

# GEOLOGY OF SANTA ROSA ISLAND, CALIFORNIA

Thomas W. Dibblee, Jr.<sup>1,2</sup> and Helmut E. Ehrenspeck<sup>2</sup>

<sup>1</sup>Department of Geological Sciences, U.C. Santa Barbara, Santa Barbara, CA 93106

<sup>2</sup>Dibblee Geological Foundation, P.O. Box 60560, Santa Barbara, CA 93160  
(805) 968-0481, E-mail: helmut98@earthlink.net

## ABSTRACT

Santa Rosa Island consists of 220 km<sup>2</sup> of grass-covered hilly terrain, severely dissected by narrow canyons, eroded into mostly marine sedimentary formations of Eocene to middle Miocene age. Over much of the northern and western part of the island, these formations are beveled and covered by marine terraces, and a veneer of Pleistocene alluvium and wind-deposited dunes and drift sand.

The sedimentary sequence in ascending order is as follows: Eocene marine South Point Formation and Cozy Dell Shale; unconformably overlain by Oligocene-lower Miocene terrestrial Sespe Formation; conformably overlain by lower Miocene marine Vaqueros Sandstone and Rincon Claystone; conformably overlain by middle Miocene marine Monterey Shale containing the Santa Rosa Island Volcanics, a newly named sequence of marine volcanoclastic rocks; grading upward into middle Miocene marine Beechers Bay Formation of mostly tuffaceous sandstone, locally containing San Onofre Breccia, and minor volcanic conglomerate upsection. The exposed sequence aggregates roughly 2,000 m, with an additional 3,400 m of marine clastic rocks of Eocene to late Cretaceous age encountered in deep test drilling. The entire sequence up through the lower Monterey Shale is intruded by pods and sills of basalt-diorite.

The island is bisected by the east-west-striking Santa Rosa Island fault of left-slip movement, as indicated by deflected stream courses. Left slip of as much as 11 km is indicated by displaced rock units. A south-side-up component is evident from the generally higher and more rugged terrain south of the fault, and from exposure of the older formations only on that side of the fault.

North of the Santa Rosa Island fault, Miocene formations are folded along the Tecolote-Black Mountain anticline and subparallel Beechers Bay syncline farther north. South of the fault, the Miocene formations are compressed along the paired, northwest- to west-trending Soledad anticline and Pedregosa syncline, with adjacent minor subparallel faults. Complexly faulted and folded Eocene formations are exposed along the southwest and south coastal part of the island.

**Keywords:** Santa Rosa Island, Northern Channel Islands, Santa Barbara Channel, southern California, geology, structural geology, stratigraphy, geologic map, geologic history, physiography, Santa Rosa Island fault, tectonics.

## INTRODUCTION

### Previous Investigations

The earliest published geologic mapping investigation on Santa Rosa Island was by Kew (1927). During that time, major oil discoveries on the nearby mainland north of the Santa Barbara Channel spurred private exploration and geologic mapping on Santa Rosa Island by many oil companies to determine its oil potential (Daily 1998). One such geologic mapping investigation was by the lead author in 1938 largely on the north side of the island.

In the early 1960s, D. W. Weaver and others at the University of California at Santa Barbara (UCSB) conducted extensive geologic research on San Miguel, Santa Rosa, and Santa Cruz islands, resulting in a volume compiled by Weaver et al. (1969), which includes a detailed geologic map of Santa Rosa Island by Sonneman et al. (1969).

Many aspects of the geology of all the California Channel Islands were addressed in a volume edited by Howell (1976). The most recent collection of papers focusing on the geology of the Northern Channel Islands is that edited by Weigand (1998).

### Purpose

The purpose of field investigations in 1996 and 1997 by Thomas W. Dibblee, Jr., John J. Woolley, and Helmut E. Ehrenspeck was to provide an updated geologic map (Dibblee et al. 1998) of Santa Rosa Island, similar to more than 80 full-color geologic quadrangles of coastal southern California published by the Dibblee Geological Foundation since 1986. A companion report on the geology of Santa Rosa Island (Dibblee and Ehrenspeck 1998) followed the publication of the map. This article and illustrations in this paper (Figures 1 through 4) are modified from that report.

## PHYSIOGRAPHY

Santa Rosa Island, second largest of the four Northern Channel Islands, lies on an east-trending submerged platform extending eastward to the Santa Monica Mountains. Santa Rosa Island is slightly south of the Northern Channel Islands alignment and is diamond-shaped in outline. At 28 km long and up to 13 km wide, it is the widest of these islands, with an area of 217 km<sup>2</sup>.

This island is a grass-covered hilly terrane dissected by narrow canyons and bordered on all but the eastern shoreline by steep wave-cut cliffs. Santa Rosa is bisected by the east-west-striking Santa Rosa Island fault (SRIF), which divides the island into two subequal halves of different physiography. The SRIF appears prominently on aerial photographs and topographic maps as a lineament, along which north-draining canyons from the south half of the island are deflected westward as they cross the fault (Figure 1).

Much of the north half of the island is sand-covered old marine terrace sloping gently northward from a dissected east-west trending ridge of bedrock hills elevated just north of the SRIF. The ridge reaches its high point of 396 m (1,298 ft) at Black Mountain. This ridge and adjacent terrace are dissected by narrow, steep-sided canyons, many of which drain northerly from the south half of the island.

Southern Santa Rosa Island is somewhat larger, higher, and more rugged, eroded to a terrane of ridges and drainage divides, with subdued crests of about 300 to 500 m elevation, separated by steep-sided, V-shaped canyons.

The main crest of the island strikes east-west from its east end almost to its west end, and is parallel to, and about 1.5 km south of, the SRIF. Near the center of the island, this crest reaches an inconspicuous high point of 479 m (1,574 ft) at Soledad Peak and 483 m (1,589 ft) at nearby Vail Peak (Figure 1).

## GEOLOGIC SETTING

Santa Rosa Island and the other three Northern Channel Islands protrude from an east-west trending submerged platform about 125 km long, which continues eastward to the Santa Monica Mountains. Together, these features form the southern boundary of the western Transverse Ranges. The island exposes some 2,000 m of mostly marine sedimentary and volcanoclastic rocks of middle Miocene to Eocene age (Figure 2). A deep test well near its south coast penetrated an additional 3,400 m of marine sedimentary rock of Eocene, Paleocene, and late Cretaceous(?) age. Presumably, this thick stratified sequence overlies oceanic basement at a depth greater than 3,370 m below sea level.

On Santa Rosa Island, the Tertiary bedrock formations are generally tilted gently to the northeast, with subordinate folds of west to northwest-trending axial traces. The east-striking, near-vertical SRIF is the only major fault that completely transects this island; other faults are of local extent only.

North of the SRIF, only the Miocene part of the sedimentary sequence is exposed, and it is gently compressed into easterly trending folds. The sequence is broken by several minor faults parallel to the SRIF.

South of the SRIF, the entire Tertiary stratigraphic sequence is exposed. The oldest units crop out on the south coast and are overlain by progressively younger units to the

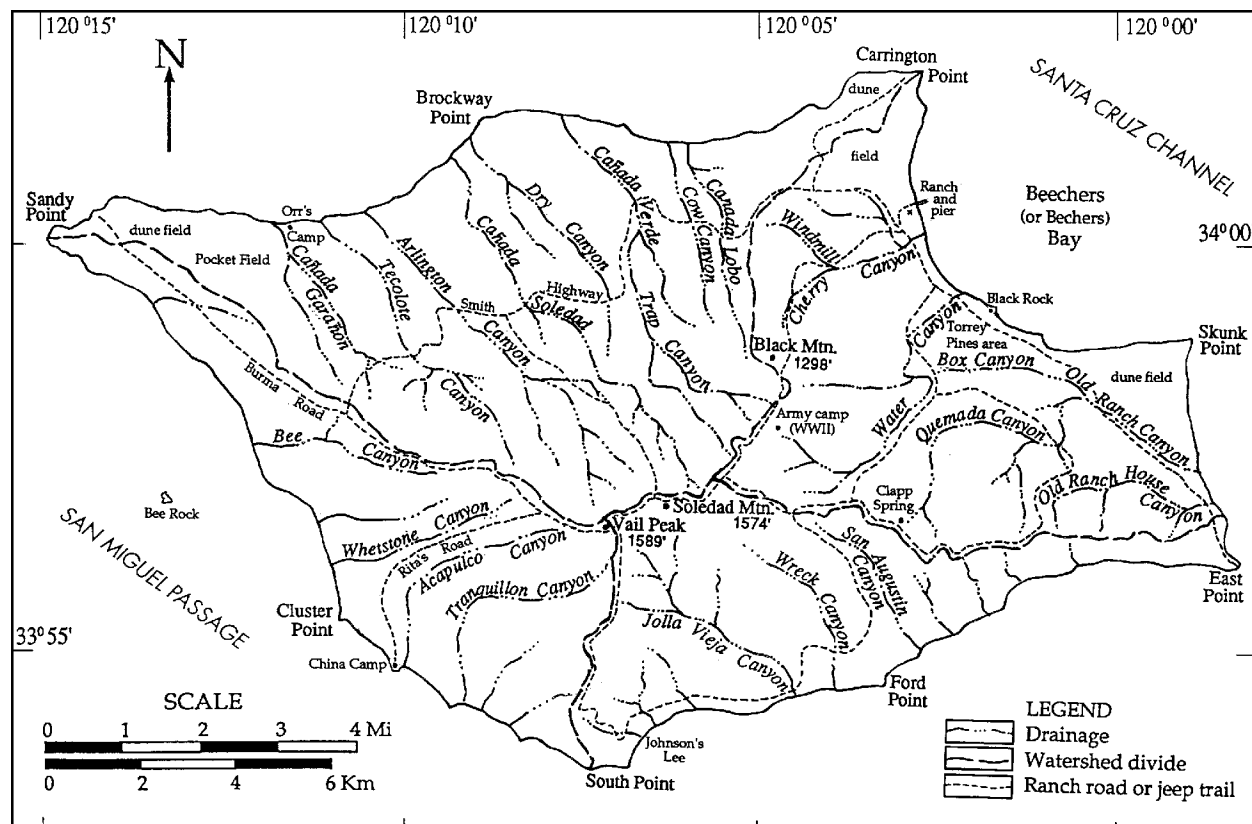


Figure 1. Drainage map of Santa Rosa Island, showing watershed divides, ranch roads, and major island locations. Note aligned canyons near the middle of the island which are deflected along the Santa Rosa Island fault.

northeastern coast. This sequence is compressed into a pair of subparallel southeast-trending folds. Near the south coast, the oldest exposed rocks, chiefly Eocene, are complexly disrupted by local faults of varying strikes.

## ROCK UNITS

### Pre-Cenozoic Crustal Basement Rocks

Crystalline basement rocks of pre-Cenozoic age are not exposed on Santa Rosa Island, but are deeply buried beneath a great thickness of Cenozoic sedimentary formations. The nearest pre-Cenozoic basement rocks are exposed on Santa Cruz Island and consist of fine-grained chlorite schist of probable Mesozoic age and diorite of late Mesozoic age (Weaver et al. 1969; Hill 1976).

### Cenozoic Stratified Rock Sequence

Santa Rosa Island exposes mostly Tertiary stratified rocks (Figure 3). The oldest exposed rocks are of marine sedimentary origin, of Eocene age, and exposed near the south coast. Including an additional Eocene to Cretaceous (?) sequence known only from deep test drilling, over 3,350 m of these subsurface strata are present on this island (Figure 2).

Most of the island is underlain by sedimentary and volcaniclastic rocks of early to middle Miocene age. These rocks were deposited under subaerial to moderately deep marine conditions. As much as 2100 m of these Miocene rocks are exposed on this island and they represent the youngest consolidated strata on the island. Marine sedimentary rocks of Pliocene-Pleistocene age were deposited in local basins, but are not present on the Northern Channel Islands.

#### South Point Formation and Older Rocks (Eocene to Cretaceous(?) Age)

The oldest rock unit exposed on Santa Rosa Island is a marine sandstone unit named the South Point Formation by Weaver and Doerner (1969) for its exposures along the south coastal part of the island. Smaller outcrops also exist just south of the SRIF on western Santa Rosa Island (Dibblee et al. 1998). Only the upper 300 m of this formation are exposed on the island, but its total thickness of about 1,000 m is known from deep exploratory test holes on the island.

The South Point Formation is composed of hard, light gray, fine- to medium-grained, arkosic (feldspar-rich) sandstone in strata roughly 1 m thick, separated by thin partings of softer sandstone or gray, crumbly, micaceous shale. The sandstone weathers to a light brown color and, in places, contains brown, iron-rich concretions up to 1 m in diameter. The sandstone is devoid of molluscan fossils. Due to its hardness, the South Point Formation resists weathering and erosion.

**Depositional Environment, Provenance and Age.** The arkosic sandstones of the South Point Formation were derived from continental granitic basement terrane. A lack of

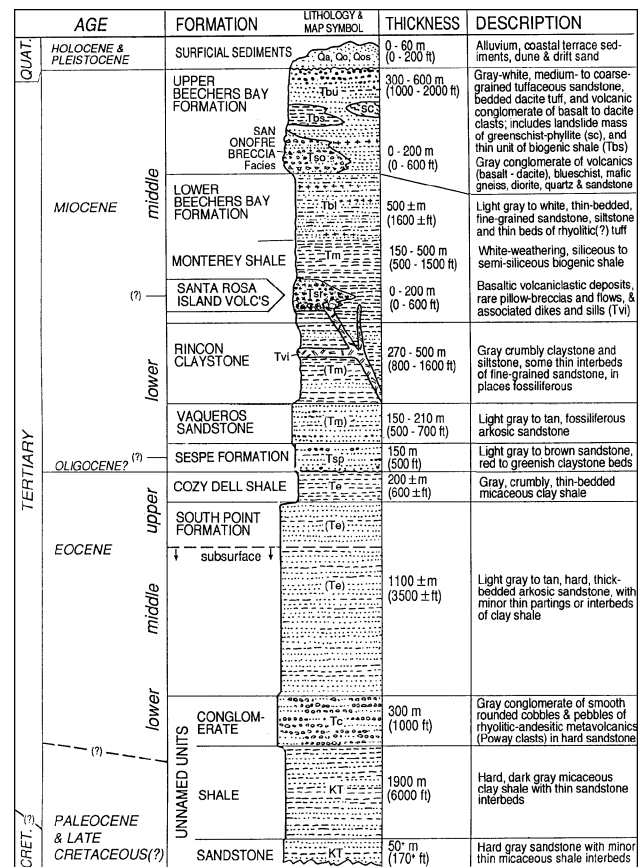


Figure 2. Stratigraphic column of Santa Rosa Island, using same formation symbols as in Figure 3.

molluscan remains suggests deposition in deep water, far from the shoreline. The massiveness and evenly fine-grained texture of the sandstone strata indicates deposition of sand-flow turbidites in a middle submarine fan environment. Crumpled bedding and other sedimentary structures indicate a paleoslope generally to the present-day north (Weaver and Doerner 1969).

Conglomerates in and below the South Point Formation (Figure 2) are composed of distinctive, smoothly rounded cobbles strikingly similar to the Eocene "Poway" conglomerates of the San Diego area. Over 30% of coarse sand grains within the South Point Formation have Poway-type compositions (Abbott et al. 1983).

Foraminiferal faunas in the South Point Formation are diagnostic of the Ulatisian and Narizian stages, or a middle Eocene age (Weaver and Doerner 1969).

#### Cozy Dell Shale (Late Eocene Age)

Conformably overlying the South Point Formation is a thin, gray, marine shale unit, named by Weaver and Doerner (1969) as the Cozy Dell Shale for its similarities to the Cozy Dell Shale of the Santa Ynez Mountains. A complete section of this shale is exposed at several places along the south coastal part of the island, where it is up to 120 m thick. This unit is missing in the southwestern part of the island, where

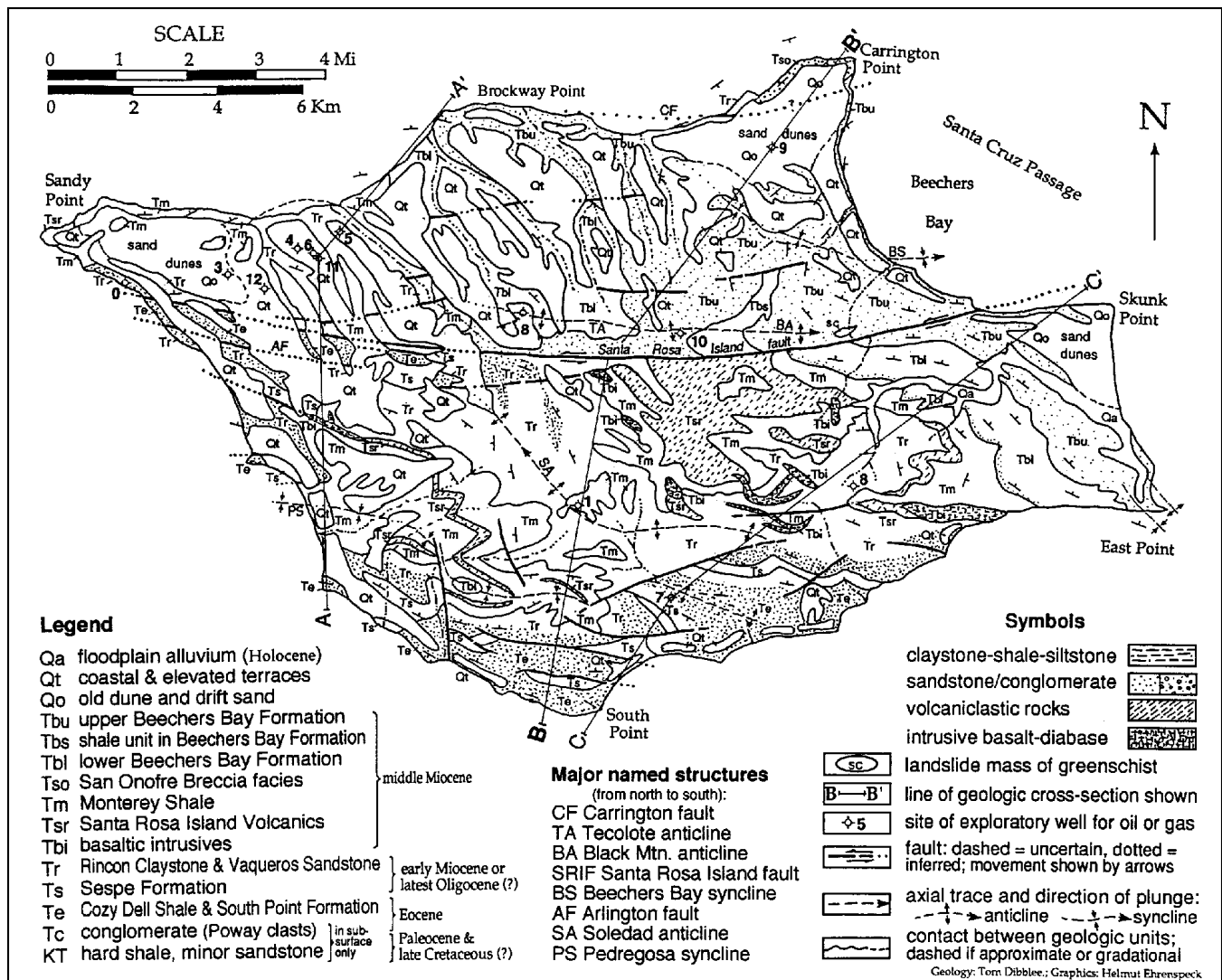


Figure 3. Generalized geologic map of Santa Rosa Island; for exploratory drill sites 0-12, see Dibblee et al. 1998.

the South Point Formation is disconformably overlain by the nonmarine Sespe Formation (Dibblee et al. 1998).

The Cozy Dell Shale ranges from highly fractured micaceous claystone to siltstone. It weathers brownish-gray at the surface and disintegrates so readily it is rarely exposed, except in canyon bottoms. It weathers to soft, clayey soil and forms a distinct topography of rounded grassy hills and slopes.

According to Weaver and Doerner (1969), the microfauna of the Cozy Dell Shale indicate a late Eocene age and suggest deposition under bathyal conditions.

#### Sespe Formation (Latest Oligocene(?)-Early Miocene Age)

Santa Rosa Island is the only Channel Island on which this terrestrial formation, so extensive on the mainland, exists. This formation is exposed only in the south part of the island and in fault slivers along the western SRIF (Figure 3).

The Sespe Formation is only about 150 m thick and thins eastward. It unconformably overlies the Cozy Dell Shale or South Point Formation with no visible discordance and is, in turn, overlain by the Vaqueros Sandstone, and in places, grades upward into it.

As described by Woolley (1978; 1998a), the Sespe Formation is mostly arkosic sandstone, silty mudstone, and granitic and volcanic conglomerate, with thin interbeds of green to red claystone. It is reddish and conglomeratic in exposures west of Johnson's Lee, but thins eastward and grades to a gray marine sandstone similar to the overlying Vaqueros Sandstone.

#### Depositional Environment, Provenance, and Age.

The Sespe Formation was deposited as alluvium on a coastal floodplain when this area was elevated slightly above sea level by regional tectonic events (Dibblee 1982a, b; 1995) possibly coupled with worldwide sea level changes (Atwater 1998). Sediments were derived largely from a now-distant Mesozoic granitic and volcanic terrane of the Peninsular Ranges of the San Diego area (Woolley 1998a).

Sedimentary structures in the Sespe Formation indicate sediment transport to the present-day north (Weaver and Doerner 1969; Woolley 1998a). These data indicate that the Sespe of this island was not derived from the nearby mainland, but was linked, prior to regional tectonic rotation, to the Sespe Formation of the Santa Ana Mountains, now far distant.

Because the Sespe Formation interfingers both upward and laterally with the lower Miocene Vaqueros Sandstone, the Sespe is probably of early Miocene age, but could be as old as latest Oligocene.

### **Vaqueros Sandstone (Early Miocene Age)**

The Vaqueros Sandstone is a shallow marine, locally fossiliferous sandstone that conformably overlies the Sespe Formation and underlies the Rincon Claystone. This unit is about 120 m in average thickness, which varies because the Vaqueros Sandstone interfingers with both the underlying Sespe and the overlying Rincon Claystone. In the southwestern part of the island, the Vaqueros thickens appreciably because the lower part of the Rincon Claystone interfingers westward into it. These two units are difficult to separate and therefore are shown undifferentiated on Figure 3.

The Vaqueros Sandstone is moderately lithified, light yellowish-gray, fine- to medium-grained, arkosic, weakly bedded to massive, and locally pebbly. Pebbles are compositionally similar to those in the Sespe.

### **Depositional Environment, Provenance, and Age.**

The shallow marine Vaqueros Sandstone sequence marks the marine transgression, or flooding, over the Sespe floodplain. Current indicators show sediment transport was to the north (Woolley 1998a). Locally, the Vaqueros Sandstone contains abundant shallow marine fossils diagnostic of an early Miocene age (Avila and Weaver 1969).

The consistent transport directions and the predominantly sandy composition of the Vaqueros, Sespe, and South Point Formations indicate that these were derived from a common source terrane, namely the Peninsular Ranges region, and that Santa Rosa Island was part of the western Transverse Ranges crustal block, later to be horizontally rotated more than 90 degrees clockwise away from that region (Woolley 1998a).

### **Rincon Claystone (Early Miocene Age)**

The Rincon Claystone directly overlies the Vaqueros Sandstone and is composed mostly of massive gray micaceous claystone, locally containing rust-colored dolomitic concretions. On Santa Rosa, this unit contains fine-grained blueschist detritus (Avila and Weaver 1969), unlike that on the nearby mainland.

Where exposed, it crumbles with ellipsoidal fracture and weathers to gray, adobe-like soil. Its grassy slopes are easily eroded and subject to landslides and soil slips.

This formation is exposed on both sides of the SRIF. To the north, it crops out extensively between Arlington and Garañon Canyons and near Carrington Point. To the south,

it is the most widely exposed formation on the island (Dibblee et al. 1998). The Rincon Claystone averages about 450 m in thickness, but, south of the SRIF, it thins westward by grading laterally into the Vaqueros Sandstone (Woolley 1978).

This formation contains some thick beds of fine-grained sandstone that appear to be interfingers from the Vaqueros Sandstone. Some of these strata contain abundant fossil oysters, indicating deposition in very shallow water. Other sandstone interbeds contain a diverse molluscan fauna characteristic of deeper-water, inner shelf deposition (Avila and Weaver 1969). The molluscan and foraminiferal assemblages both indicate an early Miocene age, mostly Saucesian stage (Weaver and Doerner 1969).

### **Monterey Shale (Early Middle Miocene Age)**

A thin unit of cream-white, weathered, semi-siliceous to siliceous, biogenic shale conformably overlies the Rincon Claystone. This shale was formerly included in the Rincon Formation by Sonneman et al. (1969), but it is so similar in lithology and age to the lower Monterey Shale of the nearby mainland, that we assign it to the Monterey Shale. It ranges in thickness from about 90 to 200 m, but may be as thick as 250 m in the southwestern part of the island. This shale unit is somewhat more resistant to erosion than the underlying Rincon Claystone.

On both sides of the SRIF, the Monterey Shale includes a unit of volcanic rocks, the Santa Rosa Island Volcanics, near or at the base. The Monterey Shale directly below the volcanics contains a microfauna assigned to the late Saucesian stage, or "late early" Miocene age; the part above the volcanics contains a Relizian microfauna, of early middle Miocene age (Weaver and Doerner 1969).

The Monterey Shale represents biogenic deposition in a deep offshore basin isolated from most terrigenous sediment input.

### **Santa Rosa Island Volcanics (Early Middle Miocene Age)**

Basaltic volcanoclastic rocks within the basal Monterey Shale on Santa Rosa Island were previously assigned to the San Miguel Volcanics by Weaver and Doerner (1969). However, the volcanics on Santa Rosa Island are not correlative with those of San Miguel Island because the latter include andesitic-dacitic rocks not found on Santa Rosa Island.

We have therefore renamed these entirely basaltic volcanic rocks for their namesake island and designated the type section as the thickest and most complete section exposed south of the SRIF; along the central divide, this section is located between the major eastward and northward drainages (Figure 1) (Dibblee et al. 1998).

**Extrusive Rocks.** The volcanic breccias exposed in the type area are most unusual and not seen elsewhere in southern California (Dibblee and Ehrenspeck 1998). They consist of gray-brown, crudely bedded strata composed entirely of basalt fragments embedded in basaltic rubble or sandstone. The presence of scattered oyster shells and occasional

pillow basalt fragments with chilled subvitreous margins indicate marine deposition.

This volcanoclastic unit was probably derived from flows shattered during contact with seawater, then transported, perhaps as debris flows into the deep marine environment of Monterey Shale deposition. This unit is up to 500 m thick near Soledad Mountain and exists within the lower Monterey Shale. Eastward along strike, and to the south and west, the Santa Rosa Island Volcanics thin to only a few tens of meters or less. The rapid thinning of this volcanic pile in most directions suggests that it was erupted and emplaced locally and is not a widespread unit.

**Intrusive Rocks.** Closely associated with the Santa Rosa Island Volcanics are scattered, shallow-intrusive feeder dikes, sills, and pods, as described by Dibblee and Ehrenspeck (1998). Most of these are intruded into the Rincon Claystone or lower Monterey Shale; a few dikes exist in the older formations. The largest intrusions are shown on the geologic map (Dibblee et al. 1998).

**Age of Santa Rosa Island Volcanics.** Two intrusions on Santa Rosa Island were dated at about 19 to 18 million years (Ma), or early Miocene age (Luyendyk et al. 1998). Volcanism must have persisted considerably beyond that time, because basaltic intrusions inject the lower Monterey Shale, of late Saucian age (circa 18 to 17 Ma), and the Santa Rosa Island Volcanics exist within the lower Monterey Shale.

#### **Beechers Bay Formation (Middle Miocene Age)**

On both sides of the SRIF, the Monterey Shale grades upward into a thick sequence of marine volcanoclastic rocks; the lower part is fine-grained, the upper part is mostly coarse-grained. The rocks range from tuffaceous shale-siltstone to volcanic conglomerate, with sandstone the predominant facies.

These clastic sediments are lithologically very different from the biogenic Monterey Shale, even though they are of similar age. Because these tuffaceous sediments are so unlike the biogenic siliceous Monterey Shale, Nuccio (1977) designated them as the Beechers Bay Formation, and we follow this designation.

On both sides of the SRIF, the clastic sedimentary series above the siliceous Monterey Shale is readily divisible into two parts. The lower part is thin bedded, gray to white, fine-grained sandstone-siltstone, roughly 500 m thick, which we designated as the lower Beechers Bay Formation. This unit grades upward into gray-white, coarse-grained, tuffaceous sandstones with local volcanic and "San Onofre" blueschist conglomerates, in total about 600 m thick (Figure 2). This part is designated as the upper Beechers Bay Formation (Dibblee et al. 1998). The entire sequence includes blueschist fragments and strata of white volcanic tuff throughout (Nuccio and Woolley 1998).

The entire Beechers Bay Formation, especially the upper part, includes complex and abrupt lateral facies variations in which fine-grained sediments grade laterally into

coarse-grained sediments, and vice versa. These are interpreted to represent deposition in various parts of a growing submarine fan complex (Nuccio and Woolley 1998). Spectacular soft-sediment structures in both units indicate a consistent westerly sediment-transport direction from sources to the present-day east (Avila and Weaver 1969).

**San Onofre Breccia Facies of Beechers Bay Formation.** A highly unusual conglomeratic unit is exposed at the base of the upper Beechers Bay Formation near Carrington Point. It is up to 200 m thick and contains a diverse assemblage of volcanic, plutonic and metamorphic (blueschist) detritus (Figure 2). This unit was mapped by Sonneman et al. (1969) as the San Onofre Breccia, for its similarities to the type unit described near Oceanside, California. The age of the San Onofre Breccia facies on this island was uncertain until Chinn and Weigand (1994) obtained a radiometric date of circa 15.8 Ma, or early middle Miocene, from a dacite clast within that facies.

**Upper Beechers Bay Formation.** This unit is exposed along the north and northeast coasts of Santa Rosa Island on both sides of the SRIF, is roughly 600 m thick, and is composed mainly of gray-white volcanoclastic sandstone that coarsens upsection. It is prominently bedded with alternating hard and softer strata, of which the hard layers protrude where weathered.

**Schist Landslide Mass.** About 2 km east of Black Mountain, the upper Beechers Bay Formation encloses an unusual pod-like mass of rusty brown-weathered, brecciated rock, identified as chlorite-phyllite or chlorite schist (Kamerling 1994). The rock is very similar to the Santa Cruz Island Schist and, apparently, is a unique landslide mass within the Beechers Bay sandstone, emplaced from an unknown source.

**Volcanic Conglomerates.** The uppermost Beechers Bay Formation includes massive volcanic conglomerates, mostly andesite, dacite and rhyolite (Weigand et al. 1998), pumiceous vitrophyre, and basalt. Spectacular exposures of these conglomerates occur at Black Rock, northeast of Water Canyon. At this location, the conglomeratic sediments appear to be mixed with, or locally injected by, basaltic lava.

**Age and Provenance of Beechers Bay Formation.** The radiometric age of about 15.8 Ma, early middle Miocene, obtained by Chinn and Weigand (1994) agrees with the Luisian microfaunal age, early middle Miocene, obtained by Avila and Weaver (1969).

Petrologic studies by Nuccio (1977) and Nuccio and Woolley (1998) indicate that this entire formation was derived from a then-nearby source area of active volcanism. The presence of blueschist fragments throughout the formation indicates that metamorphic oceanic basement was being exposed and eroded during that time. The upward coarsening of this formation indicates increasing relief of the volcanic source area.

Nuccio and Woolley (1998) concluded that the most likely volcanic source was in the vicinity of what is now Santa Catalina Island, where basaltic through dacitic volcanic rocks intrude and overlie Catalina blueschist basement. If this was the source area, the Santa Rosa Island area has since been shifted many kilometers northwestward with respect to that area.

#### **Late Quaternary Sediments (Pleistocene to Recent Age)**

Late Quaternary surficial deposits on Santa Rosa Island consist of alluvium that fills the flood plains of major canyons, older dissected alluvial deposits on wave-cut terraces, old inactive dune fields, and thin but extensive wind-deposited “drift” sand. These unconsolidated sediments were derived from the island itself, long after the older marine Tertiary formations of which it is composed were emerged and elevated in several stages during Pliocene-Pleistocene time, and are now eroded to low relief.

**Landslides.** Only moderate to large-sized landslides were mapped (Dibblee et al. 1998), and most of these exist in the Monterey Shale and Beechers Bay Formation, especially on steep slopes. An enormous number of small landslides or soil-slips on Santa Rosa Island could not be recorded at a map scale of 1:24000.

The most unusual landslide is the Lobo Canyon block slide (Dibblee et al. 1998), in which a 27-acre block of Beechers Bay Formation slid along a failed bedding plane into Lobo Canyon, as documented by Woolley (1994). The triggering event appears to have been the 1812 Santa Barbara Channel earthquake.

**Alluvium.** Surficial deposits mapped include two types: 1) alluvium that fills the bottoms and narrow flood plains of present drainages, and 2) widespread alluvial cover over the low, broad marine terraces (Figure 3) (Dibblee et al. 1998). Both types are gray-brown, reworked soil, sand and gravel, crudely bedded, and derived from the bedrock slopes. The stream-bottom alluvium typically is several meters thick and fills the lower parts of canyons to levels that vary with each canyon. The alluvial terrace material ranges from a few meters thick to locally in excess of 30 m. In many locations, the terrace alluvium yields disseminated bones of pygmy mammoth (*Mammuthus exilis*) (Agenbroad 1998).

In many canyons, the alluvial terrace is dissected by its main stream into a vertical-sided gully or barranca, from 3 to 30 m deep and similarly wide. Most of this island’s barranca formation apparently occurred from the 1840s to about 1900, coinciding with a period of overgrazing of the island by sheep. The earliest known photos of the island, taken around 1900, show the deep barrancas already in place, little different from today (Woolley 1998b).

**Dunes and Drift Sand.** The lower, wave-cut platforms of Santa Rosa Island are covered by a thin veneer of sand, now stabilized by vegetation. In late Pleistocene time, beach sand was widely eroded and redeposited as dune fields and

drift sand. Locally, as at Carrington Point, extensive dune fields were formed (Figure 3), with sand up to 50 m thick. Partial to complete remains of pygmy mammoths have been found in dune sand (Woolley 1998b), including one near Carrington Point, dated at circa 12,800 years (Agenbroad 1998).

**Wave-cut Platforms (Marine Terraces).** Seven distinct terrace levels are recognized on Santa Rosa Island, more than on any of the other three Northern Channel Islands. They range in elevation from about 6 to 300 m (Orr 1960; Figure 9 in Vedder and Howell 1980). The most extensive platforms are the 6-m and the 15 to 20-m terraces, which we mapped, undifferentiated, around most of the island (Figure 3) (Dibblee et al. 1998). While some of these terraces are covered by drift sand or alluvium, others contain marine fossil remains. These have been used to infer late Pleistocene uplift rates for the island, and to extrapolate ages of older, higher terraces. If such interpretations are correct, the age of prominent 150-to-180-m terrace remnants on the north side of Santa Rosa Island may be between 0.9 and 1.1 Ma old (Colson et al. 1995).

## **GEOLOGIC STRUCTURE**

### **Regional Structure of Northern Channel Islands Platform**

Santa Rosa Island is a small elevated part of a large east-west trending submerged platform that includes all of the Northern Channel Islands. This platform is a broad, east-trending anticlinal uplift of a thick series of upper Mesozoic and Cenozoic sedimentary and volcanic rocks, deposited on a crustal basement platform of Mesozoic metamorphic and plutonic igneous rocks.

The sedimentary rocks on this platform are gently compressed into folds that trend generally west-northwest. This deformation is the local effect of regional crustal compression during the Pliocene to Recent Coast Range orogeny, which uplifted the platform from the submerged shelf that is now the southern California borderland.

The greatest amount of regional uplift on this platform during the Coast Range orogeny appears to have been along the Santa Cruz Island Fault (SCIF), and significantly less on the Santa Rosa Island fault (SRIF). Movement on both faults has been mainly left-slip. The SRIF is of lesser magnitude and appears to curve northeastward and die out under Santa Cruz Passage before reaching Santa Cruz Island (Junger 1976). To the west, it projects northwestward beyond the south side of San Miguel Island before it dies out (Junger 1979; Figure 1).

### **Structure of Santa Rosa Island**

The generalized structure of Santa Rosa Island is shown on Figure 3 and on the geologic cross-sections of Figure 4. The SRIF bisects this island into a northern and southern structural block.

## Northern Structural Block

The structure of the northern block, up to 6 km wide, is comparatively simple. At the surface, Miocene formations are regionally tilted north to northeastward away from the SRIF but, in large part, are anticlinally folded near the fault by the Tecolote-Black Mountain anticline. Westward, the narrow south flank of this anticline is faulted out within the SRIF zone. The anticline is structurally highest or "domed" in its western part, where it exposes the Rincon Claystone. To the east, successively higher strata of the Monterey Shale and Beechers Bay Formation are involved as this anticline plunges eastward through Black Mountain.

Farther north, the Miocene strata are weakly folded into the Beechers Bay syncline, which plunges easterly toward that bay (Figure 3). Eastward and offshore under Santa Cruz Passage, this syncline terminates in the Carrington Basin.

The weakly folded Miocene formations of the north block of Santa Rosa Island are broken by many minor high-angle faults of inferred left-slip movement (Sorlien et al. 1998) parallel and probably related to the east-striking SRIF. None of these faults are traceable for more than a few kilometers; they are exposed in some canyons but not on the

intervening terraces. These faults, including the Carrington fault (Figure 3), predate the surficial cover, and none appear to be active.

## Southern Structural Block

The structure of the southern block of Santa Rosa Island, as wide as 8 km onshore, is more complex. This block progressively exposes Eocene to Miocene formations north-eastward as these formations dip generally in that direction. However, the formations are also folded along axes that trend generally west-northwest.

The most extensive fold is the Soledad anticline (Figure 3), which involves mostly Rincon Shale of the central part of this block. The fold axis trends northwestward, diagonal to the SRIF, across much of this block. Its northeast flank involves progressively younger Miocene formations that all dip northeast at low angles. Northwestward, the anticline is complexly involved with the SRIF zone, where it exposes slivers of the Vaqueros Sandstone to South Point Formations, both repeatedly faulted (Figure 4, cross-section A-A') (Dibblee et al. 1998; Figure 3).

The Soledad anticline is flanked on the southwest by the Pedregosa syncline, which is mostly within the Monterey

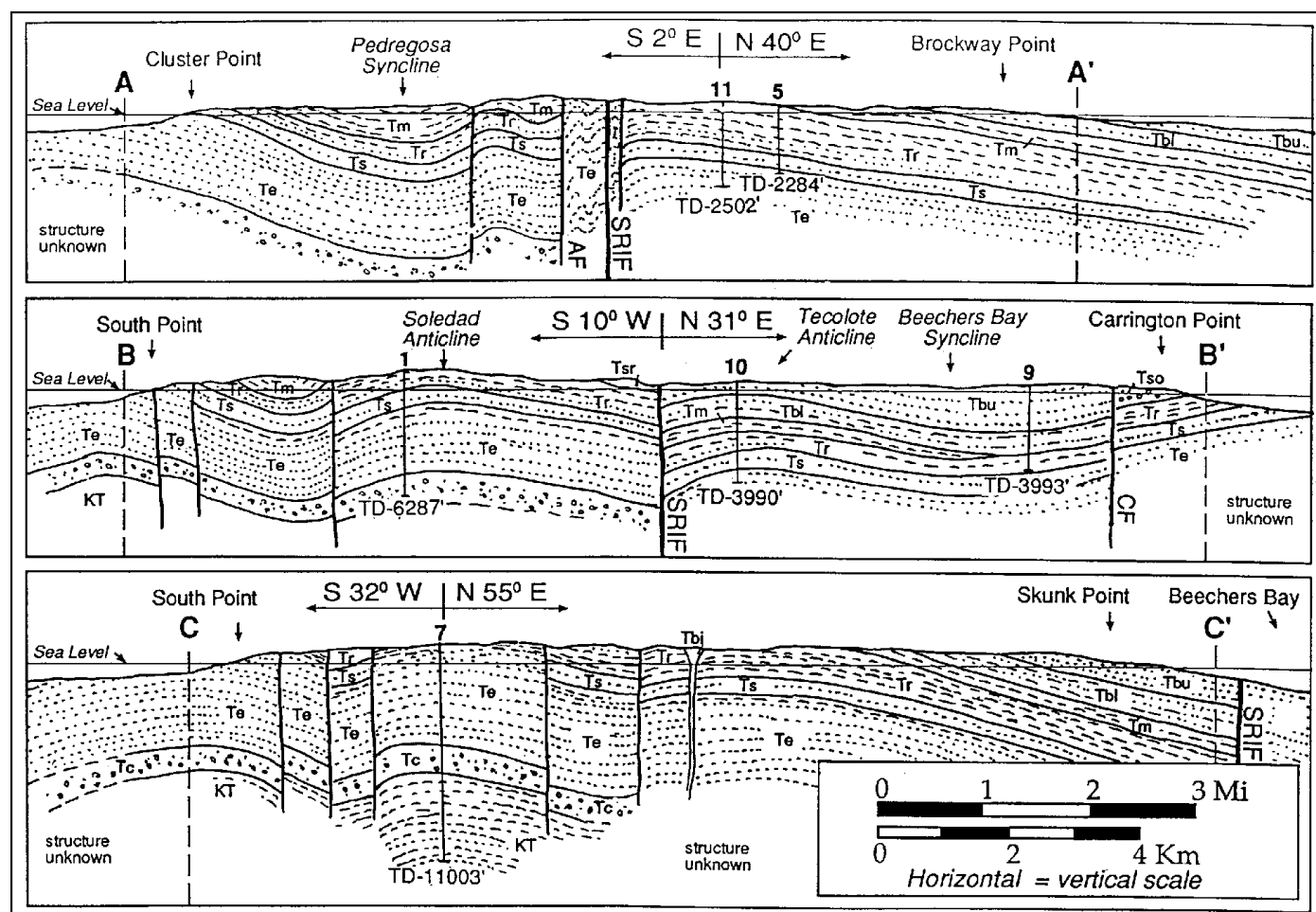


Figure 4. Geologic cross-sections of Santa Rosa Island; for legend and symbols, see Figure 3.



Shale and extends westward offshore. This syncline is offset by a north-south fault (Figure 3).

The southernmost, coastal part of this block exposes the South Point, Cozy Dell, and Sespe Formations. In local areas, these formations are complexly folded but regionally dip northward at low to moderate angles. The high-angle faults that disrupt these rocks are of variable strikes, though generally parallel to the coastline.

### **Santa Rosa Island Fault**

The Santa Rosa Island fault (SRIF) is one of the only two known major onshore faults of the Northern Channel Islands (Dibblee 1982a; b). It bisects the island in a nearly straight line with a slight northward curve to the west and east (Figure 3), and is readily apparent on aerial photos and topographic maps.

The SRIF is not exposed because it occupies a wide zone of gouge and crushed bedrock that is almost completely weathered to a thick cover of soil. No fresh exposures are seen, not even in the coastal terrace outcrops where it extends offshore. The SRIF is a single strand except along its western segment, where it is flanked by several minor parallel strands.

Left-slip movement on this fault during Pleistocene time is clearly evident from two physiographic aspects. First, the present shape of the island on a map suggests that the entire terrane north of the fault is shifted westward several kilometers with respect to the terrane south of it (Figures 1 and 3). Secondly, most canyons that drain northward across the fault from the generally higher terrane to the south are deflected westward, some more than 1 km (Figure 1).

The total cumulative left-slip displacement on the SRIF can be estimated from the Miocene formations laterally displaced by it. For example, the Santa Rosa Island Volcanics exposed at the island's west end, at Sandy Point, north of the SRIF, are displaced westward about 12 km from the same unit exposed south of the fault.

A minor vertical component of south-side-up displacement on the SRIF is apparent in its western part, where the older (Vaqueros to South Point) formations on the south side are juxtaposed against the younger (Rincon and Monterey) formations on the north side (Dibblee et al. 1998). South-side-up displacement is also evident from the island's physiography in that the terrane south of the SRIF is generally higher than that of the north side. Also, remnants of the highest (150 to 180 m) marine terrace appear to be tilted northward just north of that fault, suggestive of drag folding along the fault, south side up.

The SRIF is of Pleistocene age. Its inception was probably in Pliocene time, well after deposition of the Miocene Beechers Bay and older formations it involves. Its latest movements postdate the canyons deflected or offset by them. Most of the upper Pleistocene and Holocene alluvium on the western part of the island appears to be unbroken by the fault, with the possible exception of an exposure of terrace alluvium south of Arlington Canyon that suggests Holocene movement (Colson et al. 1995).

## **SUMMARY OF GEOLOGIC HISTORY**

### **Late Cretaceous(?) to Early Tertiary Marine Deposition**

Deposition of clastic sediments began in Cretaceous(?)–Paleocene time on a subsiding platform of oceanic basement or Franciscan rocks. Over 3500 m of sediments derived from a granitic terrane accumulated, with the South Point Formation deposited as a submarine fan, and the Cozy Dell Shale deposited in a bathyal or basin-plain environment.

### **Late Oligocene to Early Miocene Emergence, Uplift, and Resubmergence**

In latest Oligocene–early Miocene time, the submerged region emerged slightly above sea level to form a coastal plain covered by a thin veneer of nonmarine, streamlaid sediments of the Sespe Formation. Nonmarine deposition was followed by renewed subsidence and the deposition of marine sands and clays of the Vaqueros Sandstone and Rincon Claystone on a rapidly subsiding shelf of shallow to moderate depth, succeeded by deposition of deep marine biogenic sediments of the Monterey Shale.

### **Onset of Horizontal Clockwise Rotation in Early Middle Miocene**

Consistent northward sediment-transport directions obtained from the above pre-middle Miocene clastic formations indicate that these units could not have originated from the Ventura basin to the north. Instead, these directions support a model of clockwise tectonic rotation of the western Transverse Ranges block of more than 90° since middle Miocene time, based on paleomagnetic data (Kamerling and Luyendyk 1985; Luyendyk 1991; Atwater 1998). Much of this rotation occurred between 18 and 14 Ma, during Monterey Shale deposition.

### **Early Middle Miocene Volcanism and Marine Deposition**

Local basaltic intrusive and brief volcanic activity forming the Santa Rosa Island Volcanics began around 19 to 18 Ma, concurrent with the regional deposition of biogenic Monterey Shale on a deeply submerged shelf or basin.

Locally, biogenic deposits gave way to marine volcanoclastic deposits of the Beechers Bay Formation by middle Miocene time, about 16 Ma ago. These rocks were derived from nearby, active, andesitic-dacitic volcanism. Concurrently, blueschist and other basement rocks, eroded from a nearby source, were incorporated into the volcanoclastic sediments.

### **Pliocene–Early Coast Range Orogeny**

By Pliocene time (circa 5 Ma), after most rotation of the western Transverse Ranges block had occurred, compressive deformation of the early Coast Range orogeny began the development and possible emergence of the

Channel Islands platform, including what is now the Santa Rosa Island area. Pliocene marine sediments accumulated in local basins but not on the Channel Islands platform (Vedder and Howell 1980). Mainland mountain ranges began to be elevated by regional compressive deformation.

### Pleistocene-Late Coast Range Orogeny

By early Pleistocene time (circa 1.6 Ma), regional contraction caused by the late Coast Range orogeny accelerated uplift of mainland mountain ranges and renewed uplift of the north Channel Islands platform (Dibblee 1995). By mid-Pleistocene time, the Santa Rosa Island area was uplifted, largely on the SRIF, which developed around that time. Local tectonic uplift, coupled with fluctuating sea levels during middle to late Pleistocene time, created a flight of wave-cut terraces on Santa Rosa, the oldest and highest of which may exceed 1 Ma in age (Colson et al. 1995).

### Late Pleistocene to Recent Events

During sea-level lowstands associated with Pleistocene glacial episodes, Santa Rosa Island combined with adjacent islands into Santarosae, an island landmass many times its present area (Junger and Johnson 1980; Vedder and Howell 1980). Sometime in late Pleistocene time, probably during a sea-level lowstand, mammoths arrived on Santa Rosa Island and began to evolve to pygmy mammoths (Agenbroad 1998; Thaler 1998). After severely stripping the island of vegetation, pygmy mammoths became extinct around 12 thousand (ka) years ago (Woolley 1998b).

Since the maximum late Pleistocene lowstand of 18 ka, the effects of a rapid sea level rise of at least 120 m, coupled with wave erosion, reduced Santa Rosa Island to its present size. Sand eroded from beaches by prevailing west-northwest winds was deposited in several dune fields; eolianites and drift sand covered its lower slopes and marine terraces (Woolley 1998b).

The rapid sea-level advance ceased about 6 ka (Vedder and Howell 1980). Continued tectonic uplift since late Pleistocene time has elevated this island to its present height. Much of this uplift has occurred along the SRIF, with at least one surface rupture recorded in Holocene time (Colson et al. 1995). Left slip along this fault has significantly displaced all major drainages that cross it.

In the 1800s, introduction of sheep resulted in several decades of sharply accelerated island-wide erosion, causing the incisement of deep barrancas and dissection of alluvial terraces (Woolley 1998b). Removal of the sheep by about 1900 has enabled the vegetative recovery of much of Santa Rosa Island.

### ACKNOWLEDGMENTS

We wish to acknowledge field assistance by the following persons: William J. Faulkner (naturalist), Howard R. Level and Ruppen L. Zakarian (volunteer geologists), all from Channel Islands National Park, Ventura; Peter W.

Weigand, geologist, and Sandra L. Jewett, chemist, both of California State University, Northridge (CSUN); and Wendy Lou Bartlett, geologist, UCSB. Field trips were guided by John J. Woolley, geologist, and member of the Vail family of Vail and Vickers, owners of Santa Rosa Island and of its ranching operation for nearly a century. Publication funding for this map was provided by the Dibblee Geological Foundation and the Santa Cruz Island Foundation of Santa Barbara, California, including its Santa Rosa Island Chapter.

### LITERATURE CITED

- Abbott, P. L., R. R. Kies, W. R. Bachman, and C. J. Natenstadt. 1983. A tectonic slice of Eocene strata, northern part of California Continental Borderland. Pages 151-170 in La Rue, D. K. and R. J. Steel (eds.), *Cenozoic Marine Sedimentation, Pacific Margin, U.S.A.* Society of Economic Paleontologists and Mineralogists Special Publication.
- Agenbroad, L. D. 1998. New pygmy mammoth (*Mammuthus exilis*) localities and radiocarbon dates from San Miguel, Santa Rosa, and Santa Cruz Islands, California. Pages 169-176 in Weigand, P. W. (ed.), *Contributions to the geology of the Northern Channel Islands, southern California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 45.
- Atwater, T. M. 1998. Plate tectonic history of southern California with emphasis on the western Transverse Ranges and Santa Cruz Island. Pages 1-9 in Weigand, P. W. (ed.), *Contributions to the geology of the Northern Channel Islands, southern California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 45.
- Avila, F. A. and D. W. Weaver. 1969. Mid-Tertiary stratigraphy, Santa Rosa Island. Pages 48-67 in Weaver, D. W., D. P. Doerner, and B. Nolf (eds.), *Geology of the Northern Channel Islands (California)*. American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, Pacific Sections, Special Publication 12.
- Chinn, B. D. and P. W. Weigand. 1994. Petrology and geochemistry of volcanic clasts from the Miocene Beecher's Bay Formation, Santa Rosa Island, California. Pages 255-265 in Halvorson, W. L. and G. J. Maender (eds.), *The Fourth California Islands Symposium: Update on the Status of Resources*. Santa Barbara Museum of Natural History, Santa Barbara, CA.
- Colson, K. B., T. K. Rockwell, K. M. Thorup, and G. L. Kennedy. 1995. Neotectonics of the left-lateral Santa Rosa Island fault, western Transverse Ranges, Southern California. Geological Society of America Cordilleran Section, 91st Annual Meeting, Abstracts with Program 7:5:11.
- Daily, M. 1998. Santa Rosa Island geologic mapping and oil exploration, Page 2 (reverse side) on Geologic map of Santa Rosa Island, Santa Barbara County, California.

- Dibblee Geological Foundation, Santa Barbara, California. Map DF-68.
- Dibblee, T. W., Jr. 1982a. Regional geology of the Transverse Range Province of southern California. Pages 7-26 in Fife, D. L. and J. A. Minch (eds.), *Geology and mineral wealth of the California Transverse Ranges*, Mason Hill Volume. South Coast Geological Society, Santa Ana, California. Annual Symposium and Guidebook 10.
- Dibblee, T. W., Jr. 1982b. Geology of the Channel Islands, southern California. Pages 27-40 in Fife, D. L. and J. A. Minch (eds.), *Geology and mineral wealth of the California Transverse Ranges*, Mason Hill Volume. South Coast Geological Society, Santa Ana, California. Annual Symposium and Guidebook 10.
- Dibblee, T. W., Jr. 1995. Tectonic and depositional environment of the middle and upper Cenozoic sequences of the coastal southern California region. Pages 212-245 in Fritsche, A. E. (ed.), *Cenozoic paleogeography of the western United States - II. Pacific Section*, Society for Sedimentary Geology (SEPM) Book 75.
- Dibblee, T. W., Jr. and H. E. Ehrenspeck. 1998. General geology of Santa Rosa Island. Pages 49-76 in Weigand, P. W. (ed.), *Contributions to the geology of the Northern Channel Islands, southern California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 45.
- Dibblee, T. W., Jr., J. R. Woolley, and H. E. Ehrenspeck. 1998. Geologic map of Santa Rosa Island, Santa Barbara County, California. Dibblee Geological Foundation, Santa Barbara, California. Map DF-68. Scale 1:24,000.
- Hill, D. J. 1976. Geology of the Jurassic basement rocks, Santa Cruz Island, California, and correlation with other Mesozoic basement terranes in California. Pages 16-46 in Howell, D. G. (ed.), *Aspects of the geologic history of the California continental borderland*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 24.
- Howell, D. G., (ed.). 1976. *Aspects of the geologic history of the California continental borderland*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 24, 498 p.
- Junger, A. 1976. Offshore structure between Santa Cruz and Santa Rosa Islands. Pages 418-426 in Howell, D. G. (ed.), *Aspects of the geologic history of the California continental borderland*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 24.
- Junger, A. 1979. Maps and seismic profiles showing geologic structure of the Northern Channel Islands platform, California continental borderland. United States Geological Survey, Miscellaneous Field Studies Map MF-991. Scale 1:250,000.
- Junger, A. and D. L. Johnson. 1980. Was there a Quaternary land bridge to the Northern Channel Islands? Pages 33-39 in Power, D. M. (ed.), *The California Islands: Proceedings of a multidisciplinary symposium*. Santa Barbara Museum of Natural History.
- Kamerling, M. J. 1994. Paleomagnetism and tectonics of the southern California continental borderland [Ph.D. dissertation]. University of California, Santa Barbara, 217 p.
- Kamerling, M. J. and B. P. Luyendyk. 1985. Paleomagnetism and Neogene tectonics of the Northern Channel Islands, California. *Journal of Geophysical Research* 90:12,485-12,505.
- Kew, W. S. W. 1927. Geologic sketch of Santa Rosa Island, Santa Barbara County, California. *Geological Society of America Bulletin* 38:645-653.
- Luyendyk, B. P. 1991. A model for Neogene crustal rotations, transtension, and transpression in southern California. *Geological Society of America Bulletin* 103:1528-1536.
- Luyendyk, B. P., P. Gans, and M. J. Kamerling. 1998.  $^{40}\text{Ar}/^{39}\text{Ar}$  Geochronology of southern California Neogene volcanism. Pages 9-36 in Weigand, P. W. (ed.), *Contributions to the geology of the Northern Channel Islands, southern California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 45.
- Nuccio, R. M. 1977. Sedimentology of the Beechers Bay Formation, Santa Rosa Island, California [M.A. thesis]. California State University, San Diego, 49p.
- Nuccio, R. M. and J. J. Woolley. 1998. Sedimentology of the Beechers Bay Formation, Santa Rosa Island, California. Pages 91-102 in Weigand, P. W. (ed.), *Contributions to the geology of the Northern Channel Islands, southern California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 45.
- Orr, P. C. 1960. Late Pleistocene marine terraces on Santa Rosa Island, California. *Geological Society of America Bulletin* 71:1113-1119.
- Sonneman, H. (as modified and extended by D. W. Weaver, D. P. Doerner, and other anonymous authors) 1969. Geology of Santa Rosa Island. Map in Weaver, D. W., D. P. Doerner, and B. Nolf (eds.), *Geology of the Northern Channel Islands (California)*. American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, Pacific Sections, Special Publication 12. Map scale 1:24,000.
- Sorlien, C. C., E. H. McWayne, M. J. Kamerling, and J. M. Galloway. 1998. Late Cenozoic faulting and progressive folding of northern Santa Rosa Island and southwestern Santa Barbara Channel, California. Pages 121-141 in Kunitomi, D. S., T. E. Hopps, and J. M. Galloway (eds.), *Structure and petroleum geology, Santa Barbara Channel, California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 46.
- Thaler, P. F. 1998. Mammoth remains of the Channel Islands of California: A summary of geologic, biogeographic and evolutionary implications. Pages 161-167 in Weigand, P. W. (ed.), *Contributions to the geology of the Northern Channel Islands, southern California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 45.

- Vedder, J. G. and D. G. Howell. 1980. Topographic evolution of the Southern California Borderland during late Cenozoic time. Pages 33-39 *in* Power, D. M. (ed.), *The California Islands: Proceedings of a multidisciplinary symposium*. Santa Barbara Museum of Natural History.
- Weaver, D. W. and D. P. Doerner. 1969. Lower Tertiary stratigraphy of San Miguel and Santa Rosa Islands. Pages 30-47 *in* Weaver, D. W., D. P. Doerner, and B. Nolf (eds.), *Geology of the Northern Channel Islands (California)*. American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, Pacific Sections, Special Publication 12.
- Weaver, D. W., D. P. Doerner, and B. Nolf (eds.). 1969. *Geology of the Northern Channel Islands (California)*. American Association of Petroleum Geologists and Society of Economic Paleontologists and Mineralogists, Pacific Sections, Special Publication 12, 200 p., 3 geologic maps, scale 1:24,000.
- Weigand, P. W. (ed.). 1998. *Contributions to the geology of the Northern Channel Islands, southern California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 45, 196 p.
- Weigand, P. W., K. L. Savage, B. D. Chinn, and T. Reid. 1998. Composition of volcanic rocks on Santa Rosa, San Miguel, and Santa Barbara Islands, California. Pages 37-48 *in* Weigand, P. W. (ed.), *Contributions to the geology of the Northern Channel Islands, southern California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 45.
- Woolley, J. J. 1978. Sedimentology of the Tertiary Sespe and Vaqueros Formations, Santa Rosa Island, California [M. A. thesis]. California State University, San Diego, California, 72 p.
- Woolley, J. J. 1994. Lobo Canyon Landslide: Santa Rosa Island, California. Pages 297-302 *in* Halvorson, W. L. and G. J. Maender (eds.), *The Fourth California Islands Symposium: Update on the Status of Resources*. Santa Barbara Museum of Natural History, Santa Barbara, CA.
- Woolley, J. J. 1998a. Sedimentology of the Oligocene Sespe and Vaqueros Formations, Santa Rosa Island, California. Pages 77-90 *in* Weigand, P. W. (ed.), *Contributions to the geology of the Northern Channel Islands, southern California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous Publication 45.
- Woolley, J. J. 1998b. Aspects of the Quaternary history of Santa Rosa Island, California. Pages 103-111 *in* Weigand, P. W. (ed.), *Contributions to the geology of the Northern Channel Islands, southern California*. American Association of Petroleum Geologists, Pacific Section, Miscellaneous, Publication 45.