Oligocene Stratigraphy, Tectonics, and Paleogeography Southwest of the San Andreas Fault, Santa Cruz Mountains and Gabilan Range, California Coast Ranges

GEOLOGICAL SURVEY PROFESSIONAL PAPER 783

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By JOSEPH C. CLARK *and* JAN D. RIETMAN

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By JOSEPH C. CLARK and JAN D. RIETMAN

ABSTRACT

During Oligocene time, the Zayante fault bounded crystalline rocks of the Ben Lomond Mountain area in the central Santa Cruz Mountains, and the Vergeles fault bounded similar rocks in the northern Gabilan Range. Stratigraphic comparison suggests, and gravity data confirm, the continuity of the Zayante and Vergeles faults and of the adjacent tectonic blocks of these central California Coast Ranges.

Bathyal deposition during Eocene time was followed by a marked shallowing along the Zayante-Vergeles fault during Oligocene time. Continued uplift along this fault resulted in emergence of the Ben Lomond–Gabilan block to the south and in deposition along the fault of the terrestrial beds of the Zayante Sandstone in the central Santa Cruz Mountains and of the red beds of Kerr and Schenck (1925) in the northern Gabilan Range. Although later vertical movement occurred locally along this line of weakness, the Zayante-Vergeles fault had ceased to be an important structure by early Miocene time.

The Bouguer gravity field consists of a series of northwest-southeast-trending highs and lows. A prominent negative anomaly between the San Andreas and Zayante-Vergeles faults is interpreted as being produced by a thick Tertiary sedimentary cover on crystalline basement that is separated from Franciscan basement to the northeast by the San Andreas fault and from relatively shallow crystalline basement to the southwest by the Zayante-Vergeles fault. Model studies of the gravity field indicate between 6,000 and 9,000 feet of vertical displacement of the crystalline basement.

Although post-early Miocene large lateral displacement along the San Andreas fault is probable, none is evident on the northwest-trending Zayante-Vergeles fault.

INTRODUCTION

The Santa Cruz–San Juan Bautista area includes the central and southern Santa Cruz Mountains and the northern Gabilan Range of the California Coast Ranges (fig. 1). Here the active San Andreas fault has juxtaposed two major tectonic blocks with contrasting basement complexes and different stratigraphic and structural histories. These major blocks are broken by high-angle faults into smaller blocks with interdependent histories. Vertical movements of these tectonic blocks were concurrent with sedimentation and have strongly affected the Tertiary stratigraphy of the area.

Since Lawson (1914) first defined three "orographic" blocks in the San Francisco district, many geologists have described the structure of the Coast Ranges in terms of tectonic blocks. B. L. Clark's (1930) structural analysis of the Coast Ranges included a delineation of the tectonic blocks of the Santa Cruz Mountains and the Gabilan Range. According to Clark (1930, pl. 19), the northwest-southeast-trending Santa Cruz synclinorium is separated from the San Francisco Bay block to the northeast by the San Andreas fault, from the Ben Lomond block to the southwest by the Ben Lomond fault, and from the Gabilan Mountain block to the south by a fault later designated by Allen (1946) the Vergeles fault.

Recent detailed mapping and stratigraphic work in the central Santa Cruz Mountains demonstrate that during middle Tertiary time the Zayante fault was the important structure forming the boundary between a negative block to the northeast (a part of Clark's Santa Cruz synclinorium) and a positive block to the southwest. Vertical displacement of these blocks left its imprint upon their stratigraphies, the analysis of which permits a reconstruction of the history of relative movement. Stratigraphic comparison with the San Juan Bautista area to the southeast suggests, and gravity work confirms, the continuity of the Zayante and Vergeles faults and of the adjacent tectonic blocks of the Santa Cruz Mountains and Gabilan Range.

The purpose of this study is to document the effect of tectonics on the Tertiary stratigraphy of the Santa Cruz Mountains and the Gabbilan Range, and to clarify the middle Tertiary paleogeography of the area.

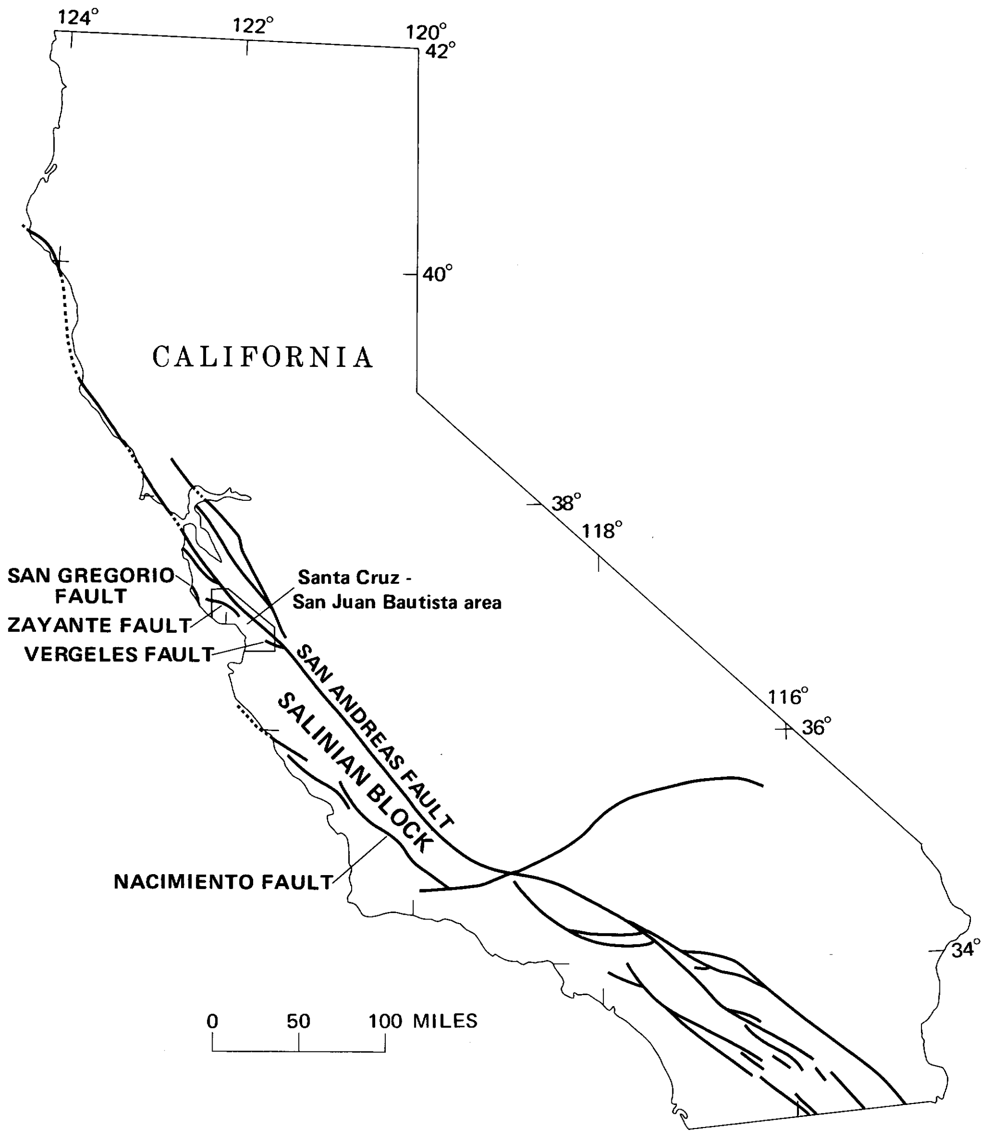

FIGURE 1.—Index map showing location of Santa Cruz–San Juan Bautista area and major faults.

PROCEDURE

The geology of the central Santa Cruz Mountains was mapped at a scale of 1:24,000 by J. C. Clark during the summer field seasons of 1960–63 and 1968. The geology of the Santa Cruz–San Juan Bautista area is compiled from this mapping and from other sources as noted in the Index to geologic mapping (pl. 1).

The stage names used throughout this report are those defined by Schenck and Kleinpell (1936), Kleinpell (1938), and Mallory (1959), based largely upon the benthonic foraminiferal sequence of the West Coast. Calcareous nannoplankton and foraminiferal correlations with the Caribbean sequence suggest that the Oligocene-Miocene Series boundary approximates the Zemorrian-Saucesian Stage boundary of the West Coast chronology, and that the Eocene-Oligocene Series boundary falls within the Refugian Stage (Bramlette and Wilcoxon, 1967, table 2; Blacut and Kleinpell, 1969, p. 7–10). Oligocene as used in this report includes the upper part of the Refugian Stage and the Zemorrian Stage.

The Bouguer gravity field is based on data from 287 stations, 208 of which were occupied by Clark and Rietman in August 1967 and September 1968. Data from 79 additional stations were provided by the California Division of Mines and Geology. Additional control for contouring near the boundaries of the mapped area was provided by the Santa Cruz and San Francisco sheets of the Bouguer gravity map of California (Bishop and Chapman, 1967; Chapman and Bishop, 1968) and by a few stations occupied by Clark and Rietman in adjacent areas.

The gravity data were obtained with a late model LaCoste-Romberg gravimeter (G–141). A subsidiary base-station network was established, and a looping technique was used in the field operations. All stations were tied into the California Division of Mines and Geology base station 254 in Santa Cruz (Chapman, 1966, p. 41).

Tidal and instrumental-drift corrections were applied separately, and the values of observed gravity were reduced to Bouguer anomalies using a density of 2.67 g/cm^3 (grams per cubic centimeter) and theoretical gravity values calculated from the International Formula (Nettleton, 1940, p. 18). Terrain corrections based on a density of 2.67 g/cm^3 were calculated for all stations through the outer radius of zone H, 5.24 km, of the U.S. Coast and Geodetic Survey system (Swick, 1942). These corrections ranged from 0 to 14.8 mgal (milligals) and averaged 1.6 mgal. Terrain corrections for zones I through O, 5.24 to 167 km, were calculated for several stations. Total contributions from these outer zones varied from 0.5 to 2.0 mgal; any variation in the Bouguer anomaly resulting from incomplete terrain corrections probably does not exceed 1.5 mgal. The gravity data on plate 1 represent the complete Bouguer anomaly.

PREVIOUS WORK

No detailed geologic map of the entire area of this report has been published. Beginning with the Santa Cruz folio (Branner, Newsom, and Arnold, 1909), several geologic maps and descriptions of parts of the area have appeared. (See "Index to Geologic Mapping," pl. 1.) The geologic compilation of the Santa Cruz (Jennings and Strand, 1958), San Francisco (Jennings and Burnett, 1961), and San Jose (Rogers, 1966) sheets of the geologic map of California covers the entire area at a scale of 1:250,000.

The geology and economic potential of the metasedimentary rocks of the northern Gabilan Range are discussed by Bowen and Gray (1959). Leo (1961, 1967) has studied in detail the granitic and metamorphic rocks of the Ben Lomond Mountain area. Additional information on the crystalline basement rocks of the Ben Lomond area and the northern Gabilan Range is included by Compton (1966) in his discussion of the Salinian block.

Published reports that deal with the Tertiary stratigraphy of the area include one by Kerr and Schenck (1925) that briefly describes the section and defines several formations near San Juan Bautista. The stratigraphy of the two tectonic blocks separated by the San Andreas fault near San Juan Bautista is more fully described by Allen (1946). Brabb (1963) discusses the Oligocene stratigraphy, and J. C. Clark (1968) summarizes the lower Tertiary section of the western part of the mapped area.

Recent papers concerned with the structure of the area include ones by Martin and Emery (1967) and Starke and Howard (1968), both of which consider the origin of the Monterey submarine canyon. The paper of Starke and Howard includes a gravity map of the area south of Watsonville. More extensive gravity coverage is provided by the Santa Cruz and San Francisco sheets (Bishop and Chapman, 1967; Chapman and Bishop, 1968) of the Bouger gravity map of California.

Subsurface structure and stratigraphy are contained in the San Andreas fault cross sections of the American Association of Petroleum Geologists (1964, 1967). Data on exploratory wells in the area are included in reports by Castro (1967) and Wilkinson (1967) and are tabulated by Jennings and Hart (1956) and the California Division of Oil and Gas in the annual reports summarizing operations of California oil fields.

ACKNOWLEDGMENTS

The writers are indebted to E. E. Brabb and T. W. Dibblee, Jr., for their generous assistance in compiling the geology of the area, their making available much unpublished information, and their helpful suggestions and criticism. The gravity section of the manuscript benefited from the critical review of H. W. Oliver. R. H. Chapman of the California Division of Mines and Geology kindly furnished unpublished gravity data. O. E. Bowen, Jr., formerly with the California Division of Mines and Geology, T. A. Baldwin of Humble Oil and Refining Co., and A. J. Macmillan of Texaco, Inc. provided useful information on exploratory wells. J. K. Aldrich assisted with the gravity survey and R. M. Gulliver with the data reduction.

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GEOLOGIC SECTION NORTHEAST OF SAN ANDREAS FAULT

The San Andreas fault in the Santa Cruz–San Juan Bautista area separates two major tectonic blocks—to the northeast, a block characterized by diverse basement rocks of the Franciscan Formation; to the southwest, the Salinian block of granitic and regionally metamorphosed basement rocks (fig. 1). The Franciscan basement rocks are in fault contact with Cretaceous clastic sedimentary and volcanic rocks, which are overlain by more than 16,000 ft of Cenozoic clastic sedimentary rocks. Southwest of the fault, the Franciscan Formation is absent, and the crystalline basement is overlain by Cenozoic clastic sedimentary and volcanic rocks having a composite thickness exceeding 20,000 ft.

The Franciscan Formation consists mainly of lithic and feldspathic graywacke and siltstone; it contains smaller amounts of altered mafic lava and pyroclastic rocks and minor amounts of radiolarian chert and conglomerate. Northeast of the Sargent fault, the clastic sedimentary rocks contain limestone lenses (Allen, 1946, pl. 1). Hornblende- and glaucophane-bearing metamorphic rocks constitute a small part of the Franciscan Formation of the adjoining New Almaden district but have not been recorded from within the area of the present report. In the structurally complex New Almaden district northeast of the Santa Cruz–San Juan Bautista area, this diverse assemblage of eugeosynclinal rocks is estimated to be at least 10,500 ft thick (Bailey and Everhart, 1964, p. 46).

Foraminifers from a limestone lens in the eastern part of the area and foraminifers and rare megafossils from limestone beds of the Franciscan Formation in the New Almaden district are diagnostic of a Late Cretaceous age (Bailey and others, 1964, p. 116–119). This age cannot be extrapolated to all the Franciscan Formation in the area because of the complex structure and stratigraphy of the diverse rock assemblage. The age of the Franciscan Formation as deduced from fossils at several localities in central and northern California extends from Late Jurassic (Tithonian) to Late Cretaceous (Turonian) (Bailey and others, 1964, p. 115–123). In the area of this report, it is considered to be of Late Jurassic(?) to Late Cretaceous age.

Rocks in fault contact with the Franciscan basement rocks include several thousand feet of Upper Cretaceous strata that resemble the miogeosynclinal rocks of the Great Valley sequence of the Sacramento and San Joaquin Valleys of central California. Most of these strata consist of interbedded feldspathic graywacke and shale; less abundant are thick beds and lenses of pebble and cobble conglomerate. Near Loma Prieta the Cretaceous rocks may include extrusive(?) volcanic rocks. South of Loma Prieta these beds locally contain mollusks indicating a Late Cretaceous age (Bailey and Everhart, 1964, p. 66).

Ultramafic rocks, mainly serpentinite, intrude the Franciscan terrane and fissures along faults that transect both the Franciscan and Upper Cretaceous rocks. Bailey and Everhart (1964, p. 64) believe that in the New Almaden area the serpentinite was largely intruded in Late Cretaceous time.

Overlying the Upper Cretaceous rocks is a sequence of Tertiary marine sedimentary rocks whose stratigraphy has still to be worked out in detail. This sequence ranges in age from Paleocene or Eocene to Miocene and is estimated to be at least 9,000 ft thick. It contains mudstone beds of Paleocene or Eocene age, arkosic sandstone beds of probable Eocene age and of Oligocene (Zemorrian) and early Miocene (Saucesian) age, and siliceous mudstone beds of Oligocene (Zemorrian) and Miocene age. The siliceous mudstone beds were mapped as Monterey Shale in the San Juan Bautista quadrangle by Allen (1946), and on the basis of recent foraminiferal dating are now known to include beds of pre-middle Miocene age.

The Purisima Formation, of Pliocene age, is unconformable upon these older Tertiary strata and upon Franciscan rocks near Sargent. The Purisima is more than 7,000 ft thick; it consists of poorly consolidated sands, silts, clays, and gravels. The lower part was deposited under shallow marine conditions, whereas the upper part was laid down under marginal marine and terrestrial conditions. This weakly consolidated formation has failed; and several landslides have occurred in the hills southeast of Sargent.

Unconformable upon the Purisima Formation north of San Juan Bautista are continental deposits of late Pliocene or early Pleistocene age referred to the San Benito Gravels of Lawson (1893). They are composed of at least 900 ft of poorly consolidated sands and gravels.

GEOLOGIC SECTION SOUTHWEST OF SAN ANDREAS FAULT

CRYSTALLINE ROCKS

Crystalline rocks of the Salinian block form the basement complex southwest of the San Andreas fault. These rocks consist of granitic intrusive and high-grade metasedimentary rocks. The most extensive exposures of these rocks are in the Ben Lomond Mountain area and at the northern end of the Gabilan Range (pl. 1).

The exposed plutonic rocks of the Ben Lomond Mountain area consist of several distinct intrusives bodies that range in composition from gabbro to granite with quartz diorite predominant (Leo, 1967). In the northern Gabilan Range, south of the Vergeles fault, the granitic rocks range in composition from quartz diorite to adamellite, adamellite predominating. Potassium-argon radiometric determinations on granitic rock from the Ben Lomond Mountain area and on quartz diorite of the Gabilan Range from 30 miles southeast of the mapped area give dates of 71.0 ± 0.9 and 79.9 m.y. (million years), respectively (California Division of Mines and Geology, 1965, p. 16; Compton, 1966, p. 277). Although these radiometric dates are Late Cretaceous, Compton (1966, p. 287) suggests on structural grounds that these younger dates record uplift and cooling and that the plutons of the Salinian block were emplaced in mid-Cretaceous time.

The granitic rocks of the Ben Lomond Mountain area and the northern Gabilan Range intrude metasedimentary rocks, primarily schists, quartzites, marbles, and calc-silicate rocks. Marbles are locally more abundant in the northern Gabilan Range, where they were termed the Gabilan Limestone by Becker (1888). Bowen and Gray (1959, p. 11) estimate that at least 8,000 ft of metasedimentary rocks are preserved in one of the larger pendants of the northern Gabilan Range. Similarities in lithology and metamorphic grade suggest that these metasedimentary rocks are correlative with the Sur Series of Trask (1926) in the northern Santa Lucia Range south of the mapped area. The metamorphic rocks of the Salinian block are generally believed to represent metamorphosed miogeosynclinal sandstone, shale, and carbonate beds. Their preintrusive age is uncertain, but Bowen and Gray (1959), who collected poorly preserved fossils from exposures in the northern Gabilan Range, suggest a Paleozoic age.

Exploratory wells south of the Zayante-Vergeles fault confirm the continuity of the crystalline basement between the Ben Lomond Mountain area and the northern Gabilan Range (pl. 1). North of the Zayante-Vergeles fault the basement is downfaulted, and in the Santa Cruz Mountains it is not exposed between the Zayante fault and the San Andreas fault. In the southeastern part of the area, a distinctive granitic body is exposed for about 6 miles southeastward from Logan and is bounded on the northeast by the San Andreas fault. These rocks, primarily hornblende quartz gabbro, are petrologically distinct from the granitic rocks exposed south of the Vergeles fault in the northern Gabilan Range. A recent potassium-argon date of 156 ± 8 m.y. on hornblende indicates that the gabbro is older than the dated granitic rocks of the Salinian block (Ross, 1970, p. 3651). Gravity data presented later in this report suggest that these distinctive gabbroic rocks extend in the subsurface to the southwest, but because of sedimentary cover, their structural relation to the other granitic rocks of the northern Gabilan Range is uncertain.

TERTIARY STRATIGRAPHY OF CENTRAL SANTA CRUZ MOUNTAINS

Sedimentary rocks of Cretaceous age are not exposed, nor are they known in the subsurface southwest of the San Andreas fault within the Santa Cruz–San Juan Bautista area. About 12 miles west of the mapped area, the Pigeon Point Formation of Late Cretaceous age crops out southwest of the San Gregorio fault (fig. 1).

Sedimentary strata within the central Santa Cruz Mountains southwest of the San Andreas fault are of Tertiary and Quaternary age. The Tertiary section consists predominantly of marine clastic sedimentary rocks ranging in age from Paleocene to Pliocene, and it is more than 22,000 ft thick (fig. 2). The section is divisible into four sedimentary rock sequences, essentially continuous, each bounded by unconformities. The basal beds of each sequence locally rest upon the crystalline basement.

The oldest sedimentary sequence is of Paleocene age and consists of erosional remnants of the Locatelli Formation of Cummings, Touring, and Brabb (1962). This formation is as much as 900 ft thick and consists of basal sandstone beds of shallow-marine origin that grade upward into siltstone beds deposited under deeper marine conditions (Clark, 1968, p. 169).

The Eocene to lower Miocene sequence ranges in age from Penutian to Saucesian and is more than 15,000 ft thick. It includes the Butano Sandstone, the San Lorenzo Formation, the Zayante Sandstone, the Vaqueros Sandstone, and the Lambert Shale. This sequence was deposited at bathyal and neritic depths and locally under terrestrial conditions.

The two younger sequences are the product of two separate and successive marine cycles of sedimentation. The older or middle Miocene sequence is about 3,000 ft thick and consists of the Lompico Sandstone of Clark (1966b) at its base and organic mudstone beds of the Monterey Formation. The younger or upper Miocene to Pliocene sequence is more than 3,500 ft thick. It includes the Santa Margarita Sandstone at its base, the Santa Cruz Mudstone of Clark (1966b), and the Purisima Formation. The basal sandstone beds of each of these two sequences were deposited in a nearshore, shallow-marine environment; the overlying mudstone beds were deposited in deeper water, but probably within the neritic zone. The Purisima Formation, of Pliocene age, represents a shallower phase of the younger sequence.

ZAYANTE SANDSTONE

Within the Eocene to lower Miocene sequence and conformable upon the San Lorenzo Formation is a succession of interbedded pebbly sandstone, conglomerate, and sandy siltstone beds that forms a lithologically distinct unit named by Clark (1966b) the Zayante Sandstone. The name is taken from Zayante Creek, along which this formation is discontinuously exposed about 2 miles northeast of the community of Zayante. The type section is designated as that exposed along Zayante Creek from the axis of an anticline (NW¼, sec. 31, T. 9 S., R. 1 W.) northward to the contact with the overlying Vaqueros Sandstone (SW¼, sec. 30, T. 9 S., R. 1 W.).

The Zayante Sandstone was included in the Vaqueros Sandstone by Branner, Newsom, and Arnold (1909) and shown as "lower Miocene marine" (Vaqueros Sandstone) and "Eocene marine" (Butano Sandstone) on the San Francisco sheet of the Geologic map of California (Jennings and Burnett, 1961).

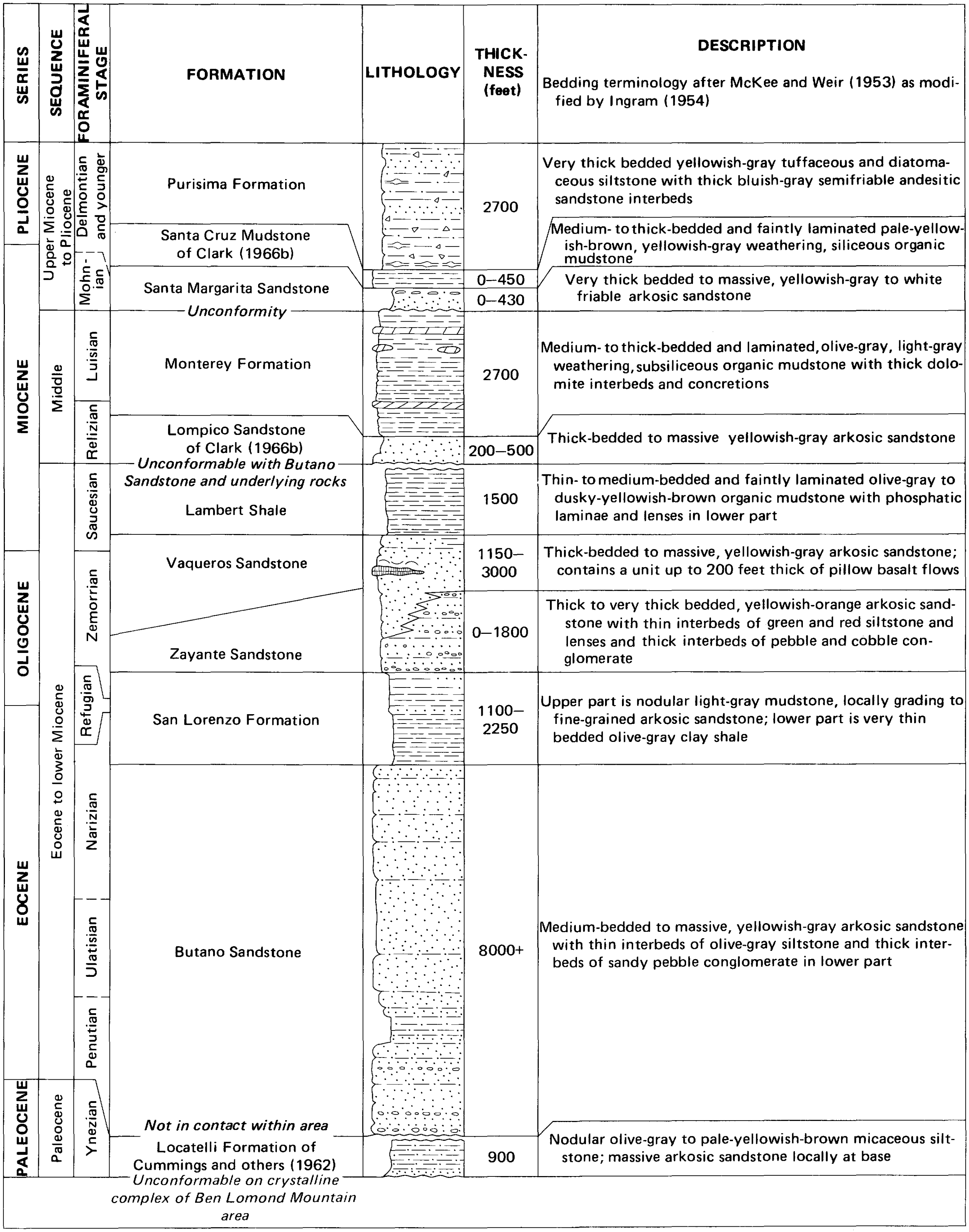

FIGURE 2.—Composite stratigraphic section of Tertiary rocks of central Santa Cruz Mountains southwest of San Andreas fault.

Surface exposures of the Zayante Sandstone extend from 2 miles east of the town of Boulder Creek eastward for a distance of about 6 miles (pl. 1). To the north the formation is in depositional contact with, or locally faulted against, the Vaqueros Sandstone; to the south it is in fault contact with the Butano Sandstone, except along Newell Creek and the adjacent canyon to the west, where it rests conformably upon the San Lorenzo Formation. This area of approximately 5 square miles is designated as the type area of the Zayante Sandstone.

The formation at the type section is about 1,600 ft thick. About 1,800 ft of the Zayante Sandstone is poorly exposed in the vicinity of Lompico Creek between the contact to the southwest with the subjacent San Lorenzo Formation and the contact to the northeast with the superjacent Vaqueros Sandstone.

The Zayante Sandstone is one of the most distinct lithologic units in the central Santa Cruz Mountains (fig. 3). It is composed predominantly of thick to very thick beds of moderately to poorly sorted pebbly medium- to coarse-grained biotite-bearing arkosic sandstone that is bluish gray where fresh but yellowish orange where weathered. Thick conglomerate interbeds, lenses, and pods are composed of well-rounded varicolored porphyritic volcanic and quartzite pebbles and cobbles, and of more angular granitic cobbles and boulders. Thin interbeds of grayish-olive poorly sorted slightly granular fine sandy chloritic siltstone are common; they locally weather to various hues of red and appear mottled. This formation most closely resembles the lower part of the Butano Sandstone but may be distinguished by the presence of greenish siltstone interbeds, greater abundance of biotite, poorer sorting, and the orange weathering color of the sandstone.

FIGURE 3.—Interbedded conglomerate and sandstone of the Zayante Sandstone, 500 ft north of Zayante fault along Newell Creek; larger clasts are granitic.

A nonmarine deposition for the Zayante Sandstone is suggested by the large-scale heterogeneity, poor sorting of individual beds, local channeling at the base of conglomerate beds both within the formation and at contacts, greenish and reddish mottling, and a complete absence of marine fossils. Because this formation is lithologically distinct from the Vaqueros Sandstone and is inferred to be nonmarine, it is separated from the Vaqueros, which is marine.

The contact between the Zayante Sandstone and the subjacent San Lorenzo Formation is placed at the base of the lowest interbedded sequence of poorly sorted medium- to coarse-grained sandstone, conglomerate, and greenish siltstone. The Zayante Sandstone is conformably overlain by, and locally intertongues with, the Vaqueros Sandstone. The contact between the Zayante and Vaqueros Formations is mapped at the base of the stratigraphically lowest thick to massive light-colored moderately to well sorted fine- to medium-grained sandstone bed.

The conformable position of the Zayante Sandstone above the San Lorenzo Formation of Eocene and Oligocene age (Narizian, Refugian, and Zemorrian Stages) and below and partly intertonguing with the Vaqueros Sandstone of Oligocene and early Miocene age (Zemorrian and Saucesian Stages) dates the Zayante Sandstone as Oligocene (Zemorrian).

The local development of the terrestrial Zayante Sandstone within the Eocene to lower Miocene sequence represents a break in marine sedimentation in the Santa Cruz Mountains resulting from tectonism initiated in Oligocene (Zemorrian) time.

OLIGOCENE OROGENY

The Butano Sandstone and the lower part of the San Lorenzo Formation were probably laid down at bathyal depths throughout the central Santa Cruz Mountains. This depositional environment is inferred from the nature of the benthonic Foraminifera and from the paucity of mollusks throughout the coarse clastic part of this section (Cummings and others, 1962, p. 186–188; Brabb, 1964, p. 674; Clark, 1966a, p. 68–69). Brabb (1964, p. 676) suggests that bathyal conditions continued during deposition of the upper part of the San Lorenzo Formation in the vicinity of the San Lorenzo River and Kings Creek, 2–3 miles north of the town of Boulder Creek.

While deepwater conditions persisted to the north, shallowing from bathyal to neritic conditions occurred east of Boulder Creek and north of the Zayante fault during deposition of the San Lorenzo Formation. Along

Newell Creek, the lower part of the San Lorenzo Formation yields deepwater Foraminifera, including costate buliminids and costate uvigerinids. The upper part of this formation is coarser grained and locally contains in abundance such relatively shallow water mollusks as *Pitar*, *Panopea*, *Solen*, and *Modiolus*. Local shallowing continued during Oligocene (Zemorrian) time, and adjacent to the Zayante fault marine conditions gave way to the terrestrial conditions under which the superjacent Zayante Sandstone was deposited.

The limited areal extent and coarseness of the Zayante Sandstone and the total absence of the San Lorenzo and Vaqueros Formations south of the Zayante fault suggest a regional uplift and emergence of the terrane south of this fault during Zemorrian time. Initial uplift along the Zayante fault probably occurred during deposition of the upper part of the San Lorenzo Formation. The rising block south of the fault furnished sediment to the adjacent basin to the north, resulting in the coarsening of the upper part of the San Lorenzo Formation and in shallower marine conditions. Continued uplift produced greater topographic relief, and coarser debris was shed northward, with the Zayante Sandstone deposited as an alluvial fan on the south margin of the adjacent marine basin. The granitic cobbles and boulders in the Zayante Sandstone, locally as much as 4 ft in diameter, record this uplift and indicate that erosion had exposed the crystalline basement to the south.

The Zayante Sandstone interfingers northward with the Vaqueros Sandstone, which in turn changes facies rapidly to the north. About 500 ft north of the Zayante-Vaqueros contact along Zayante canyon, the massive Vaqueros Sandstone includes molluscan bioherms, composed largely of the relatively shallow-water pelecypods *Dosinia* and *Crassatella*. One to 2 miles farther north along Zayante Canyon where the Vaqueros Sandstone is exposed on the north limb of a syncline, the sandstone is finer grained and includes numerous interbeds of mudstone. Mollusks appear to be absent there, but diverse foraminiferal faunas of Zemorrian age have been collected from the mudstone interbeds by McCollom (1959) and by the senior author. Throughout this Vaqueros section costate uvigerinids and costate siphogenerinids, globose Gyroidinas, and large Cyclamminas are common to abundant, indicating bathyal depths. While alluvial fans of the Zayante Formation were deposited adjacent to the Zayante fault, 1 to 2 miles north, bathyal marine sedimentation continued without interruption during deposition of the San Lorenzo and Vaqueros Formations (geologic section A–A′, pl. 1).

McCollom (1959, p. 36–37) has shown that within the central Santa Cruz Mountains the Vaqueros Sandstone thickens and becomes coarser grained toward the southwest; he postulates that this formation "seems to have had its source area somewhere to the southwest, perhaps in the vicinity of the present day Ben Lomond Mountain." Brabb (1960, p. 101–116), on the other hand, believes that the source area was more westerly, from what is now the continental shelf. We believe that the Zayante and Vaqueros Sandstones represent orogenic deposits derived from an extensive emergent crystalline terrane south of, and in close proximity to, the Zayante fault. The southwestern extent of this emergent terrane is uncertain. It included crystalline rocks of the Ben Lomond Mountain area but most probably did not include the tectonic block to the west of the San Gregorio fault (fig. 1), because mudstone beds that crop out along the present coast west of this fault and 12 miles west of the mapped area have recently yielded deep water foraminifers diagnostic of late Zemorrian age.

The Lambert Shale is conformable upon the Vaqueros Sandstone and records a decrease in the influx of coarse clastic detritus into the basin. This decrease suggests that the terrane uplifted south of the Zayante fault during Zemorrian time had been reduced to a lowland by early Miocene (Saucesian) time.

TERTIARY STRATIGRAPHY OF NORTHERN GABILAN RANGE

Sedimentary strata exposed in the northern Gabilan Range southwest of the San Andreas fault are of Tertiary and Quaternary age. The Tertiary section ranges in age from Eocene to Pliocene and consists of marine and nonmarine clastic sedimentary strata with interbedded volcanic flows and agglomerate. This section is more than 10,000 ft thick and is composed of an Eocene to lower Miocene sequence and the Pliocene Purisima Formation (fig. 4).

The Eocene to lower Miocene sequence is reported by Allen (1946, p. 27) to rest upon the crystalline basement northwest of the town of San Juan Bautista. It includes the San Juan Bautista Formation (siltstone and sandstone) of Kerr and Schenck (1925), the Pinecate Formation (massive sandstone) of Kerr and Schenck (1925), the red beds of Kerr and Schenck (1925), and extrusive andesitic volcanic rocks.

Foraminifera from siltstone beds in the lower part of the San Juan Bautista Formation indicate that these beds were laid down at bathyal depths (Castro, 1967; Waters, 1968), whereas the rest of the sequence was deposited under shallow-marine and terrestrial conditions. The conglomeratic red beds (fig. 5) were interpreted by Allen (1946, p. 29) "to be due to sea-cliff erosion along a shoreline, or possibly fanglomerate accumulation resulting from uplift of the Gabilan

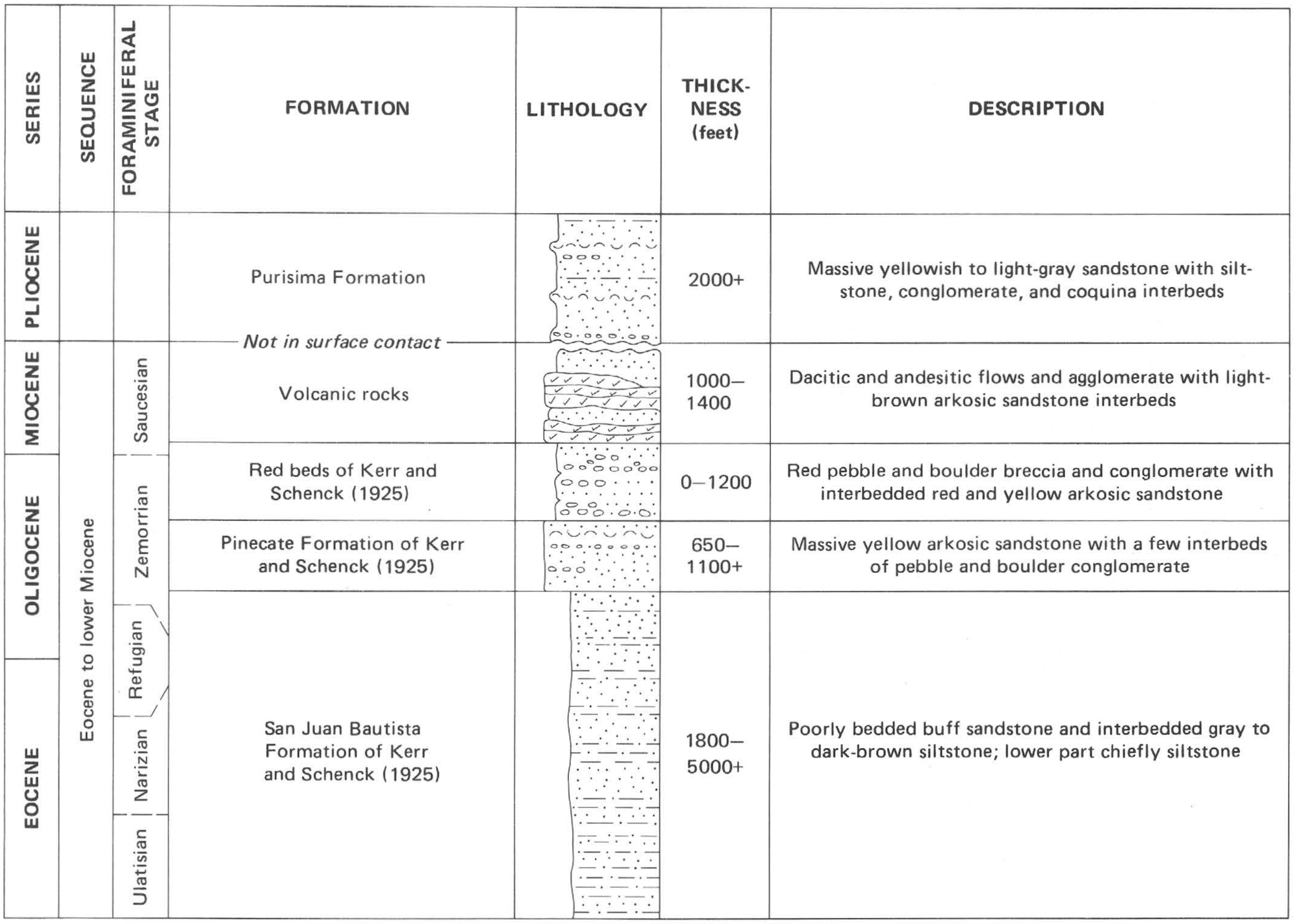

FIGURE 4.—Composite stratigraphic section of Tertiary rocks of northern Gabilan Range southwest of San Andreas fault (Kerr and Schenck, 1925; Allen, 1946; McCroden, 1949; Castro, 1967; Waters, 1968; Turner, 1968; T. W. Dibblee, Jr., written commun., 1969).

Range, probably by initial movements along the Vergeles fault."

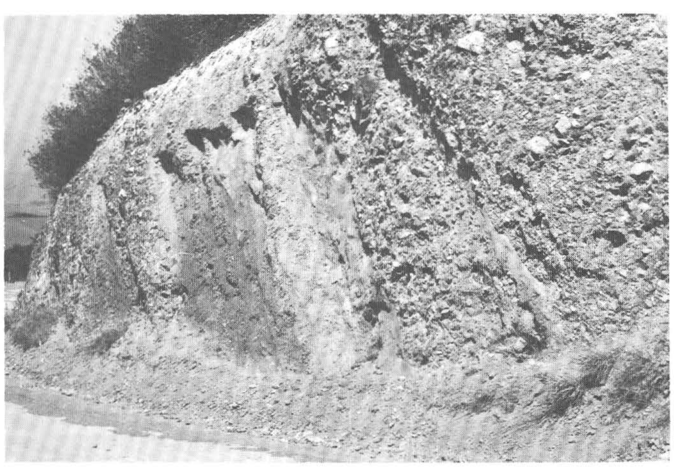

FIGURE 5.—Red beds of Kerr and Schenck (1925), dipping south along San Juan Grade, 1½ miles northeast of Vergeles fault.

The Purisima Formation, of Pliocene age, rests upon the crystalline basement near Logan but is not in surface contact with the Eocene to lower Miocene sequence. Here, it is more than 2,000 ft thick and contains abundant mollusks, indicating shallow-marine deposition.

CORRELATION WITH CENTRAL SANTA CRUZ MOUNTAINS

Although the Eocene to lower Miocene sequence of the northern Gabilan Range was probably deposited within the same basin as the correlative section in the central Santa Cruz Mountains, the lack of continuity of surface exposures and lateral facies changes between these two areas have resulted in separate rock-stratigraphic nomenclatures. The fine-grained lower part of the San Juan Bautista Formation is correlative with part of the Butano Sandstone to the northwest (Waters, 1968). The coarser grained upper part of the San Juan Bautista Formation and the overlying Pinecate Formation are partly correlative with the San

Lorenzo and Vaqueros Formations of the Santa Cruz Mountains.

The red beds appear to correlate with the Zayante Sandstone to the northwest. Although Kleinpell (1938, p. 114) postulated a Saucesian age for these red beds, a potassium-argon date of 21.6±0.7 m.y. on dacite from near the base of the volcanic section suggests a Saucesian age for the volcanic rocks and a Zemorrian to earliest Saucesian age for the underlying red beds (Turner, 1968, p. 55). Because of the probable genetic relation of the red beds to movement along the Vergeles fault, the radiometric dating is significant, for it suggests that uplift along the Vergeles and Zayante faults was approximately contemporaneous.

ZAYANTE FAULT

The Zayante fault was originally mapped by Branner, Newsom, and Arnold (1909) from the vicinity of Boulder Creek slightly south of east to the eastern edge of the Santa Cruz quadrangle. This fault continues 11 miles farther southeast to the vicinity of Corralitos, where it is covered by Quaternary sediments (pl. 1). Westward from Boulder Creek, the Zayante fault has been mapped to its juncture with the Ben Lomond fault, about 2 miles west of the Santa Cruz–San Juan Bautista area (Brabb, 1964, fig. 1).

Because of the dense vegetation and deep weathering in the area, the Zayante fault is poorly exposed; its trace is determined largely from structural and stratigraphic discordances of adjacent beds. Where the fault is exposed along Bear Creek Road about half a mile east of Boulder Creek, the Butano Sandstone and the Vaqueros Sandstone are separated by a 30-ft wide, near-vertical shear zone. One to 2 miles farther east, several minor fractures branch off from the Zayante fault at acute angles. In the vicinity of Zayante canyon, the Zayante Sandstone and the lower part of the Butano Sandstone are juxtaposed by the fault, indicating about 4,000 ft of dip separation with the north side relatively downthrown. Farther east, the fault brings the Purisima Formation into contact with the Butano Sandstone for about 3½ miles, and its continuation to the vicinity of Corralitos is marked by anomalies in the structural attitudes of the Purisima Formation.

Only locally is the fault expressed topographically (fig. 6). East of Zayante canyon, a tributary to Zayante Creek flows southward until it reaches the fault, then turns abruptly westward to follow the fault to Zayante Creek. The relatively straight course of the Zayante fault across the canyons and ridges of this area indicates that the fault is nearly vertical.

The Ben Lomond fault, as mapped by Branner, Newsom, and Arnold (1909) and locally by Brabb (1964), is an arcuate fracture that runs east and north of Ben Lomond Mountain for a distance of about 15 miles. The mapping and stratigraphy of the Felton area indicate that south of Boulder Creek this fault is a relatively minor structure, with a dip separation of less than 500 ft (geologic section A–A′, pl. 1). In contrast, gravity measurements and stratigraphic work west of Boulder Creek suggest dip separations of 3,000–10,000 ft along the northwestern part of the Ben Lomond fault (Cummings and others, 1962, p. 215). Because the suggested amount and sense of displacement on the north flank of Ben Lomond Mountain are of the same order of magnitude as that along the Zayante fault to the east, we believe that the northwestern part of the Ben Lomond fault of earlier mappers is the westward continuation of the Zayante fault. In this report, the name "Ben Lomond" is restricted to the relatively minor dislocation that trends southeastward from near Boulder Creek, through the town of Ben Lomond, to the vicinity of Felton (pl. 1).

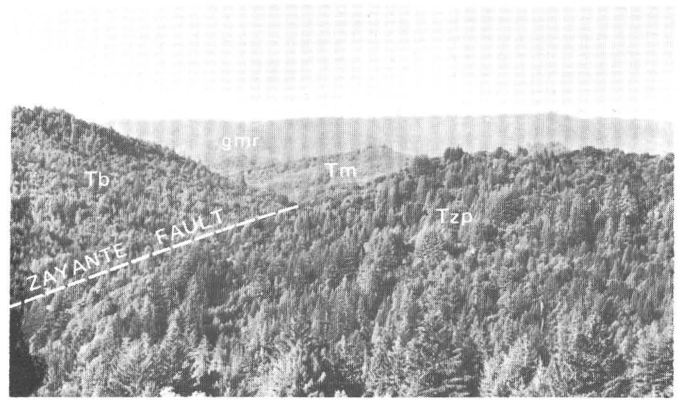

FIGURE 6.—Westward-trending valley along Zayante fault east of Zayante canyon, looking southwest toward Ben Lomond Mountain at skyline. Tb, Butano Sandstone; Tzp, Zayante and Purisma Formations; Tm, Monterey Formation; gmr, granitic and metasedimentary rocks.

VERGELES FAULT

The Vergeles fault separates the crystalline rocks of the northern Gabilan Range from the volcanic and sedimentary rocks of the Eocene to lower Miocene sequence. South of San Juan Bautista, this fault curves eastward and trends into the San Andreas fault about 2 miles east of the mapped area. To the northwest the Vergeles fault is covered by Quaternary sediments.

Where exposed along San Juan Grade, this fault is reported by Allen (1946, p. 57) to strike N. 60–80° W. and to dip 70–80° S. with vertical striations and grooves in rhyolite. Allen (1946, p. 57) states, "***Minimum vertical displacement on the fault is at least 3500 ft, the total being undoubtedly much more."

The similarities in the geometry and the middle

Tertiary history of the Vergeles and Zayante faults suggested to the writers that the Vergeles fault was a southeastward continuation of the Zayante fault with the continuity now obscured by Quaternary deposits for about 17 miles. The gravity data of this report confirm the continuity of these two major faults.

BOUGUER GRAVITY FIELD

The Bouguer gravity field (pl. 1) is composed of a series of northwest-southeast-trending highs and lows superimposed upon a regional gravity gradient that decreases eastward at approximately 1 mgal per mile. Within the mapped area, Bouguer gravity values range from a maximum of more than +36 mgal at Ben Lomond Mountain to a minimum of less than −40 mgal east of San Juan Bautista.

The Bouguer anomalies correlate well with the known geology and are generally alined with the regional structural trend. Positive anomalies are associated with exposures of the relatively dense rocks of the crystalline basement and the Franciscan Formation. Negative anomalies correspond with thick sections of Tertiary sedimentary rocks. Steep gravity gradients are associated with many of the known faults where rocks of contrasting densities have been juxtaposed at shallow depths.

The prominent positive anomaly that is partly defined in the western part of the survey area is associated with crystalline rocks of the Ben Lomond Mountain area and extends approximately 15 miles to the northwest beyond the mapped area (Chapman and Bishop, 1968). On the northeast flank of Ben Lomond Mountain, a steep gravity gradient is associated with the Ben Lomond fault from near Boulder Creek southeastward to Felton, where surface expression of the fault disappears. Here, the gravity contours trend northeastward, extending the gravity high in that direction. Scattered outcrops of granitic rocks south and east of Scotts Valley also confirm that the crystalline basement is shallow in this area.

In the vicinity of Boulder Creek, the northwest-trending gravity gradient that is related to the density contrast between the crystalline complex of Ben Lomond Mountain and the middle Miocene sequence to the east is oblique to the trend of the Zayante fault. In this area and to the east for 4 miles, the Zayante fault is not reflected in the gravity field, and a northwest-striking bench extends across the Zayante fault. Although the Tertiary section south of the fault is thinner than that to the north, the southern section has a greater density contrast with the crystalline basement that partially offsets the gravitational effects of the thickness difference. To the south, the section includes nearly 3,000 ft of relatively low-density mudstones of the Monterey Formation, whereas north of the fault, the thicker sedimentary section is composed largely of higher-density Vaqueros, Zayante, and Butano Sandstones. Farther southeast where the low-density Miocene and Pliocene sections are thinner and granitic rocks are exposed locally south of the Zayante fault, the course of the fault is approximated by a steep gravity gradient.

An elongate northwest-trending gravity maximum is associated with the crystalline rocks of the Gabilan Range (Bishop and Chapman, 1967). This anomaly extends into the southern part of the survey area, where it forms two distinct highs. The saddle between these two maximums coincides with the northwestern part of the exposed trace of the Vergeles fault. South and west of this fault, the positive Bouguer anomaly is associated with the outcrops and subsurface extension of the crystalline complex. The eastern anomaly between Pinecate Peak and Logan is associated with the distinctive gabbroic rocks that are exposed along the southwestern side of the San Andreas fault. The gravity anomaly suggests that in the subsurface this body extends southwest of the known exposures. The eastern part of the Vergeles fault appears to lack any obvious gravity expression. This may result in part from limited gravity control in this area of steep gravity gradients.

East of San Juan Bautista the gravity field is dominated by a steep gradient of approximately 25 mgal per mile associated with the San Andreas fault. Here, crystalline rocks southwest of the fault have been juxtaposed against approximately 7,000 ft of Pliocene and Pleistocene sedimentary rocks to the northeast (geologic section C–C′, pl. 1).

West of the gravity high associated with the northwestward extension of the crystalline rocks of the Gabilan Range, the gravity field decreases in response to a deepening of the basement beneath the Salinas trough. A gravity low extending eastward from Moss Landing and represented as a flexure in the contour lines has been interpreted by Starke and Howard (1968) as reflecting a buried eastward extension of the Monterey submarine canyon. The Bayside Development Vierra 1 well (pl. 1, No. 17), drilled within this low to a total depth of 7,916 ft, failed to reach the granitic basement.

Between the Ben Lomond Mountain and Gabilan Range basement outcrops, a broad saddle in the Bouguer anomaly field south of Corralitos corresponds to a depression in the crystalline basement. The general form of this depression as inferred from exploratory well data (pl. 1, Nos. 6, 7, 8, 12, 13, 14, and 15) generally follows the trend of the Bouguer anomaly contours.

One of the more prominent features of the gravity field is the northwest-trending gravity minimum that extends from just west of Pinecate Peak to the northern limit of the mapped area. This anomaly reaches a minimum value of less than −22 mgal about 2 miles east of Corralitos. The surface geology of the central Santa Cruz Mountains suggests that the anomaly is produced by a thick section of Tertiary sedimentary rocks. The northeastern boundary of this elongate low corresponds with the surface trace of the San Andreas fault. To the northwest along this fault, the Tertiary section is in contact with Franciscan basement and Upper Cretaceous rocks. In the central part of the area, a flattening of the gravity anomaly northeast of the San Andreas fault is produced by a 7,000-ft section of lower Tertiary sedimentary rocks. Farther east the gravity field rises where the Franciscan basement is exposed east of the Sargent fault.

In the southern part of the area, the southwestern boundary of this prominent gravity minimum corresponds with the surface trace of the Vergeles fault. A gravity gradient of approximately 6 mgal per mile parallels the postulated northwestern extension of the Vergeles fault. This gradient is continuous with the gradient that marks the southeastern trace of the mapped Zayante fault and is interpreted as probable confirmation of the subsurface continuity of the Zayante and Vergeles faults. The location of the concealed part of the Zayante-Vergeles fault, as shown on plate 1, is based upon a relatively straight-line connection bowed slightly southwest around the Corralitos gravity low between the mapped portions of the Zayante and Vergeles faults.

This elongate negative anomaly is interpreted as being produced by a thick Tertiary sedimentary section that is bounded on the northeast by the San Andreas fault and Franciscan basement and on the southwest by the continuous Zayante-Vergeles fault and relatively shallow Salinian basement. Additional confirmation of this interpretation is provided by surface geology, well data, and quantitative models of the gravity field. More than 14,000 ft of Tertiary section has been mapped in the central Santa Cruz Mountains. The Union Oil Teresa Hihn 1, the Texas Blake 1, and the Occidental Petroleum Bingaman 1 wells (pl. 1, Nos. 3, 5, 16), located on the north (downdropped) side of the Zayante-Vergeles fault, were all drilled to total depth greater than 7,000 ft and failed to reach basement. Other wells (pl. 1, Nos. 6, 7, 8, 12, 13, 14, 15, 18, 19) southwest of the Zayante-Vergeles fault penetrated the Salinian basement at relatively shallow depths. The Texas Blake 1 well is reported (A. J. Macmillan, written commun., 1969) to have bottomed in "Lower Miocene sands" at a total depth of 7,522 ft. If the subsurface thickness of the pre-lower Miocene section east of Corallitos approximates the 10,000 ft exposed in the central Santa Cruz Mountains, then the Tertiary section in this area could exceed 17,000 ft.

MODEL STUDIES OF GRAVITY FIELD

Three density models, corresponding to geologic cross sections *A–A′*, *B–B′*, and *C–C′* (pl. 1), have been constructed to determine if the geology, as presented, can adequately account for the observed Bouguer gravity. These density models support the interpretation that the Zayante and Vergeles faults are continuous and also give approximate depths to the basement. The models are necessarily limited by incomplete information on the regional gravity field and on the distribution and variation of rock densities.

A regional gravity field was constructed in order to eliminate from the models the gravitational effects of deep crustal structure, large-scale density variations within the basement, and density variations outside the model area. The regional field was derived from gravity data from this survey, published data from the Santa Cruz and San Francisco sheets of the Bouguer gravity map of California (Bishop and Chapman, 1967; Chapman and Bishop, 1968), and a few regional stations obtained by the writers. Regional profiles were drawn on north-south and east-west lines at 5-mile intervals across the survey area. These profiles were required to be without fluctuation and always above the observed Bouguer field. The regional gravity field (fig. 7) was constructed by contouring the regional profiles within the survey area.

The regional field, as constructed, generally decreases eastward at approximately 1 mgal per mile. The most prominent feature is a high centered on Ben Lomond Mountain. This high is primarily a reflection of the relative magnitude of the Bouguer anomaly associated with this crystalline complex as compared with anomalies associated with other Salinian complexes of similar dimensions. This suggests that the crystalline complex of Ben Lomond Mountain is denser, particularly at depth.

The residual Bouguer anomaly, which results from subtracting the regional gravity from the observed Bouguer gravity, represents the gravitational effects of density variations within the sedimentary section and between the sedimentary and basement rocks. The residual anomaly is used for comparison with the gravity computed from the models (pl. 1).

The models used to calculate gravitational effects are essentially density contrast models. Structural and stratigraphic variations are converted into density contrasts with the basement rocks and the gravitational effects calculated by computer. The computer com-

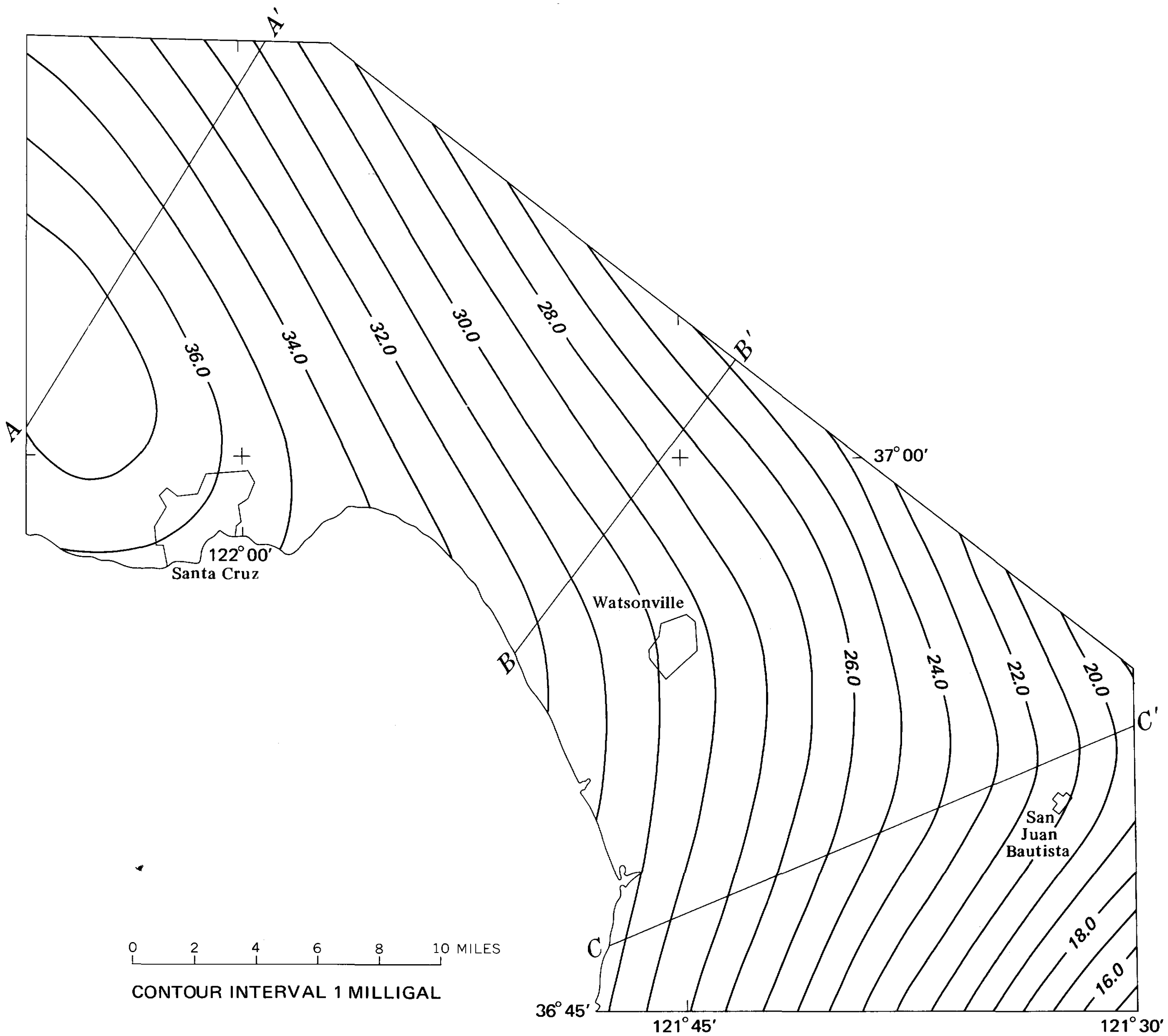

FIGURE 7.—Regional Bouguer gravity field of the Santa Cruz–San Juan Bautista area. Sections are shown on plate 1.

pared calculated and residual gravity values and, within certain constraints imposed by the known surface geology, well data, and assumed rock densities, altered the models to give a desired fit. In order to achieve a fit within the survey area, the geology was extended approximately 8 miles beyond the ends of the cross sections. In this modeling scheme, any variance in the true value of rock densities from that assumed in the models will result in an error in estimation of basement depth.

Samples for density determinations were collected from sedimentary and basement rocks throughout the mapped area. Wherever possible, wet densities were measured. Where not measured, wet density was calculated using a method described by Byerly (1966). In addition to measured densities, we used values reported by Brabb (1960) and Byerly (1966) and in several unpublished student reports at the University of California at Santa Barbara. A density of 2.67 g/cm^3 (grams per cubic centimeter) was accepted as an "average" for Franciscan basement rocks (Clement, 1965; Thompson and Talwani, 1964). The measured densities and the values we used for modeling are listed in table 1. In addition, a density of 2.17 g/cm^3 was assumed for for the thick Pliocene section east of the San Andreas fault near San Juan Bautista in order to allow for density increase with depth because of compaction and cementation.

TABLE 1.—*Measured rock densities and model densities in grams per cubic centimeter*

Rock type	Number of Samples	Measured density		Model density
		Mean	Range	
Miocene and Pliocene mudstones	22	2.05	1.60–2.25	1.97
Middle Tertiary sandstones and siltstones	27	2.35	1.90–2.40	2.37
Eocene and Cretaceous sandstones, well cemented	15	2.48	2.35–2.62	2.47
Granitic basement	18	2.70	2.65–2.74	2.67
Franciscan basement	....	......	....	2.67

To simplify the computations, a model density of 2.67 g/cm^3 was assigned to both the Franciscan and granitic basement rocks, and model densities for other rocks were selected to produce a density contrast with the basement rocks of an even multiple of 0.1.

Three density models, corresponding to geologic cross sections *A–A′*, *B–B′*, and *C–C′*, are shown on plate 1 with the associated computed Bouguer anomalies and residual Bouguer anomalies. The program used to calculate the gravitational effects of the density models is similar to the one described by Talwani, Worzel, and Landisman (1959), and has been modified to take in account and effects where a strict two-dimensional model is not applicable (Nettleton, 1940, p. 117). Minor modifications in basement depths and subsurface fault locations were made to the original density models to improve the fit between the computed and residual anomalies.

Comparison of the density models with the geologic cross sections shows the models to be in reasonable agreement with the extrapolated geology. These geologic sections were constructed prior to the analysis of the gravity data and have not been altered by the model studies. Where the density models and the geology are in agreement, we believe that the indicated depths to basement are reasonable. Elsewhere, the differences may result either from density variations not accounted for in the models or from a lack of subsurface geologic control.

Although the Zayante fault is not associated with a steep gravity gradient along section *A–A′*, the model indicates that the granitic basement is displaced approximately 6,000 ft by this fault. These gravity data also suggest that the Tertiary section between the Zayante and San Andreas faults is several thousand feet thinner and the basement correspondingly shallower than shown on the geologic cross section.

Along section *B–B′*, the geology and model indicate that the granitic basement is offset approximately 8,500 ft and 9,000 ft, respectively, by the subsurface continuation of the Zayante and Vergeles faults. The gravity data along this section support the interpretation that the granitic basement rises abruptly southwest of the San Andreas fault. Subsurface geologic control is not sufficient to determine whether this granitic uplift results from folding or faulting.

The vertical offset of the granitic basement by the Vergeles fault (section *C–C′*, pl. 1) is estimated by the geology to be 9,000 ft and by the gravity to be approximately 8,500 ft. The similarity of these estimates results largely from the subsurface control provided by the Occidental Bingaman well, which constrained the modeling program. The gravity data suggest that the granitic basement rises more rapidly east of this well than is shown on the geologic cross section.

ZAYANTE-VERGELES FAULTING AND MIDDLE TERTIARY PALEOGEOGRAPHY

The Paleocene and Eocene to lower Miocene sequences of the central Santa Cruz Mountains are strikingly similar to the correlative sections in the northern Santa Lucia Range, 60 miles to the south (Clark, 1968, p. 172–174). Dickinson (1956, p. 132) has suggested that the Church Creek Formation in the northern Santa Lucia Range and the San Lorenzo Formation of the Santa Cruz Mountains may have been deposited within the same basin. The San Juan Bautista Formation of Kerr and Schenck (1925) also would have been deposited within this basin. According to Addicott's (1968, p. 147–148) paleogeographic reconstruction, during Refugian time this basin extended southeast of San Juan Bautista with an eastern strandline that trended southward through the Santa Lucia Range.

Although the proposed continuity of these depositional basins is largely inferred from limited outcrop data, the gravity analysis of this report confirms the continuity of a thick Tertiary sedimentary section between the central Santa Cruz Mountains and the northern Gabilan Range. Thus the analysis supports the interpretation that the Santa Cruz basin extended southeastward to the San Juan Bautista area during early Tertiary time. Had the basin continued southward to the Santa Lucia area, as suggested by Dickinson and Addicott, the Zemorrian uplift along the Zayante-Vergeles fault would have separated the two areas. This faulting strongly influenced the Zemorrian paleogeography of the Santa Cruz Mountains and northern Gabilan Range.

The shallowing recorded by the upper part of the San Lorenzo Formation in the central Santa Cruz Mountains probably reflects initial movement along the Zayante-Vergeles fault. Continued uplift along this fault resulted in emergence of the crystalline basement to the south, deposition of terrestrial beds—the Zayante Sandstone and the red beds of Kerr and Schenck (1925)—along the fault, and restriction of marine conditions to an embayment to the north, the Santa Cruz Bay of Loel and Corey (1932, map 1). Thus uplift produced a northwest-southeast-trending, northeast-facing Zemorrian shoreline whose position was in close proximity to the fault. The positive block south of the fault, which included both the Ben Lomond and Gabilan Mountain blocks of Clark (1930) and is here referred to as the Ben Lomond–Gabilan block, separated the Santa Cruz basin from the Santa Lucia basin to the south.

Starke and Howard (1968) have recently postulated a terrestrial origin for the ancestral Monterey canyon. If their hypothesis is correct, this canyon may have been eroded subaerially during Zemorrian time by streams draining the southern slope of the emergent Ben Lomond–Gabilan block.

The Zayante-Vergeles fault ceased to be an important structure by early Miocene (Saucesian) time. The fine clastic deposition of the Lambert Shale north of the Zayante fault suggests that the Ben Lomond–Gabilan block had been reduced to a lowland, which was subsequently transgressed by the middle Miocene seas with deposition of the Monterey Formation.

East of Ben Lomond Mountain, the middle Miocene sequence coarsens toward the west, and on both slopes of the mountain, the Monterey Formation contains thick sandstone interbeds. These relations and marked differences in the middle Miocene faunas on opposite sides of the mountain indicate that the crystalline complex of Ben Lomond Mountain was locally high. Whether this topography represented a residual high or resulted from local upwarping of the basement during middle Miocene time is uncertain.

Later vertical movements occurred along the Zayante-Vergeles fault. Post-early Miocene displacement is indicated by grooving in volcanic rocks in the northern Gabilan Range and post-middle Miocene displacement by tectonic slivers of the Monterey Formation along the fault in the central Santa Cruz Mountains. The later displacement may have occurred in post-early Pliocene time, for the Purisima Formation is offset along this fracture. The western segment of the Zayante fault (the Ben Lomond fault of earlier workers) appears to have been inactive in post-late Miocene time, as 8 miles west of the mapped area, the Santa Cruz Mudstone of Clark (1966b) is unaffected by the fault.

Although several recent earthquake epicenters have been plotted between Watsonville and San Juan Bautista near the trace of the Zayante-Vergeles fault (California Department of Water Resources, 1964; Brabb, 1967), Quaternary deposits in the area do not appear to have been offset by the fault, and these earthquakes, including the magnitude 5.2 shock of September 14, 1963, are liklier to be related to movement along the San Andreas fault.

RELATION TO SAN ANDREAS FAULTING

Recent right-lateral slip has been documented along the mapped segment of the San Andreas fault. Surface rupture along the fault during the San Francisco earthquake of April 18, 1906 extended southward through the area to one-half mile northwest of San Juan Bautista (Lawson and others, 1908, p. 38). Right-lateral movement along the fault during the 1906 earthquake produced horizontal displacements of 4 ft about 3 miles northwest of San Juan Bautista, 3½ ft between railroad bridge abutments at Pajaro Gap, and 5 ft in a railroad tunnel at Wrights Station about 1 mile west of Lake Elsman (Lawson and others, 1908, p. 38, 111–113). Active deformation with right-lateral offset of roads and fences has been recorded along the trace of the San Andreas fault at San Juan Bautista (Nason and Rogers, 1967).

The history of this segment of the San Andreas fault has remained controversial. The marked similarity of the "lower Miocene volcanics, red beds, and marine lower Miocene and Oligocene strata" of the northern Gabilan Range west of the fault with the correlative section of the San Emigdio Mountains at the southern end of the San Joaquin Valley east of the fault suggested to Hill and Dibblee (1953, p. 448–449) approximately 175 miles of right-lateral offset along the San Andreas since early Miocene time. Other workers (Cummings and others, 1962; Oakeshott, 1966), noting the similarity in the stratigraphic sequences on opposite sides of the San Andreas fault in the northern Santa Cruz Mountains, have considered such large-scale lateral displacement along this segment of the fault to be improbable.

Recent stratigraphic work by Clark (1968) and radiometric dating by Turner (1969) have revealed that the Tertiary stratigraphy of the Santa Cruz Mountains does not preclude large cumulative slip along this segment of the fault. Oligocene and early Miocene zoogeographic and paleogeographic analysis by Addicott (1968) and detailed comparison and radiometric dating of the lower Miocene volcanic rocks of the northern Gabilan Range and of the San Emigdio Mountains by Bazeley (1961) and Turner (1969) have strengthened substantially Hill and Dibblee's hypothesis for a 175-mile displacement.

The time of initiation of right-lateral slip on the San Andreas fault system is uncertain. Page (1970, p. 685) believes that there is little geologic evidence to indicate that the San Andreas fault system existed prior to Oligocene time and even less evidence that it existed prior to the Eocene. Crowell (1968, p. 327), working in the central Transverse Ranges of southern California, has suggested that San Andreas faulting originated in early Miocene or possibly during Oligocene time. This dating is supported by the analysis of magnetic anomalies in the northeastern Pacific basin by McKenzie and Morgan (1969, p. 130), who state, "***It is difficult to understand how the right lateral motion on the San Andreas and related faults can have begun on a large scale before the Oligocene***."

An Oligocene or later origin for the right-lateral slip on the San Andreas fault system and the postulated 175-mile post-early Miocene displacement are difficult to reconcile with an apparent 350-mile offset of the Franciscan basement–Sierran basement contact (Hill and Dibblee, 1953; Hamilton, 1969, p. 2415). A possible resolution of this apparent conflict has recently been suggested by Atwater (1970, p. 3516ff.). On the basis of her study of Pacific Ocean magnetic anomaly patterns and plate theory, Atwater postulates two episodes of right-lateral slip on the San Andreas, a late Mesozoic and early Cenozoic episode and a more recent episode that she believes started not earlier than 30 m.y. (Oligocene).

If Atwater's later episode of San Andreas motion commenced during the Oligocene, then the initiation of this displacement on the San Andreas fault system and the initial movement of the Zayante-Vergeles fault were approximately contemporaneous. The Oligocene stratigraphy of the central Santa Cruz Mountains and of the northern Gabilan Range does not appear to have been influenced by topography alined with the San Andreas fault but rather was controlled by uplift along the Zayante-Vergeles fault. The stratigraphic record suggests that Zayante-Vergeles faulting may have preceded the later Cenozoic movement on the San Andreas fault, or alternatively that Oligocene displacement along this segment of the San Andreas lacked a significant component of dip slip.

Although large-scale post-early Miocene displacement along the San Andreas fault now appears probable, several lines of evidence suggest that lateral movement has not been transferred from the San Andreas to the northwest-trending Zayante-Vergeles fault. Metasedimentary clasts in the red beds of the San Juan Bautista area were clearly derived from metamorphic pendants of the Gabilan Range to the south directly across the Vergeles fault. An areally restricted biostrome composed of the tests of the irregular echinoid *Astrodapsis spatiosus* Kew in the upper part of the Santa Margarita Sandstone in the central Santa Cruz Mountains has a nearly contiguous distributional pattern across the Zayante fault.[1] Verticle grooves in the volcanic rocks of the northern Gabilan Range suggest that the latest movement along the Vergeles fault was vertical rather than lateral. Strike-slip displacement does not appear to have been superposed upon the Cenozoic high-angle movements of the Zayante-Vergeles fault.

[1]A critical northern exposure of Santa Margarita Sandstone along Zayante canyon is not shown on plate 1 because of scale.

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