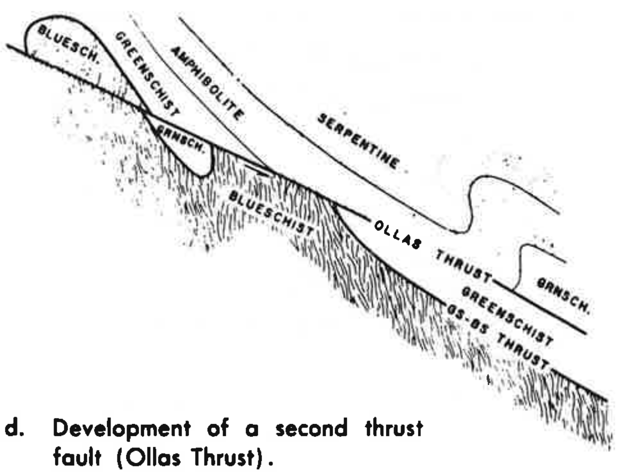
a. Idealized section through a recently initiated subduction zone, showing approximate distribution of isotherms and regions where amphibolite, greenschist and blueschist would form.



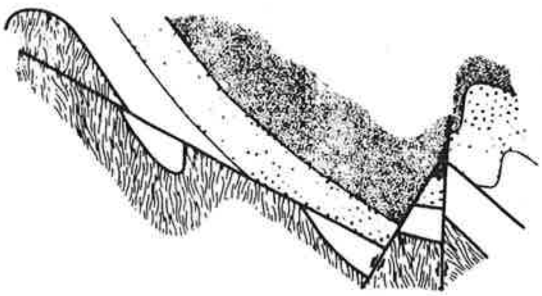
b. Schematic detail of the deep portion of a subduction zone showing a metamorphic zoning and the development of a thrust fault between the greenschist and blueschist.



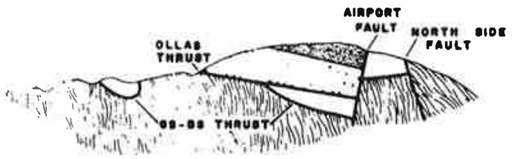
c. Folding of GS-BS Thrust and metamorphic zones.



d. Development of a second thrust fault (Ollas Thrust).



e. Normal faulting (Airport Fault and North Side Fault) caused by extension in Late Tertiary time.



f. Tilting and erosion to form structure Section A-A' of Figure 1.

For these reasons, it appears that the Catalina Schist on Santa Catalina Island represents the initiation of Mesozoic subduction in what is now the inner continental borderland.

### A Structural Scenario

Figure 2b schematically portrays the zoned metamorphic complex after it became welded to the peridotite of the hanging wall. The formation of the Greenschist-Blueschist thrust was caused by continued underthrusting beneath the higher-temperature metamorphic zones. Platt (1975) estimated a minimum displacement of 9 km for the Greenschist-Blueschist thrust. The distinctly different temperatures of formation on opposite sides of this fault indicate that faulting was postmetamorphic. Tectonic blocks of serpentinite and amphibolite within the Greenschist-Blueschist fault zone may be the result of an older thrust (not shown in Figure 2) (Platt, 1975).

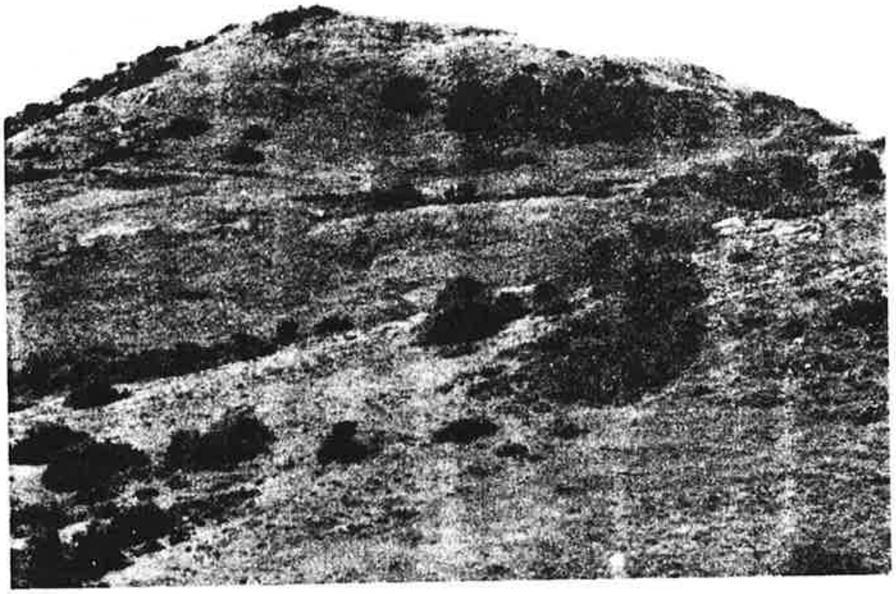


Photo 4. Serpentinite exposures northwest of the airport. The hill is capped by an eclogite that probably represents tholeiitic basalt subducted to a depth of 35-40 km and tectonically incorporated into the peridotite (now serpentinite) of the subduction zone's hanging wall.

Additional postmetamorphic underthrusting resulted in a variety of ductile and brittle responses, including folding of the entire zoned complex (Figure 2c) and displacement along the Ollas thrust (Figure 2d). Tertiary(?) normal faulting (Figure 2e), tilting, uplift, and erosion (Figure 2f) complete the scenario. Metamorphic overprinting within the Catalina blueschist facies rocks suggests that they formed at deeper structural levels (higher pressures) than did the other two units (Sorensen, 1984a and b). The blueschists, therefore, may have had a different history of uplift.

## EARLY TERTIARY: STABLE FOREARC BASIN

### Cretaceous (?) and Lower Tertiary Sedimentary Rocks

At East End Quarry, located at the eastern tip of the island (Photo 5), three sedimentary units are exposed (Vedder and others, 1979). The sediments were intruded by Miocene dacitic and gabbroic dikes and sills, which greatly obscure the sedimentary record. The upper part of this poorly preserved section is a Miocene breccia which some workers have assigned to the San Onofre Breccia (*Tsob*, Figure 1). Two pre-middle Miocene units occur below the Miocene breccia, neither of which has been named or studied in detail, although thin section descriptions are provided by Vedder and others (1979, Table 1).

The lower of the two pre-middle Miocene units is composed of interbedded siltstone, quartzofeldspathic sandstone, and conglomerate. Lithic fragments are of granitic, volcanic, and metamorphic origin, and they do not include detritus derived from the Catalina Schist. The age of these presumably marine sediments is not precisely known, but they resemble Upper Cretaceous sequences in the Santa Ana and Santa Monica mountains. The siltstones in this lower unit contain burrows that are similar to those that occur in Lower Cretaceous through Eocene strata elsewhere in southern California (Vedder and others, 1979).

Overlying these marine sediments is a sequence of nonmarine redbeds consisting of sandstone, pebble-cobble conglomerate, and minor mudstone. As with the underlying marine rocks, these were not derived from the Catalina Schist. These pre-middle Miocene redbeds may be correlative with the nonmarine upper Eocene to lower Miocene Sespe Formation of the Los Angeles Basin (Vedder and others, 1979).

### Paleogene Paleogeography

An Eocene unit that is conspicuously absent on Santa Catalina is the Poway Conglomerate. This distinctive conglomerate, which consists of 80-90 percent porphyritic rhyolite and 10-20 percent quartzite clasts, occurs in the San Diego area and on San Miguel, San Nicolas, and Santa Rosa islands (Howell and others, 1974). This distribution, along with paleocurrent data, led Howell and others (1974) to reconstruct the middle Eocene paleogeography shown in Figure 3 (see also Howell and Link, 1979, Figure 3B). The general absence of Eocene sediments from the inner borderland (Crouch, 1979) supports the interpretation that this area was a submarine high during the Early Tertiary. The recently discovered nonmarine sediments at East End Quarry, described above, are compatible with the reconstruction shown in Figure 3, and they document a previously unknown episode of subaerial deposition in the inner borderland during the Early Tertiary.

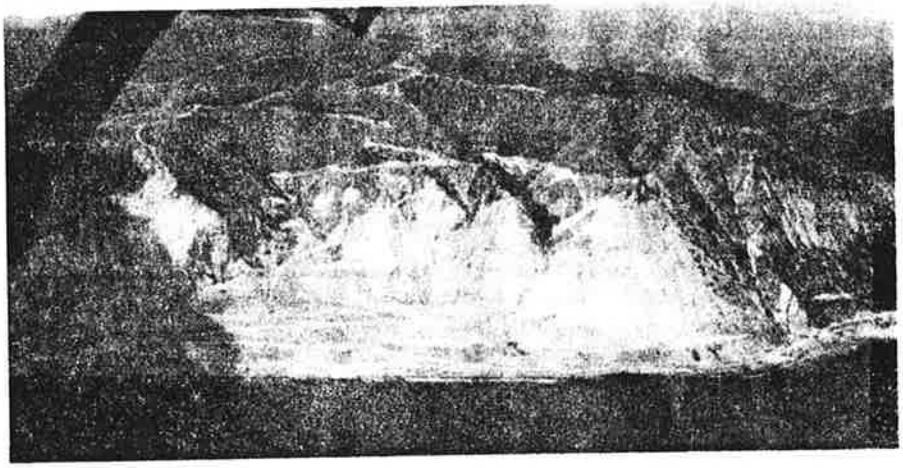


Photo 5. East End Quarry at the southeastern end of Santa Catalina Island.

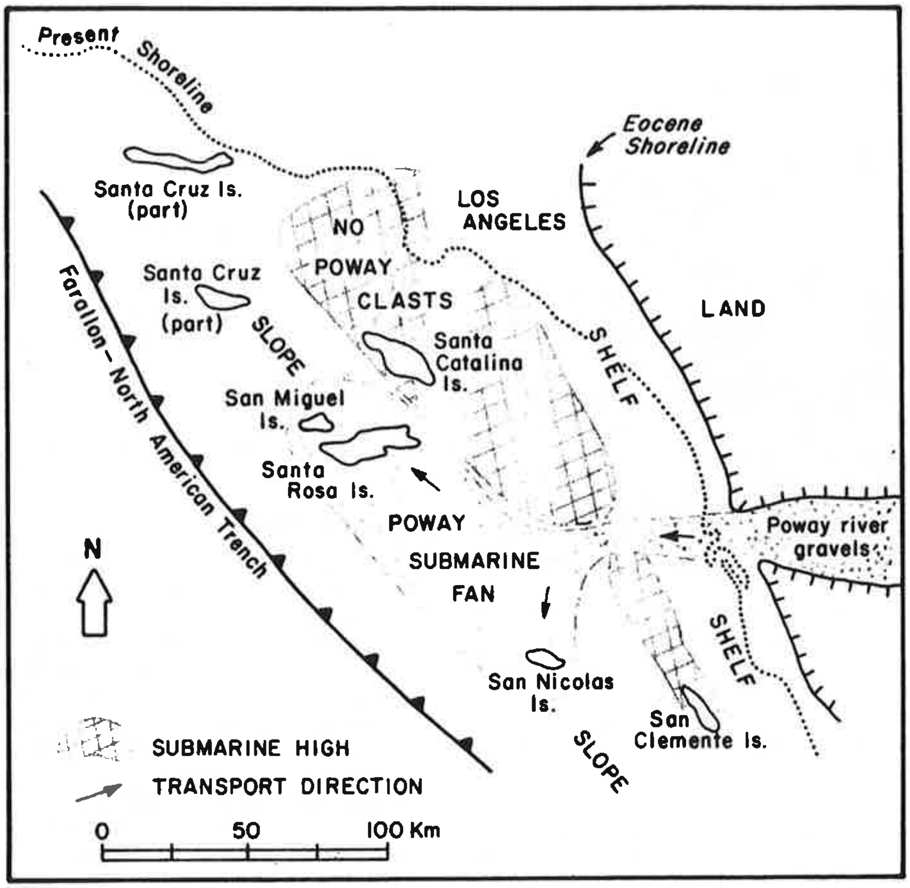


**Figure 3. Reconstructed Eocene paleogeography of the continental borderland.** ***After Howell and others, 1974.***

The striking feature of Figure 3, in addition to the absence of known Eocene deposits in the inner borderland, is the location of San Nicolas, Santa Rosa, San Miguel, and Santa Cruz islands. In order to account for the distribution of Poway Conglomerate clasts (and age-equivalent turbidite sands on Santa Cruz Island), these islands are all placed southeast of their present positions. The borderland Poway Conglomerate occurrences are seen as remnants of a bathyal submarine fan whose submarine canyon breached the high-standing inner borderland. Howell and others (1974) used this palinspastic reconstruction to argue for 120-160 km of right-lateral, strike-slip faulting in the borderland. Their putative East Santa Cruz Basin fault system runs just to the west of Santa Catalina Island, along the edge of the cross-hatched region on Figure 3.

Figure 3 is just one of several proposed Eocene reconstructions for the borderland. Crouch (1979), for example, imagined several hundred km of post-Eocene, strike-slip faulting, rather than the 120-160 km of Howell and others (1974). Yeats and others (1974), using a slightly different definition of the Poway Conglomerate, hypothesized several "small Poway-bearing microplates" undergoing east-west spreading, with no northwest-southeast, strike-slip faulting at all. In spite of such varying models concerning the precise Early Tertiary positions of portions of the present-day borderland, there is general agreement that during the Early Tertiary this region was a broad, stable, forearc basin above the eastward subducting Farallon plate (Howell and others, 1980) (Figure 4).

## EARLY AND MIDDLE MIOCENE: VOLCANIC ARCHIPELAGO

### The Catalina Pluton: A Lower Miocene Quartz Diorite Stock

The oldest-known Miocene rocks on Santa Catalina are quartz diorites of the Catalina pluton, which has yielded a K-Ar date of 19 million years (early Miocene) (Forman, 1970). This pluton is exposed throughout most of the southeastern portion of the island (Figure 1). Although highly variable, most samples are porphyritic, with plagioclase (altered to kaolin and calcite) and hornblende (altered to chlorite) phenocrysts in a medium- to fine-grained groundmass (Bailey, 1967). In the southeastern exposures of the pluton, the intrusion consists of swarms of subparallel, nearly vertical dikes of variable color, composition, and texture (Vedder and others, 1979).

Even though the main intrusion evidently occurred in the early Miocene, Vedder and others (1979) suggested that this was the beginning of a 4-5 million-year-long episode of diorite-dacite intrusions that persisted into middle Miocene. They interpreted the 14-15 million-year-old dacites of the Fishermans Cove area to be late-phase extrusions from the Catalina pluton. This interpretation of long-lasting, dacite-diorite igneous activity is supported by the presence of dacite clasts in the middle(?) Miocene San Onofre Breccia at East End Quarry. This

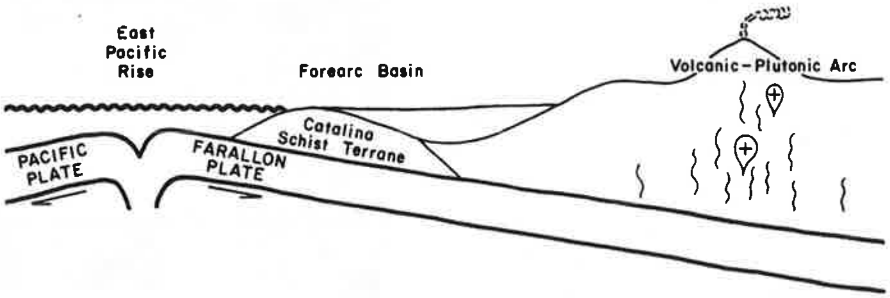


**Figure 4. Schematic cross section through southern California and Nevada during the Early Tertiary.** ***After Dott and Batten, 1981, Figure 16.24.***

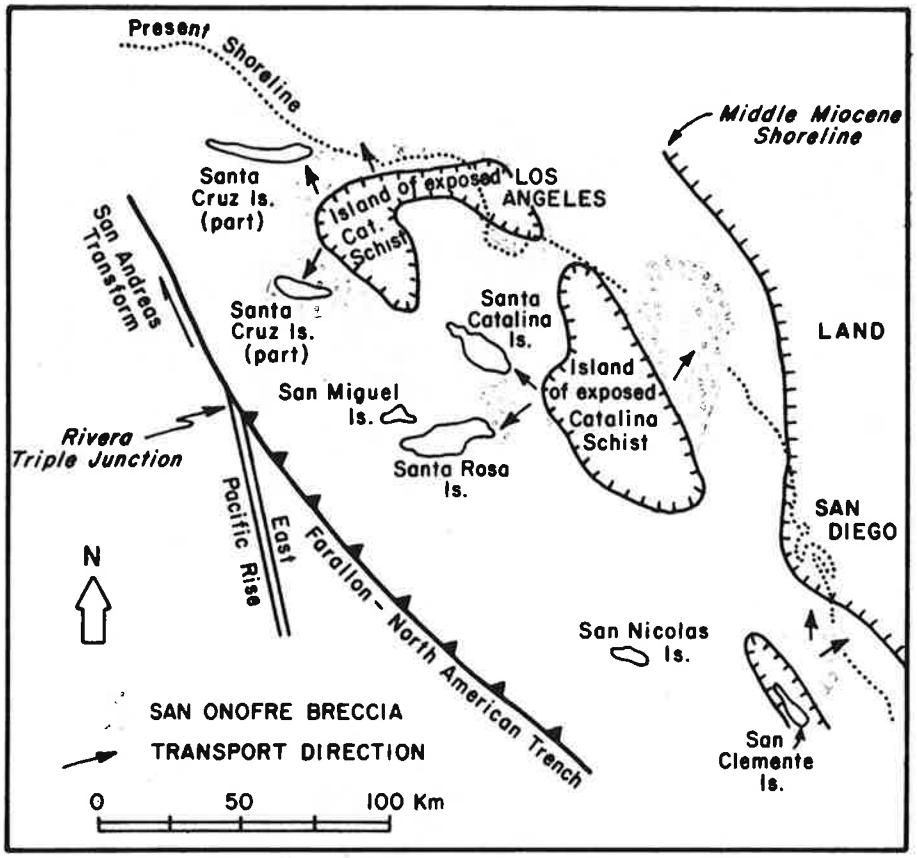


**Figure 5. Reconstructed paleogeography of the borderland during deposition of the San Onofre Breccia (early and middle Miocene). Locations of islands are shown for reference; they were not islands at the time. *After Howell and others, 1974.***

breccia was intruded by dacite dikes with modal composition similar to that of the clasts (Vedder and others, 1979). Probably early Miocene dacite was eroded, redeposited, and then intruded in the middle Miocene by dacite from the same magmatic source.

## San Onofre Breccia

The San Onofre Breccia is a lower and middle Miocene unit that crops out in coastal areas of southern California and northwestern Baja California, as well as on several islands in the California borderland. It characteristically contains a high percentage of glaucophane schist clasts, which are thought to be derived from the Catalina Schist terrane (Woodford, 1925; Howell and others, 1974; Stuart, 1979). Although the Catalina Schist is presently exposed above sea level only on Santa Catalina and on the Palos Verdes Peninsula, the widespread distribution of San Onofre Breccia indicates that in the early and middle Miocene, Catalina Schist exposures were much more extensive (Figure 5).

Two areas on Santa Catalina contain schist breccias that are probably part of the same erosional episode as the San Onofre Breccia. The first is at East End Quarry at the eastern end of the island (mapped as Tsob on Figure 1). Boulders of this breccia are used as riprap in Avalon Harbor, where they may easily be examined (Photo 6). Although this breccia has been correlated with the San Onofre Breccia by Woodford (1925) and Stuart (1979), the characteristic glaucophane schist clasts are conspicuously rare. The clast composition in the breccia at East End Quarry includes quartz schist, amphibolite, actinolite schist, tremolite(?) schist, talc schist, saussuritized gabbro, vein quartz, aphanitic to porphyritic siliceous metavolcanic rocks, porphyritic basalt, and feldspathic sandstone (Vedder and others, 1979).

Because of the presence of large (up to 30 cm), angular, disoriented clasts and the occurrence of some lenses that are nearly monolithologic, a nearby source area is suggested. Additional evidence that this breccia was locally derived is the presence of dacite clasts, which become increasingly abundant upsection.

Because of the absence of glaucophane clasts and the presence of volcanic clasts in the East End Quarry breccia, Vedder and others (1979) suggested that assigning these rocks to the San Onofre Breccia obscures important lithologic differences; they more closely resemble portions of the Blanca Formation on Santa Cruz Island.

The second occurrence of schist breccia on Santa Catalina is in the Fishermans Cove area (immediately to the right of the word "Isthmus" on Figure 1). As at East End Quarry, the volcanic clasts become more abundant upsection (Figure 6). Unlike the East End Quarry breccia, however, schist clasts include abundant blueschists, as well as greenschists. These breccias were, in places, deposited directly on a middle Miocene dacite dome and on exposed Catalina Schist. They are, in turn, overlain by middle Miocene andesites. There is little doubt that they were locally derived in a high-relief setting (Vedder and others, 1979).

The Fishermans Cove breccias, being sandwiched between lower middle Miocene volcanic rocks, are, therefore, lower middle (Luisian) Miocene in age. The

**Photo 6. Boulders of San Onofre Breccia from East End Quarry used as riprap in Avalon Harbor.**

East End Quarry breccia cannot be dated as precisely. It contains probable lower Miocene dacite clasts and could be slightly older than the breccias of the Fishermans Cove area.

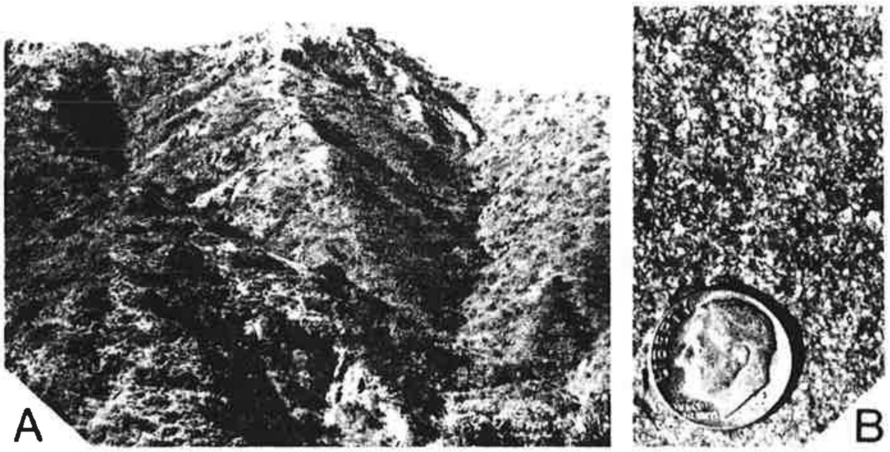


Photo 7. A. Whitleys Peak, about 3 miles northwest of Avalon (looking north). The area of the upper landslide scarp is a blocky dacite flow, the remainder of photo is andesite and basaltic andesite (Wood, 1981). B. Hand specimen of basaltic andesite from Whitleys Peak area. Phenocrysts are plagioclase (labradorite) and a three-pyroxene assemblage of hypersthene, augite, and pigeonite (Wood, 1981).

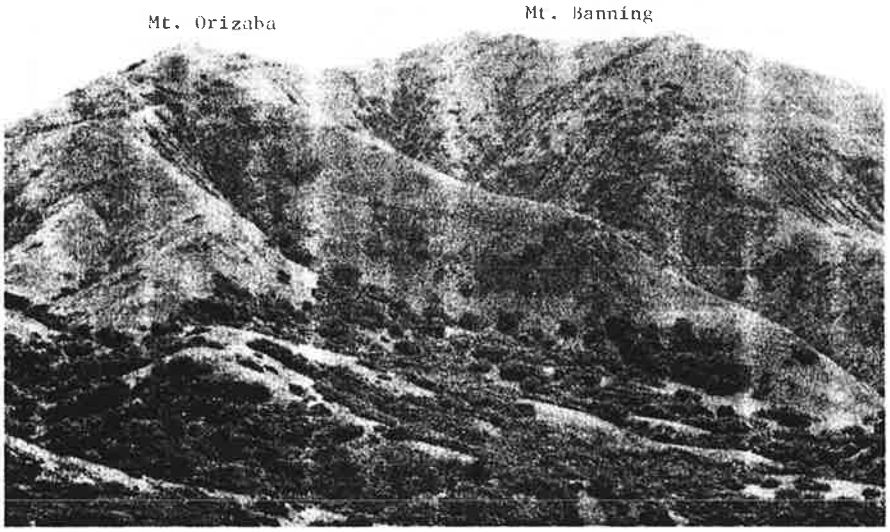


Photo 8. View southwest from airport toward Mt. Orizaba - Mt. Banning area. Most of this area is underlain by andesitic and dacitic flows. The right-hand knob of Mt. Banning is composed of fossiliferous, calcareous, volcaniclastic sandstone, which is late middle or late Miocene (Mohnian) in age and indicates a rocky, inner sublittoral environment (Vedder and others, 1979).

### Middle Miocene Paleogeography

The San Onofre Breccia has been interpreted to be a series of alluvial fan and coarse-grained marine deposits that were eroded off of a Catalina Schist source area (Stuart, 1979). Present distribution and inferred transport direction of San Onofre Breccia on the southern California mainland is shown on Figure 5, along with the reconstructed occurrence of San Onofre Breccia in the borderland; however, the middle Miocene positions of present-day San Nicolas, Santa Rosa, San Miguel, and southwestern Santa Cruz islands are in dispute (as discussed in the section on Paleogene Paleogeography). Much of the inner borderland, with its Catalina Schist basement, was exposed during the deposition of the San Onofre Breccia (Stuart, 1979, Figure 15). The absence of glaucophane schist clasts in the East End Quarry breccia is puzzling, but presumably indicates that a portion of this exposed metamorphic source area was lacking in blueschist-facies rock.

### Middle Miocene Volcanic and Sedimentary Rocks

Volcanic rocks, chiefly of andesitic and dacitic composition, cover approximately one-quarter of Santa Catalina Island (Figure 1, Photos 7 and 8). These rocks are the remnants of a small volcanic archipelago (Vedder and others, 1979). The exposures east of Isthmus Cove have been studied by Vedder and others (1979), and those in the central part of the island by Wood (1981). The volcanic rocks on Santa Catalina are probably all middle Miocene in age (K-Ar dates are 12-15 m.y.), apparently representing a 3-4 million-year-long episode of volcanism.

The volcanic stratigraphy for the island is shown in Figure 6. Formation names have not been assigned, and individual eruptive units have not been mapped. In the Fishermans Cove area (east of Isthmus Cove) schist-dacite breccia lenses (described above) directly overlie a 14-15 million-year-old dacite dome. Another dacite dome about two miles south-southeast of the airport forms Black Jack Peak (Wood, 1981). Both dacite domes have brecciated carapaces and are interpreted to be surface effusions of viscous lava (Vedder and others, 1979; Wood, 1981). The remainder of the volcanic sequence, although dominated by andesite and basaltic andesite flows and flow breccias, also includes minor olivine basalt and rhyolite (Figure 1). The volcanic section in the central part of the island is over 400 meters thick (Wood, 1981).

A variety of middle Miocene sedimentary rocks occur within the volcanic sequence (Figure 6). In the Fishermans Cove area, these are volcaniclastic breccias (Photo 9), tuffaceous shales and claystones that locally occur in beds up to 20 meters thick. Fossils in the shales and

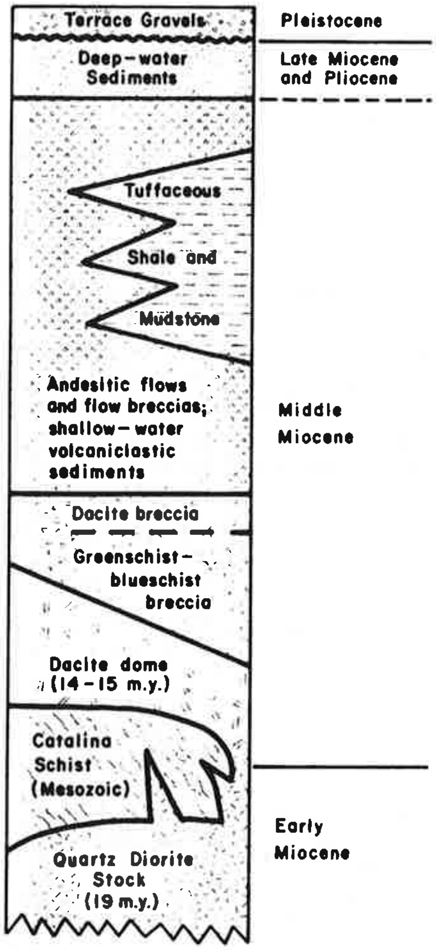


**Figure 6. Generalized stratigraphic column of the Cenozoic rocks exposed in the central part of Santa Catalina Island. No scale implied and highly schematic.** ***After Howell and others, 1979, Figure 2.***

claystones include diatoms, foraminifera, smelt and herring scales, and a variety of molluscs. All of these fossils are middle Miocene, which corroborates the middle Miocene K-Ar dates of the volcanic rocks. Furthermore, the fossils indicate sublittoral (continental shelf) environments with water depths no greater than 200 meters and in some cases probably shallower than 30 meters (Vedder and others, 1979).

Coarser-grained, volcaniclastic sediments occur in association with andesites on Mt. Banning (Photo 8) and in the region southeast of Little Harbor (Figure 1). One outcrop 2 miles south-southwest of Mt. Banning is limy sandstone (shown as "limestone" on Figure 1). These coarser sediments are locally very fossiliferous, with sea urchin spines, ostracodes, foraminifera, bryozoa, barnacles, brachiopods, snails, and clams (Vedder and others, 1979). These fossils are also middle Miocene in age and indicate shallow, inner-shelf, locally rocky environments.

**Photo 9. Middle Miocene volcaniclastic sediments in Fishermans Cove.**

### Middle Miocene Plate Tectonic Setting

The middle Miocene volcanic rocks on Santa Catalina are typical of those in the southern California borderland. Nearly continuous submarine volcanic exposures occur all the way to Patton Ridge near the western edge of the borderland. There have been two plate tectonic interpretations of these rocks (Vedder and others, 1981; Wood, 1981). The first is that they represent an island-arc sequence produced by partial melting of the subducting Farallon plate. Alternatively, it has been suggested that this middle Miocene volcanic pulse was caused by partial melting of the upper mantle related to the proximity of the East Pacific Rise (Hawkins, 1970).

The volcanic rocks in the central part of the island cannot be unambiguously classified as either calc-alkalic or tholeiitic (Wood, 1981). The basalts and basaltic andesites have tholeiitic characteristics, while the andesites and dacites indicate a calc-alkalic series. This ambiguity is most compatible with an island arc interpretation because island arcs often begin erupting tholeiitic magma and conclude with calc-alkalic magma. This phenomenon is not typical of mid-ocean ridge volcanism. Also the abundance of hypersthene andesite, which makes up about 35 percent of the volcanic rocks, is very typical of island arcs. However, other petrographic and geochemical aspects (low $K_2O$ and moderately high $TiO_2$ compositions) are not typical of arc settings and lend support to the interpretation that these rocks were derived from undifferentiated mantle material.

Based on the geology and tectonics of the entire southern California borderland there are three arguments against the island-arc interpretation (Vedder and others, 1981). The first is that middle-Miocene, intermediate-composition volcanic rocks are too widespread in the borderland to have been derived from a subduction zone. Secondly, some of these rocks (on Patton Ridge) are within 20 km of the ancestral Farallon-North American trench—anomalously close for an island arc. And last, the youngest oceanic crust off the southern California borderland is approximately 17 million years old (uppermost lower Miocene). Thus, it appears that most of the volcanic rocks in the southern California borderland formed after sea-floor spreading and subduction off the coast of southern California had already ceased. In rejecting the island-arc interpretation, Vedder and others (1981) invoked the proximity of the ancestral East Pacific Rise as the volcanic source.

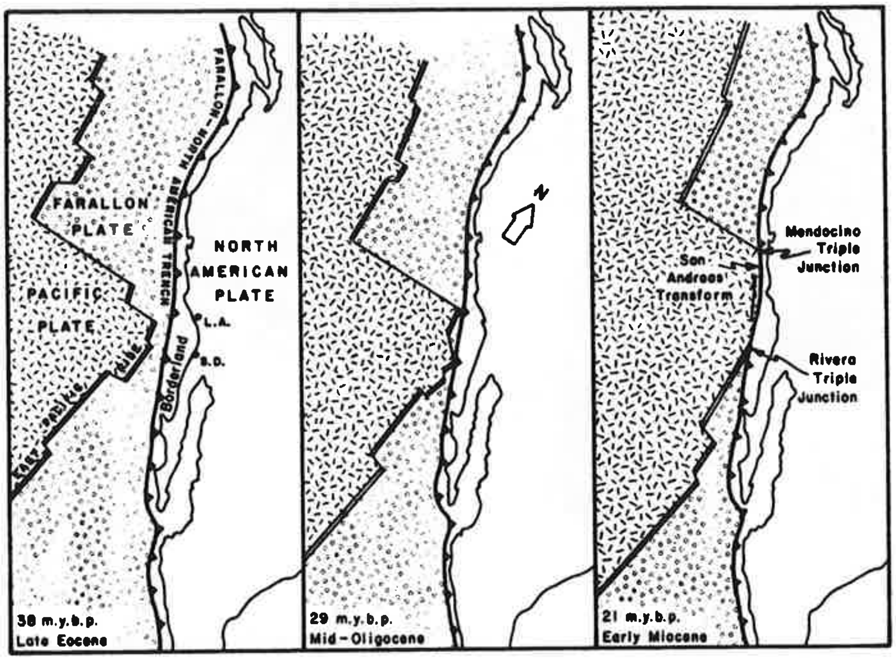


**Figure 7.** Plate interactions for three Tertiary intervals. Schematic diagram showing the relative positions of the North American, Farallon, and Pacific plates from late Eocene to early Miocene time. The first-contact between the East Pacific Rise and the Farallon-North American trench was made about 29 million years ago (mid-Oligocene), and it occurred off the coast of southern California (Dickinson, 1979). It was at this point that subduction began to cease and the San Andreas transform (the offshore precursor of the San Andreas fault) was created. This transform lengthened southward and northward, at the expense of the East Pacific Rise, as the North American plate drifted westward *After Crouch, 1981.*

The first contact between the East Pacific Rise and the Farallon-North American trench occurred about 29 million years ago (mid-Oligocene) off the coast of southern California (Figure 7) (Dickinson, 1979). At this point subduction ceased and the San Andreas transform (the offshore precursor of the San Andreas fault) was created. This transform lengthened southward and northward, at the expense of the East Pacific Rise, as the North American plate drifted westward. Because of the oblique angle between the East Pacific Rise and the North American plate, the Rivera triple junction traveled southward through late Oligocene and Miocene time presumably accompanied by a wave of volcanism (Figure 7).

If the borderland's mid-Miocene volcanic archipelago was produced by the proximity of the East Pacific Rise then these rocks were erupted at a more southerly latitude than present-day Santa Catalina Island. When the San Andreas transform shifted inland to form the San Andreas fault, in the late Miocene or early Pliocene, the Santa Catalina block was transferred from the North American to the Pacific plate and began a northward journey. During the following 5-6 million years, up to the present time, this block has probably traveled approximately 250 km northward as part of the Pacific plate (Wood, 1981). In the middle Miocene, therefore, it was located at the latitude of northern Baja California, where the southward migrating Rivera triple junction did not arrive until about 15 million years ago.

## LATE MIOCENE TO THE PRESENT: VERTICAL AND WRENCH-FAULT TECTONICS OF THE BORDERLAND

### Upper Miocene and Pliocene Sediments

Beneath the Quaternary terrace deposits on a ridge about 1 km southeast of Little Harbor are thin beds of tuffaceous sandstone and siltstone that have yielded upper Miocene and Pliocene fossils. Benthic foraminifers in the upper Miocene beds indicate a water depth of approximately 500-1,000 meters (mid-bathyal), and the Pliocene benthic foraminifers indicate lower bathyal to abyssal depths (1,000 m to more than 2,500 m) (Vedder and others, 1979).

These fossils document a late Miocene-Pliocene subsidence of the Santa Catalina structural block from near sea level to a depth of at least 1,000 meters, and perhaps twice that depth. This episode of subsidence was followed by one of uplift and subaerial exposure in the Pliocene or Pleistocene. During this Late Tertiary cycle of roller-coaster tectonics, the Santa Catalina block experienced vertical elevation changes at rates as high as one meter per thousand years (Howell and others, 1980).

### Wrench Faulting and Clockwise Rotation

The initiation of vertical tectonics throughout the borderland in Late Tertiary time signaled the transition from a stable forearc basin to an unstable continental borderland. With the origin of the San Andreas transform (Figure 7), the western edge of the North American plate began to experience wrench faulting. A series of northwest-southeast-trending dextral faults divided the region into structural blocks. Northwestward lateral translation of these fault blocks within the incipient borderland resulted in the formation of lens-shaped ridges and rhomboid-shaped "pull-apart" basins (Howell and others, 1980).

As a result of the Pacific-North American right-lateral shear couple, many structural blocks within the borderland and western Transverse Ranges have undergone clockwise rotations of about 70° to 80° (Luyendyk and others, 1980). Santa Catalina has apparently rotated at least 60°. These rotations probably began in mid-Oligocene time, with the initiation of the San Andreas transform, and ended in late Miocene time, when right-lateral faulting was largely transferred onshore to the present San Andreas fault (Luyendyk and others, 1980; Dickinson, 1981).

### Pleistocene Terraces

Santa Catalina lies midway between two areas in which Pleistocene terraces are spectacularly developed—the Palos Verdes Peninsula to the north and San Clemente Island to the south. In contrast to these neighboring borderland ridge crests, Santa Catalina is conspicuously impoverished with regard to marine terraces. This phenomenon was first noticed by Lawson (1893) who interpreted it as a "diastrophic anomaly," in which "Santa Catalina has not been subjected to the uplift which has affected the two prominent insular masses (San Clemente Island and the Palos Verdes Peninsula)." In a geology textbook published in 1931, the San Clemente-Santa Catalina-Palos Verdes distribution of marine terraces was described as follows: "Perhaps the most striking example of simultaneous opposite movements observable in neighboring portions of the earth's crust is furnished by the coast of southern California....Midway between...two rising sections of the crust, and less than twenty-five miles distant from either, is the island of Santa Catalina, which has been sinking beneath the waves, and apparently at a similarly rapid rate (Hobbs, 1931, p. 256-257)."

The diastrophic anomaly explanation was ultimately debunked by Smith (1933), who had published the first geologic map of Santa Catalina (Smith, 1897). He described a variety of geomorphic features on Santa Catalina—benches on ridges ("notched salients"), leveled summits, and an elevated embayment at Little Harbor—that together record successive episodes of marine planation and pulses of uplift. Smith explained the relatively poor development of these features as a product of hard rocks and a mature pre-Pleistocene topography. He concluded that "instead of differentiation there has been a remarkable uniformity in the general later Pleistocene movements of all the southern California islands and the neighboring mainland coast as well (Smith, 1933, p. 136)." Although there is no question about the general truth of Smith's interpretations, a recent review of the occurrences and elevations of emergent terraces in the southern California borderland clearly demonstrates that the rates of uplift have not been uniform (Vedder and Howell, 1980, Figure 9).

The most noteworthy Pleistocene feature preserved on Santa Catalina is the Little Harbor embayment. All of the ridges within a radius of about a mile from Little Harbor have flat crests. These ridges typically have a 200-300 foot cliff at their seaward ends, and they gradually rise to an elevation of about 700 feet over a distance of about 1 ¼ miles. One of these ridges, southwest of Little Harbor, is capped by terrace deposits (sandstone and conglomerate) up to a few meters thick (Figure 1). These flat-crested ridges define the former floor of the Little Harbor embayment (Smith, 1933).

Photo 10. Dissected Pleistocene constructional terrace beneath a golf course in Avalon Canyon.

Dissected terrace deposits also occur southwest of Avalon in Avalon Canyon (Figure 1, Photo 10). This is a constructional terrace which probably formed when Avalon Canyon was flooded by the sea, before the island was tectonically lifted to its present level. The precise timing and magnitude of Quaternary uplift on Santa Catalina are not known and may be impossible to determine. There is no evidence that the Santa Cruz - Catalina Ridge was ever emergent enough for Santa Catalina to be subaerially connected to any other currently existing island or to the mainland.

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# PETROLOGY OF BASEMENT ROCKS
# OF THE CALIFORNIA CONTINENTAL BORDERLAND AND THE LOS ANGELES BASIN

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abstracted for this guidebook by Patricia G. Mason

Basement rocks of the California Continental Borderland and the Los Angeles Basin are: 1) the Catalina Schist, a relatively high-pressure, low-to-moderate temperature metamorphic terrane, and 2) island arc rocks metamorphosed at relatively low pressure and low-to-moderate temperature, which include the Willows Plutonic Complex, the Santa Cruz Island Schist, and the Santa Monica Formation.

## CATALINA SCHIST

The Catalina Schist terrane consists of three tectonic units. A tectonic melange unit, characterized by blueschist facies metamorphism, is overlain by a thrust sheet of greenschist facies rocks, this sheet is overlain by an amphibolite facies unit. Previous workers (Platt, 1975; Earle, 1980; Elliot, 1976) consider the terrane as a thermal aureole developed in the downgoing slab beneath a hot, peridotitic hanging wall during initial subduction.

### AMPHIBOLITE FACIES

The upper amphibolite unit consists of a structurally coherent 300 meter thick slab of gneissic plagioclase and zoisite amphibolite, of gabbroic composition, overlain by serpentinite which contains tectonic inclusions of amphibolite facies metabasites. Present as inclusions within the serpentinite and as interlayers in the amphibolite are rare garnet-bearing quartzites and semi-pelitic schists. Chemistry and mineral assemblages indicate relatively high-pressure and moderately high-temperature metamorphism of gabbro and basalt lithology with minor cherty and argillaceous sediments.

Localities: (Sorenson, 1984)

(1) Airport-Empire Landing Road. At the locality listed "Stop 2" in Figure 1, one of the larger tectonic-block inclusions within the serpentinite and chlorite/actinolite/talc melange of the Catalina amphibolite unit is exposed. It is gneissic, with layering dominated by garnet + clinopyroxene and garnet + hornblende, although nearly monomineralic garnet layers also occur. The garnets may be rimmed by plagioclase ($An_{20-30}$). Rosettes of anthophyllite + tremolite ± talc ± chlorite may be found in the float surrounding the block. This block does not appear to have a rind.

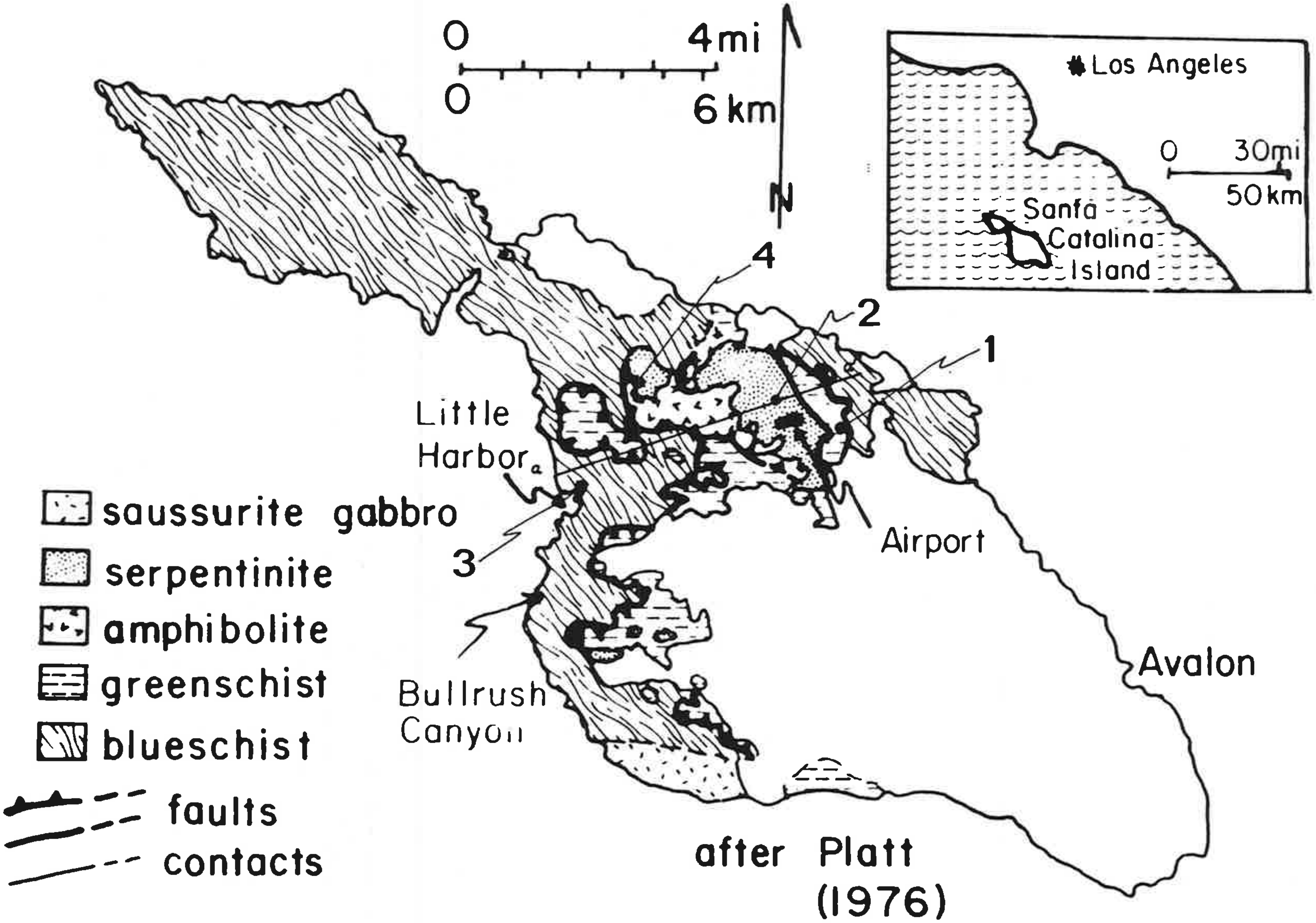

Fig. 1. Basement geology of Santa Catalina Island after J. Platt (1976). Line a-a' in Figure I-1 is the approximate line of section for Figure 2. Locations of field trip stops 1-4 are shown by their appropriate number.

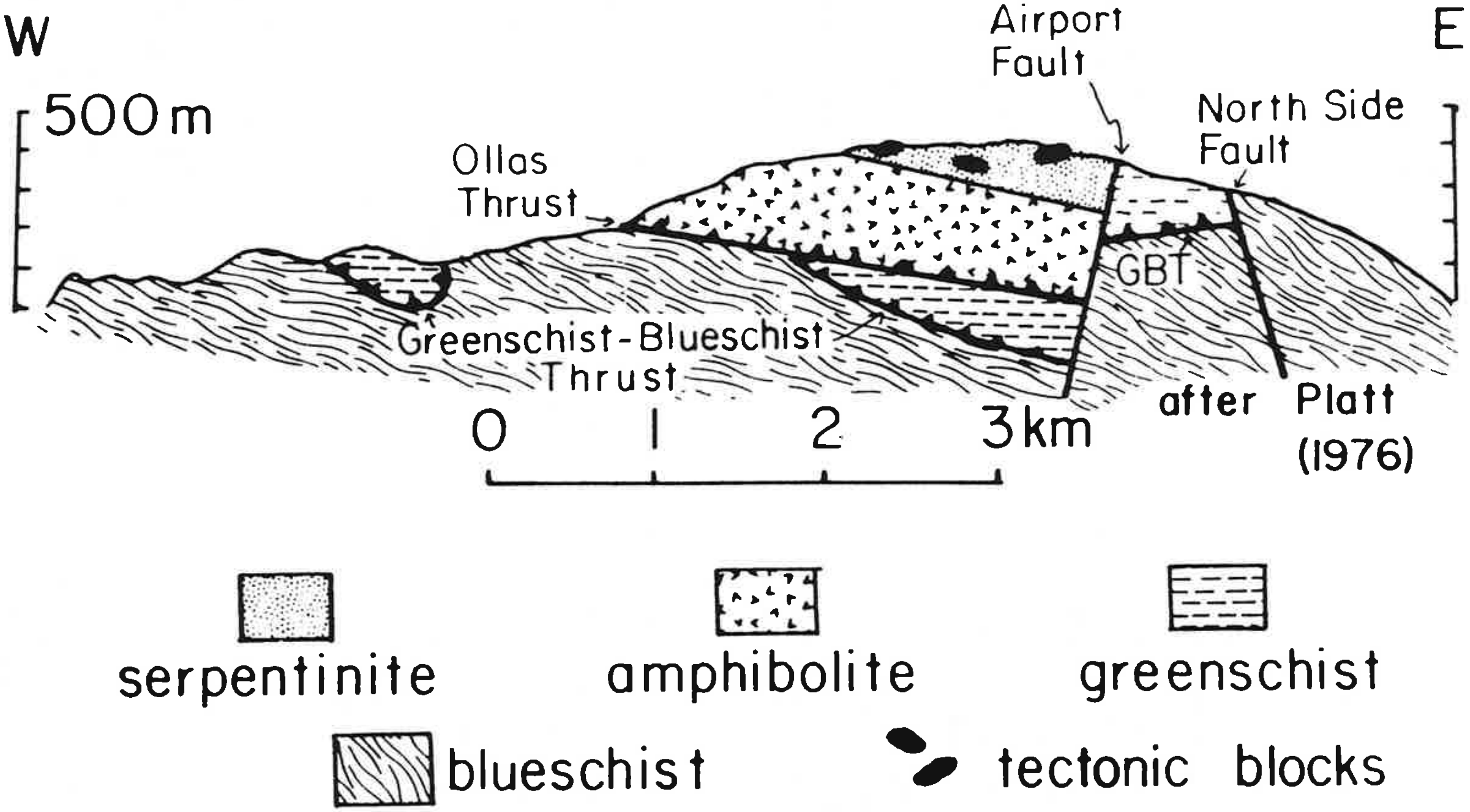

Fig. 2. Diagrammatic cross section of Santa Catalina Island after J. Platt (1976). Line a-a' in Figure I-1 is the approximate line of section.

(2) Little Harbor - Two Harbors road spur to Buffalo Corral Reservoir. At the locality listed "Stop 4" in Figure 1, mafic amphibolite of the Catalina amphibolite unit is overlain by sepentinite. The latter has a basite texture with crysotile veinlets. This unit overlies the blueschist and greenschist units exposed at Little Harbor and in the two forks of Little Springs Canyons.

During recrystallization, the rocks were associated with periodotite and subjected to metasomatism (at temperatures greater than 600 degrees Centigrade and pressure of 8-12 kilobars) which produced reaction zones or rinds surrounding the metabasites.

Detailed petrologic and geochemical study of two rind-bearing blocks within this unit was performed to determine the nature of these metasomatic effects. The extent and scale of chemical exchange between the Catalina metabsite blocks and the enclosing periodotite is much larger than that demonstrated in previous studies on sea-floor metamorphic effects on basalt and on metasomatism accompanying rodingitization. (Humphris & Thompson, 1978; Evans et al, 1981)

The lower amphibolite unit was found to be similar to fresh and altered gabbros from ophiolite suites and metamorphosed mid-Atlantic ridge gabbros in major element and REE geochemistry. Retrograde metamorphism is possibly manifested in amphibole core-to-rim zonation from horblendic to actinolitic compositions. Within the minor semipelitic schist, mineral chemistry suggests an overprint of high-fluid-pressure, lower-temperature metamorphism over the high-pressure and moderate-temperature recrystallization.

The upper unit was described by Platt (1976) as serpentinite with tectonic blocks and by Bailey (1941) as clorite/actinotlite/talc melange, serpentine, and brown hornblende. The blocks range in size from less than 0.5m to about 100 m in diameter, and vary in composition; generally tholeiitic and bearing garnet + hornblende ± clinopyroxene ± plagioclase or zoisite mineral assemblages. Some eclogitic tectonic blocks have schisctose rinds, predominantly of amphibole and layer silicates. Rinds were formed by hydration of the eclogitic mineral assemblages of the block accompanied by element exchange with surrounding ultramfic rocks, both at high temperatures and pressures,(greater than 600 degrees C and 8-12 kb) and at relatively lower pressure and temperature conditions.

The principal major-element metasomatic effect at high temperatures is Mg addition to the block, transition zone, and rind system; at relatively lower temperatures, addition of Ca is the predominant effect. Many minor and trace elements appear to have been mobile during rind formation. Rare earth elements were released from blocks, probably by breakdown of sphene during reactions linked to rind formation, and were deposited in the transition zones and rinds. Ni and Cr may have been derived from olivine, orthopyroxene, and/or clinopyroxene in peridotite. Some of the "coherent" behavior of the incompatible elements in the reaction of peridotite and basalt at elevated pressures and temperatures may result from metasomatism between basalt and peridotite.

Structurally below the amphibolite facies rocks are the Catalina greenschist facies and the underlying blueschist facies melange.

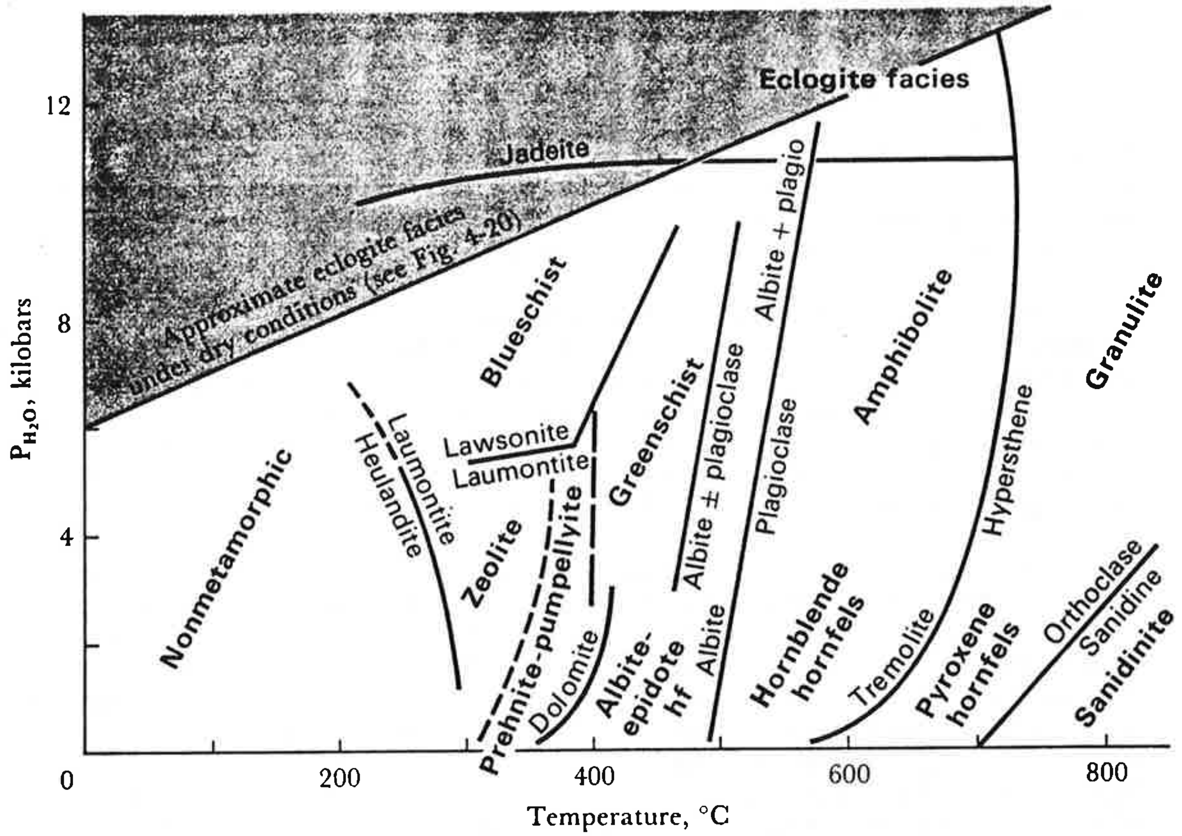

Figure 3: Metamorphic facies boundaries largely as defined by Fyfe, Turner, and Verhoogan (1958). Metamorphic facies are designated by boldface type.

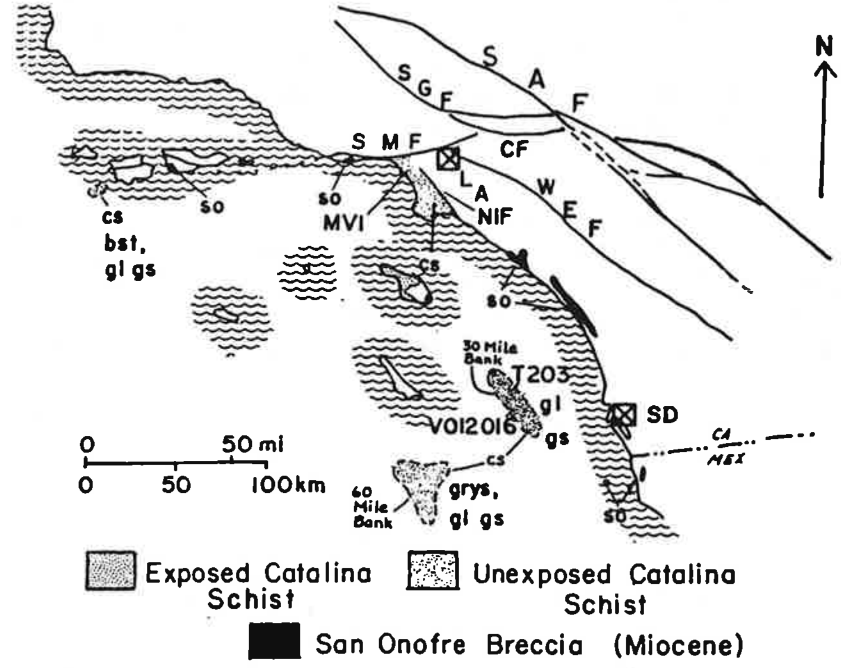

Figure 4: Generalized locations of Catalina Schist materials.

## BLUESCHIST FACIES

Blueschist facies metamorphism arises under the relatively high pressures and low temperatures of subduction zones as indicated by various petrologic and geophysical evidence (Ernst, 1977 a, b; Cloos, 1981; Carlson & Rosenfeld, 1981; Earle, 1980). Subduction zone metamorphic belts, however, also contain greenschist facies rocks, with the crossitic blue amphiboles known to be characteristic of pressure and temperature conditions transitional to those of the blueschist facies.

The predecessor rocks of these two Catalina units (blueschist and greenschist) are similar, and consist of basaltic igneous rocks, clastic, argillaceous, and cherty sediments. Seventy-five percent of the blueschist unit is metagraywacke, whereas only about forty percent of the greenschist unit consists of metagraywacke (Platt, 1976). In the blueschist rocks, relict protolithic features are retained; the greenschist rocks are thoroughly recrystallized and lack relict textures.

The blueschist melange contains metagraywacke, metashale, metaconglomerate, greenstone, quartz schist, blueschist, and eclogite blocks within a fine-grained, schistose matrix. The chemical and mineralogic characteristics of the matrix indicates that it is recrystallized from a mixture of ultramafic and clay-rich quartzose detritus. The characteristic blueschist glaucophane-lawsonite assemblage is developed in nearly all bulk compositions, including that of the matrix. This ubiquitous glaucophane + lawsonite, with a paucity of chlorite in the graywackes suggest relatively higher temperatures and/or lower pressures of recrystallization for Catalina graywackes than for the Franciscan Complex metagraywackes of Panoche and Pacheco Passes.

The best exposures of blueschist melange crop out in the canyons and cliffs of west-central Catalina Island. Figure 3 shows an exposure of melange in the spillway of the Lower Buffalo Corral reservoir, about 2 miles northeast of Little Harbor . Meter-sized blocks of blueschist, metagraywacke, and quartz schist are surrounded by schistose melange matrix, and have the boudinage features and "tadpole" shapes characteristic of melange blocks in the Coast Ranges Franciscan Complex (Cloos, 1981.)

Locality: Little Harbor seacliff. At the locality listed as "Stop 3" in Figure 1, a blueschist facies metaconglomerate block, greenstone block, and metagraywacke block are exposed in the north seacliff of Little Harbor. These can be viewed from the spit across the harbor. The melange matrix is black to gray in color, and is predominantly serpentine and chlorite.

## GREENSCHIST FACIES

The greenschist unit consists of metabasite schist (about 50%), graywacke-composition grayschist (about 40%), and quartz schist(about 10%). All three occur interlayered in a single outcrop on a scale of a centimeter to several meters. It has a limited areal extent and relative thinness (approx. 200 meters) on Santa Catalina Island, but is significant on a regional scale.

Locality: Avalon-Airport roadcut. At the locality shown as "Stop 1" in Figure 1, the Catalina greenschist unit is exposed along the Avalon-Airport road in a fault block bounded by the Airport Fault on the west, and the North Side Fault on the east (Figures 1 & 2). The roadcuts reveal grayschists, quartz schists, and mafic schists. The mafic schists are glaucophanic greenschists. The sodic amphibole crossite occurs as inclusions in epidote or albite porphyroblasts, but only rarely (if at all) in the matrix of these schists. Most matrix amphiboles are sodic actinolites or barroisites. Crossite evidently crystallized before the relatively more calcic amphiboles.

The metabasites contain mineral assemblages which indicate that structurally low glaucophanic greenschists intially recrystallized at pressure and temperature conditions approaching those of the blueschist facies, whereas structurally high metabasites originally were epidote amphibolites. Both are overprinted by relatively high-pressure greenschist facies minerals.

Platt (1976) noted the slight differences in metamorphic mineralogies in the greenschist unit. In exposures of the greenschist unit between the North Side Fault and the Airport fault blue amphibole is abundant near the lower contact with the blueschist unit, whereas biotite and garnet occur near the upper contact with the amphibolite unit. These relationships are seen at other exposures of these contacts.

A comparative study of bulk-rock geochemical data suggests that the majority of metabasites from both tectonic units are derived from ocean-floor tholeiites. Mineral chemistry of white micas indicate that the blueschist unit crystallized under relatively higher pressure and/or lower temperature conditions than did the greenschist unit. The mineral chemistry of amphiboles from greenschist unit metabasites reveals an overprint of glaucophanic greenschist crossites, barroisites, and sodic actinolites and epidote amphibolite hornblendes by rims which are relatively actinolitic in composition. Glaucophanic greenschist crossites probably formed at somewhat higher temperatures than the crossites from lawsonite + glaucophane-bearing metabasites of the blueschist unit.

## ISLAND ARC-LIKE ROCKS FROM THE CALIFORNIA CONTINENTAL BORDERLAND AND LOS ANGELES BASIN

Jurassic igneous and metamorphic rocks in part underlie the southwestern Transverse Ranges region, which includes Santa Cruz Island, the Santa Monica Mountains, and the northern-northeastern margins of the Los Angeles Basin. Among these are the Willows Plutonic Complex, the altered saussurite gabbros, the metavolcanic Santa Cruz Island Schist, and the metasedimentary Santa Monica Formation. Saussurite gabbros occur in other locations in the California Continental Borderland, notably on Santa

Catalina Island and in the subsurface of the western Los Angeles Basin. Amphibolite and greenschist facies metabasites form the basement at the northeastern margin of the Los Angeles Basin; Santa Monica Formation pelitic schist and calc-alkaline oligoclase-epidote amphibolite are juxtaposed in an oil well in the northern L.A. Basin. The petrographic and petrologic similarity of the greenschist facies metavolcanics of the Puente Hills basement and the Santa Cruz Island Schist are evidence for a relationship between these basement rocks.

Whole-rock major, minor, and trace element compositions indicate that the plutonic and metavolcanic rocks are calc-alkaline and may be parts of an island-arc complex. Saussurite gabbros of the Willows Plutonic Complex are chemically and petrologically indistinguishable from other saussurite gabbro occurrences in the California Continental Borderland.

No igneous or detrital plagioclase and pyroxene are preseved in the metavolcanics or metasediments, but relict igneous amphiboles from the metamorphic rocks resemble the amphiboles from the plutonic suite, and could have been dereived from a source like the Willows Plutonic Complex. Metamorphic chlorite, ubiquitous in the metasediments and metabasites, varies in composition, parallel with host-rock bulk chemistry. White micas from metasediments are richer in paragonite and poorer in celadonite than those in metabasites. The celadonite in metabasite micas indicates recrystallization temperatures of less than 400 deg. C at pressures less than 5 kb; the paragonite in metasediment micas suggests upper garnet to lower staurolite zone metamorphism, which is consistent with estimates of metamorphic temperatures between 400 and 550 deg. C based on the pelitic mineral assemblages. These temperatures and pressures result from a contact aureole, spatially related to pre-Late Cretaceous silicic plutons, superimposed upon regional greenschist facies (chlorite to biotite zones) metamorphism.

According to the petrologic and geochemical data, the Willows Plutonic Complex, the Santa Cruz Island Schist, and the Santa Monica Formation are probably fragments of one or more island arc-like igneous and sedimentary terranes of calc-alkaline geochemistry and relatively low-pressure greenschist-to amphibolite facies metamorphism. The greenschist and amphibolite facies rocks from the northern Los Angeles Basin also resemble island arc rocks. The saussurite gabbros of the California Continental Borderland are indistinguishable from altered portions of the calc-alkaline Willows Plutonic Complex.

The general similarities in age, petrology, and chemistry of prebatholithic suites of the Sierran and Peninsular Ranges suggest that the Santa Cruz Island Schist and Santa Monica Formation have a comparable origin. The relationship of these entities with the relatively high-pressure metamorphic terranes of the Franciscan Complex, Pelona Schist, and Catalina Schist remains problematical.

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# Mining History, Santa Catalina Island, Los Angeles County, California

GEOLOGY AND MINERAL WEALTH OF THE CALIFORNIA TRANSVERSE RANGES © South Coast Geological Society 1982

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## INTRODUCTION

Lying just 26 miles southwest of Los Angeles, across the San Pedro Basin, Santa Catalina Island's arid, rocky terrain has contributed importantly to the economy of Southern California. Mineral production consists of over 20 million tons of road metal, large stone and concrete aggregates, plus a modest yield of metallic elements from argentiferous zinc-lead deposits.

E. H. Bailey's (1941) field work enabled him to classify the basement complex as Catalina Schist of Mesozoic age related to the Franciscan Formation of central California (Fig. 1). This assembledge of bluish and greenish gray foliated chlorite and glaucophane schists which cover approximately half the surface are unique to Catalina Island (Platt 1976). The greater part of the Los Angeles Basin southwest of the Newport-Inglewood fault is underlain by Catalina Schist under a cover of 4,000-14,000 feet of younger sediments. A small outcrop of schist is found on the peak of the Palos Verdes Hills and enormous boulders of Catalina Schist occur along the coast comprising the San Onofre Breccia.

Although lead miners had dabbled in island mines for sixty years, the first really significant effort to mine base metals dates from acquisition of the island by William Wrigley, Jr. in 1919. Wrigley's promising little metal mining empire was, however, wiped out by a world wide metal market collapse a few years later.

## INDIAN PERIOD

Catalina Island served Southern California's Indian population as a principal center for steatite, a fine grained talc used for boiling pots. Steatite is soft enough to be easily carved yet is highly resistant to heat and cracking when placed directly into a fire. The mineral was quarried from easily accessible surface exposures, sometimes only necessitating removal of the soil cover. Generally, the mining operations were small scale cobble hammer and stone chisel individual efforts. It appears that it was generally the male tribal members who intermittently gathered steatite as the need arose. Most of the final working did not take place at the quarries, rather the trimmed, roughed-out block was transported to a workshop elsewhere for finishing (Wallace, 1971).

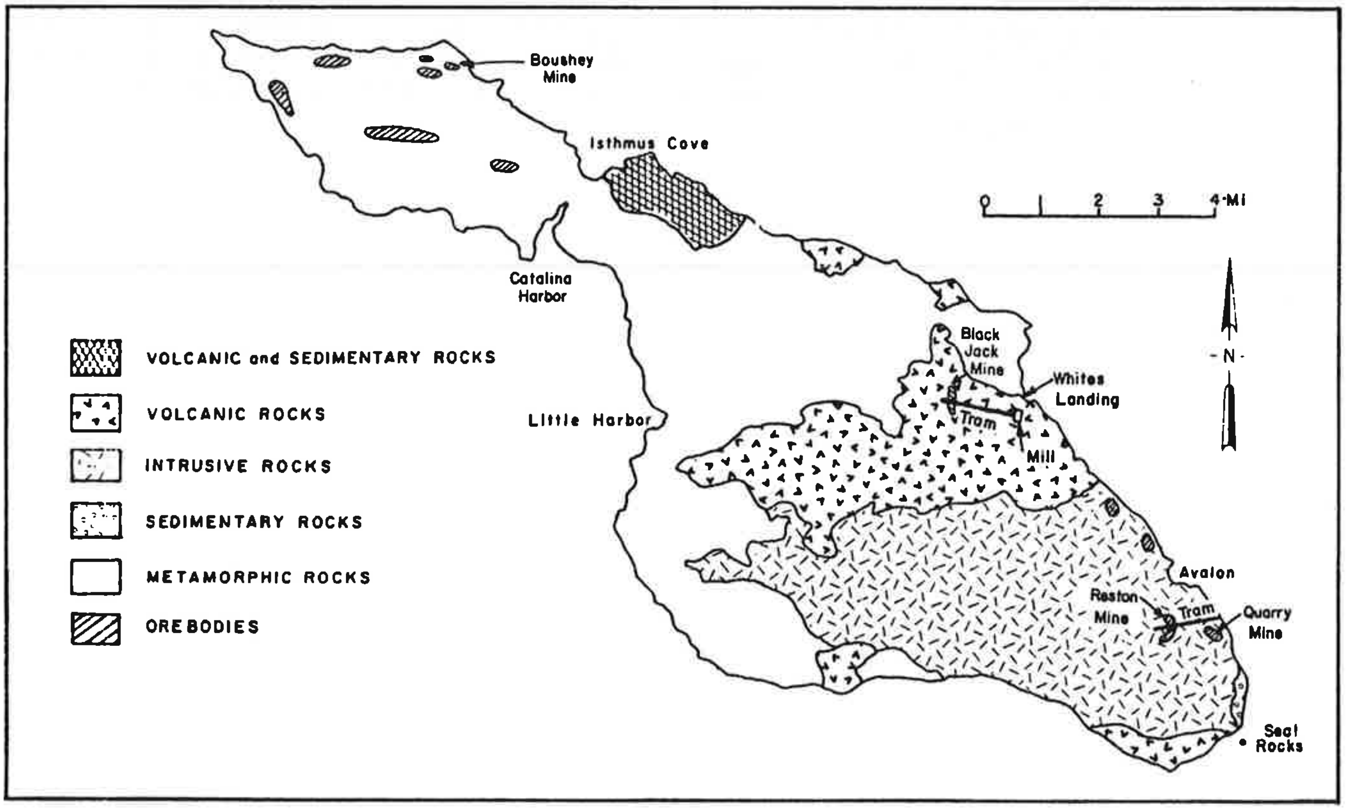

Figure 1. Generalized Geologic Map of Santa Catalina Island. Modified from Bailey, 1941; Platt, 1976; and Vedder and others, 1979.

## CIVIL WAR PERIOD

The earliest recorded mention of Catalina mineralization was by a Spaniard who reported in 1792 that some Indians at San Gabriel Mission carried galena pebble amulets imported from Catalina. Seventy years later, in the spring of 1863, a naturalist appeared in the Channel Islands collecting zoological specimens, possibly the first scientifically trained observer to land on Catalina. He confirmed the existence of argentiferous galena deposits near the Isthmus, which he understood had been known for several years. Men who were there when he visited, formed the San Pedro Mining District on April 20, 1863. They registered their Articles of Incorporation and regulations with the Los Angeles County Recorder immediately thereafter.

Hardly had this happened when Civil War alarmists clamored for Union scrutiny of mysterious activities rumored to be taking place on Catalina Island. Pacific Headquarters Command in San Francisco ordered an inquiry. Major Henry Hancock was detached from Camp Drum to make a surprise trip from the mainland. On November 26, 1863 in his report to his commander he said that of one hundred men on the island, one half were miners. He viewed their diggings and wondered whether the prospectors held " . . . highly exalted views of the vastness of its mineral wealth . . . although he was convinced that the workings showed . . . flattering promise . . . " (Figure 2).

The military then ordered all civilians to leave so that they could establish an army camp there. A Los Angeles newspaper seized upon this decision to proclaim preparedness against possible involvement by Southern sympathizers. The army was silent. Captain Benjamin R. West, Lieutenant Patrick Munday and an assistant surgeon embarked on the schooner *San Diego* with eighty enlisted men and landed at the Isthmus on New Year's Day, 1864. West's superior followed a few days later to inspect the new post. He also made a long report to Headquarters saying, "Quite recently mines of galena have been discovered, and about seventy miners are working at prospecting in various places. Copper, silver, and gold are said to exist in connection, but lead is the predominating metal throughout and has been found in many places. Whether the ledges will pay to work is being solved. . . . No great pecuniary loss can accrue to the miners by removal. They have been to no expense as yet for machinery or tools and have been but a short time here. No other work than prospecting has been done."

One historian wrote an unsubstantiated account of the Union Navy having seized " . . . a strange assortment labelled gold mining equipment." Recently a scholar of impeccable qualifications has discredited the part the Navy may have played after reviewing the entire Pacific Squadron documentation of the era. However, though it may have never fallen into military custody, such equipment was available and could, perhaps have found its way to the Isthmus.

Though the Army still did not divulge its reasons it continued occupation of the Isthmus while countering disputes whether miners should be allowed to remain on the island. Those with incorporated companies were permitted to stay. On September 14, 1864, without explanation, the garrison departed for the mainland.

While no doubt exists of the high grade of Catalina ore shipments, a San Francisco newspaper reporter described a shipment of 400 sacks of Gem of the Ocean mine ore and 46 more from the Santa Catalina Consolidated Mining Company piled on the Commercial Street wharf. The *Louis Perez* of Pierce's Southern Packet Line had brought it north. He wrote "This ore is a beautiful argentiferous galena, containing 70 to 80 percent lead, and $30 to $86 per ton in silver, little or no vein rock intermixed."

MAP OF ISTHMUS
from *The War of the Rebellion*

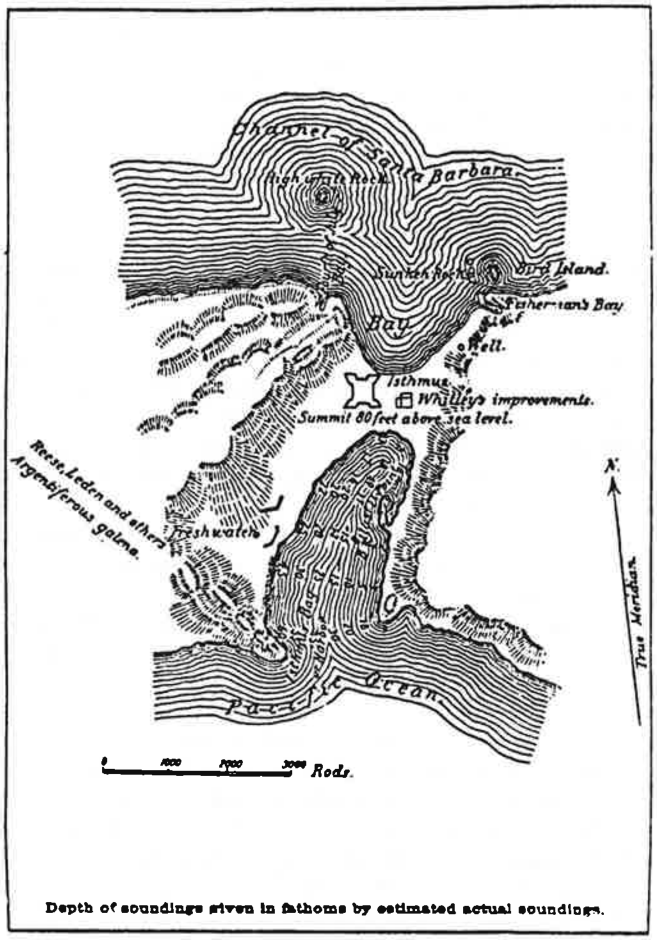

Figure 2. A Map which accompanied the report of the Major Henry Hancock, Fourth Regiment Infantry California Volunteers, November 26, 1863, to Lieutenant Colonel James F. Curtis, commanding Southern District of California. Santa Catalina Isthmus area. Scale should read yards, not rods. From: The War of the Rebellion, U. S. Secretary of War, Government Printing Office, Washington, D.C., 1897.

Doubtless it was destined to the Thomas H. Selby smelting works at Black Point on North Beach. Selby, a successful hardware merchant for many years prior to this, imported lead sheet, pipe, traps, shot and other supplies for sale. He built an enormous shot tower 180 feet high, 28 foot base, with cupola and seives on top, at Folsom and First Streets.

The reporter commented three months later, "The work of mining on Catalina is progressing rapidly. Paying ore is being taken out of the Yellow Jacket and Ne Plus Ultra in large quantities." He had earlier explained that the ore sacks weighed 170 pounds each and that, "This ore works without the slightest difficulty in a common smelting furnace, and we are assured that all that is now required to render the mines of Santa Catalina an immediate success is the erection of furnaces there, as there is already a large amount of second class ores out, which would pay well for working on the ground, and the amount which can be got out in future depends only on the amount of money forthcoming to pay expenses." Contemporary evidence proves that the mineralized zone ran behind Johnson's Landing and Cherry Valley to Arrow Point. The Army map, erroneously scaled in rods instead of yards, notes galena outcrops at the base of Mt. Torquemada marked " . . . Reese, Leden and others. . . . " Another map shows "Boushey's" and the stakers of the Monmouth claim said their site was " . . . near the Isthmus . . . the general course of the lead or vein runs northwest."

One of those who staked mining claims for himself and others was Stephen Boushey, who monumented and recorded the Small Hills mining claim. This came to be the best known claim on Santa Catalina because of frequent transfers of ownership, notably to James H. Ray, James Lick, Dr. C. M. Hitchcock and back to Boushey himself.

Boushey was back in 1867 because he bought the Small Hills mining claim for $7,000. He surfaced again in 1873 in Inyo County as a principal in the Cerro Gordo Water and Mining Company where he contracted to build a steam pumping plant and a ten-mile pipeline to introduce drinking water to Cerro Gordo from Miller Springs, ten miles away.

John Forster, John C. Downey and Max von Strobel optioned Santa Catalina Island in 1873 and promptly sent Strobel to London to negotiate a sale to British financiers who would exploit the mineral rights. He was successful in making definite arrangements but died unexpectedly of natural causes in his hotel room while awaiting signature of the papers. This deal, of course, fell through.

Another attempt to entice British financiers to exploit the metallic wealth of Catalina was sparked by sale of the Island to George Shatto in 1887. He actually entered into a firm agreement with the International Mining Syndicate to pay him $400,000 with $40,000 down, several payments beginning in six months and a balloon payment after three years. They predicated success upon using normally empty sailing vessels returning to England to carry Catalina lead ores as ballast.

The syndicate group quickly learned that mining in almost inaccessible wilderness was too expensive because they had to pick the eyes out of orebodies since only the highest grade ore would even pay its way out on muleback. Prospects were located in Grand and Silver Canyons across the mountains from Avalon, on Blackjack peak, and other places. There are still vestiges of a few of their diggings, including a 75-foot adit on a foot-wide vein and another 30-foot drive into a Silver Canyon hillside. Landslides may have obliterated others of their workings. At Blackjack a short tunnel pierced the overlying divide and from it a 33-foot-deep winze was sunk on ore. After disbursing $15,000 on an almost fruitless search, the Syndicate management opted to forfeit the down payment and bow out of the deal. The last known Catalina production during this era was shipment of some 30 tons of Isthmus ore to Selby, which reputedly brought $100 a ton in 1893.

## TWENTIETH CENTURY MINING BOOM

William Wrigley, Jr. changed the whole destiny of Santa Catalina beginning in 1919. He appointed D. M. Renton general manager and vice president of the Santa Catalina Island Company and delegated full responsibility and authority over all activities except spring training of Wrigley's Chicago Cubs baseball team. Renton was a builder with great capacity for infinite attention to detail. He knew nothing of mining when be began but was determined to learn. He soon discovered that tremendous strides in mineral industry technology had occurred since the small scale operations of the nineteenth century.

Use of electricity for motive power, compressed air equipment underground, and development of the selective flotation process of ore concentration were paramount. Add to this the use of aerial tramways for transportation of ore over rough and steep terrain and general mechanization of mining and milling operations. He organized a task force, bringing in experienced personnel who he supervised administratively while learning technology from them. It was apparent that he and they would have to sift the plethora of mining rumors and the multiplicity of unsubstantiated writing about actual and imagined Catalina mining.

## INVESTIGATION OF MYTHS AND LEGENDS

The most persistent rumor was an apochryphal account of a gold strike by one George C. Yount, a California pioneer, who arrived here in 1832 with William Wolfskill's party of hunters. Writer after writer, plagiarizing one another without acknowledgement, dated Yount's visit to the Catalina Isthmus in 1830 when he came across a gold-bearing vein visible only at low tide. The gold was identified by eye, of course. Yount was a hunter and ignored the find for decades, and then returned in an attempt to relocate the outcrop. He could never identify the place again.

All Renton needed to do was rediscover Yount's vein, if it ever existed. There was another discrepancy besides the wrong date, however, and Yount's own granddaughter pointed it out in her biography of her grandfather. She wrote, "From there he (Yount) went to the Island of San Clemente, accompanied by his friend Dr. Cooper, and his Kanaka (crew) servants. They camped on the beach . . . While on the east side of the Island they discovered at low tide a ledge rock extending into the water, from which they took samples, being sure it was gold . . . " San Clemente, hmm . . .

There is another name that figures in romantic tales of Catalina mining. Confusion in names obscures some facts but Renton could not ignore the endless legends. The name Stephen Boushey has been spelled Beauché, Boushay, Bouchette, among others. Santos Louis Bouchette was a Frenchman who arrived in California about 1828. He married and became famous for his small vineyard in the Pueblo of Los Angeles. He was survived by his widow who continued to reside in their home, after his death on October 23, 1847.

But in Catalina history this same Bouchette is credited with owning the Small Hills mining claim from which he was said to have produced ore assaying between $200 and $800 per ton, values mostly in silver and gold. It should be remembered that the claim was originally filed upon by Stephen Boushey on April 7, 1864. Nevertheless, Bouchette was supposed to have married a French dancer in Los Angeles, took her to Catalina which she abhorred and built her a magnificent house full of imported furniture. Allegedly, in 1876, he decided to take her away. He supposedly blasted the entrance to the mine to hide it forever, loaded a pile of "silver ore" aboard his small sailboat and started off with her toward the mainland. No mention is made of their ever reaching San Pedro but a rumor developed that they sold their "silver ore" in Baja California. The legendary Bouchette was never heard of again but the French wife later turned up in Paris.

Two of Renton's mining staff still live in Southern California. George H. Newman had rustled a job as a miner in the Blackjack. H. W. Soule, the Catalina Island Company's Avalon-based engineer discovered him underground and used to bring him to the surface to aid in mechanical design, underground surveying and geologic mapping. Renton was an advocate of what he considered thrifty management and used to point out Newman, saying to Soule, "Who is that fellow! Send him back to the mine." Soule, overworked and facing deadlines, used his most persuasive arguments to keep Newman, eventually getting his salary raised from the munificent sum of $4 to $5 per pay to this talented young mining geologist! The other staff member was T.A. DeVore, another technically trained engineer who worked at the Island Company's assay office.

Exploration and prospecting were energetically carried on, and the results recorded in a sample-assay book still in the files of the Santa Catalina Island Company (hereafter referred to as S.C.I.C.). The book shows who sampled what and when, describes the locality, gives assays and often the values calculated on current metal prices. One particularly important entry relates to Cherry Valley beyond the Isthmus where an old adit was cleared to permit resampling the remnants of ore exposed. "Cherry Valley," it said, "is situated at the west end of the island. Mining activities were commenced at Cherry Valley in August, 1923. Tunnel work was inaugurated on the left bank above the present Boy's Camp and assays showed from $9.18 average per ton to $33.19 av. per ton."

George Newman kindly searched his file for photographs and there found a copy of a 1927 blueprint showing a compass survey he had made of "Beauché Mine," showing the excavated drift and branch crosscut (Figure 3). The ruined, abandoned adit was completely inaccessible in 1890 when mining engineer E. B. Preston visited it on behalf of the California State Mineralogist. From old-time residents Preston learned that the workings were orignally quite extensive—some 800 feet of adits. What he was unable to do single-handed, Renton's crew of miners did with the aid of better equipment. The sample-assay book said that part of the nearly vertical vein was found 325 feet inside the portal, an oreshoot 25 feet long, " . . . pure ore about six inches wide, assayed $141.33 per ton averge." It was indeed high grade ore, one sample containing 77.7% lead with 15.2 ounces of silver, another with 64.6% lead and 15.8 ounces of silver per ton, but not a trace of gold. Metal prices were not much different in Boushey's time. Bouchette-Boushey could only have loaded his "silver-ore" aboard the little sailboat as ballast.

Renton himself did some of the prospecting. Down Silver and Grand Canyons he logged samples from the old Syndicate workings, one with 40.0 ounces of silver; another assayed 22.0 ounces of silver with 13.8% lead. Values at the latest metal market quotations were given: $48 and $43 per ton.

Only one attempt was made to work a copper deposit. The site was 350 feet above sea level on the desert-like hillside behind the old St. Catherine's Hotel. Nothing came of it although two adits were driven, one 50 feet below the other, both 120 feet long. O. A. Anderson, the assayer, considered the $750 " . . . well spent prospecting for Catalina copper."

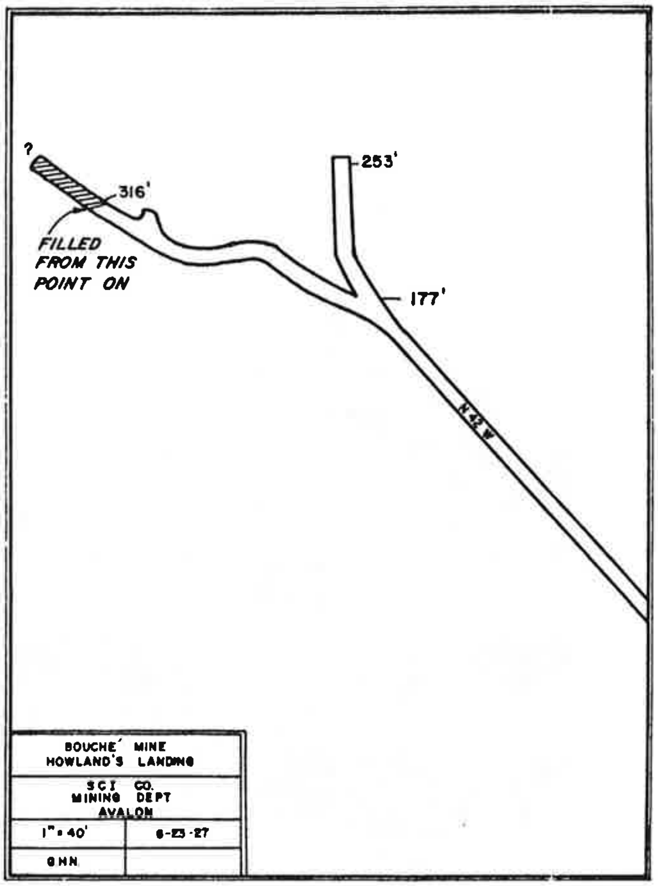

Figure 3. Blueprint of 1927 Brunton compass survey of Boushey Mine at Cherry Valley, Santa Catalina Island by George H. Newman.

The major mining activity was at the Blackjack mine (Photo 1). A colony of two-man cabins was erected on the old Miocene beach, with a boarding house to feed the miners. A truck road was graded to Avalon and a high voltage line run from the city power plant. To facilitate lowering ore from over 1,500 feet above sea level to the beach at White's Landing an aerial tramway was started. It would carry 700-pound ore buckets on its twin cables, at 90-second intervals. The three upper Blackjack levels were serviced by a 255-feet deep winze. The vein was three feet wide, heavily mineralized. A three compartment shaft was sunk on the 70° dipping vein to mine to 525 feet, the vein widened to five feet of massive sulphides below.

Meanwhile, intensive prospecting paid off. On the steep mountainside southeast of Avalon a new series of five veins was named the Renton mine (Photo 2). Road building there was prohibitively costly. Development of the orebodies was undertaken from five adits, the top one at 1085 feet above sea level, the lowest at 716 feet. Renton ore ranged from 8% to 12% zinc with only 1½ to 2% lead and silver between 2 and 3 ounces per ton, but again, no gold.

George Newman telephoned his old friend Tom DeVore to confirm what he recalled of gold assaying policy. DeVore told him that Renton considered it useless and unnecessarily costly to weigh gold content of samples routinely showing not even traces and never above 0.01 ounces per ton, worth 20¢. The determination involved dissolving silver from the Dore bead obtained from the fire assay, and reweighing the residual gold. Prospecting samples were still parted but daily mill and mine samples reported as silver, any trace gold present included.

The rock quarry was still active at Pebble Beach. Judge Ernest Windle, long the owner and publisher of the Catalina Island newspaper of Avalon, watched the mainland news for relevant

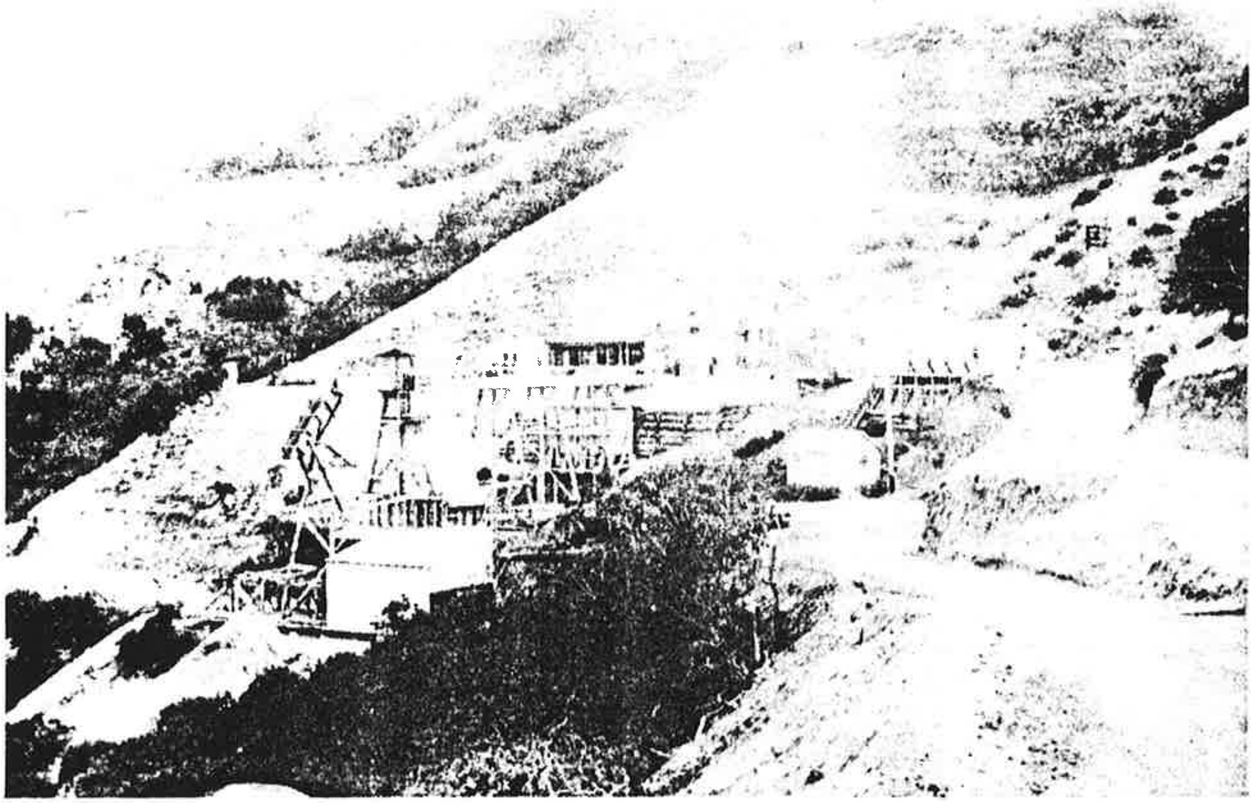

Photo 1. Headframe over 525 foot shaft, ore trestle and chute at the Black Jack mine before the aerial tramway was installed to transport ore to the flotation mill. Courtesy George H. Newman.

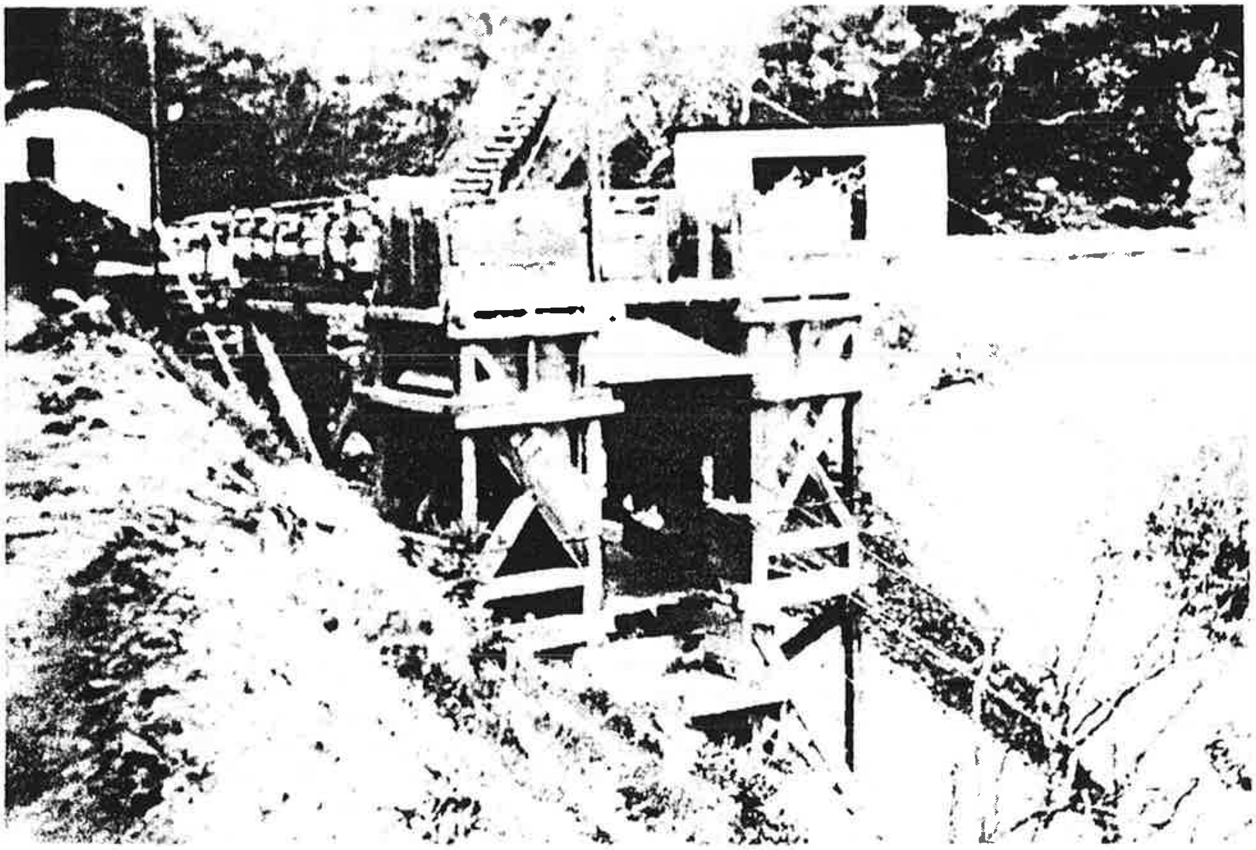

Photo 2. Under terminal of aerial tramway at Renton mine. Note cables stretching away from center to lower right. Courtesy George H. Newman.

items. He reported that "Miners were greatly enthused when they were informed that a large quantity of rock had been excavated from the west side of the rock quarry at Pebble Beach and sent to Long Beach for street improvements, that had an assay of $300 a ton. The Long Beach newspapers, in 1926, published quite a lengthy story regarding certain streets of Long Beach "paved with Catalina Silver." This was how the Quarry mine was discovered, the top of the ore hidden beneath the quarry floor until blasting uncovered it. Quarry ore used to assay 13.0% zinc, 1.1% lead and 2.5 ounces silver per ton. This the news media estimated to be worth $300 per ton. The Quarry mine was developed and the orebody followed almost to sea level.

Southwestern Engineering Company of Los Angeles undertook ore testing and design of the 100 tons per day flotation mill Wrigley agreed to build at White's Landing to convert the zinc from a lead smelter liability to a separate pay product at a zinc smelter. Getting ore from Renton and Quarry mines to the Pebble Beach crushed rock dock necessitated two more tramways. One was a 632-foot jigback aerial cableway, the other stretched 3,000 feet down from the Renton mine to the beach ore bins. A belt conveyor delivered ore from the bins to 180 and 250 ton barges.

John Windle, formerly transportation superintendent on Renton's staff, still tells how Santa Ana winds—locally known as northeasters—could occasionally disrupt the barge transport to White's Landing. His example was about when old No. 6 barge, a wooden-hulled 180-ton unit, was loaded and ready. A diesel tug took it in tow and cast off for White's. Out in the channel, halfway to its destination, off Hamilton Beach, a northeaster blew up suddently. The tug captain knowing it was impossible to tie up the barge at the pier in such a storm, turned back. The fury of the elements eliminated all possibility of running in to Avalon or getting back to the Pebble Beach dock so he rounded the island in search of a safe harbor to wait it out. Under the enormous strain the hawser parted and the barge and its ore cargo crashed against the Seal Rocks.

From White's Landing pier ore was removed from barges with a clamshell on a big stiff-leg derrick, loaded directly into dump trucks and taken to the mill ore bins not far above (Photo 3). From the bins the ore was fed into a rock crusher and reduced to golf ball size and down a chute to a Marcy ball mill. There the unique Wrigley salt water flotation process began. Selective flotation in sea water proved difficult to control. The customary chemical reagents were added but froth formation was erratic and like driving a skittish horse, one moment there was no froth, the next minute saw the cella inundated with foam. Help came in a most unexpected way in the guise of a painter who carelessly overturned a bucket of paint into the flotation circuit, with amazing results. Immediately the frothing settled down and a splendid mineral separation began. From that day on, kerosene became one of the essential flotation reagents in the circuit.

Thereafter, a 51% lead concentrate was produced regularly. It still contained 11% zinc and assayed 106 ounces per ton of silver. Formerly worthless zinc, though high in iron chemically combined with the sulphide mineral, was graded up to 48% zinc concentrate that contained only 3% lead and 9 ounces of silver. Overall recoveries were good, the tails assaying only 0.3% lead,

Photo 3. 100 ton per day capacity flotation mill built at White's Landing. Ore from Renton and Quarry mines was barged to wharf which was also used for loading concentrates shipped to smelters. Courtesy Santa Catalina Island Co.

1.3% zinc and 0.4 ounces silver per ton. The mill was equipped with appropriate moisture reducing equipment, the thickened concentrates dried on vacuum filters. In 125-pound bags the lead concentrate was sent to Asarco's Selby smelter. Zinc concentrate was sacked in 150-pound bags and shipped to Belgium to a zinc smelter. Mill tails were simply sluiced through a flume into the sea (Figure 4).

The sad sequel to Santa Catalina's little base metal industry was the killing effect of the world wide market collapse. It delivered an economic blow to Wrigley mines from whch they never recovered. Only a few years earlier Andy Norman, mine foreman at Blackjack had told Renton as they examined the newly blasted ore face, "This ore is good enough to eat." In response Renton pulled the old *Cabrillo* excursion steamer out of mothballs and loaded it with 250 tons of ore as a trial shipment to Selby. A government bulletin attests that it was worth $50 per ton. The preliminary smelter settlement check was sent to Wrigley who wrote back, on October 28, 1924, "I am returning herewith the check for $2,469.83. I am glad you sent it to me to look at. I believe I have spent not less than five hundred thousand dollars in various mining enterprises and outside of $8 I once received from a $100,000 investment this is the first real check that has been sent to me coming from a mining deal."

Regretfully, Wrigley wrote Renton again on May 20, 1927, " I just had a talk with Mr. Adams who you will remember was at one time with Selby smelters, as you know. The prices he quoted me as being current were 6.75¢ lead and 6.05¢ zinc. It appears to me that it is almost 50% less than we were obtaining for lead and zinc when we went into the business. I don't think you can possibly make any money by milling raw ore at these low prices. It would look to me as if we had better leave our ore where it is until such time as it can be manufactured at a profit."

The mill and tramways were sold off, the mine surface plant was dismantled, shafts and adit portals were fenced to keep intruders out of dangerous places. Underground workings are flooded and caved. All that remains is a memory of a valiant effort during which Newman's figures show that 519,412 tons or ore were mined.

Photo 4. Miners' cabins at Black Jack mine, Santa Catalina Island.

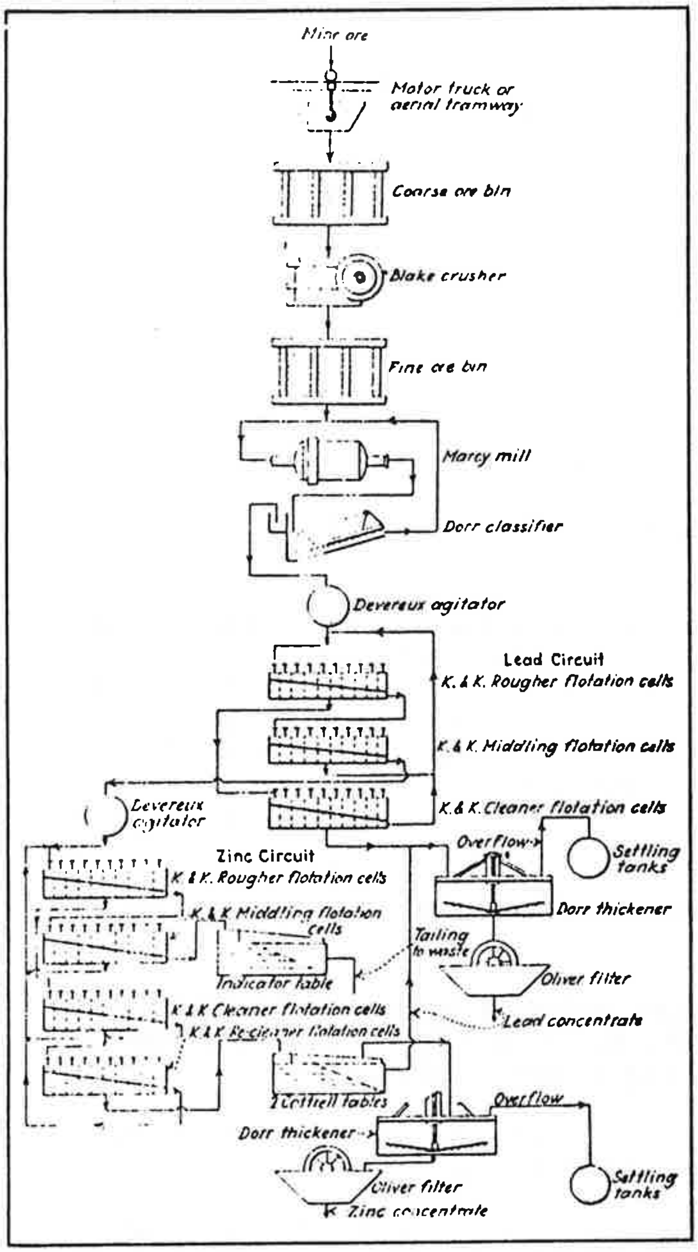

Figure 4. Flowsheet, 100 ton per day flotation mill at White's Landing. From: Engineering and Mining Journal, vol. 124, no. 7, August 13, 1927, p. 247.

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# Geology of Metallic Mineral Deposits
# Santa Catalina Island,
# California*

Harry D. Pouncey

## GENERAL GEOLOGY

### Introduction

Santa Catalina Island is located within the California Continental "Inner" Borderland Province (Crouch, 1979). The relationship of Santa Catalina Island to the major tectonic elements of southwestern North America is shown in Figure 2. Various models for the tectonic evolution of the California Continental Borderland Province are discussed by Atwater (1970), Hawkins (1970, 1975), Vedder and others (1974), Crouch (1979, 1981), Dickenson (1979, 1981), Stuart (1979), McLean and others (1976), and Howell and others (1981).

The island is comprised of three major bedrock units categorized as follows:

(1) Pre-Tertiary meta-sedimentary and meta-igneous rocks associated with the Franciscan Series (KJf, m, ls and KJfv, ub) referred to herein as the Catalina schist (KJcs) of Bailey (1941).

(2) Tertiary (hypabyssal) intrusive rocks (Ti) referred to herein as the quartz diorite porphyry (Tqdp) of Bailey (1941).

(3) Middle to Late Tertiary-Miocene volcanic rocks (Mv) referred to herein as the volcanics (Tvol) of Bailey (1941) and Wood (1981).

The generalized distribution of these three major bedrock units is shown on a "Simplified Geologic Map of Santa Catalina Island", Figure 1. The location of the mines and prospect study areas are also shown on Figure 1.

### Catalina Schist (KJcs)

The Catalina schist is a complex assemblage of metamorphic rocks and is the most extensive geologic unit exposed, underlying approximately two-thirds of the central to northwest portions of the island. Correlated with

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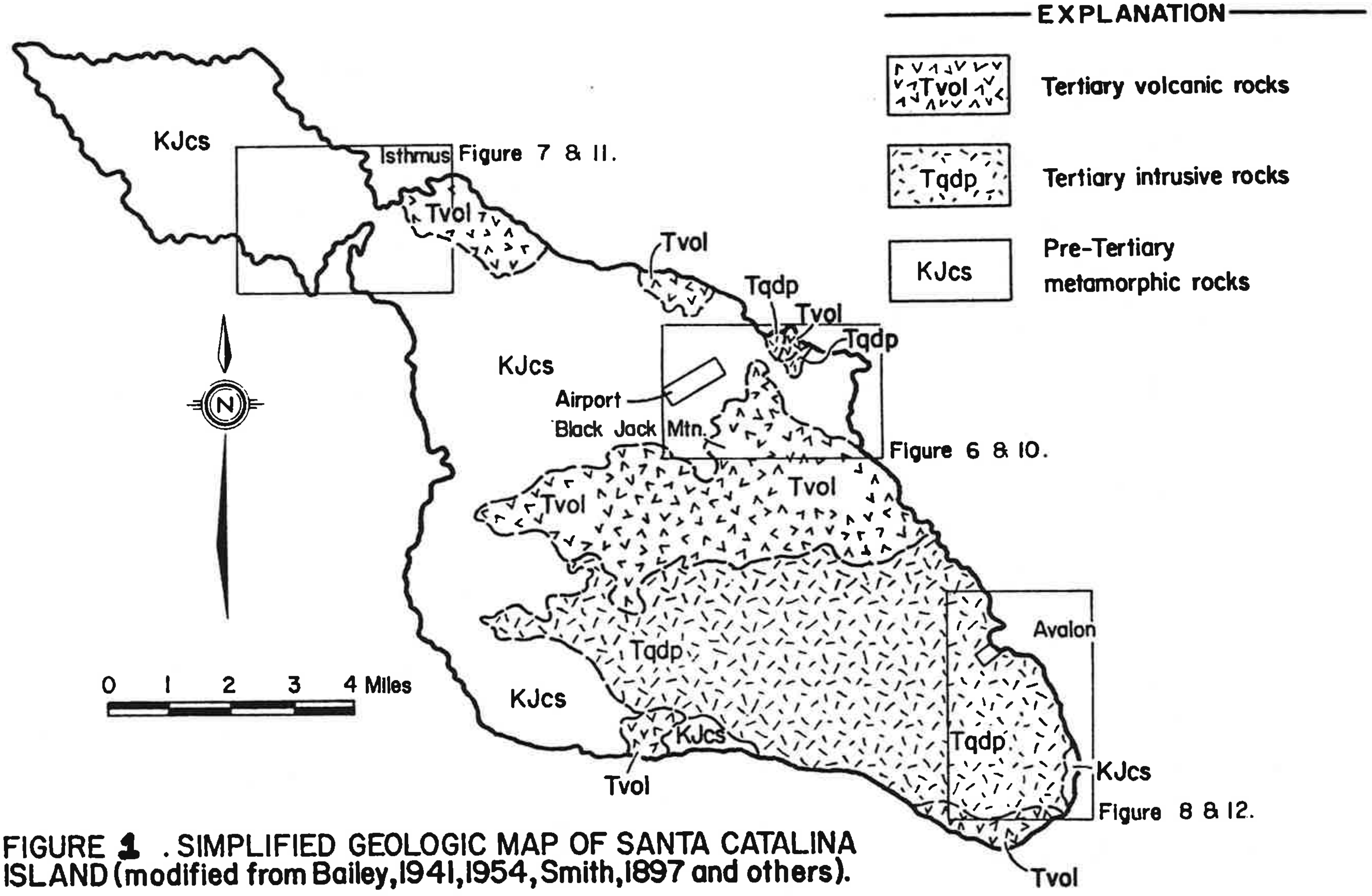

FIGURE 1 . SIMPLIFIED GEOLOGIC MAP OF SANTA CATALINA ISLAND (modified from Bailey, 1941, 1954, Smith, 1897 and others).

the Franciscan metamorphic complex of the California Coast Ranges by Woodford (1924) and Platt (1975; 1976), these rocks represent the oldest assemblage of basement rocks on Santa Catalina Island and the entire Continental Borderland Province. Once thought to be Pre-Cambrian to Paleozoic, Forman (1970) provided independent support to a Franciscan (Mesozoic) age correlation by obtaining a K-Ar date of106 mybp on a Catalina amphibolite schist sample from Rippers Cove.

The Catalina schist terrane has been subdivided by Platt (1975; 1976) into three tectonic units according to metamorphic grade. In order of increasing metamorphic grade and decreasing depth they consist of the (1) Blueschist, (2) Greenschist and (3) Amphibolite units. The three units are separated by thrust faults and the tectonic model proposed by Platt (1976) is based on an apparent inverted thermal prograde metamorphism with an eastward increase in metamorphic grade. Platt suggests that metamorphism occurred in a newly started, east dipping subduction zone where an inverted thermal gradient developed below an upper plate of hot hanging wall peridotite. The metamorhism of these rocks was caused by down thrusting in a subduction zone environment to depths of 25 to 30 kilometers within the upper mantle peridotite. The original rocks of the three units prior to metamorphism were then comprised of oceanic sediments and volcanics deposited on an oceanic basement in close proximity to a continental margin in a region of past active basaltic volcanism.

The following mines and propsects are located within the Catalina schist terrane:

Black Jack Mine
Cherry Cove Mine
Fourth of July Mines
Prospect 2 Mine
Other Miscellaneous Prospects

Based on historic records it is presumed that many other miscellaneous workings are located within the Catalina schist terrane.

## Quartz Diorite Porphyry (Tqdp)

The southeast portion of Santa Catalina Island is underlain by a large, roughly east-west trending stock-like mass of fine to coarse grained dioritic rocks that have intruded into the Catalina schist. Bailey (1941) identified the main intrusive body as a plutonic hornblende quartz diorite porphyry (Tqdp) and recognized cross cutting dikes of quartz diorite to more mafic composition. Forman (1970) assigned an age of 19 mybp to these rocks based on K-Ar dating of hornblende in quartz diorite collected near the mouth of Silver Canyon.

Intrusion and stoping of the pluton into the Catalina schist resulted in abundant inclusions of schist contained with the pluton that indicate that the roof of the intrusion was close to the present topographic surface of the island (Bailey, 1954). An apparent lack of high temperature contact metamorphism of the Catalina schist host rock indicates the roof of the intrustion may have significantly cooled prior to emplacement or contact with the schist. The emplacement event of the Catalina Island pluton "represents the beginning of a middle Miocene sequence of plutonism, orogenic uplift, erosion, subsidence, and finally volcanism" according to Forman (1970). This event appears synchronous with similar, unusually young continental plutons of the Southern California San Gabriel Mountains, which range from 16-26 mybp.

The quartz diorite porphyry pluton is reportedly unique as it represents one of the youngest exposed plutons in the world; it is also the only known "granitic-continental type" intrusion into oceanic type Franciscan rocks. It is unusual to find, out at sea on Santa Catalina Island, a plutonic intrusive so similar in age and composition to those types of rocks which would typically intrude continental crust (Forman, 1970).

The following mines and prospects are located within the quartz diorite porphyry terrane:

Renton Mine, No. Six Tunnel and the Wrigley Tunnel
Quarry Mine
Golf Link Mine
St. Catherine Prospect
Other Miscellaneous Prospects

Also, based on historic records it is presumed that many other miscellaneous workings are located within the quartz diorite porphyry terrane.

## Volcanic Rocks (Tvol)

A series of middle to late Miocene volcanic rocks have localized outcrops but mainly form an east-west major outcrop distribution extending across the central portion of the island. These volcanic rocks are mainly superjacent and subparallel to the east-west trending intrusive quartz diorite porphyry stock (Figure 1). The volcanic stratigraphic section (Tvol) post-dates both the metamorphic (KJcs) and plutonic (Tqdp) rocks. The volcanics may have actually been generated from later offshoots of the intrusive quartz diorite porphyry stock. Smith (1897) and Bailey (1941) classified the volcanics as primarily pyroxene andesite flows and flow breccias with localized dikes and flows of olivine basalt and rhyolite.

According to Wood (1981) the flows, breccias, dikes, sills and dome intrusions constitute a volcanic section exceding 400 meters in thickness within the central island area. Individual laterally discontinuous, dominantly auto-brecciated lava flows range from 2 to 10 meters in thickness. Rock types and relative percentages within the volcanic unit reported by Wood (1981) are 40% hornblende-hypersthene dacite, 35% hypersthene andesite, 17% basaltic andesite, 5% olivine basalt and 3% rhyolite.

Elemental chemistry according to Wood (1981) is transitional, exhibiting both tholeiitic and calc-alkalic character, but is best defined as $K_2O$ poor calc-alkaline in character with moderately high $TiO_2$, high $Al_2O_3$ and high $SiO_2$ with strong CaO, MgO and iron depletion.

The volcanic stratigraphic section locally contains abundant large vesicles, sublittoral marine fossils and intercalated sedimentary sequences in the later flows. Deep water foraminiferal fossil assemblages are contained within the intercalated sedimentary sequences of the later flows. Based on this petrographic and paleontologic evidence supported by K-Ar dates of 12.5 to 15 million years, Vedder and others (1979) concluded that the volcanics were emplaced during a short time interval from middle to late Miocene; the environment of deposition was initially a subaerial to shallow marine setting that later deepened from neritic to mid-bathyal depth.

No known mines or prospects are located directly or entirely within the volcanic unit. The only known near-exception is the Black Jack Mine situated at the contact of the Catalina schist, volcanic flows and a dacite dome associated spatially and temporally with the volcanics. K-Ar, dates reported by Vedder, Howell and Forman (1979), obtained from a similar dacite dome at Empires Quarry northwest of the Black Jack Mountain dacite dome, indicate a plagioclase and whole rock age of 14.2 to 14.7 mybp. They interpret the dacite dome at Empires Quarry "to have originated as a late phase, near-surface offshoot from the stocklike diorite rocks on the eastern part of the island". Although the hypabyssal (?) dacite dome rocks are dated 4 to 5 million years younger than the stocklike rocks of the quartz diorite porphyry plutonic intrusive, "it is possible that the two are genetically related", according to Vedder, Howell and Forman (1979). The Black Jack Mine is located at the contact of the Catalina schist, the volcanics and a dacite dome but earlier reports by Gieser (1927) and Tucker (1927) indicate the metallic ore zone is hosted entirely within the Catalina schist.

## Geologic History

The pre-Tertiary geologic history of Santa Catalina Island is discussed mainly by Platt (1975; 1976) and Woodford (1924). It is apparent that subduction and regional metamorphism occurred in a Japanese to Andean type continental margin tectonic setting that prevailed throughout the Mesozoic Era and into the early Cenozoic Era prior to the onset of a California type continental margin where transform faulting and wrench style tectonics were initiated during middle to late Tertiary.

Studies by Vedder, Howell and Forman (1979) of the island's volcanic and sedimentary stratigraphy have provided significant insight for resolving the Tertiary geologic history of Santa Catalina Island and the surrounding California Continental Borderland Province. A generalized stratigraphic column for Santa Catalina Island from Vedder, Howell, and Forman (1979) is shown on Figure 9. Based on several lines of evidence including the age relationships of volcanic and sedimentary sequences, paleontologic criteria and the general absence of marine strata older than middle Miocene they concluded the following:

(1) "The Santa Catalina Island area was part of a relatively high-standing ridge system for most of the lower and middle Tertiary."

(2) The youngest marine strata of the island "were deposited in water that deepened from less than 200 meters during middle Miocene time to as much as 2,000 meters at the end of Miocene time", and that during this time the area's past environment consisted of a seafloor

with localized marine basins of irregular topographic relief coexisting along with plutonic and metamorphic rock outcroppings of positive topographic relief in an active volcanic archipelago.

(3) Subsidence, probably accompanied by dwindling volcanism some 12 to 7 million years ago, obliterated the small volcanic archipelago before Pliocene time and that early Pliocene subsidence was followed by late Pliocene (?) and Pleistocene uplift of the island.

(4) Tectonics and volcanism of Santa Catalina Island are associated with the encroachment of the Pacific-Farallon Ridge and the passage of a postulated transform-ridge-trench triple junction in early Miocene time which modified the structural setting of the borderland province of offshore southern California.

The implication is that the topographic relief of the borderland area during middle and up to late Miocene time and the subsequent early Pliocene subsidence and late Pliocene (?) to early Pleistocene uplift of the island resulted from the onset of Meogene wrench-style plate tectonics that apparently have prevailed throughout the Borderland Province since early Miocene time.

The volcanic and hypabyssal intrusive (dacite dome) rocks of Santa Catalina Island were studied and described in detail by Wood (1981) in order to provide some insight to their petrogenesis and possible tectonic implications. Wood's conclusions are carefully presented but admittedly ambiguous as follows:

> Petrogenesis was related to either (a) Island arc volcanism by partial melting of subducted Farallon plate oceanic crust or diapirism within a chemically modified mantle wedge above the Farallon plate or (b) diapirism of mantle material or fractional crystallization of a basaltic magma associated with a spreading ridge system of the East Pacific Rise or Riviera Triple Junction.

The reasons for the ambiguity of Wood's conclusions are as follows:

(a) Field geology resembles a continental island arc environment with dacite-rhyolitic domes, dioritic plutonic intrusives, laharic breccias of possible pyroclastic origin and disordered, non-sequential volcanic stratigraphy but is unsupported by the paragenetic sequence, spatial and temporal relationships between volcanism and tectonism and certain aspects of the petrology and geochemistry.

(b) Major element geochemistry is transitional between tholeiitic and calc-alkalic affinity although the volcanism is best described as $K_2O$ poor and more calc-alkalic in character.

The problem is distinguishing calc-alkalic volcanic rocks of different origins as these types of volcanic rocks can be produced by either mechanism of (a) island arc volcanism or (b) fractional crystallization in a fracture zone or spreading ridge environment.

In light of the ambiguous petrographic and geochemical evidence presented by Wood (1981), he finally concludes that resolving the petrogenetic origin distinguishing between (a) island arc origin or (b) mid-oceanic ridge (MOR) origin can better be ascertained by trace element geochemistry; specifically by Sr 87/86 ratios, since MOR rocks tend to contain less radiogenic strontium.

Following late Miocene, dwindling volcanism and in time early Pliocene subsidence, Santa Catalina Island emerged to its present topographic position. Vedder, Howell and Forman (1979) indicate that the island's emergence occurred by uplift sometime during the late Pliocene (?) to Pleistocene. However, an apparent lack of Pleistocene marine terraces on Santa Catalina Island reported by Davis (1983) would infer that "there is no conclusive evidence to indicate significant uplift of Catalina Island during the Quaternary". It is apparent that the emergence of Santa Catalina Island was essentially completed sometime during the late Pliocene and has been elevated above sea level since.

## Black Jack Mine

The Black Jack Mine is located on the northwest slope of Black Jack Mountain approximately one mile southeast of the Catalina Airfield (Figure 2). During the investigation, underground mine workings were inaccessible through the buried first level portal. The only surface openings are two fenced off, steeply inclined to vertical shafts shown as dots on the location map (Figure 2). The study was confined to surface geologic mapping of the surrounding mine ara and literature research of the Santa Catalina Island Company (S.C.I.C.) mining records and publications by Preston (1890), Gieser (1927) and Tucker (1927).

The mine is located at the contact of three geologic units including Catalina schist (KJcs), the dacite porphyry of Black Jack Mountain (Tdp) and undifferentiated volcanic flows (Tuvf). According to the S.C.I.C. records and accounts by Gieser (1927) and Tucker (1927), the mineralized vein strikes about N 10-30° W, dips 60-70° NE and is hosted within the Catalina schist. The strike of the vein where the two shafts are located, appears roughly parallel to the northwest trending ridge shown on the Location Map, Figure 2.

Mine development was apparently along a single vein called the "Black Jack Vein". The size, shape grade, mineral paragenesis and zoning of the vein are described by Gieser (1927). Gieser noted the vein in the upper levels from 3 to 5 feet wide occurred in a fault zone along the contact between black quartzose shale and quartz-albite-chlorite schist with argentiferous galena being the predominant economic mineral. Sphalerite occurs at 250 feet depth and below the 400-foot level where the vein widens from 5 1/2 feet to 26 feet, sphalerite becomes the dominating economc mineral with lesser amounts of argentiferous galena. In the lowest 500-foot level, pyrite occurs containing 3 to 5 percetn copper.

Gangue minerals according to Tucker (1927) consist of hornblende, quartz, barite, calcite and muscovite; the ecomonic minerals consisting of galena and sphalerite were apparently localized within ore shoots along the vein. Tucker noted the ore shoot along the Black Jack vein from the 400-foot level to the surface was 40 feet long, 6 to 12 feet wide and was of higher grade than the ore worked along the same vein at the lower 500-foot

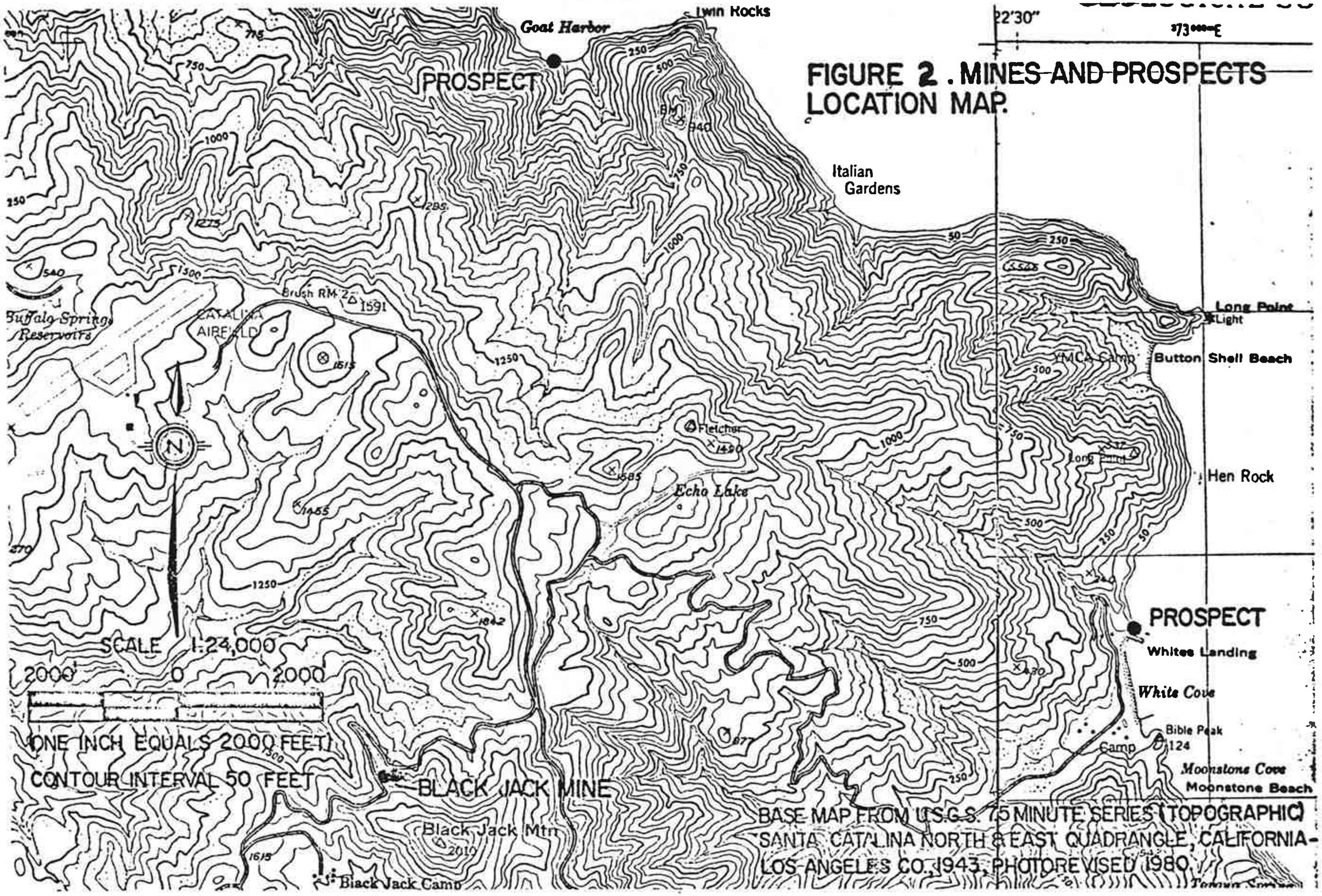

FIGURE 2. MINES AND PROSPECTS LOCATION MAP.

BASE MAP FROM U.S.G.S. 7.5 MINUTE SERIES (TOPOGRAPHIC) SANTA CATALINA NORTH & EAST QUADRANGLE, CALIFORNIA-LOS ANGELES CO. 1943, PHOTOREVISED 1980.

level. He reported the ore to carry 6% zinc, 1 1/2% lead and 2 to 3 ounces of silver per ton.

The economic mineral paragenesis appears to be depth zoned with argentiferous galena, sphalerite, pyrite and copper respectively encountered in order of increasing depth. Gieser (1927) stated that the ore deposit of the Black Jack vein is probably of the intermediate-zone type".

The total production of the Black Jack Mine before closing in 1927 ranged frmo 1,000,000 to 10,000,000 pounds of lead-zinc (Jenkins and Goodwin, 1957). The amount of undeveloped ore reserves remaining after 1923 to 1927 mining operations is uncertain.

## SUMMARY AND CONCLUSIONS

(1) The mineral deposits of Santa Catalina Island are localized in high-angle fissure veins trending north-south in Catalina schist to east-west in quartz diorite porphyry.

(2) The veins hosted within the Catalina schist contain an economic mineral assemblage dominated by argentiferous galena with subordinate amounts of sphalerite with gangue minerals consisting mainly of quartz with lesser amounts of carbonates and sulfates. The veins hosted within the quartz diorite porphyry contain an economic mineral assemblage dominated by sphalerite with subordinate amounts of argentiferous galena with gangue minerals consisting mainly of carbonates and sulfates with lesser amounts of quartz. Mineral depth zoning is evident where arentiferous galena and sphalerite are encountered along veins in order of increasing depth with pyrite and copper eventually encountered along the deepest portions of veins. Mineral depth zoning is reflected in the mineral paragenesis of copper sulfides and pyrite followed by sphalerite and argentiferous galena. The depth zoning model provides an exploration guide in determining the tops and bottoms of veins and indicates the veins hosted in the quartz diorite porphyry are deeper zoned and/or more deeply eroded than the veins hosted in the Catalina schist.

(3) Hydrothermal effects are evident by host rock alteration. Noarrow halos of argillic host rock alteration, and well developed gossans are generally pronounced along veins hosted within the quartz diorite porphyry and may provide a guide to exploration. Host rock alteration is less evident and gossans are generally either poorly developed or poorly exposed along veins hosted within the Catalina schist.

(4) Structural control by faulting is the dominating factor governing the location and form of veins and orebodies. Permeability superimposed by structure provided channels for transport of hydrothermal solutions and open spaces for mineral deposition with only minor indications of replacement. Metallic mineralization, dominated by open space filling occurs primarily along fault zones where the zone is fractured or brecciated and locally widens or bends.

Faulting along veins, dominated by dip slip to oblique slip movement, is mainly pre-mineralization with some indications of post-mineralization fault movement.

(5) The mineralization is epigenetic, being deposited along secondary structures superimpsoed on the host rocks. The metallic mineral assemblage is considered hypogene, having formed by generally ascending hydrothermal solutions. Limonitic gossans, developed in the zone of surface oxidation and weathering, are locally pronounced but no major indications of supergene enrichment are evident. The genetic classification of these deposits appears to border between Lindgren's (1913, 1933) mesothermal to epithermal zones.

(6) An age of middle to late Tertiary mineralization is established for veins hosted within the quartz diorite porphyry and is postulated for veins hosted within the Catalina schist. A common origin and single main period of mineralization for veins of both the quartz diorite porphyry and Catalina schist terranes are supported by the similarities in Pb isotopic compositions. Metallic mineralization concentrated from hydrothermal solutions is inferred to have originated at depth by convective circulation from a magmatic heat source associated with Tertiary volcanism. The mineralization event of middle to late Tertiary appears contemporaneous with a significant turning point in the structural evolutioon of the Continental Borderland Province: the turning point effected by a shift from earlier regional subduction to a California type continental margin where transform faulting and Neogene wrench-style tectonics were initiated. This middle to late Tertiary tectonic shift and corresponding mineralization event appears related to the encroachment of the Pacific-Farallon Ridge and the passage of a postulated transform-ridge-trench triple junction in early Miocene time (Vedder, et al, 1979).

(7) Ore grade mineralization has been economically developed on the island prior to a late 1920's collapse in metal market prices. The conclusion that unproven or undiscovered metallic mineralization probably exists is based on projections and modeling in accordance with sound geologic principles, but is not based on economic considerations. Future exploration efforts should consider that the metallic mineral vein deposits investigated are high grade but generally of limited extent to low tonnage.

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# THE LATE QUATERNARY GEOMORPHOLOGY OF SANTA CATALINA ISLAND AND AVALON CANYON, CALIFORNIA

by Paul Davis

## Introduction

The morphology of coastal Santa Catalina Island is unique among the southern California islands in that there is little evidence for marine terraces. This paper reviews marine terrace evidence on Santa Catalina and discusses the geochronology of late Quaternary events in Avalon Canyon related to glacio-eustatic sea levels. The location of Avalon Canyon is illustrated on Figure 1.

## Quaternary Marine Terraces of Catalina

The terms "terrace", "terrace deposits" and "bench" as used in this paper are defined as follows: "Terrace" is a gently-sloping geomorphic surface formed by the aggradation of alluvial materials marking a former level of deposition. "Terrace Deposits" are the uncemented materials underlying the terraces. The term "Terrace Surface", though seemingly redundant, is used to designate more strongly the ground surface. A "Bench" is the wave-cut platform eroded into bedrock.

Of all the Channel Islands, Catalina Island is unique by its lack of obvious wave-cut landforms. Extensive coastal stretches of the Northern and Southern Channel Islands contain broad, gently-sloping wave-cut benches, mantled with thick marine and terrestrial deposits. For example, the coastal terraces of northwestern Santa Rosa Island are so well-defined that they have been subdivided into three distinct levels, the highest at only 100 feet elevation (Orr, 1968). The lowest wave-cut bench is as much as 300 yards wide, and is capped with over 100 feet of deposits. Similar well-preserved marine platforms and terrace deposits are found on the other Northern Channel Islands (Weaver, 1969).

The Southern Channel Islands, with the lone exception of Catalina Island, are similarly endowed. San Nicolas Island,

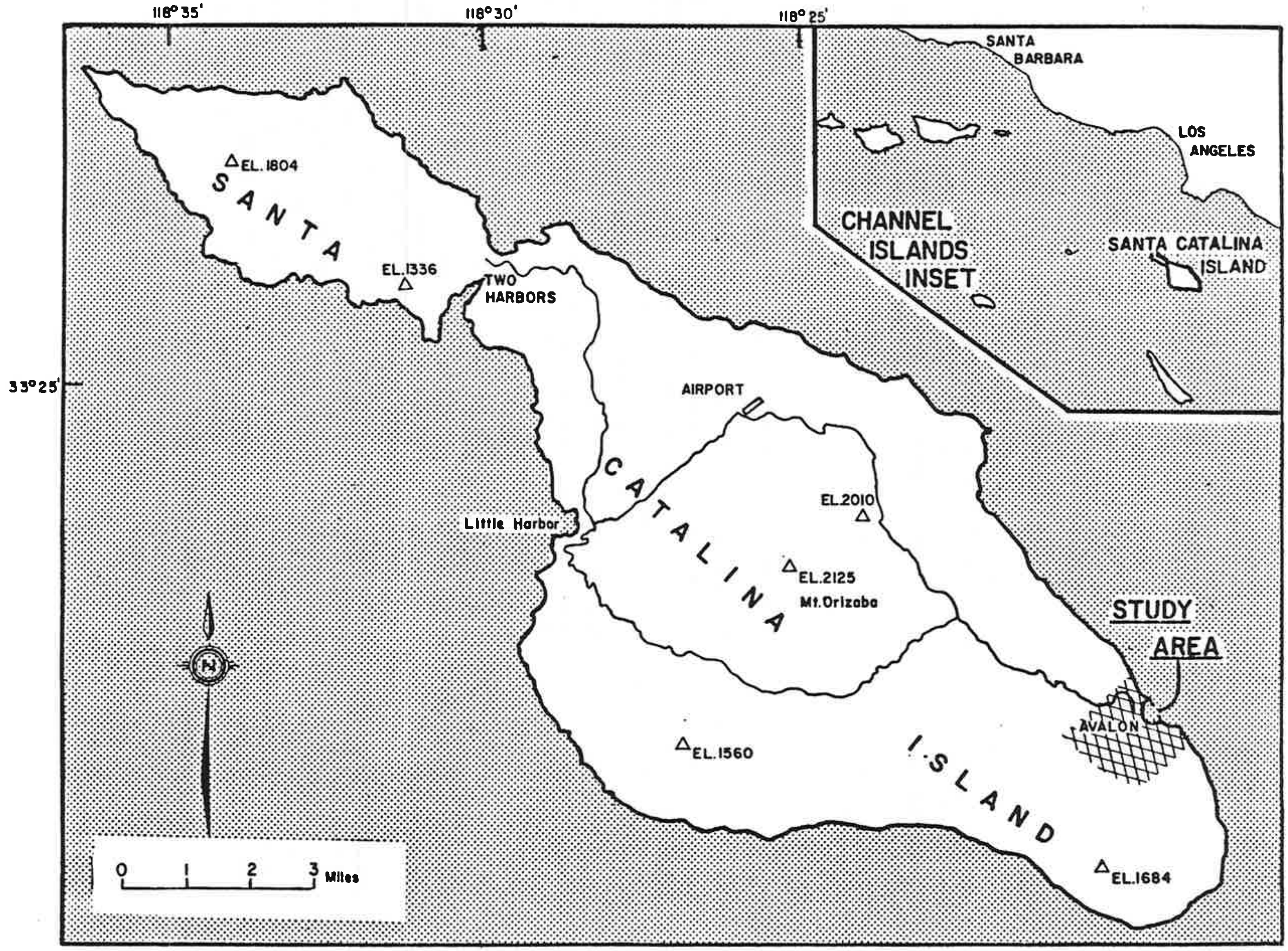


FIGURE 1 LOCATION OF STUDY AREA

for example, has several well-preserved terraces. The terrace surfaes are reportedly 1/4 to 3/4 of a mile wide, and as much as five miles in length (Vedder and Norris, 1963). Most of these platforms are mantled with horizontally-layered, fossiliferous marine sands. The surfaces of San Clemente Island and Santa Barbara Island also form a series of well-defined, beveled, wave-cut surfaces, covered, at least in part, with Quaternary marine deposits.

The best-preserved and most widespread terraces on these other islands are the lowestin elevation. There seems to be some consistency and correlatability between islands of a 25-foot elevation platform (Valentine and Lipps, 1967; Birkeland, 1972). However, investigators now are reluctant to make inter-island correlations (Vedder and Howell, 1980) in light of the unknown influence of eustatic and tectonic variables.

In stark contrast to the other islands, the Catalina coast is typified by rugged, narrow ridgelines descending in a series of irregular breaks-in-slope to a steep, wave cut cliff. The aerial photograph in Figure 2 shows the ruggedness of the coastline, which is punctuated with a handful of bays and small coves.

The ambiguity of field evidence for elevated terraces on Catalina Island has led to considerable disagreement and contradictory statements by many investigators. For example, Lawson (1893) after circumnavigating the island, concluded "there is no trace of an elevated wave-cut terrace, sea-cliff, or strand line of any kind observable on the island." Just a few years later, Smith (1897) reported two terraced areas on the island, one a 40-50 foot alluvial terrace behind Avalon, the other a beveled ridge top with scattered marine conglomerates at the Little Harbor Embayment. Later, Smith (1933) addressed the marine terrace controversy in greater detail, and concluded ". . . for the existence of marine terraces on Santa Cataline Island . . . there can be no doubt, and all (the evidence) taken together seem to furnish sufficient proof of the uplift of the island to an extent of not less than 1700 feet" (p. 136). Upon review of Smith's evidence, Shepard and others (1939) succinctly responded: "The re-examination of the evidence for Pleistocene uplift of Catalina Island developed by Smith fails for confirm his opinion" (p. 654). Bailey (1941), also critical of Smith's (1933) terrace evidence, reported: "Benches on spurs undoubtedly do exist but did not seem to the

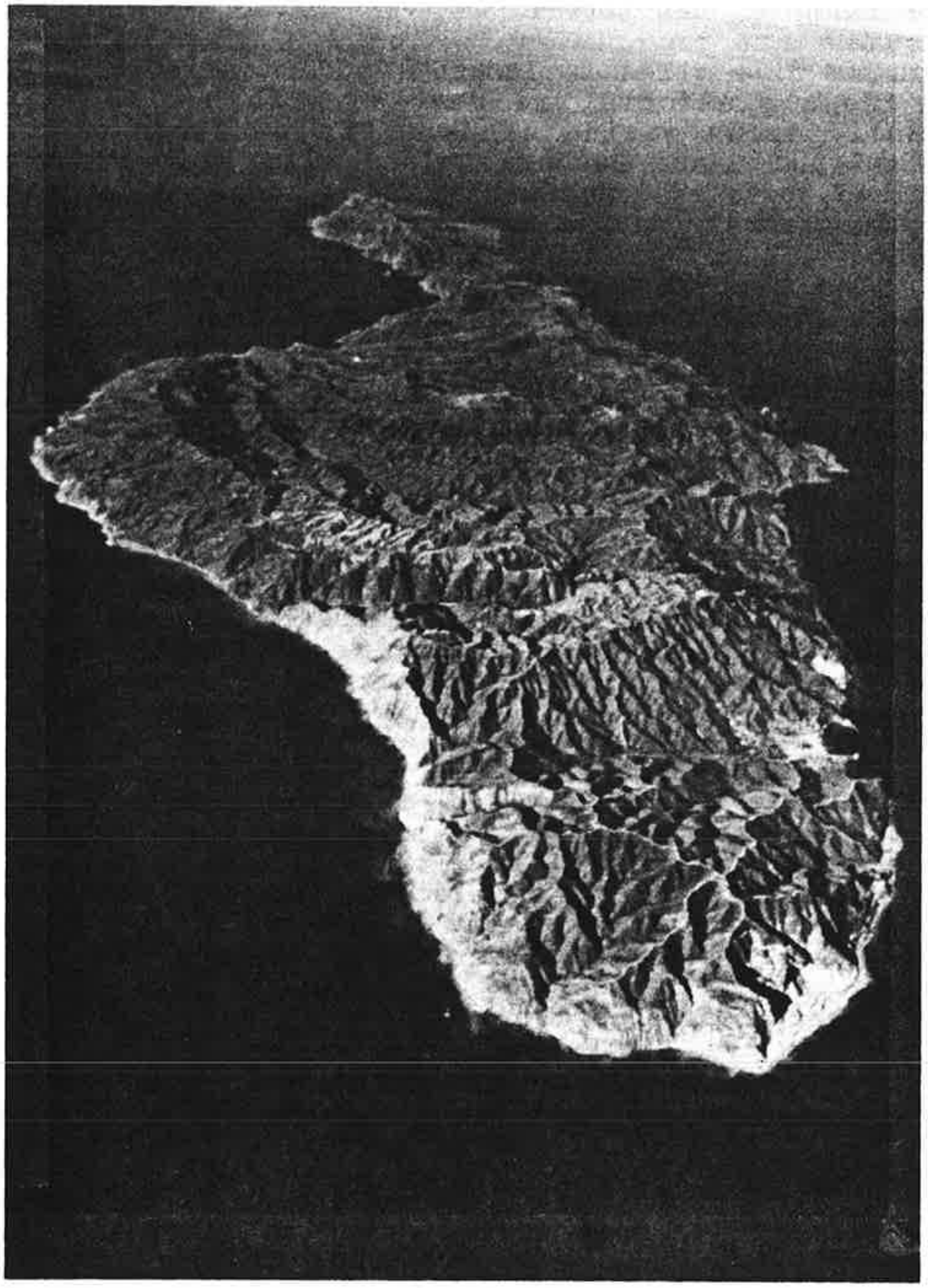


Figure 2 Northwestward aerial view of Santa Catalina Island. The rugged coastline contrasts with the broad, surf cut terraces of the other channel islands and adjacent mainland.

author to be continuous from ridge to ridge so that their origin as wave-cut features seems open to considerable doubt" (p. 177). More recently other investigators indicate that Catalina Island was probably uplifted (Emory, 1960; Ehlig, personal communication, 1982), but admit that any marine terraces are highly eroded and, therefore, evidence of uplift is unconclusive.

The publication most supportive of the presence of elevated marine terraces on Catalina Island is that of Smith (1933). He looked for terrace evidence at the three main promontories, or "salients", as he termed them. These promontories form 1) the northeast end of the island, 2) the southeast end, about two to three miles south of Avalon, and 3) the blunt southwest side south the Little Harbor (Fig. 3). Most of Smith's evidence comes from the southerly part of the island -- the southeast and southwest "salients".

Smith's indications for terracing at the southeast end were a series of "notches," or breaks-in-slope along bedrock spur ridges facing the ocean. However, these irregular ridgelines not only face seaward, but also flank Avalon Canyon and other interior canyons throughout the quartzdiorite terrane. Accordingly, the irregular profiles of these spur ridges are well explained simply by differential erosion. The plutonic bedrock, because of its complex structure and variable lithology, exhibits a wide range of weathering rates. This cause-effect relationship is particularly apparent above Avalon Canyon, where firebreaks along narrow, irregular ridgelines expose erodible shear zones and closely fractured rock juxtaposed with resistant, aphanitic dikes.

Smith (1933) also described 14 "benches", or breaks-in-slope at the blunt, southwest side of the island, a few miles south of Little Harbor. Smith failed to recognize, however, that this coastal area is underlain by an extensive, metamorphic landslide complex (Slosson and others, 1977). Most of his "benches" are tilted slide blocks or graben-like features associated with the landslide terrane.

As additional evidence for elevated, Pleistocene marine terrace deposits, Smith reported the presence of patches of "loose, water-worn pebbles" along several main ridges around Avalon and Little Harbor. Other investigators (Samaras and Gellura, 1979) likewise considered these pebbles Pleistocene in age. However, the writer has found comparable, water

Photo 3: Avalon Harbor.

worn pebbles widely scattered on ridges and some side slopes above Avalon Canyon, as well as along nearly all main ridgelines throughout the island.

The origin of these scattered pebbles is no mystery to archaeologists. A variety of stone artifacts have been found in midden sites excavated on the island (Cottrell, 1980; Reinman and Eberhart, 1980). Most of the rocks were taken from the nearby surf zone, where hard, fresh cobbles and pebbles are in unlimited supply. Some Monterey chert fragments, foreign to the Island, indicate trade with the mainland (Cottrell, 1980). The stones were used as hammerstones, pestles, manos, tarring pebbles and other purposes not determined. The tarring pebbles found were relatively fresh, and according to Cottrell (1980, p. 19), "These pebbles, averaging two centimeters in diameter, were used without alteration and were rolled around in the interior of a basket in which heated tar or asphaltum had been poured. This technique served to make the basket a waterproof container."

Many of these middens occur on prominent ridgelines, on the order of 500 feet apart in some areas (County of Los Angeles, 1975). The number of native midden sites has been estimated by Glassow (1980), who states: "Forty to fifty-five percent of Santa Catalina Island's area, which has been systematically surveyed, has yielded about 900 sites, so the island total is probably on the order of 2,100, and the density would be approximately 10.81 sites per $Km^2$ (p. 85). As a result of midden site density, rounded pebbles are ubiquitous on Catalina Island.

In addition to Smith (1933), other workers have suggested the presence of raised marine terraces on the island, although the evidence is inconclusive. A commonly-described beveled surface is the long, gently-sloping ridgeline behind Little Harbor (Fig. 3) (Shepard and others, 1939). Bailey (1941 p. 177) described ". . . isolated areas of rounded pebbles forming are strand line at an elevation of about 25 feet," as well as a small terrace at about 10 feet within the landslide complex of Slosson and others (1977). Slosson and Cilweck (1966) mentioned beach deposits at the northwestern coastline, at elevation 15 to 20 feet. Few authors describe the same features, and no mappable, unequivocal marine terrace deposits have been found.

Figure 4 shows reported terrace elevations by some of the more commonly-referenced authors. The marked differences

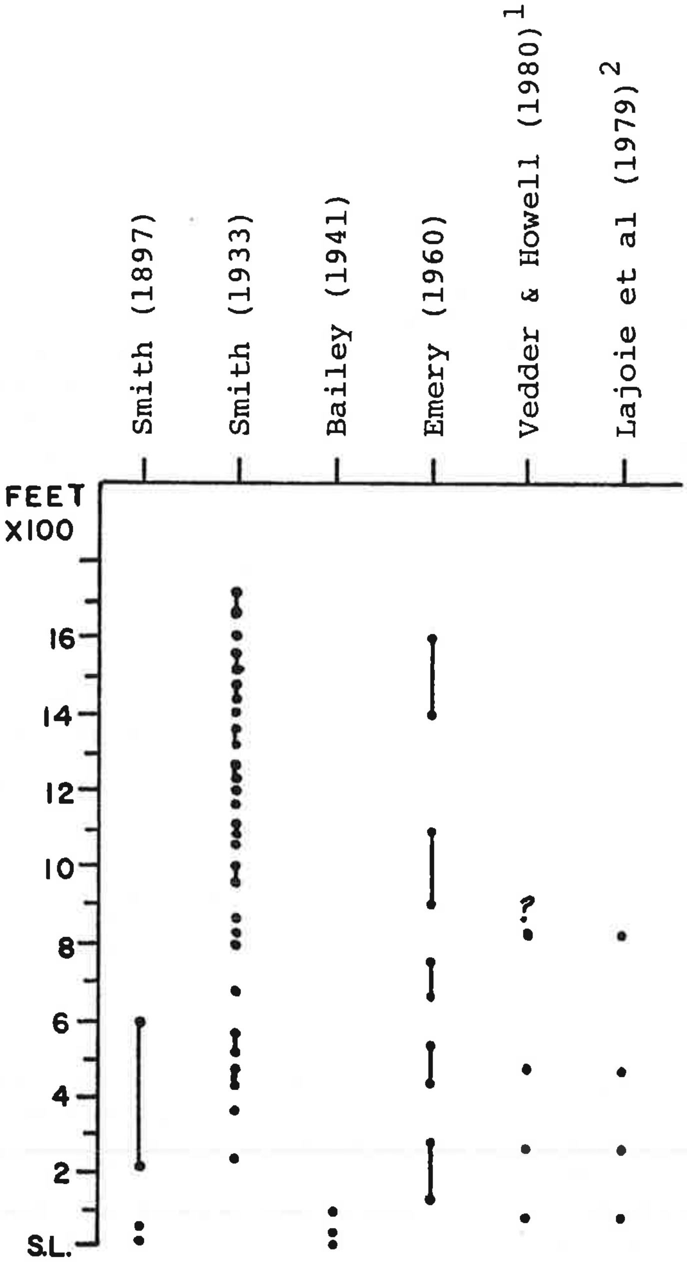


Figure 4 Reported altitudes of emergent marine terraces on Santa Catalina Island. Vertical lines represent the elevation range of individual terrace surfaces.

1. Reported reference: Smith (1933)
2. Reported reference: Vedder & Howell (1980)

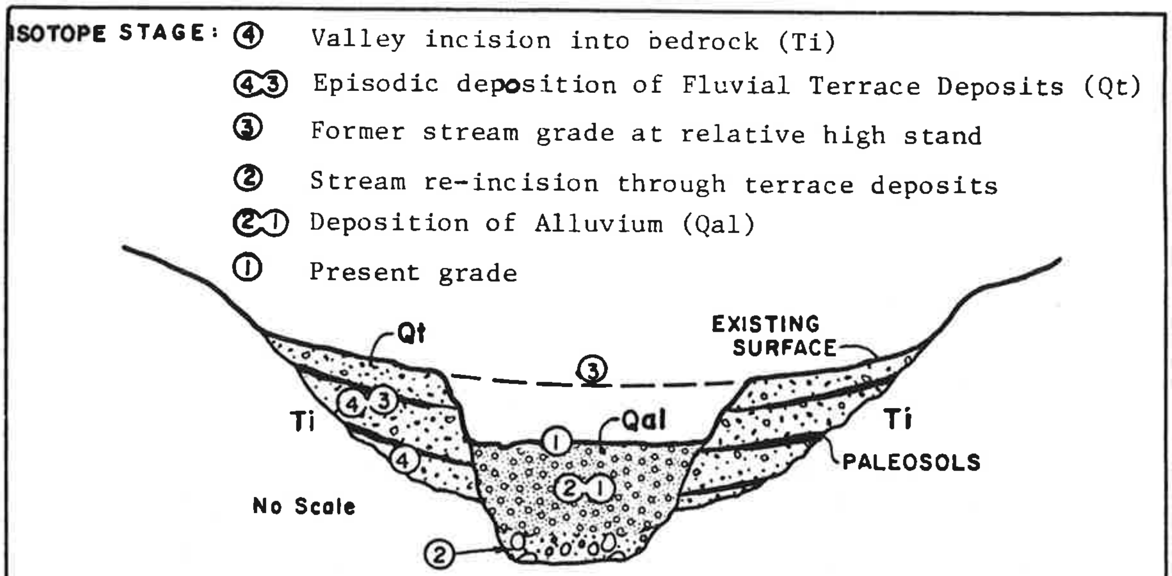
in elevations reported cannot be ascribed to investigators measuring different parts of the same terrace, such as the wave-cut platform versus the deposit cover, because there is no mappable cover. The basic disagreement among prominent investigators attests to the ambiguity of reported field evidence. It should be noted that most of the altitudes shown by Smith (1897, 1933) and Emory (1960) represent elevations of gently-sloping portions of narrow bedrock ridgelines, and have little or nothing in common with broad geomorphic terraces of the other seven islands.

As shown by this review of the literature, there is no positive evidence to indicate significant uplift of Catalina Island during the Quaternary. If such uplift had occurred, it seems highly probable that some obvious vestige of marine benching would have remained along its dozens of miles of coastline where promontories are found comprised of a variety of bedrock types. In light of this enigma, the late Quaternary history of Avalon Canyon must accordingly be based on data from the immediate area, and not from yet problematic evidence cited by earlier workers.

## Sea Level Fluctuations and Geochronology of Avalon Canyon

A geochronology of late Quaternary events in Avalon Canyon can be reconstructed using the geomorphic and stratigraphic features discussed relative to known changes in sea level. The glacio-eustatic sea level curves modified from Shackleton and Opdyke (1973) and Bloom and others (1974) have been superimposed at the same scale to show their general agreement of sea level trends (Fig. 5). The late Quaternary events in Avalon Canyon have been related to oxygen-isotope stages (1 - 4) of Shackleton and Opdyke (1973).

Based on the paucity of evidence for uplifted marine terraces on the island, the events which formed the geomorphic and stratigraphic features now present in Avalon Canyon have been reconstructed without postulated tectonic uplift. The results of at least two cycles of relative sea level fluctuations are apparent. The oldest deposits mapped are the Fluvial Terrace Deposits. The evidence is unequivocal that they were laid down at least as early as stage 3, about 40,000 to 60,000 years BP, and possibly much earlier. This is based on 1) soil profile development and soil horizon unconformities noted on Horse Trail Terrace, 2) the presence of rock clasts in



Diagrammatic profile across Avalon Canyon. Stages shown below.

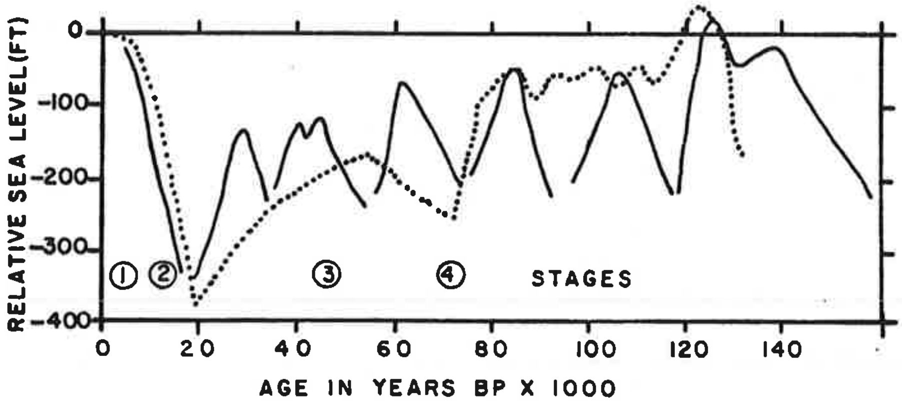


Figure 5 Geomorphic relationships across Avalon Canyon and paleosea level fluctuations. Dotted line curve and stages 1-4 modified from Shackleton and Opdyke (1973); solid line curve from Bloom and others (1974).

soils on Horse Trail Terrace which were transported prior to deep drainage incision, 3) at least a 20,000 to 25,000 year timespan necessary for development of the interbedded paleosols, and 4) the former geomorphic paleosurface, reconstructed from the upper surfaces of the terrace remnants, was graded to a former sea highstand prior to stage 2 downcutting.

The earlier cycle of relative sea level fluctuation began with erosion of the canyon floor at least during stage 4, some 70,000 years ago, and deposition of basal terrace deposit units, presently concealed. Marine transgression followed during stage 3, accompanied by stream aggradation and deposition of the estimated 70 to 80-feet of terrace deposits. The present terrace surface represents erosional remnants of the former, steeper geomorphic surface grade during (at least) stage 3 relative high stand of sea level. Subsequently, over 150 feet of stream incision occurred in response to the last major cycle of sea level drop during stage 2, approximately 17,000 to 20,000 years ago. As a result of the rapid stream incision, several tributary canyons to Falls Canyon now form hanging valleys, where Falls Canyon deepened more rapidly than the lower end of the tributaries. The last rise in sea level, since about 17,000 years ago, to its present position, has caused valley aggradation of the alluvium now present in modern Avalon Canyon.

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# SLIDE-MUDFLOW

## FISHERMANS COVE AREA, SANTA CATALINA ISLAND

(A Summary by L. Cann)

## Introduction & Background

A preliminary geologic investigation was conducted of the large ancient slide-mudflow in the Fishermans Cove near Two Harbors in 1965 (Leighton and Campbell) (See Figures 3, 4, 5). This investigation included geologic mapping and the excavation and down hole logging of six borings drilled to a maximum depth of 75' beneath the ground surface. Site specific studies were conducted related to the USC Marine Research Station and other temporary facilities in 1966 through 1968 (Crandall, Leighton and others). These studies included additional general and detailed mapping and additional subsurface exploration and testing.

The area surrounding this large ancient slide-mudflow was later investigated and mapped by Platt (1976), and by Vedder, Howell and Forman (1979), (see Figure 2).

## General Geology of the Area

The subject area is a faulted, north-dipping (strike N40-60$^{O}$E; dip 18-34$^{O}$N) sequence of interlayered volcanic and sedimentary rocks (see Figure ). Rocks of similar type have been found to exist on the seafloor at least as far as shiprock (Forman and others, 1972). The majority of the bedrock section (informally called the Fishermans Cove Sequence) is exposed in seacliffs from the east side of the isthmus cove to Blue Cavern Point and Empire Quarry. The thickness discontinuities, abrupt facies changes and non-persistent rock units characterize this bedrock sequence as shown below (Figure 1).

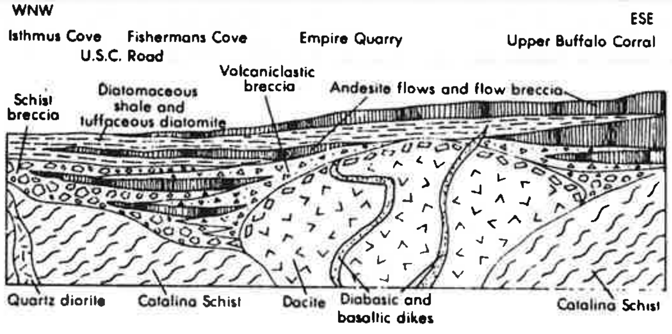
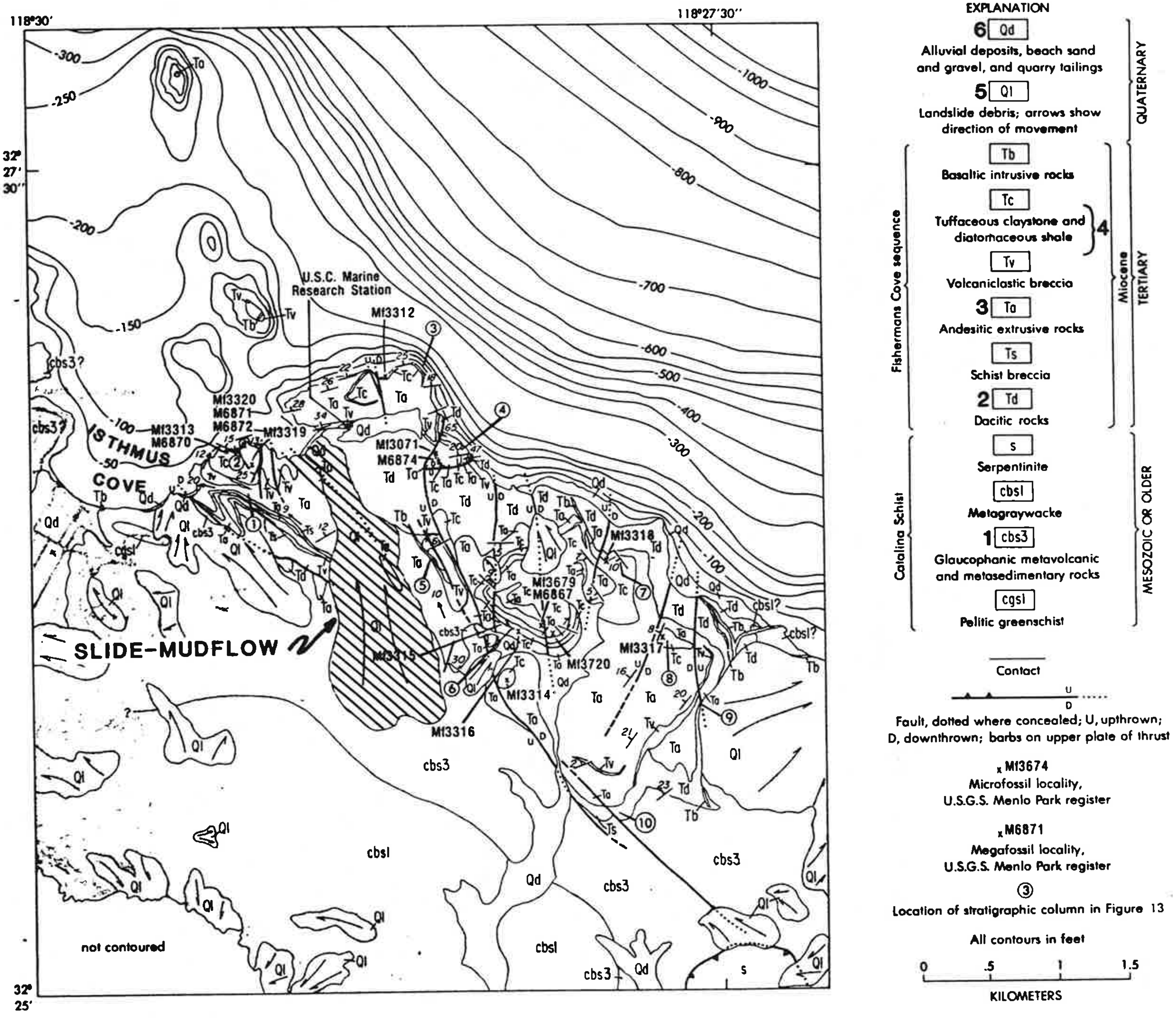
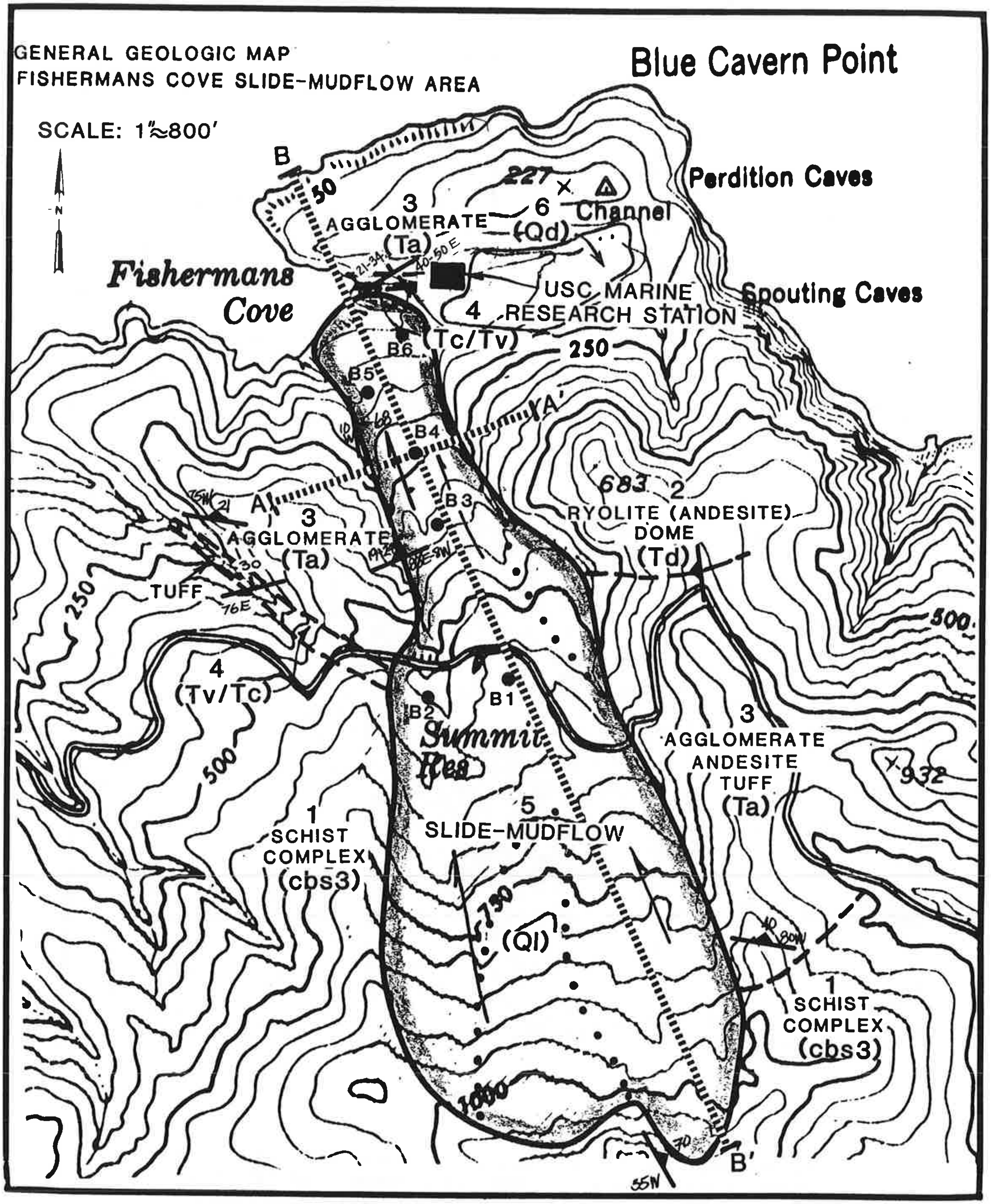


Figure 1 Diagrammatic reconstruction of Fishermans Cove sequence showing interrelations of Miocene rocks and their relation to the Catalina Schist.

**Figure 2**

Geologic map of Fishermans Cove area, northwestern Santa Catalina Island. Distribution and designation of subunits of Catalina Schist are modified from Platt (1976b), modified from Vedder, Howell, Forman; Cenozoic Paleogeography of the Western U.S.; SEPM, March 14, 1979.





SYMBOLS

50E 20 BEDDING

80E 25 FLOW STRUCTURE

10W 68 FAULT PLANE

cbs3,Ta . . . . . FROM FIGURE 2

1,2,3,4,5,6 . . . . FROM TEXT

● B6 BORING LOCATIONS

B ▮▮▮▮▮▮▮▮▮▮▮ B' CROSS-SECTIONS

Figure 3

The rock units that are exposed in closest proximity to the large ancient slide-mudflow, from oldest to youngest, are (1) a basement complex consisting primarily of glaucophane and talc schist with some minor greenstone and metasediments (cbs3); (2) a red banded rhyolite or andesite dome (Td); (3) interbedded platey and blocky dark andesite with tuffaceous and agglomeritic intervals (Ta); (4) tuffaceous claystone, diatomaceous hale and volcaniclastic breccia, (Tc/Tv); (5) slide-mudflow debris; slopewash, clayey colluvium and/or pond deposits contemporaneous in part with the landslide debris (Ql); and (6) alluvial deposits, beachsand and gravel, and quarry tailings (Qd) (See figures 2 and 3).

### Morphology of the Slide-Mudflow (See figures 3, 4, 5, 6)

| Parameter | Slide-Mudflow |
|---|---|
| Maximum Length (crown to tip) | 5,700' (See Figure 3) |
| Maximum width of foot | 900' |
| Maximum width of head | 2,100' |
| Difference in elevation (crown-tip) | 1,100' |
| Average slope angle (crown-tip) | 11° |
| Direction of movement | North to N25°W |
| Estimated maximum thickness | 200' (See cross-sections; Figure 6) |
| Measured minimum maximal thickness | 75' (See cross-sections; Figure 6) |
| General attitudes measured in bedrock volcanic sequence | Strike: N50°E to N45°W<br>Dep: 20°-23° northerly |

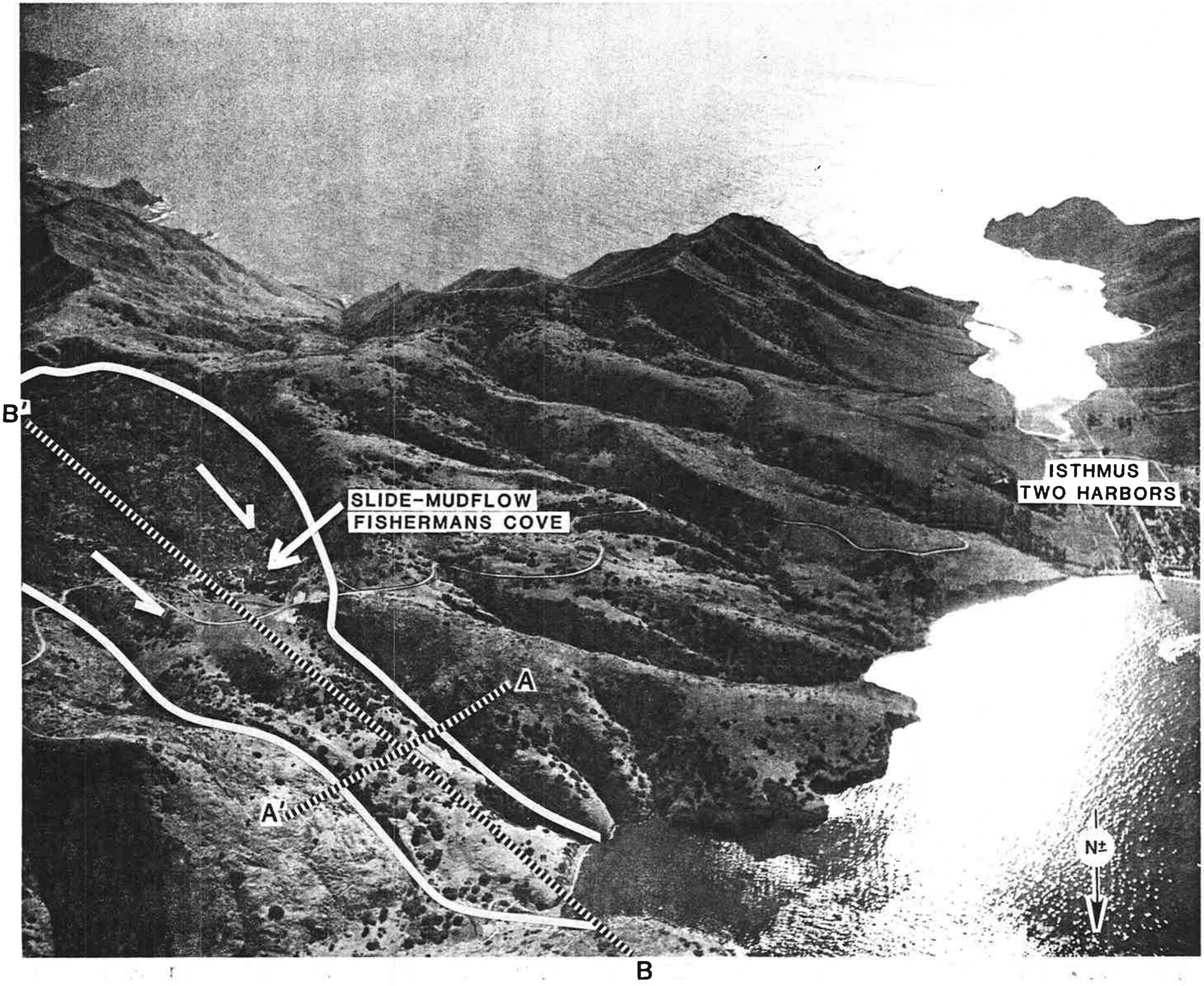
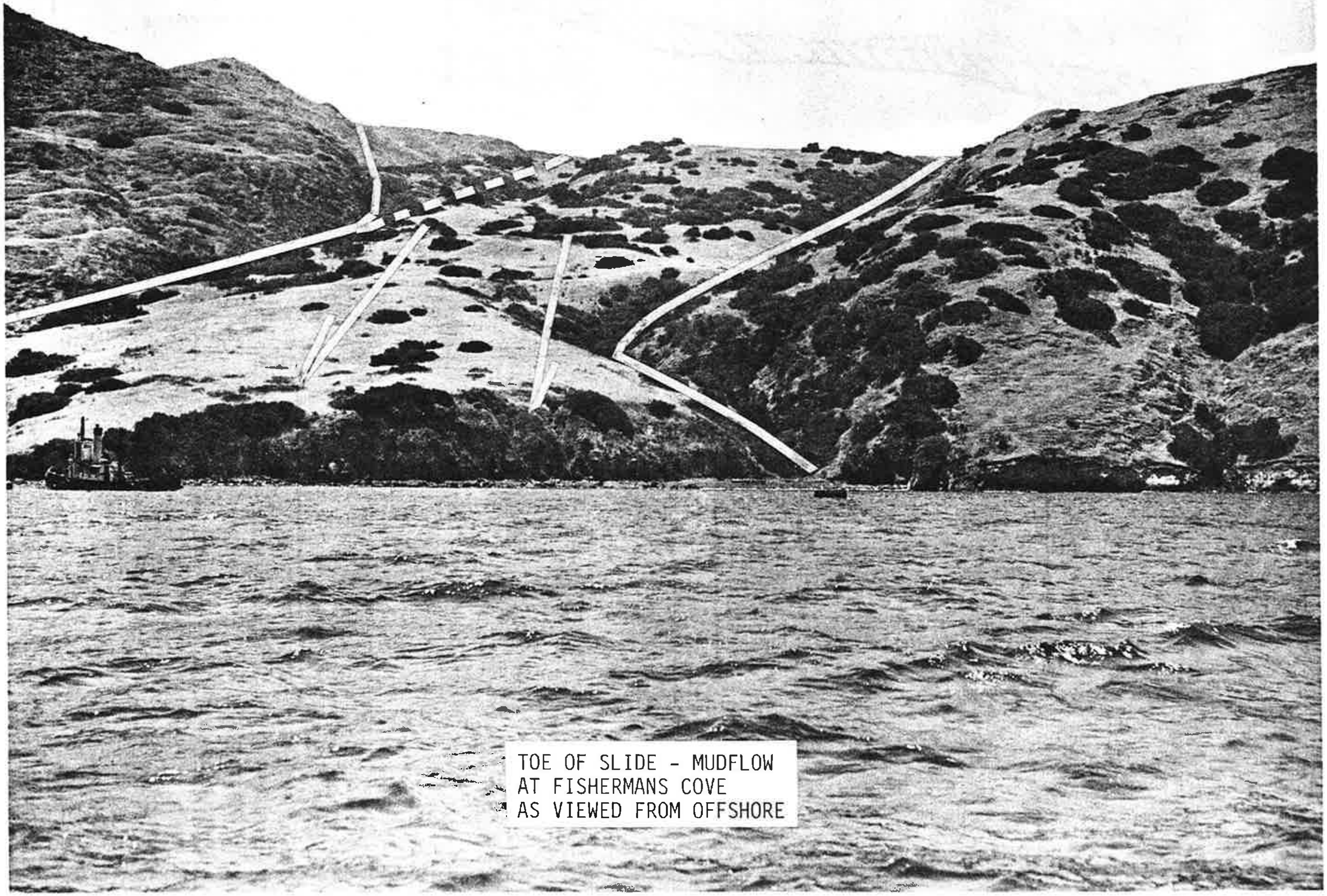
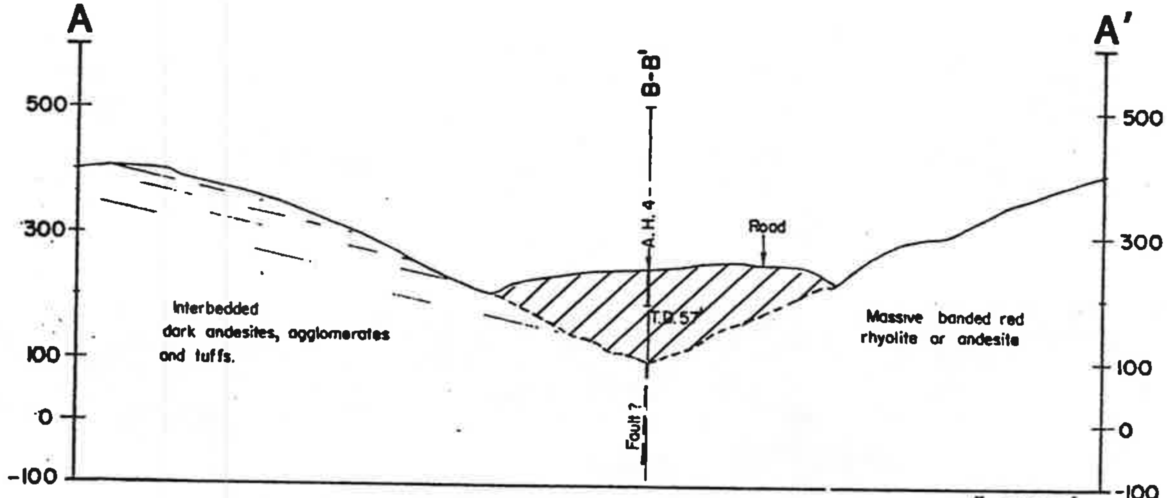


Figure 4

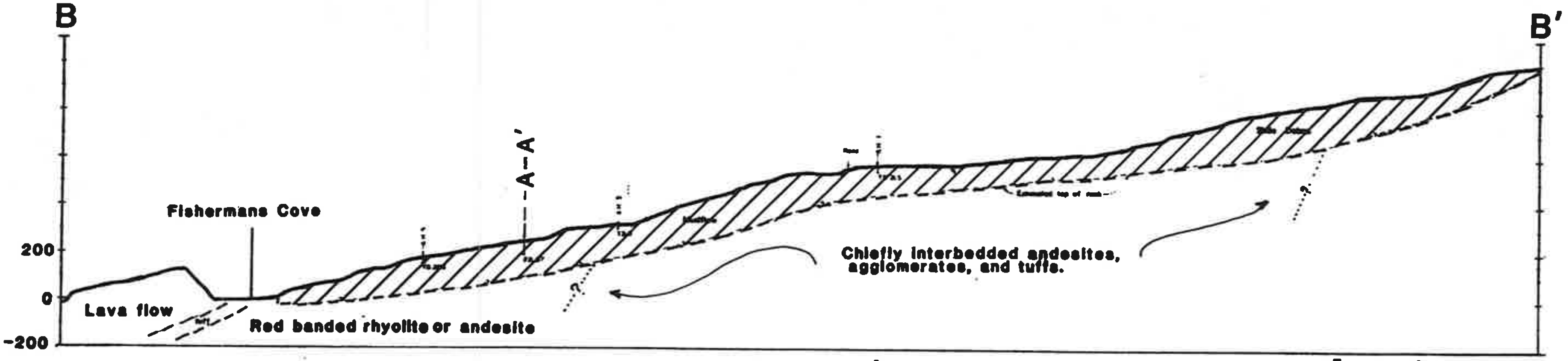


TOE OF SLIDE - MUDFLOW
AT FISHERMANS COVE
AS VIEWED FROM OFFSHORE

Figure 5



SECTION A-A' 1"≈300'



SECTION B-B' 1"≈700'

Figure 6

## Component Parts of the Slide-Mudflow Area

The complex slide-mudflow area can be divided into 4 constituent parts:

1. A large bedrock slide at the head of the present valley underlain by badly sheared and shattered glaucophane-talc schist.
2. A formerly wet mudflow that developed from the slide and behaved like wet concrete as it formed the foot of the slide and a lobate toe.
3. A basin area that developed at the head by removal of slide material and which was subsequently filled by talus accumulations of glaucophane-talc schist.
4. Islands and promontories of bedrock which occur in the mid-section of the slide and which may form at least a partial barrier against future movement (See Figure 7)

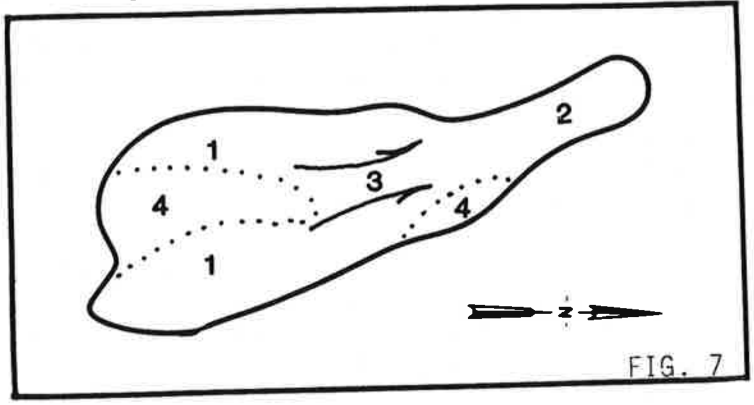


FIG. 7

## Age of the Slide-Mudflow

The principal slide-mudflow is prehistoric and probably of late Pleistocene age (over 10,000-20,000 years). Its antiquity is evidenced by the following conditions:

1. Surface runoff has carved boundary channels in volcanic bedrock locally as deep as 40 feet.

2. Indian artifacts and other signs of habitation are present on nearly every large bench or flat area.

3. Trees estimated to be 50-100 years in age grow erect and undisturbed on the slide.

4. A sea-cliff with a maximum height of 50 feet has been produced in slide debris at the present tip of the slide.

The only indication of recent movement is a small secondary slump located along the western flank near the toe (vicinity of Hole #5).

## Origin of the Slide-Mudflow

Essential conditions for the original slide-mudflow were as follows:

1. Superposition of strong volcanic rocks on badly sheared and shattered glaucophane-talc schist at the head of the slide area.

2. Headward erosion of the ancestral valley that became oversteepened and exposed the contact between these rocks.

3. Saturation by heavy rainfall of the raw slide material which then moved as viscous tongues.

4. Subsequent reactivation by slumping and flowage.

A relatively straight and deep canyon existed before the slide-mudflow occurred as is indicated by the relatively high and steep bedrock walls (see Figure 6). Although the major portion of the existing slide-mudflow probably moved as a unit, at one time, several intervals of reactivation are believed to have occurred. This is indicated by clay deposits in Hole 2, suggesting blockage of the surface drainage by slide-mudflow debris and multiple local ponding.

Rock units on opposite sides of the slide-mudflow do not correlate properly and it is suspected that the original canyon was formed along a north-northwest-trending fault zone roughly parallel to the accompanying geologic section B-B'. Evidence for this consists of (1) an apparent offset in the schist volcanic contact on either side of the slide; (2) numerous small northwest-trending fault planes observed on the west side of the slide; (3) distribution of volcanic debris within the slide mass; and (4) several topographic features which fit this hypothesis. While this hypothesis is currently favored, it is also possible to account for these features by differential erosion.

Two areas within the general outline of the slide are believed to possibly be in-place material (see Figure 7). The larger one divides the head of the slide into two separate source areas. It is believed that the westernmost of these source areas moved first as the schist is present at a much lower elevation in this location and the slide topography more subdued and less apparent. Sliding of the easternmost source area carried abundant volcanic blocks and blocked the drainage from the westernmost source to allow the colluvium and clay accumulations encountered in Hole No. 2. Intervals of reactivation undoubtedly took place interspersed with periods of alluvial and slopewash activities to account for the different horizons observed in the auger holes. Subsequent slumping of the mudflow blocks to produce the existing modified scarps and flat benches has also occurred.

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# Petrology and Geochemistry of Miocene Volcanic Rocks from Santa Catalina and San Clemente Islands, California

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**Abstract.** Major oxides and trace elements were analyzed in bulk-rock samples of middle Miocene volcanic rocks from Santa Catalina and San Clemente Islands located on the Southern California Continental Borderland. Volcanic rocks from Santa Catalina belong to the low- to medium-K calc-alkaline magma series and range in composition from basalt to rhyolite. Andesite samples have moderately fractionated rare-earth elements ($La_N/Lu_N \sim 3.4$) and have slight Eu anomalies ($Eu/Eu^*$ ranges from 0.73 to 0.94). Two subsets of andesite samples have different degrees of REE enrichment; $La_N$ averages 47 in 1 subset and 35 in the other. Spider-diagram patterns of the 2 sets are similar and exhibit only small fractionations.

Lavas on San Clemente belong to the medium-K calc-alkaline magma series and are compositionally bimodal: the dominant andesite unit has a range in $SiO_2$ content of 57 to 63 wt%, whereas the upper dacite and rhyolite units have a range of 69 to 70 wt% (rhyodacite). Andesite samples are moderately enriched in the light REE ($La_N$ averages 59), are moderately fractionated ($La_N/Lu_N = 3.7$), and have small Eu anomalies ($Eu/Eu^* = 0.74$). Spider-diagram patterns show small depletions in Ta-Nb, Sr, P, and Ti.

Volcanic rocks from Santa Catalina and San Clemente Islands belong to a group of 12 volcanic centers that were active in southern California between 17 and 13 Ma. An average initial $^{87}Sr/^{86}Sr$ value of 0.7034 ± 0.0003 (n = 7) for samples of this group implies a mantle origin. Although this group of volcanic suites is calc-alkaline, a subduction-related origin cannot be reconciled with the history of plate motion in this area. During the middle Miocene, shear between the Pacific and North American plates began to be distributed across a wide belt, perhaps as the crust was heated by rising sub-continental mantle. Resulting localized extension in the mantle may have initiated decompression melting that produced widespread volcanism in coastal southern California.

**Keywords:** California; islands; Miocene; volcanic rocks; geochemistry.

## Introduction

Igneous rocks of medial Miocene age crop out on about 17 named areas in coastal and offshore southern California, including 7 of the 8 southern California islands (Fig. 1), and are inferred to cover a significant portion of the California Borderland (e.g., Vedder et al. 1986). The cause of this widespread magmatism is unclear; theories fall into 4 general categories: (1) subduction of the Farallon plate beneath the North American plate, (2) southward migration of the Rivera triple junction, (3) overriding of the Pacific/Farallon spreading center, and (4) rifting of the lithospheric mantle as the Pacific and North American plates moved past each other. The timing of interaction between the Farallon, Pacific, and North American plates refined by Atwater (1989) effectively rules out the first 3 scenarios, and suggests that the Miocene igneous activity may have been the result of extension. In an early study of Neogene volcanic rocks in coastal southern California, Hawkins (1970) concluded that extensive volcanism originated in the mantle during regional dilation related to strike-slip faulting. Legg (1991) proposed that the extensive volcanism in the Southern California Continental Borderland was initiated by strike-slip related rifting (transtension) and that the volcanic flows on the 2 islands developed along the East Santa Cruz basin fault system that acted as a leaky transform fault. Both Santa Catalina and San Clemente Islands lie within what Crouch and Suppe (1993) term the "Los Angeles basin-inner borderland rift" and would represent rocks formed within the rift as the western Transverse Ranges block pivoted away from continental southern California. Weigand and Savage (1993) theorized that this rifting, whatever its origin, initiated decompression melting of the lithospheric mantle that resulted in the widespread Miocene volcanism.

This paper reviews previous work on volcanic rocks on Santa Catalina and San Clemente Islands, and new geochemical data are presented and discussed. It is shown below that these 2 volcanic centers share geochemical attributes with several other middle Miocene volcanic suites located south of Los Angeles in coastal and off-

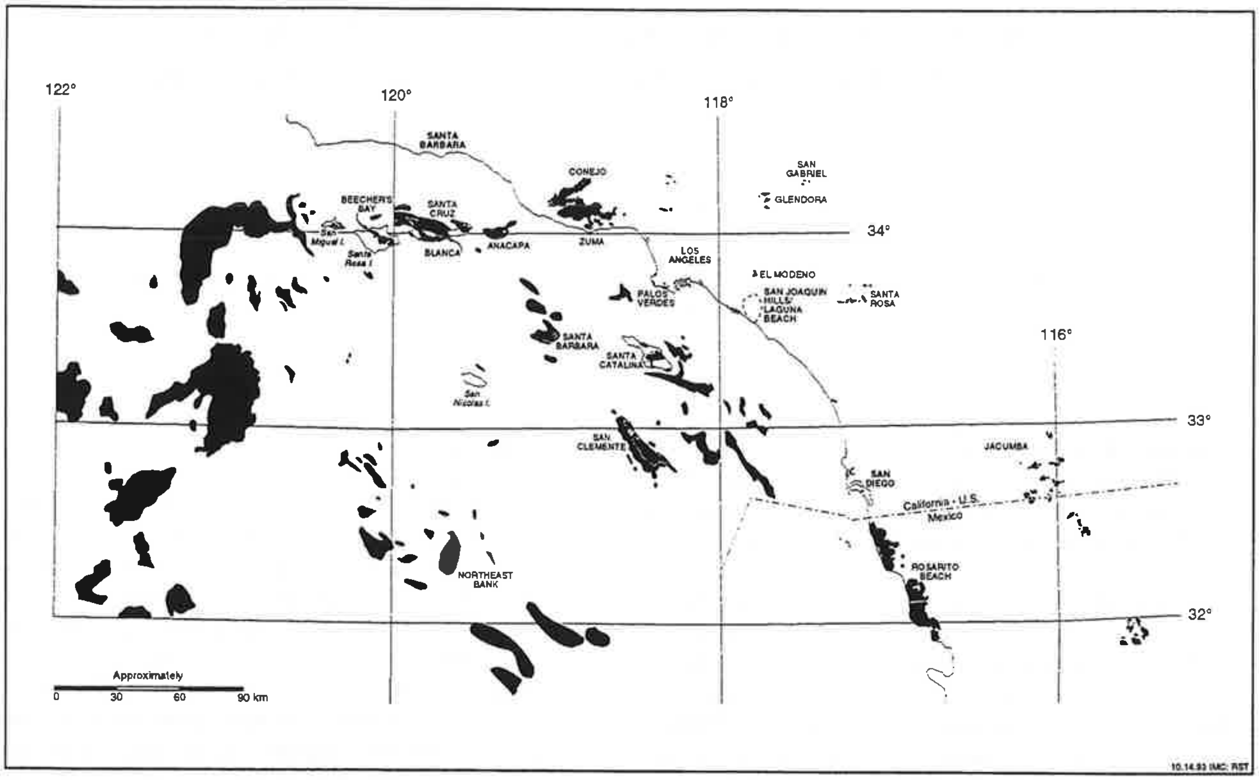

**Figure 1.** Map of Cenozoic volcanic areas in coastal and offshore southern California modified from Weigand and Savage (1993).

shore southern California and are collectively referred to as COSC (*Co*astal *s*outhern *C*alifornia) suites by Weigand and Savage (1993). The origin of these suites is then integrated into a tectono-magmatic model.

## Santa Catalina Island

Santa Catalina Island is located on the inner borderland about 30 km southwest of the Palos Verdes Peninsula (Fig. 1). Miocene igneous activity on the island took 2 forms (Fig. 2). A hornblende quartz diorite pluton intruded into Catalina Schist basement 19.5 ± 0.6 Ma (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$^2$. With the exception of a single whole-rock major-oxide analysis (Vedder et al. 1979), no geochemical work has been performed on this body.

Unconformably overlying the schistose basement and diorite pluton is a formerly extensive sequence of volcanic and sedimentary rocks now limited to 1 broad area midway between Avalon and the Isthmus and several other small areas. Volcanic rocks 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. Vedder et al. (1979) determined that volcanism began about 14.7 Ma and extended until some time after 12.4 Ma, and ascribed the igneous and depositional activity and concomitant crustal deformation to the encroachment of the Pacific-Farallon ridge and the southward passage of the Rivera triple junction. Stewart et al. (1992) measured initial Nd isotopic ratios in samples from some of the major igneous units on Santa Catalina. A basaltic-andesite flow yielded an epsilon Nd value of +9.4 and more felsic samples yielded values of +4.1 to +6.1. They interpreted these data to imply that the mafic magmas originated from depleted mantle during ridge subduction associated with triple-junction migration.

Wood's (1981) study of the volcanic rocks of the Black Jack Peak-Whitley's Peak area included detailed field descriptions, modal analyses, microprobe analyses of phenocrysts, and chemical analyses. In this area, Wood found the volcanic section to be composed of subaerially deposited lava flows, laharic breccias, and tabular and dome intrusions that exceed 400 m in thickness. He estimated the following abundances of rock types: 5% basalt,

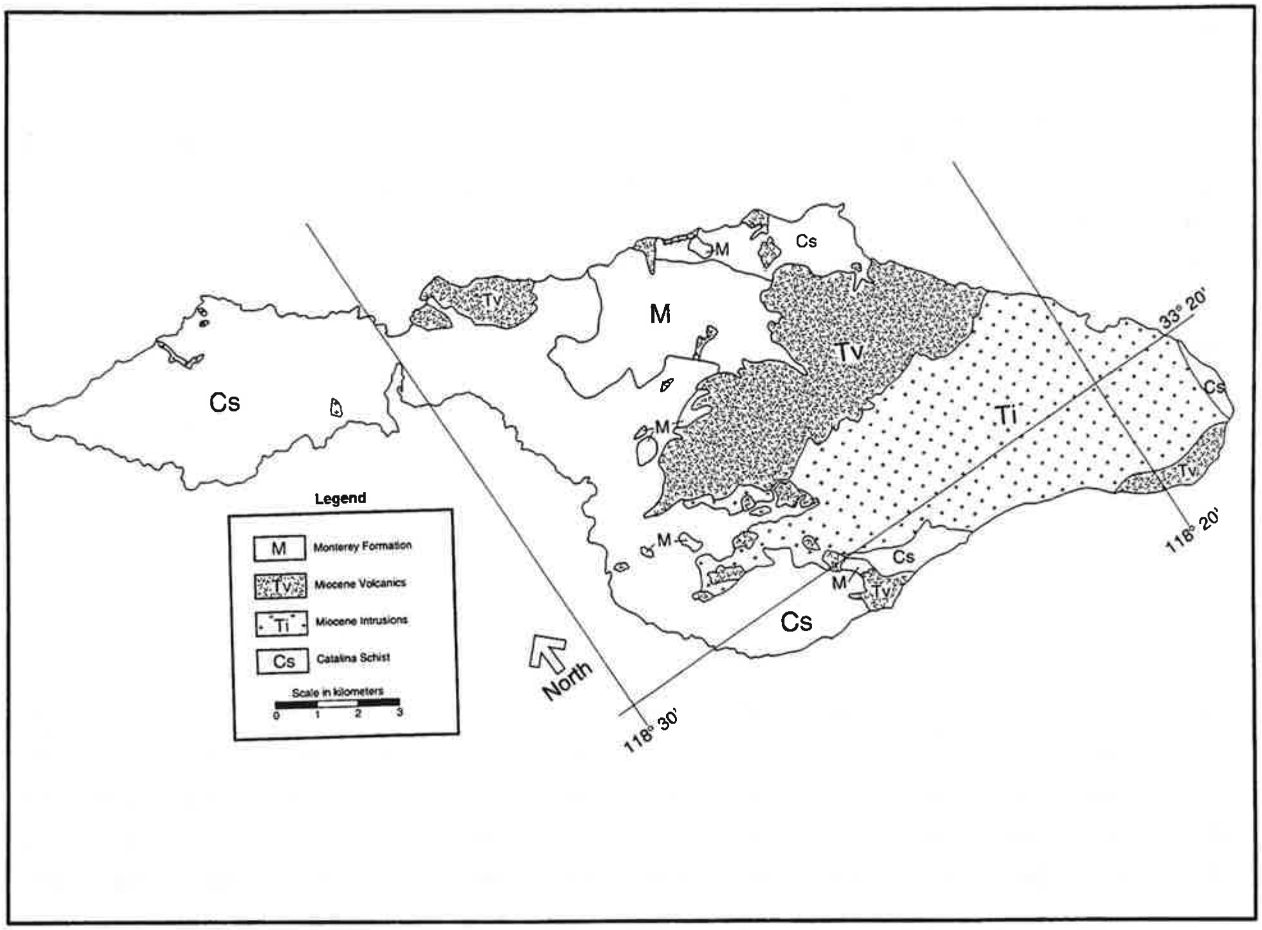

**Figure 2.** Generalized geologic map of Santa Catalina Island modified from Bailey (1985). Ti is hornblende quartz diorite and Tv is composed of a variety of volcanic and shallow intrusive units and sedimentary units.

**Table 1.** Microprobe analyses of phenocrysts from Santa Catalina volcanics (from Wood, 1981).

| | Basalt | Basaltic andesite | Andesite | Dacite |
|---|---|---|---|---|
| Olivine | $Fo_{79-77}$ | — | — | — |
| Plagioclase | $An_{64-61}$ | $An_{61-49}$ | $An_{47-42}$ | $An_{48-40}$ |
| Augite | Rare | $En_{48}Wo_{37}Fs_{16}$ | $En_{43}Wo_{39}Fs_{18}$ | Present |
| Hypersthene | — | $En_{72}Wo_{3}Fs_{25}$ | $En_{70}Wo_{2}Fs_{28}$ | Present |
| Hornblende | — | — | — | Present |
| Quartz | — | — | — | Present |

17% basaltic-andesite, 35% andesite, 40% dacite, and 5% rhyolite. A summary of Wood's (1981) microprobe analyses of phenocrysts is given in Table 1. Chemical analyses show that the suite is low- to medium-K and calc-alkaline and that moderately high $TiO_2$ (> 1.0 wt%) and the absence of Fe-enrichment typify these rocks. Hurst (1983) reported initial $^{87}Sr/^{86}Sr$ values for 2 basalt samples, 0.70294 and 0.70344. Hurst et al. (1982) suggested

**Table 2.** Analyses of andesite samples from Santa Catalina Island.

| | Ecb 1 | TA 29 | TA 22 | R 3 | TNAI | AVD | TA 12 | TA 51 | TPA5 | TDX | C 4 | C 2 | BASS |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 55.70 | 56.00 | 56.80 | 56.60 | 56.50 | 57.30 | 57.80 | 58.10 | 59.50 | 61.70 | 61.80 | 61.80 | 62.70 |
| $TiO_2$ | 1.27 | 1.25 | 1.24 | 1.34 | 1.25 | 0.90 | 0.90 | 0.88 | 0.93 | 0.57 | 1.21 | 1.27 | 0.86 |
| $Al_2O_3$ | 18.00 | 17.20 | 17.20 | 16.80 | 17.50 | 16.80 | 17.00 | 16.80 | 17.00 | 16.70 | 18.00 | 16.90 | 16.40 |
| $FeO_T$ | 6.85 | 6.07 | 6.24 | 6.36 | 6.06 | 5.20 | 5.34 | 5.24 | 5.04 | 4.06 | 5.23 | 5.52 | 4.56 |
| MnO | 0.13 | 0.12 | 0.15 | 0.17 | 0.11 | 0.12 | 0.15 | 0.14 | 0.10 | 0.09 | 0.07 | 0.10 | 0.08 |
| MgO | 4.45 | 3.94 | 4.21 | 4.13 | 4.19 | 4.87 | 4.32 | 4.30 | 4.12 | 1.38 | 1.95 | 2.10 | 3.22 |
| CaO | 8.06 | 7.36 | 7.33 | 7.53 | 8.59 | 7.57 | 6.89 | 6.93 | 6.22 | 4.13 | 5.36 | 4.65 | 5.88 |
| $Na_2O$ | 3.48 | 3.65 | 3.57 | 3.46 | 3.67 | 3.55 | 3.58 | 3.86 | 3.55 | 3.89 | 4.42 | 4.57 | 3.99 |
| $K_2O$ | 0.91 | 1.03 | 0.94 | 0.68 | 0.76 | 0.62 | 0.73 | 0.97 | 0.92 | 1.46 | 1.16 | 1.07 | 0.70 |
| $P_2O_5$ | 0.18 | 0.23 | 0.22 | 0.21 | 0.18 | 0.14 | 0.17 | 0.18 | 0.18 | 0.21 | 0.22 | 0.21 | 0.17 |
| $H_2O$ | — | 1.42 | 1.48 | — | — | — | 0.91 | 0.80 | — | — | — | 1.40 | — |
| Total | 99.03 | 98.27 | 99.38 | 97.28 | 98.81 | 97.07 | 97.79 | 98.20 | 97.56 | 94.19 | 99.42 | 99.59 | 98.56 |
| | | | | | | | | | | | | | |
| Cr | 162 | 50 | 55 | 58 | 116 | 142 | 137 | 134 | 121 | 9 | 15 | 15 | 102 |
| Ni | 65 | 49 | 61 | 70 | 57 | 60 | 58 | 54 | 72 | 42 | 0 | 59 | 102 |
| Zn | 94 | 79 | 80 | 80 | 87 | 72 | 80 | 73 | 73 | 69 | 76 | 75 | 66 |
| Sc | 25.7 | 19.2 | 19.1 | 19.1 | 21.3 | 18.6 | 18.3 | 17.4 | 16.7 | 7.6 | 14.1 | 14.4 | 14.0 |
| Rb | 31 | 35 | 41 | 12 | 17 | 20 | 26 | 31 | 35 | 35 | 32 | 48 | 18 |
| Sr | 312 | 241 | 337 | 245 | 307 | 349 | 418 | 353 | 411 | 318 | 456 | 300 | 296 |
| Cs | 1.9 | 7.7 | 5.5 | 7.0 | 2.3 | 0.6 | 0.7 | 1.0 | 1.0 | 1.5 | 58.7 | 34.9 | 6.7 |
| Ba | 358 | 568 | 619 | 537 | 614 | 334 | 373 | 316 | 337 | 581 | 831 | 626 | 458 |
| Zr | 165 | 158 | 124 | 146 | 136 | 127 | 133 | 102 | 102 | 97 | 178 | 133 | 104 |
| Sb | BD | 0.8 | 0.2 | 0.2 | 0.8 | 1.2 | 0.2 | 0.3 | 0.3 | 0.8 | 0.6 | 0.5 | 0.2 |
| Hf | 4.0 | 4.8 | 4.8 | 4.7 | 4.1 | 3.0 | 3.2 | 3.6 | 3.5 | 4.1 | 5.4 | 5.1 | 3.8 |
| U | BD | BD | BD | 1.2 | BD | 0.8 | BD | BD | BD | 0.9 | 2.2 | 1.9 | 1.6 |
| Th | 2.6 | 3.9 | 4.1 | 4.2 | 3.3 | 1.8 | 2.2 | 2.5 | 2.5 | 2.8 | 5.8 | 6.0 | 2.8 |
| La | 11.5 | 16.3 | 17.2 | 16.2 | 11.9 | 7.7 | 11.1 | 12.9 | 11.5 | 13.5 | 18.2 | 16.8 | 12.7 |
| Ce | 21.4 | 28.9 | 28.0 | 28.6 | 22.7 | 15.2 | 18.5 | 22.0 | 21.1 | 25.4 | 35.2 | 34.1 | 22.8 |
| Nd | 15.9 | 19.5 | 19.4 | 20.0 | 14.4 | 9.6 | 11.5 | 17.2 | 12.8 | 14.5 | 20.8 | 17.5 | 14.8 |
| Sm | 4.27 | 5.79 | 5.44 | 5.23 | 4.31 | 2.86 | 3.66 | 3.95 | 3.85 | 3.73 | 5.21 | 4.98 | 3.95 |
| Eu | 1.32 | 1.42 | 1.33 | 1.37 | 1.22 | 0.97 | 1.15 | 1.19 | 1.10 | 1.07 | 1.25 | 1.26 | 1.13 |
| Tb | 0.83 | 0.85 | 0.89 | 0.93 | 0.76 | 0.57 | 0.65 | 0.63 | 0.63 | 0.53 | 0.73 | 0.86 | 0.66 |
| Yb | 4.76 | 3.90 | 3.04 | 3.03 | 3.26 | 2.03 | 1.92 | 2.37 | 2.56 | 2.43 | 4.16 | 3.13 | 2.38 |
| Lu | 0.51 | 0.56 | 0.50 | 0.45 | 0.47 | 0.29 | 0.32 | 0.38 | 0.32 | 0.35 | 0.46 | 0.46 | 0.37 |

Major oxides in wt % (from Wood [1981]). $FeO_T$ is total Fe expressed as FeO. Trace elements in parts per million (ppm).

that the Catalina magmas originated in a dilational environment generated as the Rivera triple junction interacted with the North American plate.

Table 2 lists geochemical analyses of selected andesite samples from Santa Catalina. The major oxides, analyzed by atomic absorption and spectrophotometric

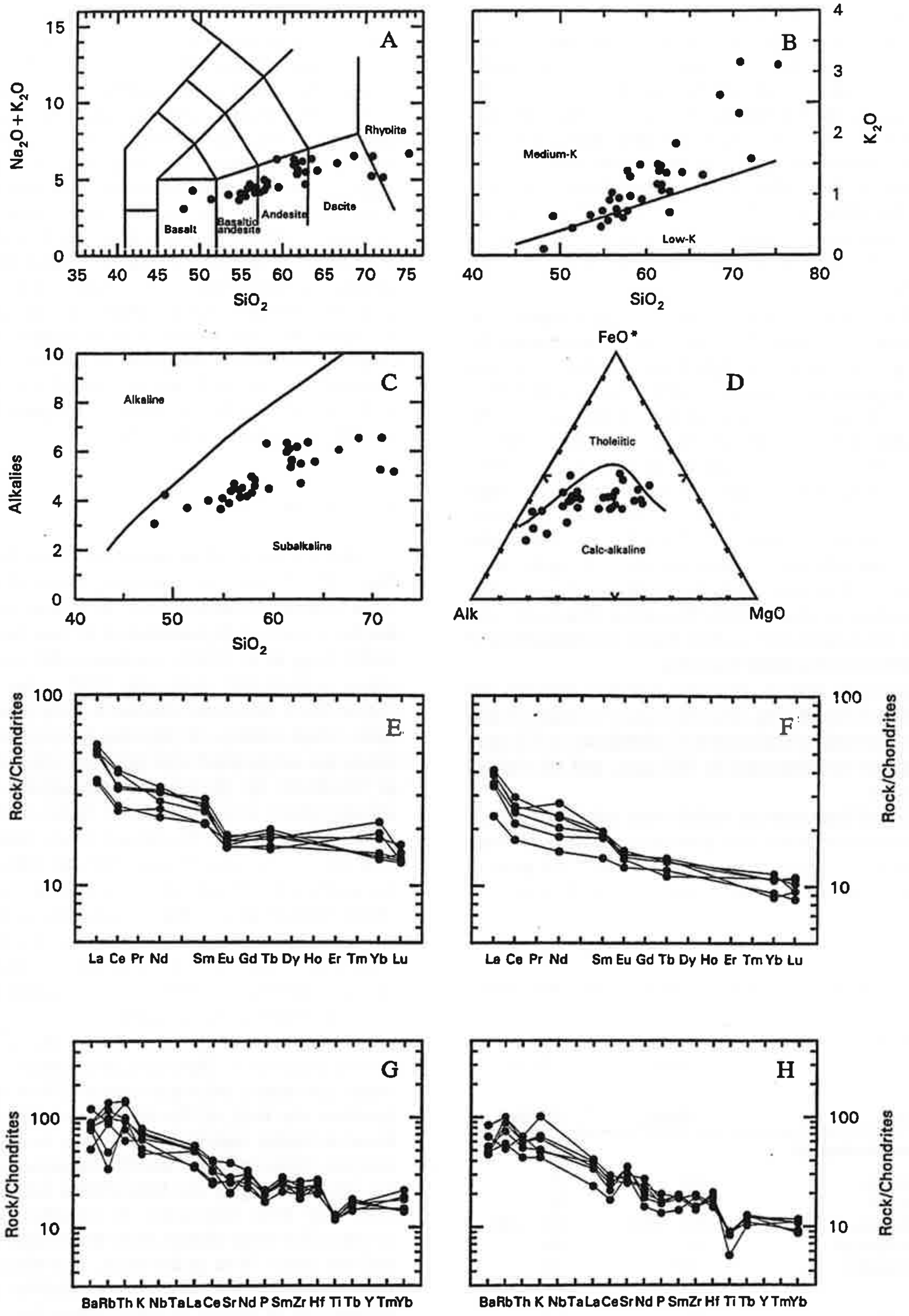

**Figure 3.** Geochemical diagrams for Santa Catalina samples. **3A.** Rock names of individual samples; boundaries from Le Bas et al. (1986). **3B.** $K_2O$ series; boundaries from Gill (1981, p. 6). **3C** and **3D.** Alkalies-silica and AFM diagrams for magma series; boundaries from Irvine and Baragar (1971). Alk = $Na_2O$ + $K_2O$. **3E.** Rare-earth element diagram for high Lu samples; normalizing data from Nakamura (1974). **3F.** Rare-earth element diagram for low Lu samples. **3G.** Spider diagram for high Lu samples; normalizing data from Thompson et al. (1984). **3H.** Spider diagram for low Lu samples.

methods, are from Wood (1981). The trace-element analyses are new and were performed by instrumental neutron activation methods. Figures 3a–d, which includes data from Vedder et al. (1979) and Wood (1981), confirms that the Santa Catalina volcanic rocks are calc-alkaline and low-K. The single available analysis of the 19.5-Ma hornblende quartz diorite (Vedder et al. 1979) is compositionally similar to andesite on Catalina with the exception of higher $Na_2O$ and lower $P_2O_5$. This similarity strengthens the conclusion by Vedder et al. (1979) that the pluton and the younger lavas have a close genetic relationship.

Plots of the rare-earth elements (REE) normalized to chondritic meteorites (Fig. 3e-f) are characterized by slight enrichment of the light REE ($La_N/Lu_N$ ~3.4) and slight negative Eu anomalies (Eu/Eu* ranges from 0.73 to 0.94, where Eu* is the concentration of Eu calculated by interpolating between its neighbors on the REE pattern). These plots reveal 2 subsets of samples, a lower $SiO_2$ group in which $La_N$ averages 47 and a higher $SiO_2$ group in which $La_N$ averages 35. Patterns on spider diagrams, also normalized to chondrites, of the 2 groups are similar and exhibit only small fractionations (Fig. 3g-h); most samples show a small negative spike for Ti and a few show a positive spike for Ce. The group of samples with higher La contents has slightly higher concentrations of all of these incompatible elements.

Although several analyzed Catalina samples are classified as basalt (Fig. 3a), none can be considered particularly primitive. The highest Ni abundance is 102 ppm, the highest Cr abundance is 162 ppm, and the highest Mg# is 65.

Crystal fractionation models were calculated using 3 representative samples that span the compositional range from basalt to rhyolite. A 2-stage model was used in which a representative basalt ($SiO_2$ = 50.0 wt%) was considered parental to a representative dacite ($SiO_2$ = 63.0 wt%), and then that dacite was considered parental to a representative rhyolite ($SiO_2$ = 71.0 wt%). Mineral analyses used were microprobe analyses of phenocrysts from Wood (1981). Results of the calculations (Table 3) yield low sums of squares of residuals (sosor) that indicate a good fit in both cases. The large amount of plagioclase suggested for both stages is consistent with its high abundance in rocks of mafic to intermediate composition. The presence of olivine and augite in the first stage corresponds to their presence in Catalina basalts; similarly, the presence of hornblende in the second stage corresponds to its common presence in Catalina dacites. These models, based on major oxides, were then tested using trace elements. Compositional trends of both compatible elements such as Ni and Cr and incompatible elements such as Rb and Zr can be successfully reproduced using the mineral assemblages of Table 3.

**Table 3.** Summary of modelling calculations for Santa Catalina samples.

| Parent | basalt | | dacite | |
|---|---|---|---|---|
| Daughter | dacite | | rhyolite | |
| % Mineral subtracted | | | | |
| Olivine | 6.1 | | 0 | |
| Augite | 22.2 | | 0 | |
| Plagioclase (% An) | 43.1 | (62) | 33.4 | (30) |
| Hornblende | 0 | | 9.4 | |
| Magnetite | 5.9 | | 3.1 | |
| % Liquid left | 22.6 | | 50.0 | |
| SOSOR | 0.14 | | 0.04 | |

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

## San Clemente Island

San Clemente Island lies about 50 km WNW of San Diego (Fig. 1). It 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). Legg et al. (1989) considered this fault to be an active, right-lateral, strike-slip fault within the broad Pacific-North American transform plate boundary. The entire island consists of Miocene volcanic rocks that in places are interbedded with Miocene sedimentary rocks or blanketed by Quaternary sedimentary rocks and unconsolidated sediments (Fig. 4; Smith 1897; 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). Unlike Santa Catalina, no older basement rocks crop out on San Clemente. Also, submarine volcanism predominated on San Clemente (Vedder and Howell 1976), whereas subaerial volcanic rocks are found on Santa Catalina.

Much of the following review of the volcanic rocks is summarized from Olmsted (1958). Andesite flows and minor pyroclastic units that exceed 600 m in thickness dominate the bulk of the island. Andesite varies from dense to highly vesicular with sparse to abundant phenocrysts. Phenocrysts are mostly plagioclase (~$An_{50}$) with less abundant augite and hypersthene. Groundmass textures vary from hyalopilitic to holocrystalline. Dacite occurs as 2 or more distinct flows that overlie the andesite and that reach 70 m in thickness. It is characterized by flow banding and is aphanitic to slightly porphyritic. Phenocrysts of mostly andesine plagioclase ($An_{45-40}$) and sparse hypersthene and augite are set in a pilotaxitic groundmass. Flows and minor tuff of rhyolite composition up to 45 m thick also overlie the andesite flows; rhyolite and dacite are not in contact with each other.

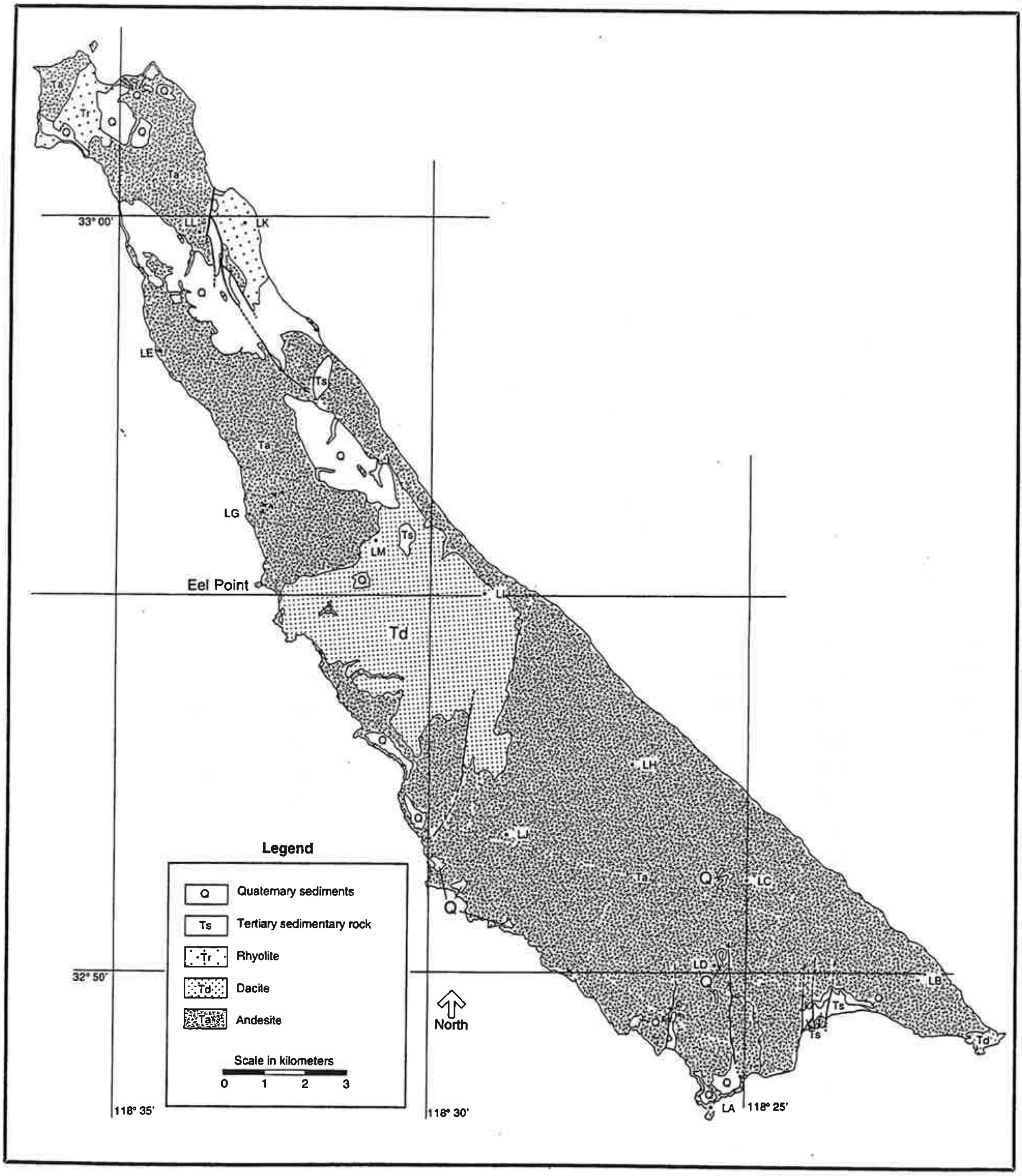

**Figure 4.** Generalized geologic map of San Clemente Island modified from Olmsted (1958).

Phenocrysts are predominantly andesine ($An_{45-40}$) and minor hypersthene, augite, and quartz.

Merifield et al. (1971) described the petrology of a core drilled at Eel Point, which is located about mid-island on the southwest coast (Fig. 4). About 364 m of andesite were encountered, which are largely not exposed on the island. The andesite is composed of phenocrysts of plagioclase (~35%), augite (~5%), and hypersthene (< 1%) set in a matrix containing variable amounts of feldspar, pyroxene, and glass. Phenocrystic plagioclase

**Table 4.** Major-oxide whole-rock analyses of samples from San Clemente Island.

| Unit<br>Site<br>Sample | Ta<br>LA<br>1 | Ta<br>LA<br>6 | Ta<br>LB<br>24 | Ta<br>LB<br>26 | Ta<br>LC<br>31 | Ta<br>LE<br>61 | Ta<br>LGA<br>69 | Ta<br>LGC<br>83 |
|---|---|---|---|---|---|---|---|---|
| $SiO_2$ | 59.14 | 57.05 | 62.62 | 61.67 | 62.40 | 58.75 | 57.72 | 58.40 |
| $TiO_2$ | 1.49 | 1.44 | 1.10 | 1.13 | 1.10 | 1.12 | 1.16 | 1.18 |
| $Al_2O_3$ | 15.86 | 15.79 | 15.52 | 15.02 | 15.73 | 15.46 | 15.90 | 15.64 |
| $FeO_T$ | 6.79 | 6.68 | 5.70 | 5.60 | 5.58 | 5.85 | 5.83 | 6.01 |
| MnO | 0.12 | 0.12 | 0.10 | 0.10 | 0.10 | 0.11 | 0.15 | 0.10 |
| MgO | 4.17 | 3.93 | 2.45 | 2.42 | 2.50 | 5.15 | 4.66 | 4.28 |
| CaO | 6.73 | 6.87 | 4.77 | 4.72 | 5.07 | 6.25 | 7.17 | 6.37 |
| $Na_2O$ | 4.55 | 5.11 | 4.84 | 4.66 | 4.39 | 4.75 | 4.13 | 8.43 |
| $K_2O$ | 1.28 | 1.21 | 1.83 | 1.87 | 1.96 | 1.49 | 1.26 | 1.26 |
| $P_2O_5$ | 0.07 | 0.23 | 0.19 | 0.20 | 0.13 | 0.21 | 19.18 | 0.03 |
| Total | 100.20 | 98.43 | 99.12 | 97.39 | 98.96 | 98.06 | 99.12 | 101.70 |

| Unit<br>Site<br>Sample | Ta<br>LGC<br>85 | Ta<br>LGC<br>86 | Ta<br>LGC<br>87 | Ta<br>LGD<br>96 | Ta<br>LGE<br>106 | Ta<br>LGG<br>109 | Ta<br>LGG<br>112 |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 58.09 | 58.19 | 58.12 | 58.52 | 57.83 | 61.70 | 60.81 |
| $TiO_2$ | 1.17 | 1.16 | 1.17 | 1.17 | 1.12 | 1.17 | 1.15 |
| $Al_2O_3$ | 16.36 | 15.82 | 15.68 | 15.79 | 16.27 | 16.04 | 15.85 |
| $FeO_T$ | 5.84 | 5.91 | 6.23 | 5.82 | 5.45 | 5.55 | 5.10 |
| MnO | 0.10 | 0.11 | 0.11 | 0.12 | 0.09 | 0.09 | 0.08 |
| MgO | 4.23 | 4.26 | 4.53 | 4.45 | 4.53 | 3.45 | 3.57 |
| CaO | 6.76 | 6.66 | 6.16 | 6.65 | 6.71 | 5.56 | 5.56 |
| $Na_2O$ | 4.35 | 4.50 | 4.30 | 4.86 | 4.69 | 4.05 | 4.02 |
| $K_2O$ | 1.24 | 1.24 | 1.24 | 1.34 | 1.35 | 1.83 | 1.86 |
| $P_2O_5$ | 0.25 | 0.21 | 0.18 | 0.19 | 0.18 | 0.18 | 0.18 |
| Total | 98.39 | 98.06 | 97.72 | 98.91 | 98.22 | 99.62 | 98.18 |

| Unit<br>Site<br>Sample | Ta<br>LGH<br>117 | Ta<br>LGH<br>120 | Ta<br>LH<br>139 | Tr<br>LK<br>165 | Ta<br>LL<br>176 | Ta<br>LL<br>179 | Td<br>LM<br>182 |
|---|---|---|---|---|---|---|---|
| $SiO_2$ | 58.80 | 59.04 | 60.50 | 69.83 | 62.13 | 61.83 | 69.26 |
| $TiO_2$ | 1.08 | 1.10 | 1.35 | 0.59 | 1.06 | 1.07 | 0.58 |
| $Al_2O_3$ | 15.39 | 15.26 | 15.66 | 15.37 | 17.10 | 16.23 | 15.12 |
| $FeO_T$ | 6.13 | 5.88 | 6.15 | 2.34 | 4.70 | 4.62 | 3.66 |
| MnO | 0.10 | 0.10 | 0.11 | 0.01 | 0.06 | 0.07 | 0.04 |
| MgO | 5.45 | 5.26 | 3.86 | 0.61 | 2.41 | 2.55 | 0.78 |
| CaO | 6.15 | 6.07 | 6.16 | 2.49 | 5.73 | 5.50 | 2.44 |
| $Na_2O$ | 4.36 | 6.29 | 4.51 | 4.47 | 4.59 | 4.43 | 5.00 |
| $K_2O$ | 1.23 | 1.30 | 1.46 | 2.49 | 1.86 | 1.90 | 2.48 |
| $P_2O_5$ | 0.03 | 0.05 | 0.22 | 0.99 | 0.18 | 0.14 | 0.12 |
| Total | 98.72 | 100.35 | 99.98 | 99.19 | 99.82 | 98.34 | 99.48 |

Site refers to collecting sites on Figure 4. Major oxides in wt %. $FeO_T$ is total Fe expressed as FeO.

ranges in composition from cores up to An$_{78}$ to rims down to An$_{47}$. Hawkins and Hawkins (1977) reported phenocryst compositions of hypersthene (W$_4$En$_{67}$Fs$_{29}$) and augite (Wo$_{38}$En$_{45}$Fs$_{17}$) in San Clemente andesite and dacite.

Merifield 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. Turner (1970) 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. Thus, volcanism lasted about 2.5 m. y. and probably longer if older volcanic rocks exist below the bottom of the core hole.

Hawkins and Divis (1975) reported initial $^{87}Sr/^{86}Sr$ values of 0.7042 on an andesite and 0.7045 on a rhyolite; Johnson and O'Neil (1984) reported an initial $^{87}Sr/^{86}Sr$ value of 0.70371 and a value for $\delta^{18}O$ of 6.8‰ on the rhyolite sample dated by Turner.

Tables 4 and 5 list whole-rock major-oxide analyses of samples from paleomagnetic drill cores (Luyendyk et al. 1988: sample numbers are keyed to sites shown on Fig. 4). These samples, largely andesite, are calc-alkaline and medium-K (Figs. 5a–d). Samples collected from Olmsted's (1958) lower andesite unit are all classified as andesite based on $SiO_2$ abundances, which range from 57.0 to 62.6 wt%. Collecting area LG represents 6 separate sites located near a dirt road that extends from near Black Point west to the coast (Fig. 4). Increasing sample numbers represent sites positioned higher in the section. Elevations range from 25 ft above sea level for site LGA to about 675 ft at site LGH. Samples from 5 of the sites are virtually indistinguishable ($SiO_2$ = 57.7 to 59.0 wt%) whereas the 2 samples from site LGG (475 ft elevation) have slightly higher $SiO_2$ abundances (60.8 to 61.7 wt%). The 2 samples from site LL, which is located in Olmsted's (1958) porphyritic andesite unit, exhibit no differences in major oxides compared to samples from the main andesite unit. The 3 samples collected from the dacite and rhyolite units are identical to each other with respect to major oxides.

Trace-element analyses of 4 representative andesite samples are listed in Table 5. Rare-earth patterns are straight (Fig. 5e) and exhibit slight light REE enrichment ($La_N/Lu_N$ = 3.7) and small negative Eu anomalies (Eu/Eu* = 0.74). Concentrations of Gd may be somewhat elevated due to analytical difficulties (M. Walawender 1993, pers. comm.), which would exaggerate these negative Eu anomalies. Spider diagrams (Fig. 5f) exhibit negative spikes for Ti, P, Sr, and possibly Ba, and a small Ta-Nb trough.

None of the analyzed Clemente samples can be considered primitive. No basalt or basaltic-andesite have been reported from the island. The highest Ni abundance is 50 ppm, the highest Cr, 169 ppm, and the highest Mg# is 61.

Results of least-squares calculations of fractional crystallization models show that andesite sample SCL 66

**Table 5.** Major-oxide and trace-element whole-rock analyses of samples from San Clemente Island.

| Unit | Ta | Ta | Ta | Td |
|---|---|---|---|---|
| Site | LC | LGA | LH | LI |
| Sample | 33 | 66 | 137 | 148 |
| $SiO_2$ | 63.40 | 58.50 | 61.10 | 69.90 |
| $TiO_2$ | 1.10 | 1.20 | 1.39 | 0.54 |
| $Al_2O_3$ | 15.30 | 15.20 | 14.80 | 14.50 |
| $FeO_T$ | 5.16 | 5.56 | 5.62 | 3.05 |
| MnO | 0.08 | 0.09 | 0.10 | 0.03 |
| MgO | 2.24 | 4.46 | 3.51 | 0.48 |
| CaO | 4.87 | 6.64 | 5.68 | 2.11 |
| $Na_2O$ | 4.36 | 3.89 | 4.32 | 5.22 |
| $K_2O$ | 1.58 | 1.33 | 1.19 | 2.24 |
| $P_2O_5$ | 0.24 | 0.18 | 0.23 | 0.10 |
| LOI | 1.16 | 1.39 | 0.93 | 1.23 |
| Total | 99.49 | 98.44 | 98.87 | 99.40 |
| V | 120 | 150 | 170 | 34 |
| Cr | 34 | 169 | 85 | 11 |
| Ni | 12 | 50 | 43 | 7 |
| Co | 13 | 24 | 22 | 5.2 |
| Cu | 22 | 39 | 35 | 11 |
| Zn | 89 | 87 | 93 | 57 |
| Sc | 15.9 | 21.6 | 20.3 | 8.39 |
| Rb | 69 | 56 | 56 | 106 |
| Sr | 250 | 250 | 260 | 190 |
| Cs | 3.0 | 1.3 | 2.1 | 1.10 |
| Ba | 510 | 320 | 360 | 600 |
| Y | 75 | 47 | 45 | 37 |
| Zr | 250 | 190 | 210 | 330 |
| Nb | 14 | 12 | 11 | 16 |
| Sb | 0.2 | 0.2 | 0.3 | 0.3 |
| Hf | 6.7 | 4.5 | 5.4 | 8.2 |
| Ta | 0.5 | 0.5 | 0.7 | 0.7 |
| U | 1.5 | 1.5 | 1.4 | 2.1 |
| Th | 4.4 | 3.8 | 3.7 | 6.1 |
| La | 24.5 | 18.7 | 15.3 | 19.2 |
| Ce | 42 | 42 | 35 | 41 |
| Nd | 26 | 23 | 19 | 20 |
| Sm | 6.15 | 5.64 | 4.71 | 4.59 |
| Eu | 1.80 | 1.49 | 1.68 | 1.14 |
| Gd | 10.1 | 8.3 | 6.4 | 6.1 |
| Tb | 1.3 | 1.2 | 0.8 | 0.9 |
| Dy | 8.9 | 7.8 | 6.5 | 5.7 |
| Yb | 4.58 | 3.53 | 3.02 | 3.18 |

Major oxides in wt %. $FeO_T$ is total Fe expressed as FeO. LOI = *L*oss *O*n *I*gnition. Trace elements in parts per million (ppm). Analytical methods listed in Weigand and Savage (1993).

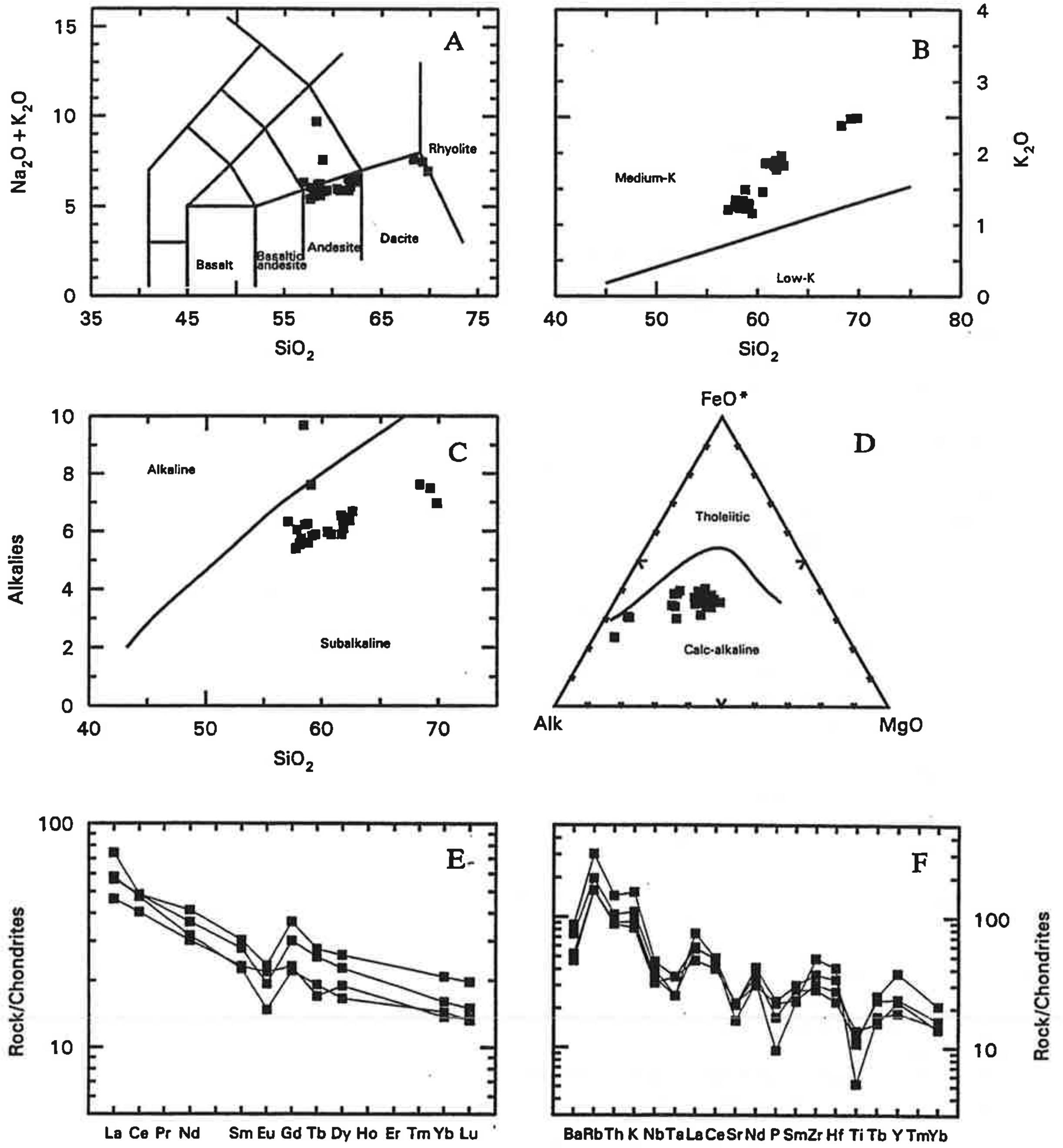

**Figure 5.** Geochemical diagrams for San Clemente samples. **5A.** Rock names of individual samples. **5B.** $K_2O$ series. **5C.** Alkalies-silica diagram. **5D.** AFM diagram. **5E.** Rare-earth element diagram. **5F.** Spider diagram.

($SiO_2$ = 58.50 wt%) can yield dacite sample SCL 33 ($SiO_2$ = 63.40 wt%) by the subtraction of an assemblage of plagioclase ($An_{50}$), augite ($Wo_{41}En_{50}Fs_{10}$), hypersthene ($Wo_4En_{80}Fs_{15}$), and magnetite (Table 6). The same parent can yield dacite sample SCL 148 ($SiO_2$ = 69.90 wt%) by the subtraction of different proportions of the same minerals. The validity of these calculations is strengthened by the fact that these are the same minerals found as phenocrysts in San Clemente andesite and the proportions are in the same order (Merifield et al. 1971). In addition, subtraction of these assemblages reproduces the variations exhibited by a variety of trace elements.

**Table 6.** Summary of modelling calculations for San Clemente samples.

| Parent | andesite<br>LGA 66 | andesite<br>LGA 66 |
|---|---|---|
| Daughter | dacite<br>LC 33 | dacite<br>LI 148 |
| % Mineral subtracted | | |
| Olivine | 0 | 0 |
| Augite | 7.9 | 13.5 |
| Hypersthene | 5.8 | 7.5 |
| Plagioclase | 14.0 | 25.0 |
| Magnetite | 1.3 | 2.8 |
| Ilmenite | 0 | 0.9 |
| % Liquid left | 70.6 | 50.1 |
| SOSOR | 0.08 | 0.04 |

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

## Comparison

Volcanic rocks from Santa Catalina and San Clemente Islands belong to a group of 12 volcanic centers that were active in southern California between 17 and 13 Ma. The analyzed samples from these COSC suites show a preponderance of andesite, are calc-alkaline and have medium or medium-to-low contents of K. Two representative $SiO_2$-variation diagrams (Fig. 6) emphasize this relative homogeneity (data sources listed in Weigand 1994). Nevertheless, each area exhibits subtle differences. For instance, the Santa Catalina samples extend over a greater $SiO_2$ range than the other areas and have somewhat lower concentrations of $TiO_2$ and $K_2O$ than those from the other areas. San Clemente samples have a somewhat higher concentration of MgO than those from the other areas. Samples from El Modeno are characterized by a very restricted range in $SiO_2$, whereas the Rosarito Beach and San Clemente suites exhibit a gap in $SiO_2$ contents. Some of the Rosarito samples also have the highest $TiO_2$ contents.

There are too few data to make many observations about trace elements. Rare-earth patterns show a modest enrichment of the light REE compared to chondrites ($La_N$ ranges from 30 to 54) and compared to the heavy REE ($La_N/Lu_N$ ranges from 3.1 to 5.3). Slight negative Eu-anomalies are shown by samples from only 2 areas; Eu/Eu* averages 0.85 for Santa Catalina andesites and 0.74 for San Clemente samples. San Clemente samples, the only ones for which reliable Ta and/or Nb data are available, exhibit a small negative Ta-Nb trough on the spider diagram.

## Discussion

All of the COSC suites belong to the calc-alkaline magma series. Although only a few samples have a reliable data for Nb and/or Ta, those from San Clemente exhibit small but distinct Nb-Ta troughs on a spider diagram, which is a characteristic of subduction-related igneous rocks (Thompson et al. 1984). The success of the fractional crystallization modelling for the Santa Cruz and Santa Catalina suites, including the ability to reproduce trace-element patterns, suggests that fractionation of a low-temperature mineral assemblage was responsible for much, if not most, of the chemical variation exhibited for these rocks. Most of the rocks in COSC suites have undergone moderate degrees of fractionation, and no COSC samples have an Mg# > 65, Ni > 110 ppm, or Cr > 260 ppm, all far lower than values thought to be repre-

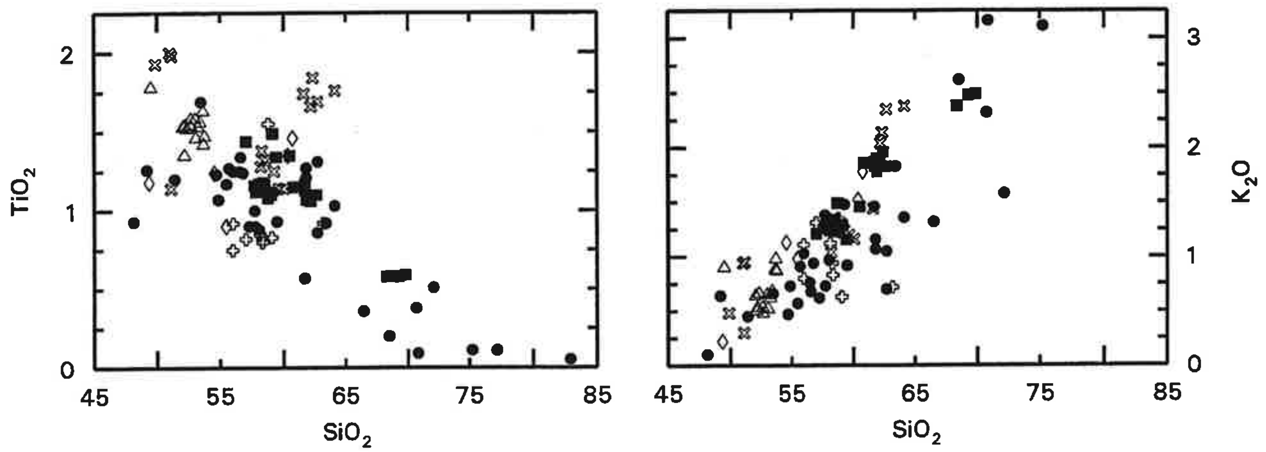

**Figure 6.** Comparison of Santa Catalina and San Clemente volcanic samples with other COSC suites. ● = Catalina; ■ = Clemente; △ = El Modeno; X = Rosarito Beach; ◇ = Palos Verdes; **cross** = Laguna Beach.

sentative of unmodified mantle melts [67, 400 to 500 ppm, and 1,000 ppm, respectively (Wilson 1989)].

Low values of both $^{87}Sr/^{86}Sr$ and $\delta^{18}O$, as well as relatively high values of epsilon Nd, in samples from these suites argue for derivation from a mantle source with little or no contribution from, or interaction with, continental crust—even for the more evolved dacite and rhyolite samples. Both the calc-alkaline nature of the volcanic rocks and the presence of a Nb-Ta depletion strongly suggest that these rocks were generated in a subduction setting. However, as outlined below, evidence from ocean-floor magnetic anomalies indicates that subduction in this area had ceased for some 3 to 10 my before volcanism began. Thus these rocks may represent calc-alkaline volcanic rocks that originated somewhere other than in a subduction environment.

The tectonic environment of magma generation responsible for the widespread volcanism in coastal and offshore southern California during the middle Miocene has generated much speculation. From sea-floor magnetic anomalies, Atwater (1989) has shown that subduction had ceased in this area 3–10 million yr before the main pulse of middle Miocene volcanism. Some authors have used paleomagnetic inclination data to suggest that the Baja-Borderland allochthon of southern California was transported from the south (e.g. Champion et al. 1986), raising the possibility that volcanism occurred in a subduction setting south of the Rivera triple junction before the Baja-Borderland allochthon was translated northward. However, sea-floor magnetic anomalies (Atwater 1989) and other evidence (Butler et al. 1991; Crouch and Suppe 1993) argue against such large-scale movements. Thus, plate configurations during the middle Miocene appear to preclude this widespread volcanic event from being related to subduction or triple-junction processes.

The tectonic environment in southern California at the time of Miocene volcanism was dominated by shear related to the dextral transform between the Pacific and North American plates. This shear affected a broad zone of continental crust that was possibly heated and softened by hot, mantle material that rose into a no-slab region created between the Mendocino and Rivera triple junctions (Henyey 1976). Across a wide area, basins were forming (Crowell 1974), large crustal blocks were rotating (Kamerling and Luyendyk 1979), and crust was rifting (Yeats 1968; Legg 1991; Crouch and Suppe 1993). This extensional environment provided an opportunity for decompression melting to develop in the lithospheric mantle, especially beneath the most highly extended areas such as the inner borderland.

Because igneous rocks belonging to the calc-alkaline magma series are currently erupting exclusively in subduction environments, prehistoric calc-alkaline suites are conventionally thought to require a subduction setting. However, Robyn (1975) interpreted some Miocene calc-alkaline volcanic rocks in eastern Oregon to have originated in an extensional rather than a subduction environment. Also, other recent studies have documented the presence of lavas with arc characteristics in non-arc settings (i.e., Lange et al. 1993; Sloman 1989). These studies suggest that the overlying mantle can stabilize fluids derived from the downgoing slab, and can subsequently yield arc-characterized magmas generated by tectonic events that postdate active subduction.

Lavas on San Clemente and Santa Catalina Islands specifically, and all related Miocene suites in coastal southern California in general, are concluded to have been generated by decompression melting beneath the Southern California Continental Borderland that was initiated by widespread extension. The lithospheric mantle source had attained its geochemical characteristics during subduction of the Farallon plate between about 220 Ma and 30 Ma. Later extension, associated with Pacific/North American shear, triggered short-lived but widespread volcanism in coastal and offshore southern California.

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