Stratigraphy, Paleontology, and Geology of the Central Santa Cruz Mountains, California Coast Ranges

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By JOSEPH C. CLARK

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CONTENTS

ILLUSTRATIONS

TABLES

STRATIGRAPHY, PALEONTOLOGY, AND GEOLOGY OF THE CENTRAL SANTA CRUZ MOUNTAINS, CALIFORNIA COAST RANGES

By

JOSEPH C. CLARK

ABSTRACT

Southwest of the San Andreas fault and northeast of the San Gregorio fault in Santa Cruz and San Mateo Counties is one of the most complete Tertiary rock sections in the California Coast Ranges. Overlying a Salinian basement complex of granitic and older metasedimentary rocks is a succession of arkosic sandstone and mudstone units, ranging in age from Paleocene to Pliocene and having a composite thickness of as much as 7,390 m. This Tertiary section is divisible into four sedimentary rock sequences which are virtually continuous, each of which is bounded by unconformities of regional extent.

Resting on the basement complex, the oldest sequence consists of erosional remnants of the Locatelli Formation of Paleocene (Ynezian) age. Basal sandstone beds of this formation contain relatively shallow-water mollusks associated with calcareous foraminifers and grade upward into siltstone of deeper marine origin that contain abundant arenaceous foraminifers.

The next younger sequence ranges from early Eocene (Penutian) to early Miocene (Saucesian) age and consists of the Butano Sandstone, San Lorenzo Formation, Zayante Sandstone, Vaqueros Sandstone, and Lambert Shale. Bathyal deposition was followed by local shallowing during Oligocene (Zemorrian) time.

The two younger sequences are the products of two separate and successive marine cycles of sedimentation. The older cycle was a middle Miocene (Relizian and Luisian) event that produced a widely transgressive, basal sandstone unit, the Lompico Sandstone, and an overlying organic mudstone unit, the Monterey Formation. The younger cycle was initiated in late Miocene (Mohnian) time and likewise produced a transgressive, basal sandstone unit, the Santa Margarita Sandstone, and an overlying siliceous mudstone unit, the Santa Cruz Mudstone. The basal sandstone beds of each of these two sequences were deposited in a nearshore, shallow-marine environment, whereas the overlying mudstone beds were laid down in deeper water, but probably at neritic depths. A later and shallower phase of the younger cycle is recorded by the Purisima Formation of Pliocene age.

Southwest of the San Gregorio fault, typical crystalline rocks of the Salinian block are not exposed, and porphyritic rhyolite that crops out near Pescadero to the north may form part of the basement. There, more than 2,600 m of Upper Cretaceous marine strata of the Pigeon Point Formation is overlain unconformably by more than 500 m of marine clastic sedimentary and volcanic rocks that range in age from Oligocene (Zemorrian) to Holocene. This Cenozoic section includes the Vaqueros(?), Monterey, and Purisima Formations, which are complexly folded and faulted in exposures north and east of Año Nuevo Point.

The San Gregorio fault is part of an active zone, about 3 km wide, east of Año Nuevo Point that includes at least five northwest-trending faults from the Año Nuevo fault on the west to minor faults at Greyhound Rock to the east. Marked contrasts in the Mesozoic and Cenozoic sections across the San Gregorio fault suggest past large-scale lateral displacement.

The Zayante fault was an important structure during Oligocene (Zemorrian) time that displaced the crystalline basement approximately 2 km and strongly influenced the Oligocene stratigraphy of the area. South of this fault, Salinian basement is extensively exposed and occurs at relatively shallow depths, with the overlying Tertiary strata tilted and deformed into broad, open folds. North of the Zayante fault, the basement is not exposed and the strata are more strongly deformed and locally overturned.

INTRODUCTION

Southwest of the San Andreas fault in the central Santa Cruz Mountains of Santa Cruz and San Mateo Counties is one of the most complete Tertiary stratigraphic sections in the California Coast Ranges. Detailed field mapping and stratigraphic analysis permit the subdivision of this Tertiary section into 11 formations that compose four sedimentary sequences of regional aspect.

This report describes in detail the petrology, stratigraphic relations, paleontology, inferred age, and depositional environment of each formation, with the areal distribution of each shown on the geologic maps at a scale of 1:24,000. Because of marked differences, the stratigraphic sections on opposite sides of the San Gregorio fault are treated separately. Comparison of the sections across this fault and across the Zayante fault reveals probable major lateral and vertical displacement on these faults during Cenozoic time.

The purpose of this study is to determine accurately the complex stratigraphy of the Tertiary sedimentary rocks exposed in this part of the Santa Cruz Mountains in order to clarify questionable or erroneous stratigraphic interpretations by previous workers and to provide a basis for more meaningful comparisons with contemporaneous sections elsewhere along the active San Andreas and San Gregorio faults.

GEOGRAPHY

The Santa Cruz Mountains comprise that part of the California Coast Ranges that extends for about 120 km from the Golden Gate on the northwest to the Pajaro River on the southeast. These mountains lie between the San Francisco Bay and the Santa Clara Valley on the east and the Pacific Ocean on the west.

The area described in this report embraces about 455 km^2 on the southwestern slope of the Santa Cruz Mountains in western Santa Cruz and southwestern San Mateo Counties. It covers the Año Nuevo 7½-minute, Davenport 7½-minute, and Felton 7½-minute quadrangles, issued in 1955 by the U.S. Geological Survey, and the Santa Cruz 5×11-minute quadrangle, issued in 1954 (fig. 1).

The topography of the area is moderately rugged, with elevations ranging from sea level to over 800 m along the crest of Ben Lomond Mountain. This flat-topped mountain forms a drainage divide, to the east of which the area is dissected by the canyons of the San Lorenzo River and its youthful tributaries. The southeastward-flowing San Lorenzo River follows the trace of the Ben Lomond fault from Boulder Creek to the vicinity of Felton, whereas its southward-flowing tributaries traverse the northwest-southeast structural trend of the region. The courses of two such tributaries. Mountain Charlie Gulch and Bean Creek, locally trend westward along the Zayante and Bean Creek faults, respectively. To the west of the Ben Lomond divide, Majors, Liddell, San Vicente, Scott, Waddell, and other creeks that flow southward directly into the Pacific Ocean have cut a series of narrow, steep-sided canyons into the terraced southwestern slope of the mountain.

The region has a cool-summer Mediterranean climate with moderate to heavy rainfall in the winter months of November through March. Average annual rainfall ranges from a minimum of about 50 cm along the coast to about 150 cm on top of Ben Lomond Mountain. Coastal fog prevails during the dry sumer months and spreads inland at night.

The area is covered by very dense vegetation composed of the coast redwood, mostly in the canyons, and a heavy mixture of deciduous and evergreen trees and shrubs. Some ridges are covered by impenetrable chaparral, composed mainly of manzanita and chamise. Coastal terraces are in pasture or under cultivation; brussels sprouts are the principal crop on the lowest terrace.

Because of the abundant vegetation and deep weathering, fresh bedrock exposures are extremely rare and are usually restricted to canyon bottoms, roadcuts, and sea cliffs. Outcrops along canyons are commonly cloaked by moss, ferns, and poison oak. Slumps and slides are common, especially where slopes are underlain by mudstone.

PROCEDURE

The geology of the central Santa Cruz Mountains was mapped during the summer field seasons of 1960 to 1963 and 1967 to 1969. Field data and collecting localities were plotted directly on U.S. Geological Survey topographic maps at a scale of 1:24,000. Because of the heavy vegetation, aerial photographs (U.S. Dept. of Agriculture, 1956 coverage) were of limited value in mapping geology but aided in finding exposures and in solving location problems. Bedding terminology is that of McKee and Weir (1953), as modified by Ingram (1954). Rock colors were determined by visual comparison to the color chart of Goddard and others (1951).

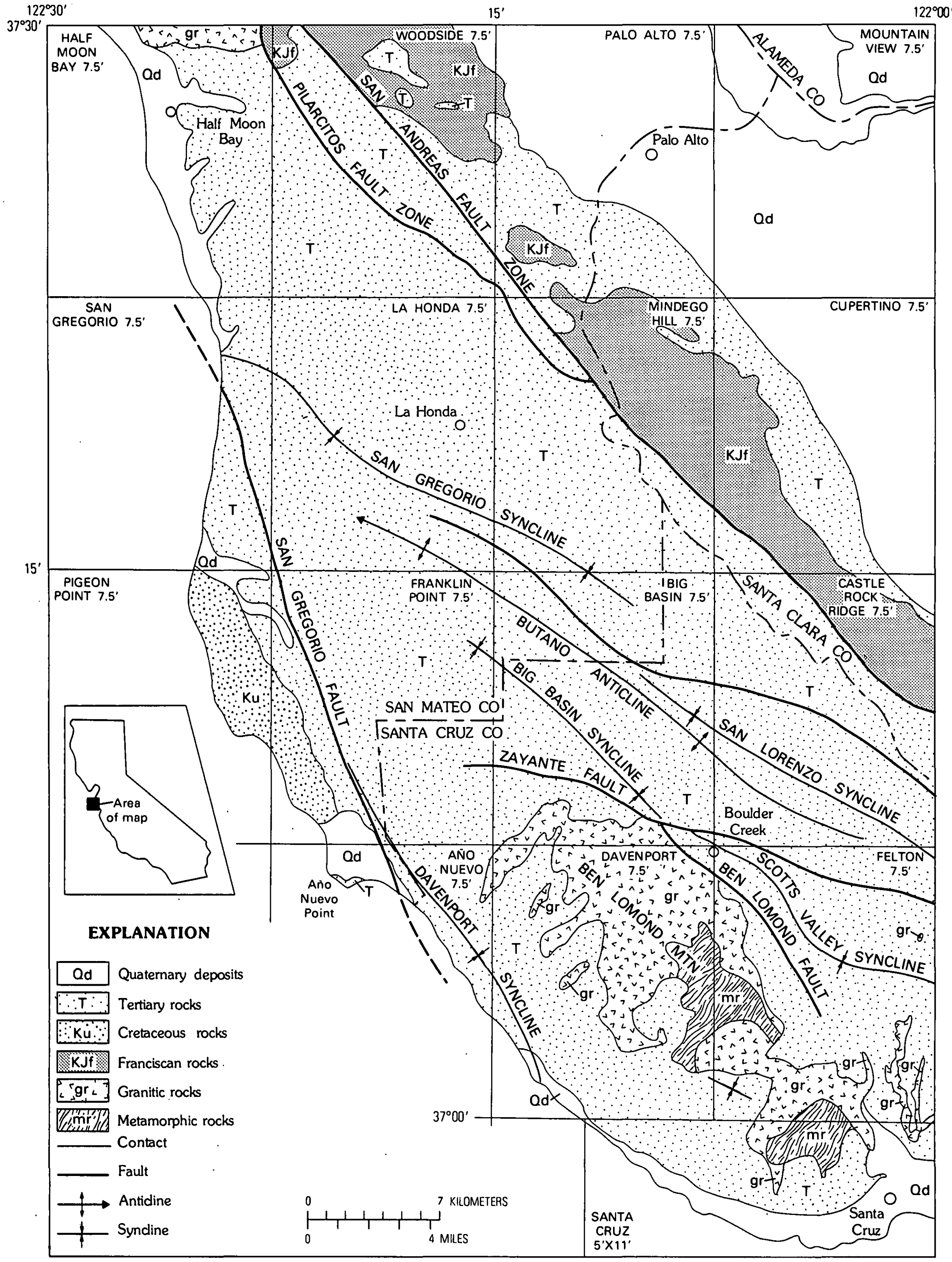
The Tertiary stage names used throughout this report are those defined by Schenck and Kleinpell (1936), Kleinpell (1938), and Mallory (1959), largely on the basis of the benthonic foraminiferal sequences of the Pacific Coast. Assignment of these provincial, time-stratigraphic units to those of standard sections in Europe has been a matter of disagreement for many years among paleontologists and stratigraphers and is not yet definitely resolved. Major differences have concerned assignment of the Oligocene Series and placement of the Miocene-Pliocene Series boundary.

Recent correlations utilizing calcareous nannofossils and planktonic foraminifers suggest that the Refugian Stage of the Pacific Coast foraminiferal chronology falls within the late Eocene of international usage and that the Refugian-Zemorrian Stage boundary of local usage approximates the Eocene-Oligocene Series boundary (Brabb and others, 1971; Poore and Brabb, 1977). Similarly the Zemorrian-Saucesian Stage boundary has been shown, on the basis of nannofossils and planktonic foraminifers, to approximate the Oligocene-Miocene Series boundary (Brabb and others, 1977, fig. 2).

Potassium-argon dating of volcanic rocks by Turner (1970, p. 100–101) indicates an age of 22.5 m.y. for the Zemorrian-Saucesian boundary. Utilizing this date in his attempt to relate Cenozoic planktonic foraminiferal zonation and geologic stages to a radiometric scale, Berggren (1969) suggests that the Zemorrian-Saucesian boundary closely corresponds to the base of the Aquitanian Stage and to the European Oligocene-Miocene boundary. Accordingly, the Zemorrian Stage in this report is considered to be approximately synchronous with the Oligocene Series.

The Mohnian and Delmontian Stages of Kleinpell[1] have been commonly regarded as upper Miocene by Pacific Coast foraminiferal specialists (Kleinpell and Weaver, 1963; Bandy and Arnal, 1969). In the California megainvertebrate chronology, the "Jacalitos"

[1]Pierce (1972) and Barron (1976) believe that the Delmontian is partly coeval with the Mohnian Stage.



Base from Brabb, Clark, and Throckmorton (1977)

FIGURE 1.—Generalized geologic map of the northern and central Santa Cruz Mountains.

Stage (Weaver and others, 1944), characterized by the fauna of the so-called Jacalitos Formation (lower part of the Etchegoin Formation of current usage, Dibblee, 1973) of the Coalinga district, traditionally has been regarded as the standard for the lower Pliocene of the Pacific Coast (Durham and Addicott, 1965, p. A16). Evidence presented by Durham and Addicott (1965, p. A17), by Clark (1968b), and later in this report suggests that the Miocene-Pliocene Series boundary of the Pacific Coast megafaunal chronology falls within the Mohnian-Delmontian sequence of the forminiferal chronology.

The Miocene-Pliocene boundary of this report follows the 1959 recommendations of the Mediterranean Neogene Committee of the International Geological Congress that places the top of the Miocene Series at the top of evaporitic beds in southern Italy assigned to the Messinian Stage (Repenning and Tedford, 1977, p. 3-5). More recent radiometric dating (Berggren, 1972; Berggren and Van Couvering, 1974) suggests that this European Miocene-Pliocene boundary is about 5 m.y. This usage places strata of the "Jacalitos" Stage that had been called Pliocene along the Pacific Coast in the upper Miocene (Addicott, 1972, fig. 3). Berggren and Van Couvering (1974, p. 27) postulate that this Miocene-Pliocene boundary falls within the Delmontian Stage of Kleinpell, as originally suggested by Kleinpell (1938, p. 181).

PREVIOUS WORK

The first comprehensive publication on the geology of the Santa Cruz Mountains was the Santa Cruz folio (Branner and others, 1909), which included the area of the present report. In the 1950's, in order to resolve stratigraphic inconsistencies of this folio, graduate students at Stanford University, largely under the guidance of the late Professor Hubert G. Schenck, initiated a series of detailed mapping projects (scale 1:24,000) of critical areas in the Santa Cruz Mountains. These investigations resulted in numerous unpublished theses and reports and in a publication on the geology of the northern Santa Cruz Mountains by Cummings, Touring, and Brabb (1962). This publication, covering an area north of the present study, and the Santa Cruz folio form the standard references of the geology of the region.

Part of the folio mapping and the more recent Stanford mapping, together with unpublished oil company mapping, are incorporated into the Santa Cruz sheet (Jennings and Strand, 1958) and the San Francisco sheet (Jennings and Burnett, 1961) of the Geologic Map of California. These two sheets, at a scale of 1:250,000, cover the northern and central Santa Cruz Mountains and the entire area of this study. The writer's preliminary mapping of parts of the central Santa Cruz Mountains has been released in several open-file reports of the U.S. Geological Survey (Clark, 1970a, b; Brabb, 1970).

Eldridge (1901) and Newsom (1903) reported on the bituminous sandstone deposits on the southwestern slope of Ben Lomond Mountains, and these deposits were later mapped by Page and Holmes (1945). The crystalline rocks of the Ben Lomond Mountain area have been investigated by Fitch (1931), more extensively by Leo (1961, 1967), and have been included in regional studies of the Salinian block by Compton (1966) and Ross (1972). The accessory minerals from these crystalline rocks were studied by Spotts (1962), and the mineralogy of some metamorphic rocks at Santa Cruz was described by Gross, Chesterman, Dunning, and Cooper (1967).

The earliest known published record on paleontological material from the west coast of North America concerns "petrified bones of a cylindrical form" from the sea cliffs near Santa Cruz (Buckland, 1831, as quoted in Merriam, 1921, p. 237). Since that time, fossil remains from this area have been included in reports on megainvertebrates by Arnold (1906, 1908a, b), Schenck (1936), Reinhart (1943), and Hall (1962), Mitchell and Repenning (1963), Barnes (1971, 1972), Savage and Barnes (1972), Domning (1972), and Repenning and Tedford (1977); on stratigraphy by Kleinpell (1938) and Cummings, Touring, and Brabb (1962); and on paleoecology by Addicott (1966).

Measured sections and invertebrate faunas of Paleogene rocks from this and contiguous areas are included in a report by Brabb, Clark, and Throckmorton (1977). Significant biostratigraphic papers from nearby areas that describe the local succession of Paleogene foraminifers include those of Sullivan (1962a), Fairchild, Wesendunk, and Weaver (1969), Smith (1971), and Poore and Brabb (1977).

Recent papers that deal with the stratigraphy of parts of the area include Hall, Jones, and Brooks (1959), which defines the Pigeon Point Formation of Late Cretaceous age and includes a generalized geologic map west of the San Gregorio fault. Brabb (1964) discusses the Oligocene stratigraphy, and Clark (1968a) records the Tertiary sequences southwest of the San Andreas fault. The Oligocene stratigraphy and tectonics of the area are included in a study by Clark and Rietman (1973).

In addition to the last-named study, other reports that postulate extensions of mapped faults in the region are by Martin and Emery (1967), Ross and Brabb (1973), and Greene, Lee, McCulloch, and Brabb (1973). The potential hazard of mapped faults in the area is evaluated by Hall, Sarna-Wojcicki, and Dupré (1974). An earthquake intensity zonation of the area is shown on a map by McCrory, Greene, and Lajoie (1977), and seismic activity is summarized by Griggs (1973).

The geology of contiguous offshore areas to the south and to the west is included in reports by Greene (1977), by Hoskins and Griffiths (1971), and by McCulloch, Clarke, Field, Scott, and Utter (1977).

Various aspects of the geomorphology of this area have been investigated by Rode (1930), Alexander (1953), Bradley (1956, 1957, 1965), Bradley and Addicott (1968), and Bradley and Griggs (1976). The distribution in Santa Cruz County of Quaternary deposits, except landslides, is shown by Dupré (1975), and that of landslide deposits by Cooper-Clark and Associates (1975).

The erosion and sedimentation potential of two drainage basins south of Santa Cruz is discussed by Brown (1973). Ground water occurrence in the Scotts Valley area has been studied by Akers (1969) and in the western Santa Cruz Mountains by Akers and Jackson (1977).

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The writer is indebted to numerous persons whose generous assistance has contributed to the completion of this study. Suggestions by Earl E. Brabb, Thomas W. Dibblee, Jr., and Helen Beikman were particularly helpful.

A. Myra Keen of Stanford University and Warren O. Addicott of the U.S. Geological Survey checked many megainvertebrate identifications of the writer and kindly provided much useful paleoecologic information. Most of the echinoid identifications were made by J. Wyatt Durham of the University of California at Berkeley. The writer is especially grateful to Robert M. Kleinpell for his counsel on Miocene stratigraphic problems and for his examination of critical Oligocene and Miocene foraminiferal assemblages. Professor Yokichi Takayanagi of Tohoku University, Sendai, Japan, kindly identified Paleocene, early Eocene, and middle Miocene planktonic foraminiferal faunules. Paleontologists of Atlantic-Richfield Company, Humble Oil and Refining Company, Mobil Oil Company, and Shell Oil Company furnished foraminiferal and stratigraphic data. Fossil identifications and statements regarding their age and environmental significance not otherwise credited are by the writer.

J. F. Evernden and John Obradovich provided potassium-argon age determinations. Chester A. Wallace assisted with the petrography, and David P. Doerner of the University of California at Santa Barbara processed microfossil samples and assisted with the photography.

The early part of this study was supervised by a research committee composed of the late S. W. Muller, William R. Dickinson, and Ben M. Page of Stanford University.

GEOLOGIC SETTING

In the Santa Cruz Mountains the active San Andreas fault and its ancestral branch, the Pilarcitos fault, have juxtaposed two major tectonic blocks with contrasting basement complexes and with differing stratigraphies (fig. 1). The block to the northeast is characterized by heterogeneous rocks of the Franciscan assemblage. This assemblage, of Late Jurassic to Late Cretaceous age, is in fault contact with Upper Cretaceous clastic sedimentary rocks of the Great Valley sequence, which in turn are overlain by more than 5,000 m of Cenozoic clastic sedimentary rocks.

Southwest of the San Andreas and Pilarcitos faults and northeast of the San Gregorio fault, crystalline rocks of the Salinian block form the basement complex. Cretaceous strata are absent, and Cenozoic clastic sedimentary and volcanic rocks with a composite thickness in excess of 10,000 m rest upon the crystalline basement.

Southwest of the San Gregorio fault, typical crystalline rocks of the Salinian block are not exposed, and over 2,600 m of Upper Cretaceous clastic sedimentary strata crops out along the coast. Resting unconformably upon these strata is approximately 1,200 m of Cenozoic clastic sedimentary and volcanic rocks that differ from those to the northeast.

CRYSTALLINE ROCKS

NORTHEAST OF SAN GREGORIO FAULT

The crystalline rocks northeast of the San Gregorio fault are best exposed along the core of Ben Lomond Mountain, where an elongate granitic complex includes several large high-grade metasedimentary relics (fig. 1). This crystalline complex is lithologically similar to that exposed in other parts of the Salinian block.

The exposed plutonic rocks consist of several distinct intrusions that range in composition from gabbro to granite. An intrusive unit consisting mainly of quartz diorite underlies about threequarters of the surface area of the exposed complex. The quartz diorite is light gray, typically medium grained, hypidiomorphic granular, and contains 47 to 64 percent plagioclase (An_{28-55}), 16 to 31 percent quartz, 0 to 12 percent potassium feldspar, 2 to 19 percent biotite, and 0 to 14 percent hornblende, with accessory sphene, epidote, magnetite, zircon, apatite, and tourmaline (Leo, 1961; 1967, p. 36). The quartz diorite grades to granodiorite on the south slope and east of Ben Lomond Mountain.

The next largest intrusive unit, the Smith Grade pluton of Leo (1967), covers about 8 km^2 along Empire and Smith Grades. It consists of a moderately coarse-grained leucocratic rock that ranges in composition from granite to adamellite. Accessory red-brown biotite and pink almandine-spessartite garnet are characteristic of this rock. Compton (1966, p. 285) reports that biotite clusters in this pluton are lineated parallel to mineral and fold lineations in nearby schists and quartzites. Several small, isolated adamellite plugs also intrude the metasedimentary rocks of the crystalline complex.

Three small bodies of gneissic granodiorite are exposed along the crest of Ben Lomond Mountain. Their foliation, produced by subparallel bands of red-brown biotite and green hornblende, parallels the foliation of the adjacent schists (Leo, 1967, p. 32).

A distinctive gabbro forms a plug covering an area of about 1 km^2 west of Empire Grade and composes several small plugs in quartz diorite to the east. The gabbro consists of plagioclase (An_{39-94}), green-brown hornblende, cummingtonite, biotite, and rare hypersthene with accessory quartz, ilmenite, apatite, sphene, and rutile (Leo, 1967, p. 34). Leo (1967, p. 34) reports that the contact between the larger gabbro body and the quartz diorite to the north and west appears to be gradational.

Granitic rocks of the Salinian block have been dated by the potassium-argon method as ranging from 70 to 90 m.y. (Cretaceous) in a number of places (Curtis and others, 1958). Biotite from granitic rock of Ben Lomond Mountain has yielded a potassium-argon date of 71.0±0.9 m.y. (California Division of Mines and Geology, 1965, p. 16), and sphene from quartz diorite a fission-track age of 86.9±6.5 m.y. (Naeser and Ross, 1976). These ages are probably not the age of crystallization of these granitic rocks, but most likely represent a postintrusive event or events. Compton (1966, p. 287) suggests that the potassium-argon ages record uplift and cooling and that the plutons of the Salinian block were initially emplaced in mid-Cretaceous time. Likewise, Naeser and Ross (1976, p. 419) believe that the sphene ages of the Salinian block all appear to be reset by an intrusive event and (or) uplift 70 to 90 m.y. ago.

The granitic rocks of the crystalline complex intrude metasedimentary rocks that make up much of the southern part of Ben Lomand Mountain. Leo (1967) estimates that these metasedimentary rocks are approximately 90 percent quartzites and pelitic schists and 10 percent marbles and calc-silicate rocks. He postulates that regional metamorphism was accompanied by intrusion of the gneissic granodiorite and granite-adamellite and was followed by contact metamorphism during the emplacement of the gabbro and quartz diorite. Ross (1972, p. 14), on the other hand, believes that the evidence for the older age of the granite-adamellite is equivocal and seems to favor the interpretation that these leucocratic rocks are a late differentiate of the granitic suite.

Originally miogeosynclinal sandstone, shale, and carbonate beds of Paleozoic or Mesozoic age, the metasedimentary rocks are the oldest rocks in the area. Similarities in lithology and metamorphic grade suggest that these metamorphic rocks are correlative with the Sur Series of Trask (1926) in the northern Santa Lucia Range, about 65 km to the south.

East of Ben Lomond Mountain, the crystalline basement surface has been downwarped beneath the Scotts Valley syncline and locally reappears in Bean Creek on the north limb of this fold. North of the Zayante fault, the basement has been downfaulted and is not exposed between this fault and the San Andreas fault to the northeast (fig. 1).

Granitic rocks can be mapped eastward from the Felton quadrangle into the adjoining Laurel quadrangle (Diblee and others, 1978). Exploratory wells between the margin of the Gabilan Range, about 32 km to the southeast, confirm the continuity of the crystalline basement between these two areas (Clark and Rietman, 1973, p. 1). Metasedimentary rocks that are lithologically similar to those of the granitic complex are exposed in the northern Gabilan Range and have also been correlated with the Sur Series (Allen, 1946, p. 20).

The crystalline basement surface slopes steeply southwest of Ben Lomond Mountain under Tertiary sedimentary rocks. The Shell Davenport core hole No. 1 (pl. 1), located less than 1.6 km down San Vicente canyon from quartz diorite outcrops, did not penetrate granitic rock until reaching a depth of 1,260 m. Farther west, but still to the northeast of the San Gregorio fault, the Texas Company Poletti well reached adamellite at a depth of 2,800 m, indicating that the basement surface descends over 2,750 m in 3.6 km. On a deep-penetration seismic profile off the coast, the basement surface appears to dip steeply westward into the offshore continuation of the San Gregorio fault (H. G. Greene, oral commun., 1974).

SOUTHWEST OF SAN GREGORIO FAULT

Although basement rocks are not exposed within the mapped area west of the San Gregorio fault, porphyritic volcanic rocks that crop out south of

Pescadero Road about 16 km to the north may form part of the basement complex. These volcanic rocks are finely brecciated and contain quartz, plagioclase (An_{20-28}), and orthoclase(?) phenocrysts, locally as much as 3.5 mm in diameter, in a devitrified silicic matrix. The matrix consists of relict microspherulites and interstitial quartz, possibly some potassium feldspar, clay minerals, including chlorite, and some microgranular hematite. The microspherulites are composed of microcrystalline and composite quartz, and the original radial structure is preserved in some.

The quartz phenocrysts, plagioclase composition, abundant quartz in the groundmass, and low percentage of ferromagnesian minerals suggest that the original rock was highly silicic and probably a rhyolite. Metamorphism of the rock was limited to dynamic distortion of the phenocrysts, granulation along narrow bands, and perhaps low-grade thermal metamorphism of clay devitrification products to chlorite.

Although these distinctive volcanic rocks are shown as "Miocene basalt" on the San Francisco sheet of the Geologic Map of California (Jennings and Burnett, 1961), they differ lithologically from any of the exposed Tertiary volcanic rocks in the Santa Cruz Mountains. The contact between the porphyritic rocks and the Pigeon Point Formation that crops out to the west and to the south is not exposed, but the prevailing southwestward dip of the Pigeon Point Formation suggests that it overlies the volcanic rocks. Thus, the porphyritic rhyolite may form part of the basement southwest of the San Gregorio fault and is probably of Cretaceous or older age.

STRATIGRAPHY NORTHEAST OF SAN GREGORIO FAULT

Sedimentary strata southwest of the San Andreas fault and northeast of the San Gregorio 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 having a composite thickness within the area of this report of as much as 7,390 m (fig. 2). This section is divisible into four major sedimentary rock sequences, which are virtually continuous, and each is bounded by unconformities. The basal beds of each sequence locally rest upon the crystalline basement.

The oldest or Paleocene sequence is as thick as 270 m and consists locally of basal sandstone beds of shallow-marine origin that grade upward into siltstone beds deposited under deeper-marine conditions. The Eocene to lower Miocene sequence is over 3,000 m thick. It consists predominantly of sandstone and mudstone beds deposited at bathyal and neritic depths and locally under terrestrial conditions. The two younger sequences, the middle Miocene and the upper Miocene to Pliocene sequences, are more than 900 m and 3,000 m thick, respectively. They record two separate and successive marine cycles of sedimentation. The basal sandstone beds of each of these two sequences were deposited in a near-shore, shallow-marine environment, whereas the overlying siliceous mudstone beds were laid down in deeper water, but probably at neritic depths.

PALEOCENE SEDIMENTARY SEQUENCE

The oldest sedimentary sequence consists of erosional remnants of the Locatelli Formation of Paleocene age. This formation was named by Brabb (1960b) and Cummings, Touring, and Brabb (1962) for exposures on the north flank of Ben Lomond Mountain, about 1.6 km north of the Davenport quadrangle. Within the area of this report the beds assigned to the Locatelli Formation were mapped incorrectly as part of the Vaqueros Sandstone by Branner, Newsom, and Arnold (1909) and are included in the "Lower Miocene marine" (Vaqueros Formation) on the San Francisco sheet of the Geologic Map of California (Jennings and Burnett, 1961).

In the central Santa Cruz Mountains, outcrops of the Locatelli Formation are limited to the vicinity of the crystalline complex of Ben Lomond Mountain (pl. 2). Best exposures are in the Smith Grade-Empire Grade area, where this formation locally extends over the crest of Ben Lomond Mountain. Isolated exposures occur along Hubbard Gulch and Manson Creek on the east flank of the mountain and along Majors Creek on the south slope of the mountain. More extensive exposures are in the Gold Gulch area south of Felton and to the east in the vicinity of Henry Cowell Redwoods State Park.

The Locatelli Formation is characteristically a nodular micaceous sandy siltstone. The siltstone is olive gray where fresh and weathers pale yellowish brown to dark yellowish brown. It commonly contains carbonaceous matter and large arenaceous foraminifers. As much as 240 to 270 m of this siltstone is preserved in the Smith Grade-Empire Grade area. Megafossiliferous basal sandstone beds are locally developed in the Smith Grade area and along an unnamed, westward-flowing tributary to the San Lorenzo River near the northern boundary of the state park. This sandstone, which may be thick as 24 m but is locally faulted along Smith Grade, grades upward into siltstone.

In its type area to the north, the Locatelli Formation is reported to rest nonconformably upon the crystalline basement—the basal contact is exposed only along Gold Gulch—and is overlain unconformably by the Lompico Sandstone and Santa Margarita Sandstone.

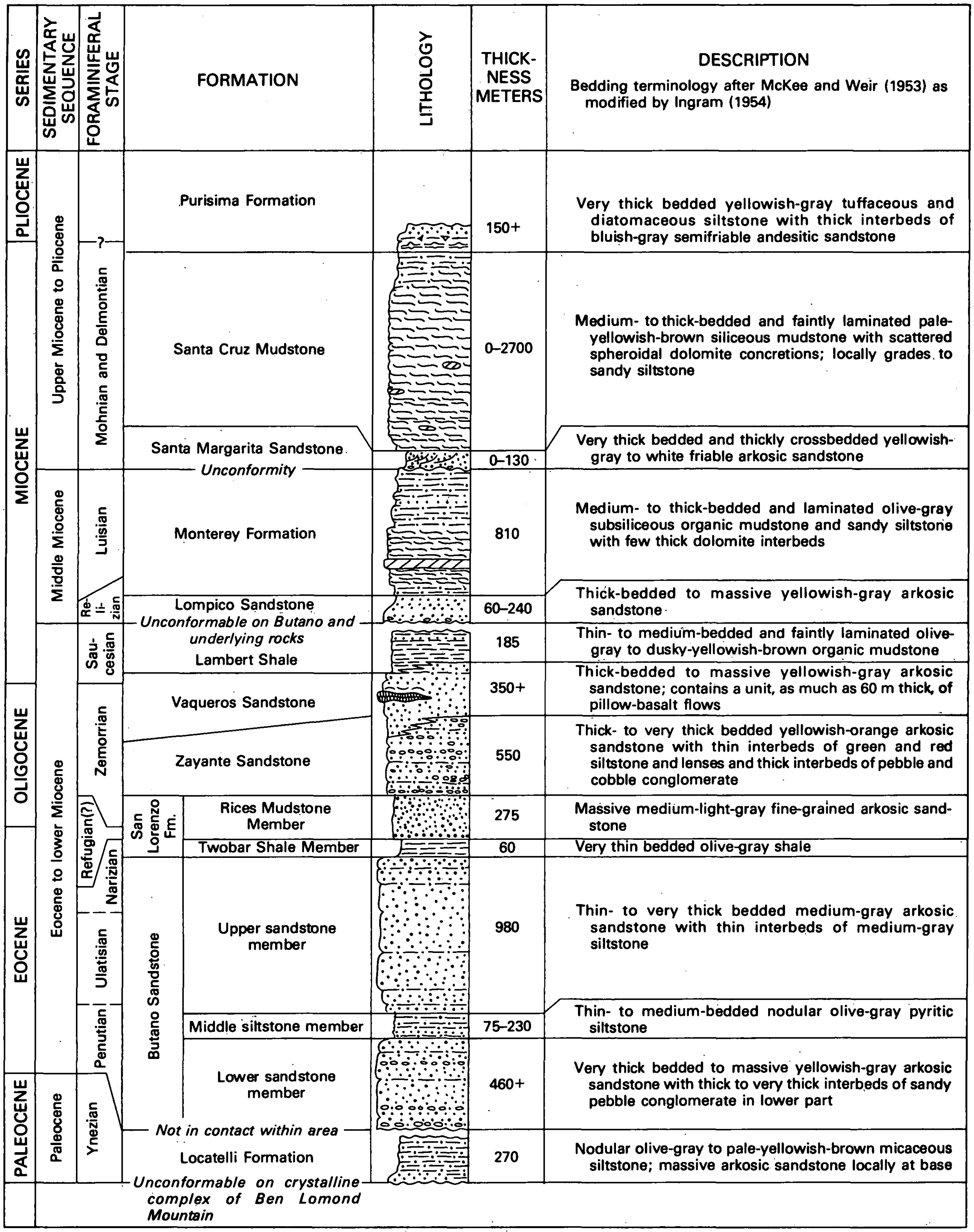

FIGURE 2.—Composite stratigraphic section of Tertiary rocks of the central Santa Cruz Mountains northeast of San Gregorio fault.

Megafossils are locally common in the basal sandstone beds of the Locatelli Formation and are listed on table 1. *Cucullaea mathewsonii*, *Perissolax tricarnatus*, *Pholadomya nasuta*, *Turritella infragranulata*, and *T. pachecoensis* have all been recorded by Weaver (1953, p. 28–29) from his Vine Hill Sandstone of the typical Martinez sequence in Contra Costa County and together with *Cidaris martinezensis* are considered on the Pacific Coast as diagnostic of a Paleocene ("Martinex") age.

Associated with these Paleocene megafossils in the basal sandstone beds is a predominantly calcareous foraminiferal fauna, whereas the superjacent siltstone section is barren of megainvertebrates and yields foraminiferal assemblages that are almost exclusively arenaceous (Clark 1966a, table 2; Brabb and others, 1977, table 5). The Locatelli contains such characteristic early Tertiary benthonic species as *Anomalina regina, Dentalina alternata, Pseudouvigerina naheolensis, Robulus* aff. *R. midwayensis,* and *Vaginulina suturalis*.

Most of the arenaceous foraminifers in the siltstone section range from Late Cretaceous into the early Tertiary. *Ammodiscus glabratus, Haplophragmoides coronata,* and *H. excavata* have their highest reported occurrence in the *Bulimina escavata* Zone of the Ynezian Stage (Mallory 1959, p. 26). The upper stratigraphic range of these arenaceous species together with the lower range of many of the calcareous taxa suggests an Ynezian Age for the Locatelli Formation. A more restricted zonal assignment is uncertain because of conflicting range data; however, the similarity of the fauna to that of the Vine Hill Sandstone suggests an assignment to the *Silicosigmoilina californica* Zone.

TABLE 1.—*Paleocene megainvertebrates from the Locatelli Formation*

[USGS localities are listed under "Fossil Localities"]

Fossil	USGS Cenozoic loc. M4667	M4668	M4669	M5065	M5066
Gastropods					
Perissolax tricarnatus Weaver	×	×	....	....	....
Surculities(?) sp	....	....	×	....	....
Turritella cf. T. infragranulata Gabb	×	×	....	....	....
Turritella pachecoensis Stanton	×	×	....	×	....
Turritella cf. *T. pachecoensis* Stanton	....	....	....	....	×
Pelecypods					
Acila sp	×	....	×	....	....
Cucullaea mathewsonii Gabb	....	....	×	....	×
Cucullaea mathewsonii Gabb(?)	×	....	....	....	....
Glycymeris sp	×	....	....	....	....
Lucinoma sp	×	×	....	....	....
Nuculana sp	×	×	....	....	×
Pholadomya nasuta Gabb	×	....	....	....	....
Pinna n. sp	×	....	....	....	....
Scaphopod					
Dentalium sp	×	×	....	....	....
Echinoids					
Cidaris martinezensis Kew	×	....	....	....	....
Periaster n. sp	×	....	....	×	....
Pericosmus sp	×	....	....	....	....
echinoid spines	....	....	×	....	....
Arthropod					
Raninoides sp	....	×	....	....	....

Planktonic foraminifers identified by Berggren and Aubert (1977, p. 2–3) from the Locatelli Formation include *Subbotina triloculinoides, S. triangularis, S. velascoensis, Acarinina mckannai, A. acarinata,* and *Morozovella aequa* and are diagnostic of late Paleocene (P4–P5 Zone) age. Of stratigraphic significance is the association within the same sandstone bed (USGS loc. M4669) of late Paleocene planktonic foraminifers with Ynezian Stage benthonic foraminifers and *Cucullaea mathewsonii,* a so-called Martinez Stage mollusk.

Paleontological evidence indicates that the Locatelli Formation was deposited under progressively deepening marine conditions. The basal sandstone beds, locally containing abundant echinoids and thick-shelled mollusks, were deposited in a neritic environment. The foraminiferal assemblages of these beds are characterized by a diversity of nodosariids with a relatively large number of species but few individuals of each. This diversity together with a paucity of miliolids, a group common in warm shallow water, suggests that the sandstone beds were deposited at neritic depths probably greater than 30 m. This depth estimate is supported by the local abundance of the pelecypod *Cucullaea,* a genus that today in the Indo-Pacific province commonly occurs between depths of 17 and 170 m (Nicol, 1950, p. 343). The presence of *Pinna* and species of *Turritella* and the diversity of the foraminiferal assemblages suggest tropical to subtropical temperatures.

The superjacent siltstone beds of the Locatelli Formation, which are characterized by arenaceous foraminifers, were deposited in deeper water. The development of this arenaceous assemblage may have been favored by muddy bottom conditions, and the paucity of calcareous benthonic foraminifers suggests cold-water conditions, such as might have existed at bathyal to abyssal depths. Dominantly arenaceous assemblages are found living at such depths today, as for example in the Peru-Chile trench, where arenaceous forms compose over 90 percent of the population below 3,000 m (Bandy and Rodolfo, 1964, p. 833), and in the Gulf of California, where arenaceous specimens average 85 percent of the population at depths greater than 2,750 m (Phleger, 1964, p. 389). The presence of *Glomospira charoides, Haplophragmoides coronata,* and *Hyperammina* cf. *H. elongata,* species that today favor a bathyal to abyssal habitat, also supports a deep-water interpretation for the siltstone beds. Pelagic globigerinids, although rare throughout the formation, indicate the existence of open-sea connections.

EOCENE TO LOWER MIOCENE SEDIMENTARY SEQUENCE

The Eocene to lower Miocene sequence consists of sedimentary rocks ranging in age from Penutian to Saucesian, which are poorly exposed in the northern part of the Felton quadrangle and locally exposed on the south slope of Ben Lomond Mountain. The sequence includes the Butano Sandstone, the San Lorenzo Formation, the Zayante Sandstone, the Vaqueros Sandstone, and the Lambert Shale.

BUTANO SANDSTONE

To the massive sandstone beds exposed on Butano Ridge, 11 km north of the area, Branner, Newsom, and Arnold (1909) gave the name "Butano Sandstone." Subsequent field mapping, supported by micropaleontology, has demonstrated that the Butano Sandstone is more extensively distributed in the central Santa Cruz Mountains than shown in the Santa Cruz folio, and the beds mapped as Butano in this report were assigned to the Vaqueros Sandstone by those early workers.

The Butano Sandstone that crops out in the structurally complex northern part of the Felton quadrangle is here subdivided into three informally named members:

LOWER SANDSTONE MEMBER

The lower sandtone member crops out in the northeastern part of the area south of the Zayante fault, where best exposures are along the upper part of Bean Creek and along Zayante Road. This sandstone is very thick bedded to massive, very light gray to yellowish gray, poorly to moderately sorted, medium to coarse grained, and arkosic. The terrigenous mineral composition of this sandstone as determined by point count (200 points per specimen) is given in table 2. Orthochemical minerals include dolomite cement, authigenic pyrite, and leucoxene from the alteration of sphene and ilmenite. Medium-dark-gray siltstone clasts that average 2 cm in diameter and locally are elongated as much as 11 cm are common in the sandstone. This member also contains a few thin interbeds of olive-gray, pyritic siltstone.

Characteristic of the lower part are thick to very thick interbeds of conglomerate composed of well-rounded quartzite and varicolored porphyritic volcanic pebbles and cobbles and of more angular granitic boulders as long as 2.8 m. Thin carbonaceous laminae are common in the upper part of this member.

Between Bean Creek and the conformable contact with the overlying middle siltstone member, only the upper 460 m of the lower sandstone member is exposed. An additional 1,060 m of the lower part of this member is exposed to the east in the Laurel quadrangle, where its conglomeratic beds appear to rest upon granitic basement along the West Branch of Soquel Creek (Dibblee and others, 1978).

The sandstone is barren of mollusks. Stratigraphically undiagnostic, arenaceous foraminifers, including large Bathysiphons and *Trochammina* sp., and pyritized radiolaria and plant stems(?) are sparse in the siltstone interbeds. Microfossils from the superjacent middle siltstone member indicate that the lower sandstone member is Penutian (early Eocene) or older. The apparent unconformable relationship of a lithologically similar section of the Butano Sandstone to the underlying Locatelli Formation on the north flank of Ben Lomond Mountain (Cummings and others, 1962, p. 183) suggests that the lower sandstone member is younger than Ynezian.

MIDDLE SILTSTONE MEMBER

Gradationally above the lower sandstone member lie the less resistant nodular beds of the middle siltstone member. Exposures of this member are commonly slumped and are restricted to the Zayante canyon-Mountain Charlie Gulch area south of the Zayante fault.

The siltstone is thin to medium bedded and nodular; it is olive gray where fresh and weathers moderate yellowish brown. It is pyritic and includes scattered, disk- and rod-shaped siderite concretions that weather dark yellowish orange. Thin interbeds of laminated and graded, medium- to fine-grained, arkosic sandstone are rhythmically interbedded in the lower part. These sandstone interbeds (L49, table 2) are cemented by sparry calcite and are lithologically similar to those of the lower sandstone member.

TABLE 2.—*Terrigenous mineral composition, in percent, of the Butano Sandstone*

[Sample locations are shown on plate 2]

Informal subdivision of Butano Sandstone	Lower sandstone member		Middle siltstone member	Upper sandstone member
Sample No.	L44	L129	L49	L12
Quartz	36	38	45	42
Orthoclase	14	18	15	24
Microcline	7	6	9	3
Plagioclase (An_{12-32})	10	11	10	10
Granitic rock fragments	20	12	15	2
Silicic volcanic rock fragments	12	10	2	2
Low-grade metamorphic rock fragments	2	1	<1	---
Sedimentary rock fragments	---	<1	<1	---
Biotite	---	<1	<1	7
Muscovite	<1	<1	---	1
Chlorite	---	<1	<1	4
Zircon	---	<1	---	---
Apatite	---	<1	---	---
Sphene	---	<1	<1	<1
Rutile	---	<1	---	---
Epidote	---	---	<1	1
Garnet	---	---	<1	---
Opaque minerals	---	<1	2	4

Along Zayante canyon, the middle siltstone member is between 180 and 230 m thick. To the west along an intermittent tributary to Zayante Creek (SW1/4 sec. 36, T. 9 S., R. 2 W.), this member is poorly exposed and is estimated to be about 75 m thick.

Poorly preserved and commonly pyritized organic remains, including small plant stems(?), occur in this siltstone unit. Calcareous planktonic foraminifers are common locally and are associated with a few arenaceous and diverse calcareous benthonic specimens. Small, thin-shelled pelecypods, including *Lucina* sp., *Nuculana* sp., and *Propeamusium*(?) sp., are rare.

The lowest diagnostic microfauna occurs approximately 30 m stratigraphically above the contact with the subjacent lower sandstone member (Clark, 1966a, table 3; Brabb and others, 1977, table 4). At that locality, the abundant planktonic foraminiferal fauna is diagnostic of an early Eocene age, and the joint occurrence of the calcareous benthonic species, *Anomalina garzaensis, Anomalina* aff. *A. regina, Gyroidina orbicularis* var. *obliquata, Hoeglundina eocenica,* and *Siphonina wilcoxensis,* suggests a late Penutian age. Calcareous nannoplankton from this same stratigraphic level are also diagnostic of a Penutian age (F. R. Sullivan, written commun., 1974). As Sullivan believes that nannoplankton collected from near the base of the superjacent upper sandstone member are also of Penutian age, a late Penutian age is indicated for the entire middle siltstone member, although the lower 30 m is not well dated.

UPPER SANDSTONE MEMBER

Conformably above the middle siltstone member lies the upper sandstone member, which is correlative with at least the upper part of the Butano Sandstone in its type locality to the northwest. This member is discontinuously exposed in a narrow band south of the Zayante fault from Zayante Creek westward to the northern boundary of the area. North of the Zayante fault, the upper sandstone member is exposed along Newell Creek where it grades upward into the Twobar Shale Member of the San Lorenzo Formation.

In general, this sandstone member becomes thinner bedded and finer grained upward. The lower part as exposed along Zayante and Lompico Creeks is medium-gray, moderately sorted, granular, mediumgrained arkosic sandstone with a few interbeds of sandy pebble conglomerate. Higher in the section along Love Creek, but still south of the Zayante fault, the sandstone is well sorted and fine grained. Thin interbeds of medium-gray siltstone that contain foraminifers are scattered through the section south of the fault. In Newell Creek canyon north of the Zayante fault, thin to medium sandstone beds are graded and alternate with thin foraminifer-bearing siltstone beds, which become more numerous near the contact with the superjacent San Lorenzo Formation. Biotite is common in these fine-grained arkosic sandstone beds (L12, table 2), which are cemented by sparry calcite.

Because of faulting and discontinuity of exposures, the thickness of the upper sandstone member is difficult to estimate. Approximately 740 m of this member crops out south of the Zayante fault, and about 240 m is exposed in Newell Creek north of the fault.

Nannoplankton from a siltstone interbed near the base of the upper sandstone member east of Zayante Creek are diagnostic of a Penutian age, whereas siltstone interbeds along Lompico Creek yield Ulatisian nannoplankton (F. R. Sullivan, written commun., 1964). Associated with the nannoplankton are stratigraphically less diagnostic foraminifers, and at one locality along Lompico Creek are several specimens of the nuculid bivalve *Acila* (*Truncacila*) cf. *A.* (*T.*) *decisa*, a species that on the Pacific coast has been recorded from beds of Paleocene and Eocene age (Schenck, 1936, p. 53). These specimens of *Acila* were the only megafossils found in the upper sandstone member. The joint occurrence of the foraminifers *Bulimina corrugata* and *Gyroidina soldanii* var. *octocamerata* in the Love Creek section indicates that at least the upper 110 m of the upper sandstone member that crops out south of the Zayante fault is of late Ulatisian or early Narizian age.

Diagnostic Narizian foraminifers were collected by Brabb (1960a, p. 35) from outcrops of this member about 3 km to the northwest along Bear Creek south of the Zayante fault. Thus, the Butano beds truncated by the Zayante fault are progressively younger to the west.

In the upper sandstone member, within the Felton quadrangle, the lowest stratigraphic occurrence of foraminifers diagnostic of Narizian age is along Newell Creek north of the Zayante fault, where *Planularia markleyana* and *Uvigerina garzaensis* occur approximately 185 m and 135 m, respectively, below the contact with the superjacent San Lorenzo Formation.

THICKNESS

The total estimated thickness of the Butano Sandstone in the northern Felton quadrangle is about 1,670 m, but the amount of section that is cut out by the Zayante fault is not known. An additional 1,060 m of the lower sandstone member that crops out to the east in the Laurel quadrangle produces a composite section of approximately 2,730 m. This thickness is similar to the 2,750 m estimated by Cummings, Touring, and Brabb (1962, p. 186) for the Butano Sandstone of the northern Santa Cruz Mountains, of which about 1,830 m crops out in the type area of Butano Ridge.

AGE

The Butano Sandstone of the Felton quadrangle ranges from Penutian (early Eocene) to Narizian (middle and late Eocene) age. The lower sandstone member is not well dated; it is late Penutian or older. As the arenaceous foraminiferal fauna of this member does not resemble that of the Locatelli Formation, and a correlative section to the northwest appears to overlie the Locatelli Formation unconformably, the lower sandstone member is probably younger than Ynezian. The middle siltstone member yields nannoplankton and benthonic foraminifers diagnostic of a late Penutian age. Most of this member that crops out south of the Zayante fault contains microfossils diagnostic of Ulatisian to Narizian age, whereas benthonic foraminifers from the upper 185 m of section along Newell Creek are diagnostic of Narizian age.

Planktonic foraminifers identified by Berggren and Aubert (1977, p. 3) from the middle siltstone member and the lower part of the upper sandstone member as exposed along Zayante and Lompico Creeks include *Subbotina linaperta, S. turgida, Acarinina acarinata, A. coalingensis, A. wilcoxensis,* and *Morozovella subbotinae*, which are diagnostic of an early Eocene (P8 Zone) age.

The Butano Sandstone was provisionally referred to the Oligocene by Arnold (1906, p. 16) because of its conformable position below the megafossiliferous San Lorenzo Formation. Foraminifers diagnostic of a late Eocene age were subsequently reported from the upper part of the Butano (Schenck, 1936, p. 69; Sullivan, 1962, p. 247). Cummings, Touring, and Brabb (1962, p. 186) report that faunas older than Narizian have not been collected from the Butano Sandstone in the northern Santa Cruz Mountains but that the lower 1,850 m is not well dated. The older section of the northern Felton quadrangle, therefore, has provided new information on the lower and middle Eocene succession of the Santa Cruz Mountains and has resulted in an extension of the age of the Butano Sandstone to include the early and middle Eocene.

BUTANO(?) SANDSTONE

In correlating the three informally named members of the Butano Sandstone that are mapped in the northern part of the Felton quadrangle with other sections in the Santa Cruz Mountains, the writer (1968a, p. 170-174) suggested that a section in the Davenport quadrangle that is exposed along San Vicente canyon on the southwest slope of Ben Lomond Mountain may be correlative with the lower sandstone member.

This steeply dipping section consists predominantly of yellowish-gray medium-grained arkosic sandstone in beds 1 to 10 m thick that commonly grade upward to greenish-gray sandy pyritic mudstone. The section includes very thick interbeds of sandy cobble conglomerate, containing well-rounded dark silicic porphyry and light-colored quartzite pebbles and cobbles with granitic boulders as much as 1 m long. Light-yellow-gray sandy mudstone clasts as much as 30 cm long occur in both the sandstone and conglomerate beds.

Although the base of this Butano(?) section is not exposed along San Vicente canyon, structural attitudes suggest that the section overlies the quartz diorite that crops out upcanyon. In a railroad cut on the west side of the canyon, 42 m of section is exposed and is unconformably overlain by a bituminous sandstone bed of the Santa Margarita Sandstone.

Arenaceous foraminifers are rare in the mudstone and include large specimens of *Bathyisphon eocenicus, Trochammina*(?) sp., and *Haplophramoides*(?) sp. Small pyrite clusters may represent internal molds of globigerinids. Although this fauna is stratigraphically undiagnostic, faunal and lithologic similarities suggest a correlation with the lower sandstone member of the Butano Sandstone.

SAN LORENZO FORMATION

The San Lorenzo Formation was named by Arnold (1906, p. 16) for exposures of shale and fine-grained sandstone along the San Lorenzo River, about 4 km north of the town of Boulder Creek. Arnold assigned an Oligocene age to this formation—the first unit to be so dated in California—because of its conformable position beneath the Vaqueros Sandstone and its megafossil fauna, which he listed (1906, p. 17) and later described (1908a). Foraminifers diagnostic of Narizian (late Eocene) age were subsequently reported by Sullivan (1962) from the lower part of the formation. Brabb (1964) subdivided the San Lorenzo Formation into a lower Twobar Shale Member of Narizian (late Eocene) age and an upper Rices Mudstone Member of Refugian and Zemorrian (late Eocene and Oligocene) age, with the type section along Kings Creek about 7 km north of Boulder Creek, and postulated a possible disconformity between these two members.

Best exposures of the San Lorenzo Formation within the area were previously along Newell Creek, where the Twobar Shale and Rices Mudstone Members cropped out discontinuously along the canyon bottom.

This section is now covered by the water of Loch Lomond. Two kilometers to the west along Love Creek, only the Rices Mudstone Member is exposed, and the Twobar may be faulted out of the section (pl. 2).

TWOBAR SHALE MEMBERS

The Twobar Shale Member is conformable above the Butano Sandstone. The gradation from the sandstone beds of the Butano to the less resistant shale beds of the overlying San Lorenzo Formation is marked by a broadening of Newell Creek canyon. The shale is typically very thin bedded and laminated; it is olive gray where fresh and weathers moderate yellowish brown. The lower part contains a few thin interbeds of well-sorted fine-grained sandstone and light-colored phosphatic lenses. The upper 20 m is nodular and includes several thin to medium glauconitic interbeds. This member is about 60 m thick along Newell Creek.

Foraminifers occur throughout the shale section, but calcareous forms are generally leached and poorly preserved in surface exposures. Some fresh samples yield abundant specimens of the planktonic foraminifer *Globigerina* sp. Other microfossils include radiolaria, which are locally common to abundant, and a few sponge spicules. Large fish scales are common. The only mollusk collected from this member is the mud pecten *Delectopecten peckhami*, external molds of which are common in the upper part.

The joint occurrence of *Bulimina corrugata* and *Uvigerina churchi* in the lower part of the Twobar Shale Member along Newell Creek is diagnostic of a Narizian age and indicates that the contact between the Butano Sandstone and the San Lorenzo Formation falls within the Narizian Stage.

RICES MUDSTONE MEMBER

Along Newell Creek, the contact between the Twobar Shale and Rices Mudstone Members is mapped at the abrupt change from thin-bedded nodular mudstone to massive, more resistant sandstone. There, the Rices Mudstone Member is composed of well-sorted, very fine to fine-grained, biotite-bearing, arkosic sandstone with scattered round carbonate concretions that average 30 cm in diameter. The sandstone is medium light gray where fresh and pale yellowish brown where weathered. At the base of this member is a 20-cm-thick bed of slightly granular medium-grained glauconitic sandstone. A few thin interbeds of pebble to cobble conglomerate occur near the top of this member and represent tongues of the overlying Zayante Sandstone.

The Rices Mudstone Member is estimated to be as thick as 275 m along Newell Creek. Along Love Creek, approximately 240 m of this member crops out between the Zayante fault to the south and the contact with the superjacent Zayante Sandstone to the north.

Although in the type area to the northwest the Rices Mudstone Member is conformably overlain by the Vaqueros Sandstone, along both Love and Newell Creek canyons this member is conformably overlain by the Zayante Sandstone.

Organic remains generally are not so abundant in the Rices as in the Twobar. Foraminifers are rare to absent in this coarser grained member, whereas mollusks are locally common. Arnold (1908a, p. 371-372) recorded *Priscofusus hecoxae* from the San Lorenzo Formation on Love Creek, and the present writer collected from the lower part of the Rices Mudstone Member on Love Creek the following molluscan fauna:

Acila sp.
(?)*Pleurotoma perissolaxoides* Arnold
Tellina cf. *T. lorenzoensis* Arnold
Yoldia sp.

Along Newell Creek, mollusks are locally abundant and include:

Dentalium sp.
Lucinoma sp.
Modiolus sp.
Panopea sp.
Pitar sp.
Solen sp.

In addition, *Balanus* sp. occurs in the upper part of this member.

From approximately 15 m above the base of the Rices Mudstone Member along Newell Creek, Brabb (1960a, p. 184) collected the foraminifer *Uvigerina gesteri*. As he found this species to be diagnostic of a Zemorrian age in the Big Basin area (1960a, fig. 20), he suggests that Refugian strata may be missing along Newell Creek. Although other stratigraphically diagnostic foraminifers have not been recorded from this member along Newell Creek, its stratigraphic position beneath the Zayante Sandstone, which intertongues to the north with the Vaqueros Sandstone of Zemorrian to early Saucesian age, indicates that the Rices is not younger than Zemorrian. Along Bear Creek, 5.4 km northwest of the Newell Creek section, where the Rices Mudstone Member is overlain conformably by the Vaqueros Sandstone, Kleinpell (1938, p. 111) assigns at least the upper 300 m of the San Lorenzo Formation which is synonymous with Brabb's Rices Mudstone Member, and the lower 600 m of the superjacent Vaqueros Sandstone to the lower Zemorrian Stage. Thus, although the lower part of the Rices along Newell Creek may be Refugian, most of this section probably falls within the lower Zemorrian Stage.

ZAYANTE SANDSTONE

In the northern part of the Felton quadrangle, the Vaqueros Sandstone as mapped by Branner, Newsom, and Arnold (1909) includes in its lower part a probable nonmarine unit of pebbly sandstone, conglomerate, and sandy siltstone. This unit was differentiated from the marine Vaqueros Sandstone and named by the writer (1966b) the Zayante Sandstone, for exposures on Zayante Creek. The type section extends along Zayante Creek from the axis of an anticline (NW1/4 sec. 31, T. 9 S., R. 1 W.) northward to the contact with the overlying Vaqueros Sandstone (SW1/4 sec. 30, T. 9 S., R. 1 W.) The exposed Zayante Sandstone extends for about 10 km from Love Creek on the west near the boundary with the Castle Rock Ridge quadrangle eastward to Mountain Charlie Road in the western part of the Laurel quadrangle.

The Zayante Sandstone is shown as parts of the "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).

The Zayante Sandstone consists predominantly of thick to very thick beds of moderately to poorly sorted, pebbly, medium- to coarse-grained, biotite-bearing, arkosic sandstone. The sandstone is bluish gray where fresh but weathers yellowish orange. Thick interbeds, lenses, and pods of conglomerate contain well-rounded varicolored porphyritic volcanic and quartzite pebbles and cobbles and more angular granitic cobbles and boulders, which locally are as much as 1.2 m in diameter. Distinctive thin interbeds of grayish-olive, poorly sorted, slightly granular, sandy, chloritic siltstone that is locally mottled with various hues of red and green are common. The large-scale heterogeneity, the poor sorting of individual beds, the mottled greenish and reddish coloration, and the local channeling at the base of conglomerate beds both at the base and within the formation, together with the complete absence of marine fossils, suggest that the Zayante Sandstone is nonmarine.

This formation at the type section is about 500 m thick. Structural attitudes along Lompico Creek suggest that approximately 550 m of the Zayante Sandstone is present between the contact to the southwest with the subjacent Rices Mudstone Member of the San Lorenzo Formation and the contact to the northeast with the superjacent Vaqueros Sandstone.

The Zayante Sandstone conformably overlies the Rices Mudstone Member along both Love and Newell Creek canyons. This lower contact is placed at the base of the lowest interbedded sequence of poorly sorted, medium- to coarse-grained sandstone, conglomerate, and greenish siltstone. A few thin interbeds and lenses of conglomerate occur below the contact as mapped along Love Creek and along the ridge separating Newell and Lompico Creeks (sec. 26, T. 9 S., R. 2 W.). The Zayante Sandstone is conformably overlain by and locally intertongues with the Vaqueros Sandstone; the upper contact is drawn at the base of the stratigraphically lowest, thick to massive, light-colored, moderately to well sorted, fine- to medium-grained sandstone bed. Where exposed, this upper contact is sharp, and the basal sandstone bed of the Vaqueros locally contains greenish siltstone clasts that resemble the siltstone of the underlying formation.

The conformable position of the Zayante Sandstone above the Rices Mudstone Member of the San Lorenzo Formation of Refugian(?) and Zemorrian (Eocene? and Oligocene) age and below and partially intertonguing with the Vaqueros Sandstone of Zemorrian and early Saucesian (Oligocene and early Miocene) age brackets the Zayante Sandstone as Zemorrian (Oligocene).

In Major Creek canyon in the southwest corner of the Felton quadrangle, a sequence of beds that is lithologically similar to the Zayante Sandstone is exposed for a distance of about 300 m and is tentatively referred to the Zayante Sandstone (pl. 2). The finer grained beds of this sandstone and siltstone sequence display the characteristic greenish hue of the formation, but conglomerate interbeds are fewer and contain smaller clasts than in the type area. Although contacts along Majors Creek are not exposed, these beds tentatively assigned to the Zayante Sandstone appear to overlie the granitic basement and to be overlain by the Lompico Sandstone of middle Miocene age.

VAQUEROS SANDSTONE

"Vaquero sandstone" was the name given by Hamlin (1904, p. 14) to "a rather coarse uniformly gray, white or light-yellow quartzose sandstone" that is well developed in Los Vaqueros Valley on the eastern slope of the Santa Lucia Range. Hamlin reported that in the type area this formation rests nonconformably on the crystalline basement and on pre-Miocene ("older than the Neocene") sedimentary rocks and is overlain by the Monterey Shale. The name "Vaquero" was soon extended to strata in the Santa Cruz Mountains 120 to 160 km northwest of the type area by Haehl and Arnold (1904), who applied it to lithologically similar rocks that appeared to occupy the same stratigraphic position and to contain a fauna similar to the one listed by Hamlin (1904, p. 14).

Strata originally included in the Vaqueros Sandstone in the Santa Cruz Mountains by Branner, Newsom, and Arnold (1909) are now known to range in age from Paleocene to Pliocene. The name is now restricted to marine strata of Zemorrian (Oligocene) and Saucesian (early Miocene) age. In the Felton quadrangle, this formation is restricted to the northeastern part, where it crops out north of the contact with the subjacent Zayante Sandstone and south of the contact with the superjacent Lambert Shale on the south limb of the San Lorenzo syncline and reappears on the overturned north limb of this fold (pl. 2).

The Vaqueros is primarily thick-bedded to massive, moderately sorted, slightly granular medium-grained to well-sorted fine-grained arkosic sandstone. The sandstone is light gray to medium gray where fresh and yellowish gray to moderate yellowish brown where weathered. A few thick to very thick interbeds of olive-gray to dusky-yellowish-brown mudstone are in the upper part. A lignite interbed in coarse-grained sandstone along Love Creek just north of the mapped area (SE1/4 sec. 21, T. 9 S., R. 2S., Castle Rock Ridge quadrangle) was mined for local use around the turn of the century.

Approximately 76 to 80 m stratigraphically above the contact with the underlying Zayante Sandstone is a series of pillow basalt flows. These flows are best exposed to the west side of Zayante Road (SW1/4 sec. 30 T. 9 S., R. 1 W.), where they are approximately 60 m thick and form a prominent east-trending ridge between Zayante and Lompico Creeks. The basalt flows are discontinuously exposed for about 8 km from an isolated occurrence in the Castle Rock Ridge quadrangle about 200 m beyond the northern limit of the mapped area southeastward to exposures in the Laurel quadrangle about 2½ km beyond the eastern boundary of the area.

The basalt flows contain pillows, from 15 to 30 cm in diameter, interstratified with minor amounts of flow breccia, consisting of angular pebble-size basalt fragments cemented by sparry calcite. The basalt contains phenocrysts of plagioclase (labradorite) as much as 5 mm long, euhedral phenocrysts of olivine (usually altered to iddingsite, "bowlingite," and magnetite), and a groundmass composed of microlites of plagioclase (labradorite-andesine) partly enclosed in augite, with subordinate amounts of glass (altered to celadonite), magnetite and (or) ilmenite, and apatite. The texture ranges from subophitic to intersertal, and the basalt is locally vesicular and amygdaloidal; the amygdules are composed mainly of opal and chalcedony. Spheroidal weathering is common, and the basalt is deeply weathered to a characteristic moderate-yellowish-brown to reddish-brown soil.

These basalt flows are lithologically similar, occupy a similar stratigraphic position, and are partially contemporaneous with the Mindego Basalt of Dibblee (1966), the type section of which is near the town of La Honda, 26 km to the northwest (fig. 1). As these basalt flows do not appear to have been laterally continuous with those mapped by Dibblee, the name "Mindego" is not applied to them.

In the northeastern part of the area, the Vaqueros Sandstone conformably overlies the Zayante Sandstone and is conformably overlain by the Lambert Shale. In this area, the Vaqueros, including the intercalated basalt flows, is between 350 and 440 m thick. To the north in the Castle Rock Ridge quadrangle, where the Zayante Sandstone is absent along the overturned north limb of the San Lorenzo syncline, the Vaqueros Sandstone conformably overlies the Rices Mudstone Member of the San Lorenzo Formation and is approximately 920 m thick.

Directly overlying the basalt flows in the Vaqueros Sandstone along Zayante canyon are molluscan bioherms, composed largely of the pelecypod genera *Dosinia* and *Crassatella* and locally containing a varied gastropod fauna (table 3). Except for a few basalt pebbles, these bioherms are composed almost entirely of shells and shell debris that are solidly cemented by calcium carbonate, and their occurrence is restricted to the top of the basalt flows. Similar bioherms or even individual mollusks were not observed elsewhere in this formation. Foraminifers

TABLE 3.—*Megainvertebrates from the Vaqueros Sandstone*

[USGS localities are listed under "Fossil Localities"]

Fossil	USGS Cenozoic loc.	
	M5049	M5050
Gastropods		
Astraea aff. A. morani Loel and Corey	×	×
Bruclarkia santacruzana (Arnold)		×
Calyptraea cf. *C. inornata* (Gabb)		×
Conus owenianus Anderson		×
Cymatium n. sp.		×
Oliva sp.		×
Olivella cf. *O. Pedroana* var. *subpedroana* Loel and Corey		×
Scaphander(?) sp.	×	
Searlesia sp.		×
Turritella inezana Conrad	×	×
Pelecypods		
Anadara(?) sp.	×	
Chione latilaminosa Anderson and Martin	×	×
Chlamys sespeensis (Arnold)		×
Crassatella granti (Wiedey)	×	×
Dosinia margaritana Wiedey	×	×
Dosinia margaritana var. *projecta* Loel and Corey	×	×
Glycymeris sp.	×	×
Macrochlamis magnolia (Conrad)	×	×
Mytilus cf. *M. expansus* Arnold		×
Trachycardium vaquerosense (Arnold)	×	×
Vertipecten cf. *V. perrini* (Arnold)	×	
Barnacle		
Balanus sp.	×	
Echinoids	×	

are common and fish scales sparse in the mudstone interbeds in the upper part of the formation.

Foraminiferal faunas diagnostic of Zemorrian (Oligocene) age have been recorded from the Vaqueros Sandstone of the adjoining Castle Rock Ridge and Laurel quadrangles (Kleinpell, 1938, p. 111; Burchfiel, 1964, p. 403; Clark, 1966a, p. 60; Fairchild and others, 1969, p. 19 and p. 23–24; and Brabb and others, 1977, table 7). Within the Felton quadrangle, the bioherms above the basalt flows within the Vaqueros Sandstone (table 3) yield *Crassatella granti, Dosinia margaritana* var. *projecta, Macrochlamis magnolia, Turritella inezana, s.s.,* and other stratigraphically diagnostic molluscan representatives of the *Turritella inezana* Zone, which Kleinpell (1938, fig. 14) correlates with his Zemorrian Stage. This faunule, together with the noteworthy absence of *Turritella ocoyana*, is diagnostic of an "Upper" or "Uppermost Vaqueros horizon" of Loel and Corey (1932, p. 136–138) and of the "Vaqueros Stage" of Addicott (1972).

Along Zayante Creek, mudstone interbeds within the Vaqueros Sandstone that are 30 to 45 m stratigraphically along the top of the basalt flows yield abundant calcareous foraminifers. The joint occurrence there of *Eponides nanus*, *Siphogenerina kleinpelli, S. mayi,* and *Uvigerinella obesa* is diagnostic of the *Siphogenerina transversa* Zone of the Saucesian Stage and indicates that at least the upper 185 m of the Vaqueros Sandstone on the south limb of the San Lorenzo syncline is of early Saucesian (early Miocene) age.

A potassium-argon date of 24.1 m.y. on plagioclase feldspar from the basalt flows within the Vaqueros Sandstone that was obtained by J. F. Evernden (Clark, 1966a, p. 59) has recently been revised by Turner (1970, p. 100–101) to 23.1⅞0.7 m.y. This date is significant because the preceding mega- and microfossil data indicate that these flows along Zayante canyon are upper Zemorrian and stratigraphically close to the Zemorrian-Saucesian Stage boundary.

LAMBERT SHALE

The Lambert Shale was named by Dibblee (1966) for a thick sequence of shale, siltstone, and mudstone exposed along Peters Creek in the Mindego Hill quadrangle, 19 km north of the mapped area (fig. 1). In the type area, this formation conformably overlies the Vaqueros Sandstone and is overlain by the Monterey Shale and yields foraminifers diagnostic of Zemorrian and Saucesian ages (Dibblee, 1966).

The Lambert Shale is poorly exposed along the axis of the San Lorenzo syncline in the northeast corner of the Felton quadrangle. Better exposures are to the north along Zayante Creek and to the east along Mountain Charlie Gulch, where this formation is discontinuously exposed along the overturned north limb of the syncline. These beds were mapped as Monterey Shale by Branner, Newsom, and Arnold (1909).

The Lambert Shale is typically thin- to medium-bedded and thinly laminated, olive-gray to dusky-yellowish-brown, organic mudstone that is locally semisiliceous. The mudstone contains silt to very fine sandstone grains of quartz, plagioclase, microcline, orthoclase, biotite, basalt fragments, and glauconite. Most of the terrigenous particles are angular, and the feldspar grains are generally fresh. The matrix of the mudstone consists of clay, collophane, iron oxides, and finely disseminated bituminous matter, with microcrystalline carbonate (dolomite?) lower in the section and opaline silica locally higher in the section. A distinctive feature is the occurrence in the lower part of the formation of graded pale-yellowish-brown phosphatic laminae and lenses that give the mudstone a banded appearance. A few, thin, laminated, well-sorted, fine-grained and thick, graded, medium-grained arkosic sandstone interbeds occur in the upper part.

Approximately 450 m of the Lambert Shale crops out along Mountain Charlie Gulch just east of the area. About 185 m of this formation is preserved along the San Lorenzo syncline in Zayante Creek to the north.

The Lambert Shale is conformable above the Vaqueros Sandstone. The Vaqueros-Lambert contact is well exposed on the steeply dipping, slightly overturned, north limb of the San Lorenzo syncline both along Zayante Creek (SW1/4 sec. 19, T. 9 S., R. 1 W., of Castle Rock Ridge quadrangle) and along Mountain Charlie Gulch (SW 1/4 sec. 29, T. 9 S., R. 1 W., Laurel quadrangle). This contact is placed at the lowest occurrence of well-bedded mudstone in a predominantly mudstone section. To the south along Mountain Charlie Gulch, the Lambert Shale is unconformably overlain by the Santa Cruz Mudstone.

Organic matter is abundant in the Lambert Shale. In addition to that in the matrix, bitumen occurs as very thin, wispy inclusions that are elongate to 2 mm parallel to the lamination. Calcareous foraminifers are common in the lower part of the section, where most of the tests are crushed and filled with sparry calcite, whereas arenaceous varieties are more numerous in the upper part. Diatoms and sponge spicules are less common lower in the formation but more abundant higher, where the mudstone is semisiliceous. Phosphatic fish scales and fragments are common throughout. Mollusks are notably absent from this entire unit.

Foraminifers from the Lambert Shale along Mountain Charlie Gulch (Clark, 1966a, table 5; Brabb and other, 1977, table 7) include *Dentalina quadrulata, Siphogenerina kleinpelli, S. transversa,* and *Uvigerinella obesa* var. *impolita*, which are diagnostic of Saucesian (early Miocene) age, although those from the upper 120 m of this section are not definitely diagnostic.

DEPOSITIONAL ENVIRONMENT OF EOCENE TO LOWER SEDIMENTARY MIOCENE SEQUENCE

The Butano Sandstone and the Twobar Shale Member of the San Lorenzo Formation were probably laid down at bathyal depths throughout the northern and central Santa Cruz Mountains. The development of the arenaceous foraminiferal assemblages from the siltstone interbeds of the lower sandstone member of the Butano Sandstone may have been controlled by muddy bottom conditions, but the complete absence of calcareous forms, the uniformity of the fauna, and the abundance, locally in flood proportions, of large specimens of *Bathysiphon* suggest deposition in cool, deep (bathyal-abyssal) water. Bandy and Rodolfo (1964, p. 833) report that, in the Peru-Chile trench, large specimens of *Bathysiphon* "are significant members of the abyssal foraminiferal faunas."

The foraminifers from the middle siltstone member suggest bathyal depths. The more abundant benthonic species include such deep-water forms as *Asterigerina crassaformis, Bulimina* cf. *B. pyrula* of Mallory (1959), and large specimens of *Bathysiphon eocenicus*. The relative abundance of the nodosariids, on the other hand, suggests depositional depths no greater than bathyal. A common species of nodosariid, *Dentalina consobrina,* favors a bathyal habitat in the present-day seas.

The upper sandstone member of the Butano Sandstone and the overlying Twobar Shale Member of the San Lorenzo Formation yield deep-water foraminifers, including costate buliminids and costate uvigerinids. The paucity of mollusks throughout the coarse clastic part of this Eocene section is consistent with a deep-water interpretation.

Clark and Nilsen (1972) have recently interpreted the Eocene paleogeography of central California as consisting to the west of an irregular continental borderlands of islands separated by deep marine basins. They postulate that the Butano Sandstone of the Santa Cruz Mountains was deposited as a large deep-sea fan by turbidity currents that transported sediment northward from the vicinity of the present-day Monterey Bay. The relative abundance of potassium feldspars (table 2) suggests that this sediment was derived mainly from a potassium-rich granitic terrane.

While deep-water conditions continued to the north of the mapped area (Brabb 1964, p. 676), shallowing from bathyal to neritic depths occurred during deposition of the San Lorenzo Formation in the northern Felton quadrangle. Along Newell Creek, the Rices Mudstone Member is coarser grained than contemporaneous beds to the north and locally contains in abundance such shallow-water mollusks as *Panopea, Pita, Solen,* and *Modiolus*. Shallowing continued during Zemorrian time, and in the northern Felton quadrangle marine conditions were succeeded by the terrestrial conditions under which the Zayante Sandstone was deposited.

Because of the limited areal extent and coarseness of the nonmarine Zayante Sandstone and the total absence of the marine San Lorenzo and Vaqueros Formations to the south of the Zayante fault, Clark and Rietman (1973) have postulated a regional uplift and emergence of the terrane south of this fault during Zemorrian time. The Zayante and Vaqueros Sandstones represent orogenic deposits that were derived from this emergent and largely crystalline terrane to the south of and proximal to the Zayante fault.

The Zayante Sandstone was probably deposited as an alluvial fan along the fault, whereas 1½ to 3 km to the north, bathyal marine sedimentation continued without interruption during deposition of the San Lorenzo and Vaqueros Formations. During the later phase of Zayante Sandstone deposition, subsidence began in the northern part of the area, and a southward transgression of the sea resulted in deposition of the Vaqueros Sandstone. Lignite formed locally under marginal marine conditions. Into this transgressive sea, basalt flowed, locally producing banks upon which shallow-water molluscan representatives of the *Turritella inezana* Zone thrived.

Continued subsidence together with a decrease in the influx of coarse clastic detritus resulted in deposition of the organic mudstone beds of the Lambert Shale. A bathyal environment for these beds is suggested by the common to abundant occurrence of *Bolivina marginata, Siphogenerina transversa, Uvigerinella obesa*, and less common species that Bandy and Arnal (1969, p. 788-791) assign to their upper, middle and lower bathyal biofacies. The association of the flat, unornamented species *Bolivina marginata* with these laminated strata is in accord with Harman's (1964, p. 90) observation that "Flat bolivinid species in laminated sediment generally lack apical spines, costae, and marginal keels in contrast to those in homogeneous sediment." He postulates that *Bolivina marginata* and morphologically similar bolivinids favor an oxygen-deficient habitat, which could account for the absence of mollusks in the Lambert Shale.

MIDDLE MIOCENE SEDIMENTARY SEQUENCE

Resting with marked angular discordance upon the previously deformed Eocene to lower Miocene sequence are the local deposits of a marine sedimentary cycle of middle Miocene (Relizian to Luisian) age. This middle Miocene sedimentary sequence consists of a widely transgressive basal sandstone unit, the Lompico Sandstone, and an overlying organic mudstone unit, the Monterey Formation.

LOMPICO SANDSTONE

A transgressive sandstone unit at the base of the middle Miocene sequence was named the Lompico Sandstone by Clark (1966b), for exposures in Lompico Creek, where this formation is about 150 m thick in the vicinity of the community of Lompico. The type section is 1.6 km southeast of Lompico, where the lower 82 m of this formation is well exposed along the northwest side of Zayante Road (SW1/4 sec. 36, T. 9 S.., R. 2 W., Felton quadrangle).

On the north limb of the Scotts Valley syncline, the Lompico Sandstone is exposed discontinuously east of Lompico Creek, but to the west it can be traced almost continuously to the northern boundary of the Felton quadrangle (pl. 2). On the east slope of Ben Lomond Mountain, this formation is exposed almost continuously for about 10 km from the vicinity of Boulder Creek to south of the town of Felton. On the southwest slope of Ben Lomond Mountain, the Lompico Sandstone crops out along Baldwin, Majors, and Laguna Creek canyons (pl. 1-2).

The Lompico Sandstone as here mapped was referred to the Vaqueros Sandstone by Branner, Newsom, and Arnold (1909) and is shown as "Lower Miocene marine" and thus not differentiated from the Vaqueros Formation on the Santa Cruz sheet (Jennings and Strand, 1958) and on the San Francisco sheet (Jennings and Burnett, 1961) of the Geologic Map of California. Although Brabb (1960a, p. 68) properly interpreted the stratigraphic relationship of these sandstone beds near Boulder Creek and included them within his "Formation A of the Monterey Group," he assigned the correlative beds that crop out along Majors Creek to the Vaqueros Sandstone, as had Page and Holmes (1945).

At the type section, the Lompico Sandstone contains 1.5 m of basal conglomerate with a few granitic and more abundant dark porphyry and light quartzite pebbles in a medium-grained sandy matrix. The lower third of this section consists of thick beds of light-gray, moderately sorted, granular medium-grained, biotite-bearing arkosic sandstone. Calcareous concretionary interbeds include abundant barnacle fragments and a few pelecypod valves. The upper two-thirds of the type section is massive yellowish-gray, buff-weathering, well-sorted, fine-grained arkosic sandstone.

The terrigenous mineral composition of the Lompico Sandstone as determined by point count (200 points per specimen) is given in table 4. The feldspars are fresh to highly altered; in general, the microcline is least altered and the plagioclase the most. Orthochemical minerals include sparry calcite, which cements these sandstones; potassium feldspar occurs locally as overgrowths on feldspar grains; and sphene is altered locally to leucoxene.

The Lompico Sandstone is approximately 150 m thick along Zayante, Lompico, and Newell Creeks. Along strike, this formation thins both to the east and to the west and is about 60 m thick along the San Lorenzo River at the northern limit of the Felton quadrangle. On the east slope of the Ben Lomond Mountain, structural attitudes indicate that the Lompico Sandstone thickens to the south from approximately 60 m in the Boulder Creek-Clear Creek area to about 100 m in the Marshall Creek-Manson Creek area. On the southwest slope of Ben Lomond Mountain this formation reaches a maximum thickness of about 240 m along Majors Creek canyon, where it forms conspicuous cliffs. To the west, the Lompico Sandstone thins, and the upper part of the formation intertongues with siltstone beds of the superjacent Monterey Formation. Along San Vicente canyon, the Shell Davenport core hole No. 1 penetrated about 135 m of this sandstone before reaching granitic basement.

Although the contact of the Lompico Sandstone with the underlying Butano Sandstone is not exposed at the type section or elsewhere along the north limb of the Scotts Valley syncline, a pronounced angular unconformity is indicated by the great discordance in strike, almost opposite direction of dip of the two formations, and westward overlap of all three members of the Butano Sandstone by the Lompico Sandstone.

Along Ben Lomond Mountain, the Lompico Sandstone rests noncomformably upon the crystalline basement, and locally as along Fall Creek, rounded granitic boulders form a thick conglomerate at the base of the exposed sandstone section. The contact with granitic rocks is exposed in Clear Creek near

Brookdale and to the south along Baldwin Creek. The Lompico Sandstone locally rests unconformably upon the Locatelli Formation and along Majors Creek canyon appears to overlie the beds tentatively referred to the Zayante Sandstone.

The Lompico Sandstone is conformably overlain by the Monterey Formation. This gradational contact is well exposed along Lompico Creek (SW1/4 sec. 35, T. 9 S., R. 2 W.), where the sandstone becomes progressively finer grained upward, and the upper contact is placed at the lowest occurrence of bedded mudstone. In the type section, the sandstone likewise decreases in grain size upward, but the contact with the overlying Monterey Formation is covered. On both flanks of Ben Lomond Mountain, the Lompico Sandstone and the Monterey Formation intertongue, and the contact is mapped at the base of bedded mudstone where mudstone predominates in the section.

From sandstone beds that are included here in the type section of the Lompico Sandstone, Arnold (1906, p. 83) collected the type of *Leptopecten andersoni*, where it occurs with *Chlamys* (*Hinnites*) *multirugosus, Chlamys sespeensis* var. *hydei*, and *Balanus* cf. *B. estrellanus*. On the east slope of Ben Lomond Mountain, the Lompico Sandstone is relatively unfossiliferous. Arnold (1906, p. 83) recorded *Leptopecten andersoni* from "near Felton," and his unpublished field notes of 1902 confirm that this species together with *Dosinia mathewsoni* was collected from this formation in the town of Felton. Along Manson Creek, the writer collected *Panopea* sp., indeterminate gastropods, and numerous plant fragments; to the south along Gold Gulch, a coquina bed in the Lompico is composed of *Balanus* fragments and a few specimens of *Ostrea*.

Megafossils are more common and diverse in the Lompico Sandstone on the southwest slope of Ben Lomond Mountain, and those collected by the writer from scattered exposures along Baldwin, Majors, and Laguna Creek canyons are listed in table 5. The large, bell-shaped echinoid *Vaquerosella coreyi* is abundant through a 7.7 m thick section of thick to very thick, medium-grained sandstone beds that are conspicuously exposed along the steep canyon walls. These echinoid beds can be traced northward from the southern part of Majors Creek canyon to where they dip beneath the exposed section to reappear 2.4 km to the northeast along a westward-flowing tributary of Majors Creek.

Siltstone interbeds within the Lompico Sandstone along Majors Creek yield a limited foraminiferal fauna with numerous specimens of the shallow-water taxa *Ammonia beccarii* and *Buccella oregonensis*.

Anadara rivulata, Leptopecten andersoni, Lyropecten crassicardo, Vaquerosella andersoni, and *V. coreyi* are diagnostic of middle Miocene age and of the "Temblor Stage" of Addicott (1972). On the north limb of the Scotts Valley syncline from Bean Creek west to Newell Creek, benthonic foraminifers from the lower part of the superjacent Monterey Formation are diagnostic of late Relizian age and thus restrict the latest age of the underlying Lompico Sandstone to Relizian. To the west in the vicinity of Boulder Creek, where foraminiferal faunas from the lower part of the overlying Monterey include *Valvulineria miocenica* and *Siphogenerina* cf. *S. reedi*, which are diagnostic of Luisian age, the age of the Lompico Sandstone probably extends into early Luisian.

In siltstone interbeds of this formation along Majors Creek, the joint occurrence of *Bolivina imbricata, Florilus incisus*, and *Valvulineria williami* is diagnostic of Relizian age, as a similar fauna from the overlying Monterey Formation along Laguna Creek. Thus, on the southwest slope of Ben Lomond Mountain, the Lompico Sandstone appears to be restricted to the Relizian Stage, whereas to the east of Ben Lomond Mountain, this formation probably ranges from Relizian into the Luisian Stage.

The Lompico Sandstone extends eastward into the Laurel quadrangle, where fossiliferous beds are exposed along Vinehill Road and along Blackburn Gulch, about 3 km east of the Felton quadrangle (Dibblee and others, 1978). These are the easternmost known of this formation.

In the northern Santa Cruz Mountains, sandstone beds that are locally found at the base of the Monterey Formation, designated the Woodhams Shale Member by Cummings, Touring, and Brabb (1962), are correlative with the Lompico Sandstone but were not differentiated by these workers. Transgressive sand-

TABLE 4.—*Terrigenous mineral composition, in percent, of the middle Miocene sequence*

[Point-count analyses by C. A. Wallace. Sample locations are shown on plates 1 and 2; L79 is from San Lorenzo River in Boulder Creek, 60 m north of Felton quadrangle]

Rock Unit	Lompico Sandstone				Monterey Formation	
Sample No	L75A	L75B	L79	L95	L70	L10
Quartz	55	53	57	61	61	66
Plagioclase (An_{10-28})	26	20	7	7	7	11
Orthoclase	12	8	19	21	19	12
Miocene	---	<1	8	9	2	3
Granitic rock fragments	2	5	6	1	1	1
Metamorphic rock fragments	<1	---	<1	---	1	<1
Volcanic rock fragments	<1	<1	2	1	3	<1
Sedimentary rock fragments(?)	---	<1	<1	<1	<1	---
Biotite	6	13	1	<1	4	4
Chlorite	<1	<1	---	---	<1	<1
Muscovite	---	---	<1	---	<1	---
Zircon	<1	<1	---	<1	<1	<1
Sphene	<1	<1	---	<1	<1	---
Apatite	---	<1	---	---	---	---
Epidote(?)	---	<1	---	---	<1	---
Tourmaline	---	---	<1	<1	---	---
Garnet	---	---	<1	<1	<1	---
Clinozoisite	---	---	---	<1	<1	---

stone beds that rest on quartz diorite on the southern slope of Montara Mountain in the Half Moon Bay quadrangle (fig. 1) are probably correlative with the Lompico Sandstone because they have a similar lithology, fauna, and stratigraphic position.

MONTEREY FORMATION

The Monterey Formation was named by Blake (1856) for exposures of diatomaceous and siliceous shale near the town of Monterey about 50km south of the area of this report. In the type area this formation is of Luisian, Mohnian, and Delmontian (middle and late Miocene) age (Kleinpell, 1938, fig. 14). Organic mudstone strata within the central Santa Cruz Mountains that were originally mapped as the Monterey Shale by Branner, Newsom, and Arnold (1909) are here assigned to the Lambert Shale, Monterey Formation, and Santa Cruz Mudstone.

The Monterey Formation in the area of this report is restricted to a succession of organic mudstone beds of late Relizian and Luisian (middle Miocene) age that are conformable above the Lompico Sandstone. This formation crops out on the east slope of Ben Lomond Mountain and underlies the Scotts Valley syncline, where it is well exposed along Newell and Zayante Creeks. On the southwest slope of Ben Lomond Mountain, the Monterey Formation is discontinuously exposed along Smith Grade and is poorly exposed along Laguna, Yellow Bank, and East Branch of Liddell Creeks.

As exposed along Newell, Lompico, and Zayante Creeks on the north limb of the Scotts Valley syncline, the Monterey Formation consists of semisiliceous organic mudstone that grades upward into micaceous and carbonaceous sandy siltstone. The lower mudstone section has a maximum thickness of about 580 m and is typically medium to thick bedded and irregularly laminated. Only locally is the mudstone sufficiently fissile to be properly termed shale. Upon exposure, this olive-gray mudstone weathers to light gray, probably from the leaching or oxidation of bituminous matter in the matrix, and becomes lighter in weight and punky.

Angular, silt to very fine sand-size grains of quartz, plagioclase, orthoclase, microcline, and biotite are scattered throughout the mudstone and locally are concentrated in thin, discontinuous laminae. Very fine grains of glauconite are scattered throughout, and pyrite occurs as finely disseminated, angular grains that locally fill chambers and replace walls of calcareous foraminifers. Collophane occurs in the matrix and as discrete light-colored rounded inclusions that are as much as 3 cm long and are most abundant about 150 m above the base of the formation; from this level the inclusions progressively decrease in size and abundance upward.

Several thick interbeds of grayish-orange-weathering dolomite occur in the lower part of the mudstone section (fig. 3). At least four bentonite interbeds that are from 4 cm to 30 cm thick and consist of relatively pure montmorillonite are also in the lower part of this section. Sandstone interbeds are absent from the lower mudstone section along Newell, Lompico, and Zayante Creeks.

The mudstone grades upward into micaceous and carbonaceous sandy siltstone that is best exposed near the axis of the Scotts Valley syncline along

TABLE 5.—*Megainvertebrates from the middle Miocene sequence on the southwest slope of Ben Lomond Mountain*

[USGS localities are listed under "Fossil Localities"]

Rock unit	Lompico Sandstone										Monterey Formation		
USGS Cenozoic locality	M5064	M5061	M5062	M5063	M5069	M5068	M5058	M5067	M5055	M5060	M5056	M5057	M5054
Gastropods													
Calyptraea filosa (Gabb)		×											
Nassarius(?) sp.											×	×	
Ocenbra cf. *O. topangensis* Arnold		×											
Oliva sp.	×												
Polinices(?) sp.	×												
Turritella ocoyana Conrad								×					
Turritella cf. *T. ocoyana* Conrad							×						
Turritella n. sp.													×
Pelecypods													
Amusium lompocensis (Arnold)													×
Anadara (*Cunearca*) *rivulata* (Wiedey)							×						
Anadara(?) sp.		×											
Chione aff. *C. latilaminosa* Anderson & Martin													×
Crassostrea cf. *C. titan* Conrad									×				
Clycymeris sp.		×	×										
Leptopecten andersoni (Arnold)											×		
Lyropecten crassicardo (Conrad)				×						×			
Macoma sp.		×									×		
Ostrea sp.	×												
Pecten sp.	×					×			×				×
Indeterminate pelecypods												×	
Echinoides													
Vaquerosella andersoni (Twitchell)						×							
Vaquerosella coreyi Durham		×	×	×	×								
Barnacle													
Balanus sp.	×	×				×			×	×			

Newell and Zayante Creeks, where it is 245 m thick (fig. 4). The siltstone is very thick bedded and irregularly laminated. In many exposures the bedding is indistinct, and the rock characteristically displays a flaky weathering. Coarse silt to fine sand constitutes as much as 50 percent of the siltstone, and a few very coarse granitic grains are scattered in this section. Biotite, commonly altered to chlorite and iron oxides, is abundant and together with finely disseminated bituminous matter colors the siltstone olive black. Outcrops commonly are covered with a thin yellowish film of jarosite.

The siltstone section contains a few thick interbeds of arkosic sandstone that commonly are friable and grade continuously upward from medium sand to silt. Thick interbeds and biscuit-shaped concretions of microcrystalline dolomite are conspicuous in this part of the Monterey Formation and locally produce rapids and falls where they strike across streams.

Westward from the Newell-Zayante Creek area, the entire Monterey Formation becomes coarser grained and less well bedded and contains thick to very thick arkosic sandstone interbeds, which are mineralogically similar to the underlying Lompico Sandstone (spls. L70 and L10, table 4). Thus, the Monterey beds that crop out on the east flank and on the southwest slope of Ben Lomond Mountain are lithologically more similar to the upper siltstone section of the Newell-Zayante Creek area than they are to the lower mudstone section.

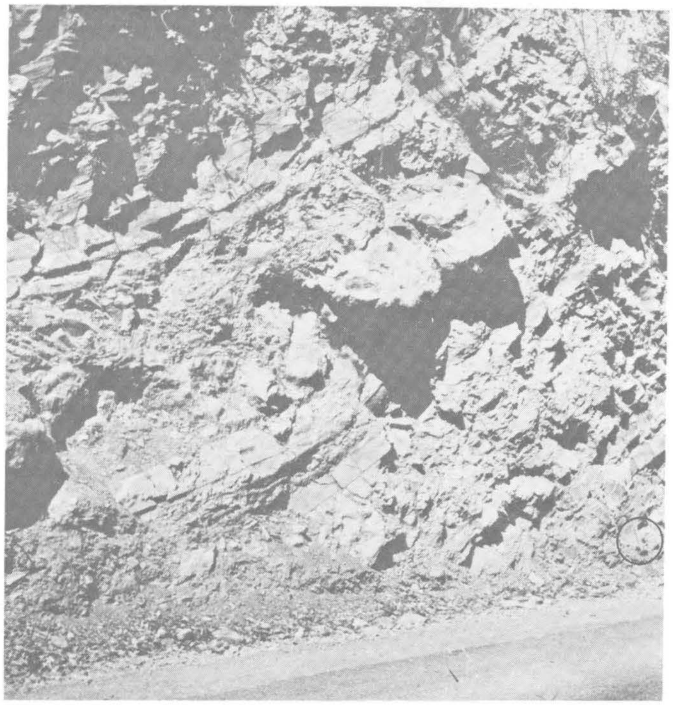

FIGURE 3.—Mudstone beds in lower part of Monterey Formation on north limb of Scotts Valley syncline. View west across Zayante Road (NE¼ sec. 2, T. 10 S., R. 2 W., Felton quadrangle).

On the north limb of the Scotts Valley syncline, the Monterey Formation is as much as 810 m thick. Along Laguna Creek on the southwest slope of Ben Lomond Mountain, structural attitudes suggest that about 370 m of this formation is preserved along the axis of a shallow east-west-trending syncline. About 5 km farther west, the Shell Davenport core hole No. 1 penetrated more than 600 m of mudstone with interbedded sandstone of the Monterey before reaching the Lompico Sandstone.

The Monterey Formation conformably overlies the Lompico Sandstone and is unconformably overlain by the Santa Margarita Sandstone. This unconformable contact is well exposed at numerous localities along the Scotts Valley syncline, where the basal conglomeratic beds of the Santa Margarita rest with angular discordance and with local relief upon the more steeply dipping beds of the Monterey (fig. 5).

South of Boulder Creeek, sandstone interbeds within the lower part of the Monterey locally contain *Leptopecten andersoni*. Mollusks from the lower 150 m of the Monterey Formation on the north limb of the Scotts Valley syncline include:

Anadara (Scapharca?) obispoana (Conrad)
Anadara (Scapharca?) obispoana subsp. *perdisparis* (Wiedey)
Cyclocardia montereyana (Arnold)
Yoldia impressa Conrad
naticid gastropods

Arnold (1908a, p. 380–381) collected the type of *Mactra montereyana* from the lower part of the Monterey section along Love Creek (NW1/4 sec. 33, T 9 S., R. 2 W.) and the type of *Cyclocardia montereyana* from the correlative section along Newell Creek (N1/2 sec. 34. T. 9 S., R. 2 W.). The type of *Anadara obispoana perdisparis* also comes from this lower part of the Monterey Formation, as Reinhart (1943, p. 72) reports the type locality is "Near center of south line of SE1/4 sec. 36, T. 9 S., R. 2 W." *Anadara obispoana* and *Yoldia impressa* are locally so numerous that disarticulated molds of these pelecypods cover the entire surface of slabs of mudstone that are split parallel to the stratification.

Higher in the Monterey section of the Scotts Valley syncline, the molluscan fauna is characterized by the common occurrence of the mud pecten *Delectopecten peckhami*. Mollusks are absent from the upper 250 to 300 m of this Monterey section.

In this same area, calcareous benthonic foraminifers are common to abundant in the lower 600 m of the formation, where they are concentrated locally in thin discontinuous laminae. Higher in the section, these calcareous microfossils decrease in relative abundance and are succeeded by a few arenaceous forms in the upper 150 to 210 m of section along Newell and Zayante Creek.

Plant remains occur throughout the Monterey Formation, and some slabs of mudstone that are split parallel to the bedding display beautifully preserved imprints of leaves. Three Monterey samples from along Newell and Lompico Creeks yield abundant gymnosperm pollen, mostly pine, and a variety of angiosperm pollen, with hickory and oak most common (W. R. Evitt, oral commun., 1961).

Other organic remains include phosphatic fish scales and vertebrae, which are scattered throughout the formation, and a few isolated shark teeth. Diatoms and sponge spicules are also present throughout but are more common in the upper part of the formation. Nowhere are the diatoms sufficiently concentrated to form diatomite.

The common mollusks of the Scotts Valley syncline section are missing from the Monterey Formation on the southwest slope of Ben Lomond Mountain. Mollusks collected by the writer from siltstone beds and sandstone interbeds that crop out along Laguna Creek canyon are listed in table 5 (USGS locs. M5056, M5057, M5054).

The foraminiferal faunas of these two areas also differ markedly, for calcareous foraminifers are rare in the siltstone beds on the southwest slope of Ben Lomond Mountain, where along Laguna Creek and in the Shell Davenport core hole No. 1 they are dwarfed and include numerous shallow-water representatives.

Between Newell and Bean Creeks on the north limb of the Scotts Valley syncline, the joining occurrence of *Bulimina* cf. *B. pseudoaffinis, Lenticulina hughesi, L. simplex. L. smileyi,* and *Valvulineria californica obesa* in the lower 60 m of the Monterey Formation is diagnostic of late Relizian age. *Valvulineria californica s.s.* and *V. miocenica,* both of which do not range below the Luisian Stage, occur higher in the section but are absent from this lower part, indicating that the

FIGURE 4.—Siltstone beds in upper part of Monterey Formation on north limb of Scotts Valley syncline. View west across Newell Creek Road (NW¼ sec. 3, T. 10 S., R. 2 W., Felton quadrangle).

Relizian-Luisian Stage boundary falls within the lower 60 to 120 m of the Monterey Formation of this area. A minimum of 500 m of section along Newell Creek and of 400 m of section along Lompico and Zayante Creeks can be referred to the Luisian Stage on the highest occurrence of *Florilus costiferus*, which does not range above this stage. The highest occurrence of *Valvulineria depressa* further restricts 340 m of Monterey section along Newell Creek and 275 m of section along Lompico Creek to the lower Luisian. The uppermost 220 m of the formation along Zayante Creek lack stratigraphically diagnostic foraminifers but are tentatively referred to the Luisian.

In the vicinity of Boulder Creek and on the east flank of Ben Lomond Mountain, foraminifers from the lowest part of the Monterey Formation commonly include *Valvulineria miocenica* and are thus diagnostic of Luisian age, indicating that locally to the west the lower part of this formation is younger.

The Monterey Formation on the southwest slope of Ben Lomond Mountain is not so well dated. Along Laguna Creek from about 180 m above the base of the formation, a foraminiferal fauna that includes *Bolivina imbricata, Cibicides americanus, Florilus incisus*, and *Valvulineria williami* is diagnostic of Relizian age (Clark, 1966a, table 11, loc. JC62-15).

The Monterey Formation extends eastward from the area into the western part of the Laurel quadrangle, where it locally contains *Anadara obispoana* and foraminifers diagnostic of Luisian age. This formation is also discontinuously exposed in the northern Santa Cruz Mountains, where it has been referred to the Woodhams Shale Member of the Monterey Formation by Cummings, Touring, and Brabb (1962, p. 194-195) and mapped as Monterey Shale by Dibblee (1966).

FIGURE 5.—Unconformable contact between the Monterey (Tm) and Santa Margarita (Tsm) Formations on north limb of Scotts Valley syncline (NW¼ sec. 6, T. 10 S., R. 1 W., Felton quadrangle).

DEPOSITIONAL ENVIRONMENT OF MIDDLE MIOCENE SEQUENCE

The Lompico Sandstone represents the transgressive basal part of the middle Miocene sequence. Relatively shallow-water mollusks, including *Leptopecten, Ostrea,* and *Panopea,* and abundant fragments of the barnacle *Balanus*, together with the local occurrence of shallow-water foraminifers, indicate that these sandstone beds were laid down in a nearshore, shallow-marine environment. They were deposited as the area resubmerged after an extensive interval of uplift and erosion.

The mudstone section in the lower part of the Monterey Formation accumulated as subsidence progressed; approximately 600 m of fine clastic sediment was laid down in progressively deeper water. The molluscan fauna in the lower part of this mudstone is characterized by the common occurrence of *Anadara obispoana*. This arcid pelecypod, which at several localities shows a complete gradation from juvenile to adult forms, some of which have articulated valves, suggests relatively shallow depths. Reinhart (1943, p.12) notes that "most of the Arcidae . . . inhabit the littoral and sublittoral zones and the shallower part of the neritic zone," and A. M. Keen (oral commun., 1963) reports that a recent homeomorph in the Gulf of California has been dredged from depths down to 110 m.

Higher in this mudstone section, the foraminiferal fauna is dominated by inflated Valvulinerias of the *Valvulineria californica* group, and the molluscan fauna by the mud pecten *Delectopecten peckhami*. This section was deposited in deeper water but probably still within neritic depths. Kleinpell (1938, p. 14) refers to "the presence of *Valvulineria* closely related to the Reliz Canyon species in shallow water off the western coast of central Mexico," and Bandy and Rodolfo (1964, p. 825) report that inflated Valvulinerias that are similar to the Miocene forms of California are the most abundant foraminifers in their shallowest sample from a depth of 180 m in the Peru-Chile trench. The genus *Delectopecten* suggests depths greater than 55 m, as Woodring and Bramlette (1950, p. 93) record that this genus has been dredged from depths 55 to 180 m off the California coast and has also been found in deeper water.

Basinal deepening probably continued during deposition of the highest part of the mudstone section that is exposed in the Newell-Zayante Creek area. There, foraminiferal faunas are characterized by the common occurrence of the striate uvigerinid *Uvigerinella* cf. *U. obesa*, whereas inflated Valvulinerias and mollusks are absent. Although Bandy and Arnal (1969, p. 789–790) assign *Uvigerinella obesa* to their middle bathyal fauna (600 m±300 m), they (1957, p. 2048) earlier report that striate uvigerinids are one of the characteristic forms of the outer shelf fauna off the west coast of Central America.

The upper siltstone section probably records a time when more rapid sedimentation outpaced subsidence and the sea became shallower. The impoverishment of the fauna in this part of the section possibly resulted from a restriction that produced toxic bottom conditions in the local basin.

On the southwest slope of Ben Lomond Mountain, shallow-water conditions probably persisted after deposition of the Lompico Sandstone through deposition of the siltstone beds of the Monterey Formation. The Monterey section in the Shell Davenport core hole No. 1 yields only shallow-water foraminiferal faunas that include such characteristic forms as *Ammonia beccarii, Buccella oregonensis, Buliminella elegantissima*, and *Elphidium hughesi*.

The westward coarsening of the Monterey Formation from the Newell-Zayante Creek area and the appearance of numerous arkosic sandstone interbeds in the sections on both flanks of Ben Lomond Mountain indicate that the crystalline complex of Ben Lomond Mountain was a topographic high, possibly an island, that supplied clastic detritus to adjacent areas of deposition. The marked faunal contrast in the lower part of the middle Miocene sequence on opposite sides of the mountain suggests that this high separated these two areas of deposition, at least during Relizian time. On the north limb of the Scotts Valley syncline, the lower part of the Monterey Formation becomes younger toward the west, suggesting that east of Ben Lomond Mountain transgression was from east to west, and the Ben Lomond topographic high was probably transgressed during Luisian time.

UPPER MIOCENE TO PLIOCENE SEDIMENTARY SEQUENCE

Unconformably overlying the middle Miocene sequence is a succession of sedimentary rocks that records a marine sedimentary cycle that was initiated in late Miocene (Mohnian) time. This upper Miocene to Pliocene sedimentary sequence consists of a shallow-water transgressive sandstone unit, the Santa Margarita Sandstone, a deeper water siliceous organic mudstone unit, the Santa Cruz Mudstone, and a shallow-water unit, the Purisima Formation.

SANTA MARGARITA SANDSTONE

Branner, Newson, and Arnold (1909, p. 5) assigned the "distinctive formation consisting of pure white sand overlain by white shale" that crops out in the vicinity of Scotts Valley in the eastern part of the area to the Santa Margarita Formation. The northward extension of this name to the Santa Cruz Mountains by these early workers (1909, p. 5) was "based upon the stratigraphic, lithologic, and paleontologic similarity" of these beds to the type Santa Margarita of the upper Salinas Valley, about 240 km to the south.

The Santa Margarita Sandstone is most extensively developed along the Scotts Valley syncline between the community of Ben Lomond and Scotts Valley. Excellent exposures are in the several commercial sand pits of this area, where the sand locally is being quarried for construction use.

Sandstone beds that discontinuously crops out on the southwestern slope of Ben Lomond Mountain and are locally bituminous are assigned here to the Santa Margarita Sandstone. These beds were included incorrectly in the Vaqueros Sandstone by Branner, Newson, and Arnold (1909), were assigned a Vaqueros and (or) Monterey "age" by Page and Homes (1945), and are shown as "Lower Miocene marine" (Vaqueros Formation) on the San Francisco sheet of the Geologic Map of California (Jennings and Burnett, 1961). Best exposures are in the several abandoned quarries along the ridges between Majors, Baldwin, and Laguna Creeks, where the bituminous sandstone was worked for road material from 1878 to 1915, and along Sandy Flat Gulch, where the sand is being actively quarried for construction use.

The Santa Margarita is typically very thickbedded to massive, thickly crossbedded, well-sorted, slightly granular medium to fine arkosic sand (fig. 6). In fresh exposures the sand is yellowish gray but appears brilliant white along ridges. Large, nearly vertical burrows, as much as 5 cm in diameter, are common in the sand and stand out with slight relief on weathered outcrop surfaces.

The Santa Margarita is generally friable but is locally calcareous and firm where fossiliferous. Along San Vicente canyon where it overlies marble of the crystalline basement, this sandstone is solidly cemented by sparry calcite and displays columnar jointing. On the southwest slope of Ben Lomond Mountain, the sandstone is locally bituminous, and the bitumen content varies both laterally and vertically (for details, see Page and Homes, 1945).

The terrigenous mineral composition as determined by point-count analysis (200 points per specimen) is given in table 6. The feldspar grains range from fresh to highly altered; microcline generally is the least altered and plagioclase the most. Orthochemical minerals include sparry calcite, which locally forms large poikilitic crystals cementing the sandstone, and potassium feldspar, which commonly mantles detrital feldspar grains as clear overgrowths and locally cements the rock. A few glauconite pellets and rare phosphatic bone fragments occur in some specimens.

Cobble- and pebble-bearing gravel beds and lenses are common in the lower third of the Santa Margarita that crops out on the south limb of the Scotts Valley syncline. Near Mount Hermon, these gravel beds are as much as 8 m thick and contain numerous abraded vertebrate bones and teeth. The percentage composition of the gravel as determined by thin-section analysis of 100 pebbles from a very thick bed along Lockhart Gulch (sample L37; SE1/4 sec. 1, T. 10 S., R. 2 W.) is:

Granitic (leucocratic granite to quartz diorite)	20
Biotite-quartz schist	6
Quartzite (metaquartzite and quartzarenite)	12
Meta-arkose and metasubarkose	8
Arkosic sandstone	6
Sandy siltstone and mudstone (Monterey)	6
Chert (including Franciscan?)	2
Silicic volcanic (virtric tuff, rhyolite, rhyodacite, and porphyry)	37
Basalt	3
	100

In general, the granitic, schist, and siltstone clasts predominate among the cobbles and are rounded, whereas the silicic volcanic, quartzite, and basalt clasts are restricted to pebble size and are typically well rounded. The sandy siltstone and mudstone cobbles commonly display molluscan burrows.

The Santa Margarita Sandstone reaches a maximum thickness of 130 m in the Olympia area along the axis of the Scotts Valley syncline. To the south along Bean Creek, this formation is about 98 m thick and thins to the southeast, nearly pinching out along Redwood Drive near the eastern limit of the area. Along the Glenwood syncline in the northeastern part of the area, the Santa Margarita is less than 12 m thick and thins to the east. There, limited exposures and the present map scale do not permit its differen-

TABLE 6.—*Terrigenous mineral composition, in percent, of the Santa Margarita Sandstone and Santa Cruz Mudstone*

[Point-count analysis by C. A. Wallace. Number in parentheses gives number of specimens point-counted in composite sample; sample locations shown on plates 1 and 2]

Rock unit	Santa Margarita Sandstone					Santa Cruz Mudstone
Sample No.	L1(2)	L63(6)	L123	L126	L128	L132(2)
Quartz	57-68	30-59	11	68	70	60-66
Plagioclase (An_{20-40})	11-12	7-16	31	2	7	6-8
Orthoclase	8-18	9-17	9	11	12	12
Microcline	2-5	6-12	40	6	3	<1
Granitic rock fragments	5-8	8-30	7	9	4	0-3
Metamorphic rock fragments	0-<1	<-4	---	<1	2	<1-4
Sedimentary rock fragments	<1	0-<1	<1	2	<1	0-<1
Volcanic rock fragments	2	2-5	<1	1	2	---
Muscovite	0-<1	0-<1	---	---	---<1-6	
Biotite	<1-2	0-<1	3	<1	<1	0-<1
Chlorite	---	0-<1	<1	---	--- 0-2	
Sphene	<1	0-<1	---	---	---	---
Zircon	<1	0-<1	<1	<1	<1	0-<1
Tourmaline	0-<1	0-<1	---	<1	<1	<1
Garnet	0-<1	0-<1	<1	---	---	---
Zoisite	---	---	---	<1	---	---
Clinozoisite	---	---	---	---	<1	0-<1
Epidote(?)	---	---	<1	---	---	---

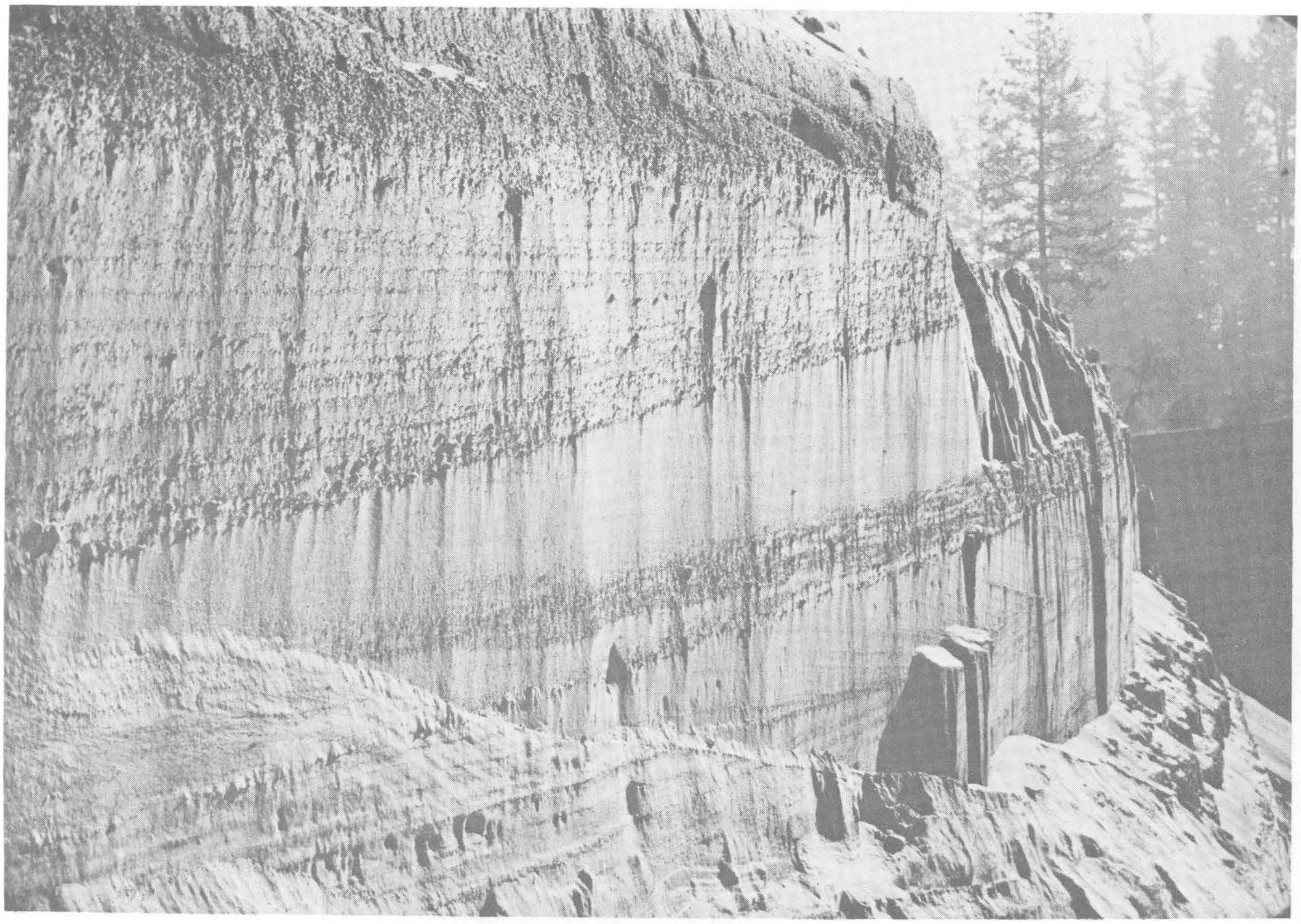

FIGURE 6.—Crossbedded sand with thick gravel interbeds, Santa Margarita Sandstone. View east in Santa Cruz Aggregates sand pit (SW¼ sec. 14, T. 10 S., R. 2 W., Felton quadrangle).

tiation at the base of the Santa Cruz Mudstone.

On the southwest slope of Ben Lomond Mountains, the thickest section of Santa Margarita is about 1.6 km to the northeast of the community of Bonnie Doon, where it is more than 95 m thick. Along the coast to the west, the Texas Company Poletti well penetrated 88 m of this sandstone before reaching the granitic basement at a depth of 2,800 m. About 3 km northeast of this well along Big Creek and Berry Creek, this formation locally pinches out, whereas farther north along Scott Creek and its tributaries, the Santa Margarita is between 6 and 12 m thick.

The Santa Margarita Sandstone is unconformable on older rocks and is conformably overlain by the Santa Cruz Mudstone. Along the Scotts Valley syncline, this sandstone rests unconformably upon the Monterey Formation (fig. 5). South of Mount Hermon the Santa Margarita may rest unconformably upon the Lompico Sandstone and in the vicinity of Henry Cowell Redwoods State Park is unconformable on the Locatelli Formation. From Scotts Valley south to the city of Santa Cruz, this sandstone is nonconformable upon the crystalline basement.

On the southwest slope of Ben Lomond Mountain, the Santa Margarita Sandstone rests unconformably upon the Monterey Formation and upon the Lompico Sandstone of the middle Miocene sequence and nonconformably upon the crystalline basement. Along San Vicente canyon, bituminous beds of the Santa Margarita locally rest with marked angular discordance upon the steeply dipping beds of the Butano(?) Sandstone.

In the Scotts Valley area, an abrupt change from yellowish-gray well-sorted fine-grained arkosic sandstone above occurs from 2 to 4.5 m below the conformable contact with the overlying Santa Cruz Mudstone. This distinct change in color and texture is marked by a gently undulatory surface, above which is a discontinuous pebble bed, from 15 to 30 cm thick, that contains well-rounded granitic pebbles, a few molluscan-bored sandstone cobbles, and scattered bones. Extending downward from this surface are circular burrows, as much as 46 cm long, that are filled with the overlying "greenish" sand. Above this surface, the sandstone is slightly glauconitic and grades continuously upward into the overlying Santa Cruz Mudstone.

On the southwest slope of Ben Lomond Mountain, sand from the Santa Margarita locally has intruded the overlying Santa Cruz Mudstone as sills and crosscutting veinlets and dikes. Where bituminous, these intrusive sandstone bodies are more resistant to erosion than the enclosing mudstone beds, as along the coast near the mouth of Baldwin Creek, where several intersecting bituminous sandstone dikes protrude above the present wave-cut bench.

East of Ben Lomond Mountain, the Santa Margarita Sandstone yields a diverse megafauna. Along much of the Scotts Valley syncline, several thick to very thick, slightly granular, medium- to coarse-grained sandstone beds contain numerous tests and fragments of the irregular echinoid *Astrodapsis spatiosus*. The top of these echinoid-bearing beds is from 7.5 to 15 m stratigraphically below the contract with the overlying Santa Cruz Mudstone.

The *Astrodapsis* beds occupy a section as much as 18 m thick on the north limb of the syncline and are well exposed on the Weston Ranch (USGS loc. M5155; NE1/4 sec. 1, T. 10 S., R. 2 W.), where a 60-m-thick echinoid-bearing bed caps a ridge that is locally known as "sand dollar hill" (figs. 7 and 8). To the south, the stratigraphic section containing the echinoids thins, and these beds do not extend south of the vicinity of Bean Creek. To the north along the Glenwood syncline about 280 m east of Zayante Creek (USGS loc. M5112; NW1/4 sec. 30, T. 9 S., R. 1 W.), these echinoid-bearing beds form a 4-m-high cliff over which plunges the water of an unnamed tributary to Zayante Creek.

Megafossils from these echinoid-bearing beds (USGS locs. M5155 and M5086) include:

Echinoids:[2]
- *Astrodapsis* cf. *A. arnoldi* Pack
- *Astrodapsis spatiosus* Kew
- Cidarid spines

Brachiopod:
- *Discinisca cumingi* Broderip

Gastropods:
- *Nucella*
- *Nucella lima* (Gmelin)
- *Nucella* sp.

Pelecypods:
- *Lyropecten estrellanus* (Conrad)
- ?*Patinopecten healeyi* (Arnold)

Barnacle:
- *Balanus* sp.

Shark teeth

Along Bean Creek canyon (USGS locs. M5052 and M5053) from beds in the upper part of the Santa Margarita Sandstone that are stratigraphically above the *Astrodapsis* beds, the writer collected the following molluscan fauna:

- ?*Calicantharus* sp.
- *Glycymeris grewingki* Dall
- *Patinopecten healeyi* (Arnold)
- *Solariella peramabilis* Carpenter
- *Nucella lamellosa* (Gmelin)
- *Naticid gastropods*

From Scotts Valley south to Santa Cruz, the *Astrodapsis* beds and mollusks are absent, and the fossil fauna of the Santa Margarita is almost entirely vertebrate. The following vertebrate fauna was collected largely by C. A. Repenning and the writer from scattered localities along the Scotts Valley syncline (USGS locs. M1036, M1037, M1038, and, 1105), from along Bean Creek on the south margin of the syncline (UCMP locs. V4004, V5244, and V5555; USGS loc. M1039), and from Scotts Valley south to Santa Cruz (USGS locs. M1035 and M1106) and were identified, except as noted below, by C. A. Repenning:

Birds

Camel[3]

Cetaceans:[4]
- Balaenopterid
- Delphinid near *Lamprolithax*

Desmostylians:
- *Desmostylus hesperus* Marsh
- *Paleoparadoxia tabatai* (Tokunaga)

Fish:
- *Smilodonichthys* sp.
- Teleost vertebrae

Horses:
- *Archaeohippus* cf. *A. mourningi* (Merriam)
- *Hipparion* cf. *H. forcei* Richey
- *Hipparion* cf. *H. mohavense* Merriam
- *Pliohippus* sp.[3]

Mastodon:
- ?*Gomphotherium* sp.[3]

Pinnipeds:
- ?*Allodesmus* sp.
- Desmatophocine[4]
- *Imagotaria downsi* Mitchell
- *Pithanotaria starri* Kellogg

[2]Echinoid identifications by J. Wyatt Durham. *Astrodapsis spatiosus* is the dominant faunal element; the other associated megafossils are rare.

[3]Identified by D. E. Savage (written commun., 1959).

[4]Identified by L. G. Barnes.

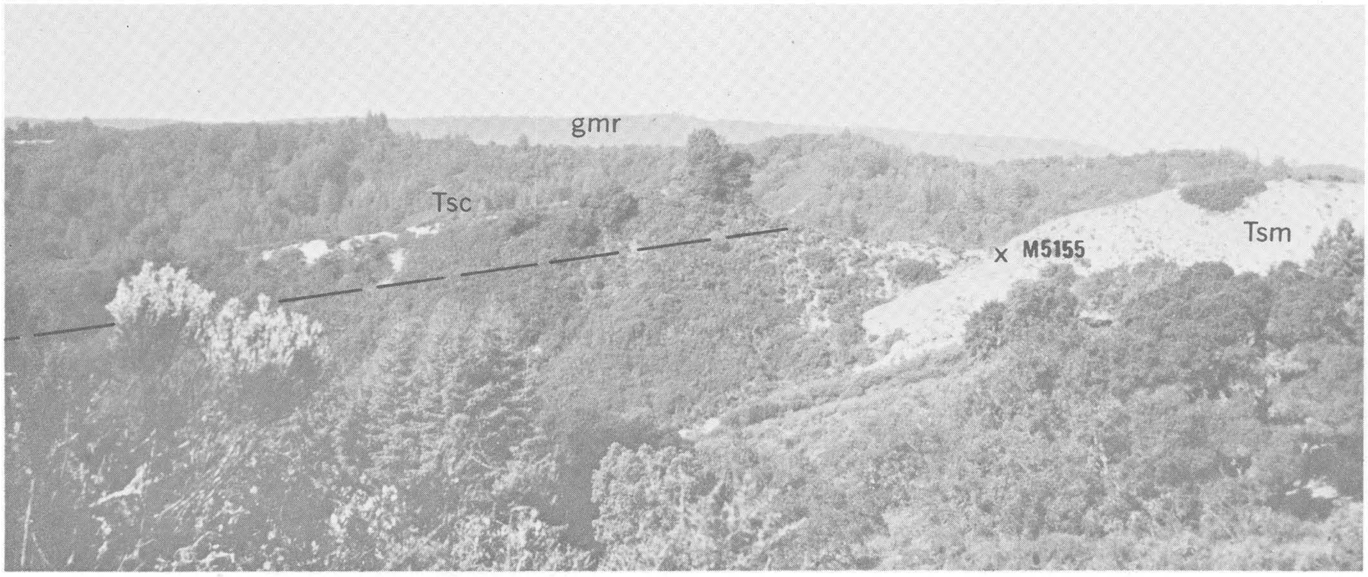

FIGURE 7.—*Astrodapsis* beds in Santa Margarita Sandstone form ridge in right foreground. View west toward USGS locality M5155. Ben Lomond Mountain forms distant skyline; gmr, granitic and metasedimentary rocks; Tsm, Santa Margarita Sandstone; Tsc, Santa Cruz Mudstone.

Sharks:
- Large suite including:
  - *Charcharodon* sp.
  - *Hexanchus* sp.
  - *Isurus* sp.
  - *Galeocerdo* sp.

Sirenians:
- *Halianassa vanderhoofi* Reinhart[5]

Desmostylian teeth and land-mammal remains are rare and have been collected only from the gravel beds in the lower part of the formation in the Bean Creek area. Sirenians and cetaceans commonly occur throughout the Santa Margarita and locally consist of almost entire skeletons, whereas pinnipeds seem to be restricted to the upper part of the formation.

Megafossils are rare in the Santa Margarita Sandstone on the southwest slope of Ben Lomond Mountain and consist predominantly of scattered vertebrate remains. Northeast of Bonnie Doon, the writer observed a single, poorly preserved specimen of *Pecten*. The writer collected a few shark teeth from gravel beds along Sandy Flat Gulch, a single sirenian phalanx from massive sandstone beds on the west bank of Peasley Gulch (USGS loc. M1107), and an isolated sirenian rib from a pebbly coarse-grained sandstone bed on the west side of San Vicente canyon. C. A. Repenning and the writer noted fish and cetacean bones and collected the tarsal elements of the pinniped, *Imagotaria downsi*, from the upper part of the Santa Margarita on the east side of Moore Creek canyon (fig. 9; USGS loc. M1108).

The occurrence of primitive *Hipparion* in the lower part of the Santa Margarita is diagnostic of an early Clarendonian age of the North American land-mammal chronology, which vertebrate workers consider to be latest Miocene (Savage and Barnes, 1972). *Desmostylus*, which is also from the lower part of the section, is not known to range above the late Miocene of the West Coat megafaunal chronology (Mitchell and Repenning, 1963, table 1; Domning, 1972).

Although Branner, Newsom, and Arnold (1909) assigned a late Miocene age to the Santa Margarita Sandstone, mollusks and echinoids from the upper part of this formation are diagnostic of an early Pliocene age in the West Coast megainvertebrate chronology. *Astrodapsis spatiosus* has been considered a Miocene or Pliocene taxon, although "mollusks of undoubted Pliocene age" occur at the type locality (Durham and Addicott, 1965, p. A16). Along the Scotts Valley syncline, a provincial Pliocene age is suggested for the *Astrodapsis* beds by the association of a split-ribbed pecten, tentatively referred to *Patinopecten healeyi*, and of *Astrodapsis* cf. *A. arnoldi*, both of which are considered diagnostic of Pliocene age.

The molluscan assemblage from stratigraphically above the *Astrodapsis* beds along Bean Creek canyon is diagnostic of a provincial Pliocene age, for it includes *Patinopecten healeyi* and the gastropods *Solariella peramabilis* and *Nucella lamellosa*, both

[5]Type locality (=UCMP V4004) is Santa Cruz Aggregates sand pit (SE1/4 sec. 14, T. 10 S., R. 2 W.).

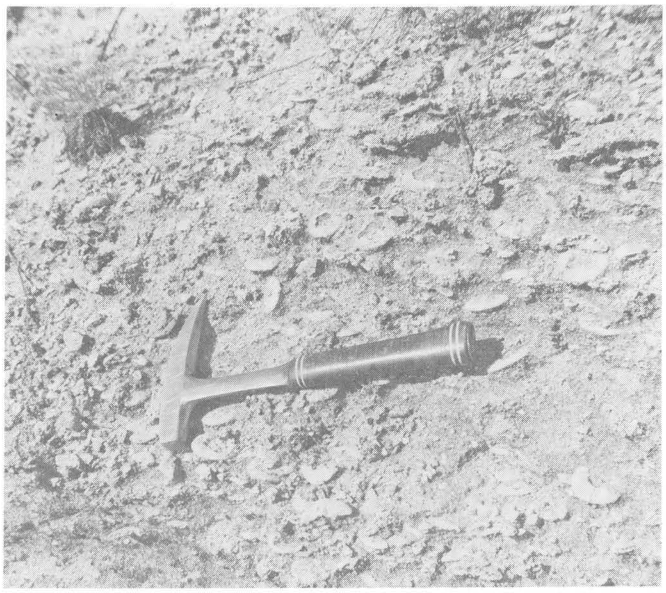

FIGURE 8.—*Astrodapsis* bed in Santa Margarita Sandstone at USGS locality M5155 (NE¼ sec. 1, T. 10 S., R. 2 W., Felton quadrangle).

of which have not been recorded from pre-Pliocene rocks in California.

Thus, the Miocene-Pliocene Series boundary of the provincial megainvertebrate chronology appears to fall within the Santa Margarita Sandstone of this area between the *Desmostylus*-bearing gravel beds in the lower part of the formation and the *Astrodapsis* beds in the upper part.

In the West Coast foraminiferal chronology, the Santa Margarita Sandstone is of Mohnian and Delmontian age . Along the Scotts Valley syncline, this formation rests with angular discordance upon the more strongly deformed beds of the Monterey Formation of late Relizian and Luisian age. The lower part of the Santa Margarita may be assigned to the Mohnian Stage, on the basis of correlation of these beds with the Mint Canyon Formation of southern California, the upper part of which contains a similar Clarendonian land-mammal fauna. The Mint Canyon in turn is unconformably overlain by the marine Castaic Formation, in part of Mohnian age (Durham and others, 1954, p. 66). Radiometric dating by Turner (1970, fig. 9) confirms that the Clarendonian land-mammal stage is at least partly correlative with the Mohnian Stage. *Astrodapsis spatiosus* has been correlated with the upper Delmontian (Kleinpell, 1938, fig. 14; Hall, 1962, fig. 5). Foraminifers from the type section of the overlying Santa Cruz Mountains are diagnostic of early Delmontian age.

The preceding dating suggests that the Miocene-Pliocene Series boundary of the West Coast provincial megainvertebrate chronology falls within the Mohnian-Delmontian sequence of the West Coast foraminiferal chronology. On the basis of recalibration of the California provincial benthic chronologies (Berggren, 1972; Berggren and Van Couvering, 1974), however, the Santa Margarita Sandstone of this area is of late Miocene age in terms of the European standards.

SANTA CRUZ MUDSTONE

Santa Cruz Mudstone was the name proposed by the writer (1966b) for the siliceous organic mudstone beds that conformably overlie the Santa Margarita Sandstone. These rocks were mapped by Branner, Newsom, and Arnold (1909) as the Santa Margarita Shale to the east of Ben Lomond Mountain and mapped by them and most subsequent workers as Monterey Shale to the west. The name Santa Cruz Mudstone is applied to these organic mudstone beds

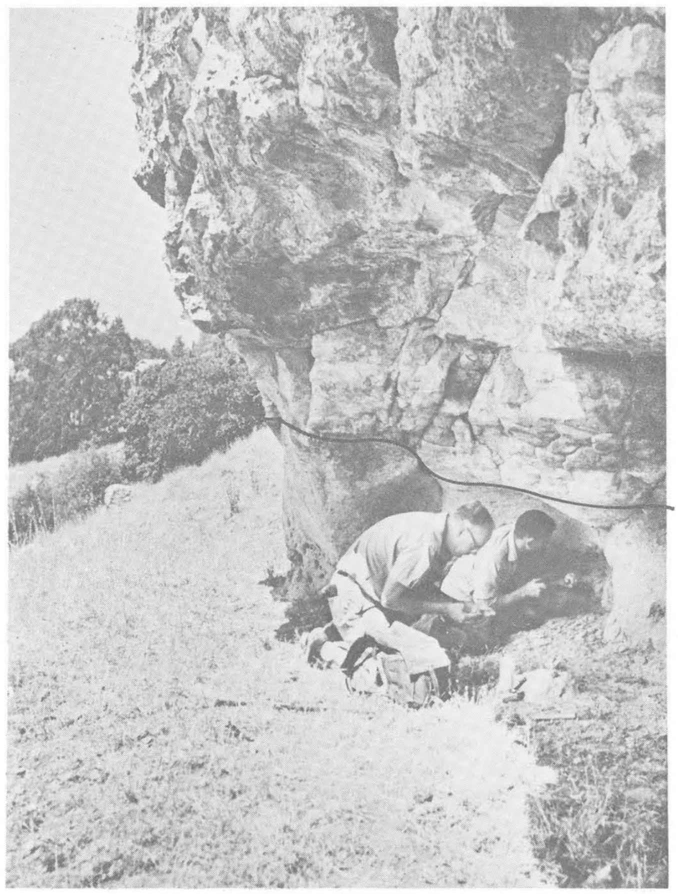

FIGURE 9.—Santa Margarita Sandstone-Santa Cruz Mudstone contact on east side of Moore Creek canyon. View north toward USGS locality M1108 (SE¼ sec. 15, T. 11 S., R. 2 W., Santa Cruz quadrangle).

FIGURE 10.—Santa Cruz Mudstone capped by marine terrace sand at Natural Bridges Beach State Park near Santa Cruz. View west toward lowest emergent marine terrace.

in order to differentiate them from the middle Miocene sequence of organic mudstone beds, to which the present writer has restricted the name Monterey.

The type section is within the Santa Cruz 5×11-minute quadrangle and is at the western limits of the city of Santa Cruz, from which the name is taken. This section is exposed from its base, which overlies the Santa Margarita Sandstone on the east side of Moore Creek canyon (SE1/4 sec. 15, T. 11 S., R. 2 W.), southward 2.4 km down Moore Creek canyon to the coast at Natural Bridges State Park, then eastward for 1.6 km along the sea cliffs to the contact with the overlying Purisima Formation (S1/2 sec. 23, T. 11 S., R. 2 W.).

The type section is about 140 m thick and consists of medium- to thick-bedded and laminated siliceous organic mudstone (figs. 10 and 11). The mudstone where fresh is olive gray to dark yellowish brown but weathers yellowish gray to nearly white with blocky fractures. In the upper part of the type section, thin, discontinuous lenses and interbeds of porcelanite are darker colored and more brittle than the thicker, less siliceous mudstone beds with which they alternate. Rounded, spheroidal to discoidal carbonate concretions are scattered along bedding planes in the upper part of the type section and are commonly elongate parallel to the bedding.

At the base of the type section, the conformable contact between the friable sandstone of the Santa Margarita below and the more resistant mudstone of the Santa Cruz Mudstone above is marked by a pronounced break in slope (fig. 9). The overlying Purisima Formation rests with slight angular discordance upon the Santa Cruz Mudstone along the sea cliffs at the top of the type section. At the base of the Purisima is a glauconitic and slightly phosphatic, pebbly sandstone bed as much as 60 cm thick, containing rounded granitic and prophyritic volcanic pebbles and cobbles, molluscan-bored siliceous mudstone cobbles, and scattered bones and teeth. Molluscan borings that extend downward from the contact into the underlying siliceous mudstone are filled with this glauconitic sandstone.

Silt to very fine, angular to subangular terrigenous grains are scattered throughout the mudstone and locally concentrated in thin, irregular laminae, with elongate grains oriented subparallel to the lamination. This terrigenous material is more abundant in the lowermost part of the formation and is common in the section west of Waddel Creek in the Año Nuevo quadrangle, where locally the rock is a sandy silt-

FIGURE 11.—Santa Cruz Mudstone, containing thin porcelanite lenses and interbeds and carbonate concretions, overlain by Purisima Formation (Tp) in sea cliffs below West Cliff Drive, Santa Cruz (sec. 26,, T. 11 S., R. 2 W., Santa Cruz quadrangle).

stone. The percentage composition of terrigenous minerals from this western section as determined by point-count analysis (200 points per specimen) is given in table 6. Glauconite grains are scattered throughout the section.

Diatom frustules, siliceous sponge spicules, and phosphatic fish remains, mainly scales, occur throughout the formation. Diatoms predominate and locally may constitute as much as 70 percent of the mudstone. At a few localities, minute, rod-shaped, external molds of sponge spicules are common. The opaline cementation of this mudstone probably results from the diagenetic redistribution of silica from the diatoms and sponge spicules.

Spheroidal dolomite concretions that weather moderate yellowish brown are conspicuous in coastal exposures but rare elsewhere. Bedding is irregular, and this block-weathering mudstone typically lacks fissility. Upon weathering, the mudstone bleaches nearly white, becomes punky, and is locally referred to as "chalk rock." Weathered outcrop surfaces are usually coated with a thin yellowish film of jarosite. As this siliceous mudstone weathers mechanically, slopes and ridges underlain by the Santa Cruz Mudstone are commonly covered by angular chips and slabs of this rock.

East of Ben Lomond Mountain, the Santa Cruz Mudstone thickens westward from a featheredge in the eastern part of the Felton quadrangle to more than 74 m along the ridge west of Zayante Creek, but there the top of this formation has been removed by erosion. On the southwestern slope of Ben Lomond Mountain, this mudstone unit thickens from about 140 m in the type section to more than 385 m in the Shell Davenport core hole No. 1, about 13 km to the northwest. It is more than 2,700 m thick in the Texas Company Poletti well, 7 km farther to the northwest. But at both of these well sites the upper part of the formation has been removed by erosion.

The Santa Cruz Mudstone is conformable above the Santa Margarita Sandstone, with which it does not appear to intertongue. On the southwestern slope of Ben Lomond Mountain, sand from the underlying Santa Margarita locally has intruded the Santa Cruz

Mudstone as sills and crosscutting veinlets and dikes, which in places are bituminous. Along Big Creek and Berry Creek in the Davenport quadrangle, where the Santa Margarita Sandstone locally is absent, the Santa Cruz Mudstone rests directly on quartz diorite.

The Santa Cruz Mudstone is unconformably overlain by the Purisima Formation at the type section and in exposures 3 km to the north in the city of Santa Cruz, where diatomaceous beds of the Purisima rest with slight angular discordance on siliceous mudstone beds. In the Scotts Valley area to the north, this upper contact is conformable and is placed at the base of the lowest thick yellowish-gray tuffaceous and diatomaceous siltstone bed. Sand from the overlying Purisima may also locally intrude the Santa Cruz Mudstone, for the andesitic sandstone that fills two large discordant intrusions in coastal exposures near the mouth of Yellow Bank Creek is petrographically similar to Purisima sandstone.

Marine diatoms and sponge spicules in the Santa Cruz Mudstone are commonly preserved as molds. A dolomite concretion from a cut along Highway 1 near Majors in the Santa Cruz quadrangle that was dissolved in dilute hydrochloric acid yielded a few large, well-preserved diatoms, a few sponge spicules, and sparse radiolaria. The diatom flora included the shallow-water genera, *Arachnoidiscus* and *Isthmia*, but lacked stratigraphically diagnostic taxa (J. A. Barron, oral commun., 1978).

Pollens are locally abundant, and a sample from the type section of the Santa Cruz Mudstone from 3 m stratigraphically below the unconformity with the overlying Purisima (USGS loc. Mf2187) was analyzed by W. R. Evitt, who states (written commun.,1965):

> The assemblage of organic microfossils consists almost entirely of angiosperm and gymnosperm pollen grains; pteridophyte spores are virtually absent.
>
> The most abundant angiospermous element is pollen of *Quercus* (oak). In addition grains from several representatives of the family Juglandaceae (*Juglans*, walnut; *Carya*, hickory; and *Pterocarya*) and the genus *Alnus* (alder) are common. Other constituents include grass, several types of the family Copositae (aster family), Ericaceae (heath family), and a large assortment of others in smaller number.
>
> The gymnosperms are represented by pollen of two basically different morphological types; disaccate grains of the pine type, and asaccate spherical grains of *Taxodium*-type.

Foraminifers are rare in the Santa Cruz Mudstone. Calcareous species recently identified by A. D. Warren (written commun., 1978) from the upper part of the type section (USGS loc. Mf2187) include;

Bolivina obliqua Barbat and Johnson
Bolivina tumida Cushman
Bolivina vaughani Natland
Buliminella elegantissima (d'Orbigny)
Nonionella miocenica Cushman
Valvulineria araucana (d'Orbigny)
Virgulina pontoni Cushman

Warren believes that this fauna is diagnostic of an early Delmontian (Miocene) age.

From the Santa Cruz Mudstone that crops out northeast of California Highway 1 and west of Waddell Creek in the Ano Nuevo quadrangle, Brabb (1960a, p. 180, loc. EB472) records *Virginulina subplana, Pulvinulinella pacifica, Eponides tenera, Globigerina* sp., and *Cibicides* sp. and states that this foraminiferal fauna is "restricted to the Purisima formation."

Megafossils, other than fish remains, are exceedingly rare in the Santa Cruz Mudstone. Arnold (1908b, p. 403-406) described an ophiuroid, *Amphiura santaecrucis*, from exposures of this formation "immediately southeast of Scotts Valley." In the Scotts Valley area, the writer has collected about a dozen molds of the pelecypod *Lucinoma* cf. *L. annulata*, a few specimens of *Yoldia* sp., and a single, crushed spatangoid echinoid, *Megapetalus* sp. (identified by J. W. Durham, oral commun., 1965). *Megapetalus* is reported to range from late Miocene to early Pliocene(?) in southern California (Zullo and Durham, 1962, p. 525).

In nodular mudstone float from the northeast side of Highway 1 west of Waddel Creek, the writer has collected the pelecypods *Acila* cf. *A. semirostrata* and *Yoldia* sp. and small irregular echinoid spines. This undoubtedly is the same locality from which a nuculid bivalve was collected that Schenck (1936, p. 80) incorrectly identified as *Acila gettysburgensis*, which in fact is *Acila semirostrata,* according to W. O. Addicott (oral commun., 1974), who has recollected this Pliocene species there. From beach exposures just west of this locality, the writer collected a few thin-walled echinoid plates that were tentatively referred to *Megapetalus* sp. by J. W. Durham (written commun. from W. O. Addicott, 1969). In coastal exposures east of Wilder Creek and about 1.6 km west of the type section, the writer noted a single mammalian (sirenian?) rib.

The conformable position of the Santa Cruz Mudstone above the Santa Margarita Sandstone dates it in the Scotts Valley area as not older than early Pliocene in the provincial megainvertebrate chronology. The recorded mega- and micro-faunas from this formation are diagnostic of a Pliocene, probably early, age in this provincial chronology and of Delmontian age in the foraminiferal chronology. The Santa Cruz Mudstone thus falls within that interval that until recently on the West Coast had been considered early Pliocene but in terms of the European standards is late Miocene.

A potassium-argon date of 6.7±0.6 m.y. (J. D. Obradovich, written commun., 1964) on glauconite from the base of the Purisima immediately above the type section indicates that the subjacent Santa Cruz Mudstone is not younger than late Miocene or Hemphillian in the land-mammal chronology (Repenning and Tedford, 1977, table 1). Diatom floras from lower beds of the overlying Purisima Formation (USGS locs. Mf3678, Mf3677, Mf3676, table 7) are diagnostic of a late Miocene and early Pliocene age of the North Pacific diatom chronology (J. A. Barron, written commun., 1977).

The Santa Cruz Mudstone can be mapped northward from the Año Nuevo quadrangle across the Franklin Point quadrangle and into the southern part of the La Honda quadrangle, where it is conformably overlain by the Purisima Formation (Cummings and others, 1962, p. 200). Throughout this area, the Santa Cruz Mudstone is extensively exposed northeast of the San Gregorio fault but does not crop out southwest of the fault.

The Santa Cruz Mudstone is thicker bedded, less fissile, and less siliceous than the porcelaneous beds of the typical Monterey Formation (Aguajito Shale Member of Bowen, 1965). Although the Santa Cruz Mudstone is not well dated, it is probably younger than most of the type Monterey, which is middle and late Miocene (Luisian, Mohnian, and Delmontian Stages of Kleinpell, 1938). East of Monterey, the Monterey Formation is conformably overlain by the Santa Margarita Sandstone, whereas in the Santa Cruz Mountains the Santa Cruz Mudstone is conformable upon the Santa Margarita Sandstone.

The Santa Cruz Mudstone more probably correlates with the Pancho Rico Formation of the Salinas Valley, which is partly semisiliceous mudstone and generally overlies the Monterey Shale or the Santa Margarita Formation. The Pancho Rico Formation yields a megainvertebrate fauna diagnostic of an early Pliocene age ("Jacalitos" Stage) in the provincial chronology, which is now considered latest Miocene (Addicott, 1978, p. 85).

The Santa Cruz Mudstone also correlates with lithologically similar beds that crop out near Bolinas, 120 km to the northwest, where they were included in the Monterey Shale by Galloway (1977). E. E. Brabb and the writer recently have collected mudstone samples from sea cliff exposures near Bolinas that yield *Bolivina obliqua* and other benthic foraminifers diagnostic of an early Delmontian (late Miocene) age (A. D. Warren, written commun., 1978).

PURISIMA FORMATION

The Purisima Formation was the name applied by Haehl and Arnold (1904, p. 22) to "an extensive series of conglomerates, fine-grained sandstones and shales" that are typically developed in the vicinity of Purisima Creek of the present Half Moon Bay quadrangle. These workers believed that this formation was of early and perhaps middle Pliocene age.

Within the Santa Cruz Mountains the Purisima Formation is most extensively developed in the Half Moon Bay, San Gregorio, and La Honda quadrangles, its type area, where it is as thick as 1,725 m. It was subdivided into five members and is of Pliocene age, probably early to late Pliocene, in the provincial megainvertebrate chronology (Cummings and others, 1962, p. 1974-212).

Northeast of the San Gregorio fault in the area of the present report, the Purisima Formation is exposed only in the eastern part of the Felton and Santa Cruz quadrangles (pl. 2), where it consists of very thick yellowish-gray tuffaceous and diatomaceous siltstone beds with thick yellowish-gray to locally bluish-gray andesitic sandstone interbeds.

Abundant silicic glass debris in the siltstone and dark andesitic fragments in the sandstone serve to differentiate the Purisima Formation from all older sedimentary rock units in the area. The glass debris occurs as cuspate shards and pumice fragments that are isotropic and have a refractive index of 1.50. Diatoms and sponge spicules are associated with the glass debris. In the lower part of the formation, glass debris predominates in the northern part of the area, whereas in the city of Santa Cruz, the lower beds are more diatomaceous. This diatomite is well exposed in cuts along High Street and Highland Avenue in Santa Cruz.

The bluish sandstone interbeds have their lowest stratigraphic occurrence approximately 25 m above the base of the formation. This sandstone is well sorted and fine grained and contains abundant andesitic fragments and a heavy-mineral assemblage that is characterized by hypersthene, basaltic hornblende, augite, and green and brown hornblende. The distinctive bluish hue of these sandstones, apparently the result of an authigenic montmorillonoid coating on the grains (Lerbekmo, 1957), is only locally developed, whereas compositionally similar sandstone interbeds to the west of Scotts Valley are commonly brownish. The bluish sandstones are similar to the "blue" sandstone beds of other Pliocene formations in the eastern Coast Ranges, including the Tehama, Neroly, San Joaquin, and Etchegoin Formations.

West of Scotts Valley, where this unit is discontinuously exposed along ridgetops, the Purisima Formation has a maximum thickness of 60 m. Southeast of

Scotts Valley, it is more extensive and as much as 150 m remains, although the upper part has been removed by erosion. Along the Glenwood syncline to the north, as much as 180 m of this formation is poorly exposed in the Felton quadrangle, whereas more than 820 m of the Purisima is preserved along this structure in the Laurel quadrangle to the east (Buford, 1961).

The Purisima Formation rests conformably upon the Santa Cruz Mudstone in the Felton quadrangle. To the south in the city of Santa Cruz, this same contact is unconformable and is well exposed on the west side of Rincon Street and in the sea cliffs below West Cliff Drive at the type section of the Santa Cruz Mudstone. The Purisima Formation is unconformably overlain by Pleistocene terrace deposits in the vicinity of Santa Cruz.

Mollusks are rare in the lower part of the Purisima Formation. From the lower 60 m that is exposed west of Scotts Valley, the writer has collected:

?*Chlamys hericius* (Gould)
Lucinoma cf. *L. annulata* (Reeve)
Macoma sp.
Neptunea (*Sulcosipho*) *tabulata* (Baird)
Yoldia sp.

In this area, *Lucinoma* cf. *L. annulata* is the most characteristic form.

Mollusks are locally more common higher in the formation, and the fauna collected by the writer from the hills southeast of Scotts Valley includes:

Acila (*Truncacila*) *castrensis* (Hinds)
Crepidula cf. *C. onyx* Sowerby
Forreria coalingensis (Arnold)
Macoma cf. *M. planiuscula* Grant and Gale

There, the nuculid bivalve *Acila* (*Truncacila*) *castrensis* is locally abundant.

Marine vertebrate remains occur in the Purisima Formation, and the contained mammalian fauna is quite distinct from the fauna of the older Santa Margarita Sandstone. A few fish vertebrae are scattered in siltstone beds in the vicinity of Scotts Valley. Vertebrate remains, including large cetacean bones, are more common in this formation within the city of Santa Cruz, where they are observed in the sea cliffs as early as 1827 (VanderHoof, 1951, p. 109-110).

C. A. Repenning and the writer collected sirenian ribs, a single, poorly preserved sirenian tooth, and the remains of an aberrant walrus (?*Dusignathus santacruzensis* Kellogg) from the glauconitic basal beds of the Purisima Formation (USGS loc. M1109). This sirenian tooth has recently been identified as *Metaxytherium jordani* (=*Halianassa vanderhoofi*) by Domning (1972), who reports this as the highest known stratigraphic occurrence of this species. The type of *Dusignathus santacruzensis* Kellogg (1927) most probably was collected from cliff exposures of the Purisima above Cowell Beach north of Point Santa Cruz (Mitchell, 1962, p. 20-21). Mitchell (1962) has described other walrus remains from 340 m west of Point Santa Cruz and the remains of a specialized sea lion (Arctocephaline otariid cf. *Arctocephalus* sp.) from 150 m west of Point Santa Cruz. Stenodelphinine porpoise remains have also been collected from the Purisima Formation at Santa Cruz (L. G. Barnes, written commun., 1974).

The Purisima Formation is primarily of Pliocene age, although in the vicinity of Santa Cruz the lowermost beds are of late Miocene age. As previously discussed, a potassium-argon age on glauconite from the base of the formation at Santa Cruz dates the lower part as not younger than late Miocene or Hemphillian in the land-mammal chronology. Diatom floras from south of Scotts Valley and from Santa Cruz (table 7) are diagnostic of late Miocene and of early Pliocene age in the North Pacific diatom chronology (J. A. Barron, written commun., 1977). Stratigraphically higher beds of the Purisima that crop out in the sea cliffs near Capitola about 5 km east of Santa Cruz yield abundant mollusks diagnostic of late Pliocene age in the provincial chronology (Addicott, 1969, p. 80-81). For these upper Purisima beds near Capitola, Repenning and Tedord (1977, p. 67) suggest a latest Hemphillian or Blancan mammalian age (latest early Pliocene or late Pliocene).

The Purisima Formation of the Felton and Santa Cruz quadrangles may correlate with the lower Pliocene Tahana Member of Cummings, Touring, and Brabb (1962), which these workers in turn correlated with the Jacalitos Formation of former usage of the San Joaquin Valley. The Purisima Formation of this area also correlates with the Drakes Bay Formation of Galloway (1977) that crops out east of Point Reyes, 140 km to the northwest. The writer has collected a similar diatom flora from the type section of the Drakes Bay Formation that is diagnostic of earliest Pliocene age and correlates with subzone b of North Pacific diatom Zone X (J. A. Barron, written commun., 1977).

DEPOSITIONAL ENVIRONMENT OF UPPER MIOCENE TO PLIOCENE SEDIMENTARY SEQUENCE

The Santa Margarita Sandstone represents the transgressive basal part of the upper Miocene to Pliocene sequence. Large-scale current crossbedding indicates that the sand was laid down within the zone of surging wave and current action. R. Larry Phillips, who has studied the sedimentology of this unit at the

University of California at Santa Cruz, believes (oral commun., 1976) that along the Scotts Valley syncline the beds probably were deposited as a channel complex in a high-energy, shallow-marine environment. There, cross-bedding measurements indicate that current directions generally ranged from south through west.

Abundant sirenian remains suggest shallow-water conditions, as VanderHoof (1941, p. 1985) notes that "sea-cows are widely distributed littoral marine mammals." Desmostylians apparently favored a similar habitat, for "their bones and teeth are usually found in littoral marine deposits" (Mitchell and Repenning, 1963, p. 3). Some of the sirenian and cretacean skeletons are preserved almost intact, suggesting quick burial after death or protection in a sheltered environment such as a local embayment. The local abundance of gravel in the Mount Hermon area indicates proximity to the mouth of a river that also transported fragmentary terrestrial mammal remains to this shallow sea.

The concentration of *Astrodapsis* tests in the upper part of the Santa Margarita Sandstone also suggests shallow-marine conditions, *Echinarachnius,* the closest living relative of this irregular echinoid, favors an inner neritic habitat along the northwestern coast of North America. The gastropod *Nucella lima*, which occurs in the *Astrodapsis* beds, is most commonly found living today between the strand line and a depth of 27 m (Hall, 1960, table 6). The fragmentation of many of the *Astrodapsis* tests probably resulted from strong wave and current action that completely destroyed the more fragile tests of associated cidarids, leaving only their more resistant spines preserved.

The sparse molluscan fauna that occurs locally (USGS locs. M5052 and M5053) in the upper part of the Santa Margarita consists predominantly of two species, *Glycymeris grewingki* and *Solariella peramabilis*. The genus *Glycymeris* ranges from the intertidal zone to a depth of 365 m along the West Coast today (Keen, 1963, p. 105). *Solariella peramabilis* is distributed along the West Coast from San Diego to Alaska (Grant and Gale, 1931, p. 839), where its bathymetric range is from 5 to 247 m and averages 27 to 37 m. Although the modern genus *Patinopecten* may indicate modern depths (Durham and Addicott, 1965, p. A18), *P. healeyi* is commonly associated with relatively shallow-water mollusks and echinoids in other Pliocene deposits of California. *Calicantharus* is an extinct genus, but its closest living relatives are inner neritic (W. O. Addicott, oral commun., 1974). This limited molluscan evidence suggests an inner neritic depositional depth for the upper part of the Santa Margarita Sandstone.

TABLE 7.—*Selected diatoms and silicoflagellates from the Purisima Formation*

[Identities and age determinations by J. A. Barron]

USGS microfossil locality	Mf3677	Mf3678	Mf3676	Mf3675
North Pacific diatom zone and subzone	Xa	Xb	Xb	Xb
Diatoms:				
Denticula cf. *D. kamtschatica* Sabelina	-	×	-	-
Lithodesmium minusculum Grunow	×	×	×	-
Notzschia sp. (aff. *N. miocenica* Burckle?)	-	×	×	×
Nitzschia reinholdii Kanaya and Koizumi	×	-	×	×
Nitzschia sp	-	×	×	-
Rouxia californica Peragallo	×	-	-	-
Syncdra jouseana Sheshukova-Poretzkaya	×	-	-	-
Thalassiosira antiqua (Grunow) Cleve-Euler	×	×	×	×
Thalassiorsira convexa var. *aspinoisa* Schrader	-	-	-	×
Thalassiosira lineata Jouse	×	×	×	×
Thalassiosira miocenica Schrader	-	-	×	-
Thalassiosira nativa (of Schrader)	×	×	×	×
Silicoflagellates:				
Dictyocha aspera clinata Bukry	×	×	-	-
Distephanus boliviensis frugalis Bukry	-	-	×	-

The lateral variation in the thickness of the Santa Margarita Sandstone resulted from transgression over an irregular topographic surface; the formation thins markedly and locally pinches out onto ancestral highs. The continuity of the *Astrodapsis* beds from the Olympia area near the axis of the Scotts Valley syncline, where the sandstone is about 130 m thick, to the north limb of the syncline, where it is between 15 and 37 m thick, demonstrates that, in this area at least, the thinning occurs in the lower part of the formation. The coincidence of the thickest section of the Santa Margarita with the axis of the Scotts Valley syncline suggests that downwarp may have been active during deposition of the sands, while nearby granitic areas remained as highs, perhaps islands, in the transgressive sea. The thinning of the sandstone onto such a granitic high is clearly seen along Redwood Drive in the southeastern part of the Felton quadrangle (sec. 30 and 31, T. 10 S., R. 1 W.), where the formation thins northward from 24 m to 5 cm in a distance of slightly more than 1.6 km.

The pebble bed near the top of the Santa Margarita Sandstone probably represents a submarine lag gravel. This bed records the beginning of slower deposition with the development of a bored zone at its base together with a local concentration of marine mammal bones and glauconite. Progressively less coarse clastic detritus reached the area as basinal subsidence began.

The Santa Cruz Mudstone was deposited as the area submerged below the zone of effective wave and current action. During deposition of this formation, the supply of coarse clastic detritus was greatly reduced, pyroclastic debris began reaching the basin, and diatoms flourished. *Lucinoma* cf. *L. annulata* in the lower part of the mudstone is similar to the living species that today ranges from San Diego northward to Kodiak Island and lives in depths from 27 to 68 m off Puget Sound and from 15 to 247 m off San Pedro. This species thus suggests shelf conditions. The limited foraminiferal fauna from the upper part of the type section (USGS loc. Mf2187) is also diagnostic of shelf conditions, and *Buliminella elegantissima* suggests inner neritic depths.

Rhyolitic ejecta followed by andesitic debris reached the basin in significant quantities during deposition of the Purisima Formation to produce shallower conditions. The mollusks from the area suggest inner neritic depths, and those collected by the writer from the adjacent Laurel quadrangle include such shallow-water representatives as *Siliqua lucida* and *Solen* sp., which are diagnostic of depths of less than 45 m. The Purisima Formation is more widespread in the Santa Cruz Mountains than the Santa Cruz Mudstone and records a Pliocene continuation of a marine transgression that began with deposition of Santa Margarita Sandstone in late Miocene time.

STRATIGRAPHY SOUTHWEST OF SAN GREGORIO FAULT

Sedimentary strata exposed southwest of the San Gregorio fault (fig. 1) are of Mesozoic and Cenozoic age and differ markedly from the strata northeast of the fault. The Mesozoic section consists of more than 2,600 m of marine clastic sedimentary rocks, assigned to the Pigeon Point Formation of Late Cretaceous age. These Cretaceous strata crop out along the coast north of the mapped area and have been penetrated in the subsurface of the Año Nuevo quadrangle. Unconformable upon and locally faulted against the Pigeon Point Formation are more than 520 m of clastic sedimentary and volcanic rocks that range in age from Oligocene (Zemorrian) to Holocene. This Cenozoic section includes the Vaqueros(?), Monterey, and Purisima Formations, which are complexly folded and faulted in exposures north and east of Año Nuevo Point.

PIGEON POINT FORMATION

The Pigeon Point Formation was the name applied by Hall, Jones, and Brooks (1959) to Upper Cretaceous strata that are discontinuously exposed along the coast from Pescadero Beach in the southwest corner of the San Gregorio quadrangle southward to midway between Franklin and Año Nuevo Points in the Franklin Point quadrangle (fig. 1). These strata do not crop out in the area of the present report but were penetrated in the Richfield Steele core hole No. 1, about 1½ km north of Año Nuevo Point.

In the coastal exposures this formation consists of a heterogeneous sequence of interbedded sandstone, mudstone, and conglomerate, which displays a variety of sedimentary structures. Lowe (1972), who has studied the sedimentology of this sequence, informally subdivides it into two parts: a lower 1,800 m of thick units of interbedded sandstone and mudstone, and an upper 900 m of bedded conglomerate, of interbedded conglomerate, pebbly mudstone, and coarse-grained sandstone, and of crossbedded fine-grained sandstone. He interprets the lower part as having been deposited in part by turbidity currents on the continental slope or on the uppermost continental rise, and the upper part as representing submarine canyon or slope fill and shallow shelf sediments.

The sand grains are angular to subangular and composed predominantly of quartz (45 to 80 percent), feldspar (20 to 50 percent), and lithic fragments (10 to 30 percent), of which volcanic and granitic clasts are more abundant than metamorphic and sedimentary types (Tyler, 1972, p. 544). The conglomerate consists mainly of well-rounded pebbles and cobbles of silicic volcanic, plutonic (mostly quartz diorite), and metasedimentary rocks. This lithology suggests that the sediments were derived largely from the crystalline rocks of the Salinian block and from a silicic volcanic terrane. The porphyritic rhyolite that apparently underlies the Pigeon Point Formation about 16 km north of the mapped area and west of the San Gregorio fault may represent a part of this volcanic terrane. The relative abundance of lithologically similar volcanic clasts and the postulated northeast to southwest paleocurrent movement for the sediments of the Pigeon Point (Tyler, 1972, p. 553) are consistent with this source interpretation.

The base of the Pigeon Point Formation is not exposed. At Pescadero Beach, this formation is overlain with marked angular discordance by conglomerate and sandstone beds that were referred to the Vaqueros(?) Formation by Hall, Jones, and Brooks (1959) and were included in the Mindego Formation by Cummings, Touring, and Brabb (1962). To the south and inland, the Pigeon Point Formation appears to be overlain unconformably by the Purisima Formation of Pliocene age. In sea cliff exposures 2.2 km north of Año Nuevo Point, very thick sandstone beds of the Purisima rest with clear angular discordance upon the more steeply dipping beds of the Pigeon Point. This unconformity was probably penetrated in the Richfield Steele core hole, as Upper Cretaceous strata were intersected at a depth of 49 m beneath the Purisima Formation.

Estimates of the thickness of the Pigeon Point Formation range from more an 2,600 m (Hall and others, 1959, p. 2856) to 3,000±m (Branner and others, 1909), but the larger estimate included 230 m of the

Monterey Formation that crops out at Año Nuevo Point. The Richfield Steele core hole penetrated about 780 m of the Pigeon Point Formation but failed to reach its base.

Fossils listed by Branner, Newsom, and Arnold (1909) and by Hall, Jones, and Brooks (1959) are diagnostic of Campanian and probably Maestrichtian age. Foraminifers identified by R. L. Pierce (written commun., 1963) from the Richfield Steele core hole range in age from "probably Goudkoff's D-1 zone" (Maestrichtian) downward to "Goudkoff's F-2 and (or) G-1 zone" (Campanian, Santonian, and (or) Coniacian). The lower and upper age limits of the Pigeon Point Formation have not been determined.

VAQUEROS(?) FORMATION

Strata referred to the Vaqueros(?) Formation by Hall, Jones, and Brooks (1959, fig. 2) crop out north and east of Año Nuevo Point. About 1.6 km north of this point and 460 m north of the mapped area within the Franklin Point quadrangle, beds of this formation are exposed at low tide below the beach for a distance of 210 m. There, the Vaqueros(?) consists predominantly of olive-gray to dusky-yellowish-brown bioturbated siltstone; bedding is defined by a few thick, graded, very fine to fine-grained arkosic sandstone interbeds. In limited exposures near the upper part of the beach, the siltstone includes thin phosphatic lenses, which were not observed in the fresh outcrops at low tide, and is locally cut by numerous thin sandstone dikes.

Approximately 85 m of section is discontinuously exposed and stratigraphically isolated below the beach, where the beds are folded into a syncline, the northern limb of which becomes vertical and is locally overturned. Locally these siltstone beds contain abundant calcareous foraminifers characteristic of lower bathyal depths (Brabb and others, 1977, table 8). *Siphogenerina nodifera* is diagnostic of Zemorrian (Oligocene) age, and the joint occurrence there of *S. nodifera* with *S. mayi* in the upper part of this section is diagnostic of late Zemorrian age. The uppermost part of this section may extend into Saucesian (early Miocene) age, for the stratigraphically highest faunal assemblage is of late Zemorrian or early Saucesian age.

About 370 m east of Año Nuevo Point, the Vaqueros(?) Formation is exposed along the beach and sea cliffs near the axis of an anticline, the central part of which is occupied by volcanic breccia. This formation consists there of laminated dusky-yellowish-brown phosphatic mudstone interbedded with medium- to fine-grained glauconite-bearing arkosic sandstone. East of a volcanic headland, where about 12.5 m of the Vaqueros(?) is exposed in the sea cliffs, sandstone predominates in the lower part of the section, whereas contorted and sheared mudstone makes up most of the upper part (fig. 13). West of the volcanic outcrops, where about 13 m of this formation is discontinuously exposed below the beach, the lower part of the Vaqueros(?) includes dark-yellowish-brown burrowed siltstone beds that resemble those exposed to the north in the Franklin Point quadrangle.

The volcanic breccia is highly altered and cut by siliceous and dolomitic veins. One rock is fine grained and microporphyritic, with microphenocrysts of plagioclase (labradorite) as much as 1.4 mm long and of pyroxene ghosts that range from 0.80 mm to 1.2 mm and are completely altered to clay, probably montmorillonite, and calcite. The groundmass consists largely of a felted mass of plagioclase microlites, most of which appear skeletal, and of clay, which is probably an alteration product. Quartz occurs locally between feldspars and in interstices. Calcite is common and is probably a replacement and alteration product; locally it fills amygdules. The texture, feldspar composition, and tentative identification of pyroxene suggest that this rock is probably a tholeiitic basalt. Other volcanic blocks are more felsic and are probably andesite.

On the east flank of the anticline, sandstone beds of the Vaqueros(?) Formation locally appear to rest upon the volcanic breccia. Two large blocks of mudstone are included in the breccia just west of this contact.

The mudstone beds of the Vaqueros(?) Formation are faulted against the siliceous beds of the Monterey Formation on the east flank of the anticline (fig. 13), whereas to the west the Vaqueros(?)-Monterey contact appears to be gradational.

Mudstone beds within this Vaqueros(?) section yield deep-water calcareous foraminifers diagnostic of Saucesian and Relizian ages (Brabb and others, 1977, table 8). The stratigraphically lowest faunas are from the discontinuous intertidal exposures just west of the volcanic rocks and include *Bulimina alligata, Cibicies dohertyi, C. floridanus, Dentalina quadrulata, Siphogenerina multicostata, S. transversa,* and *Uvigerinella obesa impolita*, which together are diagnostic of Saucesian, probably early Saucesian age. The sheared mudstone beds from the upper part of the section east of the volcanic rocks yield foraminifers diagnostic of Relizian age. *Siphogenerina* cf. *S. hughesi* from the lower part of this sheared section is suggestive of early Relizian age. Higher in the sheared section taxa characteristic of the Pseudosaucesian facies of Beck (1952) are associated with middle Miocene (probably Relizian) species. The foraminiferal dating thus suggests that the Vaqueros(?) Formation that crops out north of Año Nuevo Point is older than most, if not all, of the section east of the point.

The base of the Vaqueros(?) Formation is not exposed in the vicinity of Año Nuevo Point. It probably rests unconformably on the Pigeon Point Formation in the subsurface, for the conglomerate and sandstone beds at Pescadero Beach in the San Gregorio quadrangle that were mapped as Vaqueros(?) Formation by Hall, Jones, and Brooks (1959) and yield *Macrochlamis magnolia*, which is diagnostic of late Zemorrian or early Saucesian age (W. O. Addicott, written commun., 1977) lie with marked angular discordance on steeply dipping beds of the Pigeon Point. At Pescadero Beach, these beds of the Vaqueros(?) Formation appear to be overlain by volcanic breccia that is more highly altered but petrologically similar to that east of Año Nuevo Point.

MONTEREY FORMATION

The Monterey Formation is well exposed in the sea cliffs north and east of Año Nuevo Point and on Año Nuevo Island. This formation consists predominantly of thin-bedded and thinly laminated, olive-gray to dusky-yellowish-brown, siliceous mudstone. The siliceous beds are brittle and fractured and locally alternate with thin beds of less siliceous mudstone and slightly glauconitic siltstone. In the eastern sea cliff exposures, a color banding is produced by a few dolomitic mudstone interbeds that weather pale yellowish brown.

More than 215 m of the Monterey Formation is gently folded between Año Nuevo Island and the contact with the underlying Vaqueros(?) Formation to the east. Farther east of the east flank of the anticline, about 67 m of this formation crops out between the Año Nuevo fault and the contact with the overlying Purisima Formation. The contact with the subjacent Vaqueros(?) Formation appears to be gradational, whereas the contact with the superjacent Purisima Formation is clearly unconformable. This upper contact is well exposed in the sea cliffs about 640 m east of Año Nuevo Point, where a 1.2-1.5-m-thick basal conglomerate bed of the Purisima composed largely of siliceous Monterey cobbles rests with slight angular discordance on the siliceous beds of the Monterey (fig. 12).

The Monterey Formation contains a few cetacean bones, fish scales, and a diverse microfauna. Diatoms are locally common, siliceous sponge spicules and radiolaria are less abundant, and calcareous foraminifers occur locally, where they are typically poorly preserved and rarely silicified. The foraminifers are characteristic of the upper bathyal biofacies (300±185m) of Bandy and Arnal (1969) and are diagnostic of middle Miocene age (Brabb and others, 1977, table 8). The joint occurrence of *Bolivina advena* var. *striatella, Valvulinera* cf. *V. californica* var. *obesa*, and of *V.* cf. *V. depressa* is diagnostic of late Relizian to early Luisian age. *Florilus incisus* suggests that at least part of this section is restricted to the upper Relizian.

PURISIMA FORMATION

The Purisima Formation that crops out east of Año Nuevo Point and west of the San Gregorio fault is informally subdvided into a mudstone member and a sandstone member.

The mudstone member is exposed above a beach east of its unconformable contact with the underlying Monterey Formation (fig. 12) and west of the Green Oaks fault that brings it into contact with the sandstone member. The lowermost part of the mudstone section is medium to thick bedded, but to the east it is nodular and highly fractured and bedding is not apparent. The mudstone is light olive gray where fresh but weathers with a light-brown limonite coating. It contains thin laminae of sand and is slightly glauconitic. The mudstone contains abundant diatoms, a few fish fragments, and a few small pelecypods.

A sample collected from near the base of the sea cliff that is approximately 15 m stratigraphically above the base of this mudstone section provided the following diatoms identified by J. A. Barron (written commun., 1977):

Denticula kamtschatica Sabelina
Nitzschia fossilis (Frenguelli) Kanaya
Nitzschia cf. *N. reinholdii* Kanaya and Koizumi
Thalassiosira antiqua (Grunow) Cleve-Euler
Thalassiosira oestrupii (Ostenfeld) Proshkina-Lavrenko

Barron believes that this flora correlates with North Pacific diatom Zone IX of early Pliocene age, which, however, is younger than the traditional early Pliocene of the West Coast megainvertebrate chronology. This correlation indicates that these mudstone beds of the Purisima are younger than the lower tuffaceous and diatomaceous siltstone beds of the Purisima that crop out south of Scotts Valley and in Santa Cruz (table 7).

About 76 m of this mudstone is exposed above the unconformity with the underlying Monterey Formation. It is unconformably overlain by Pleistocene terrace deposits. Because the mudstone and sand-

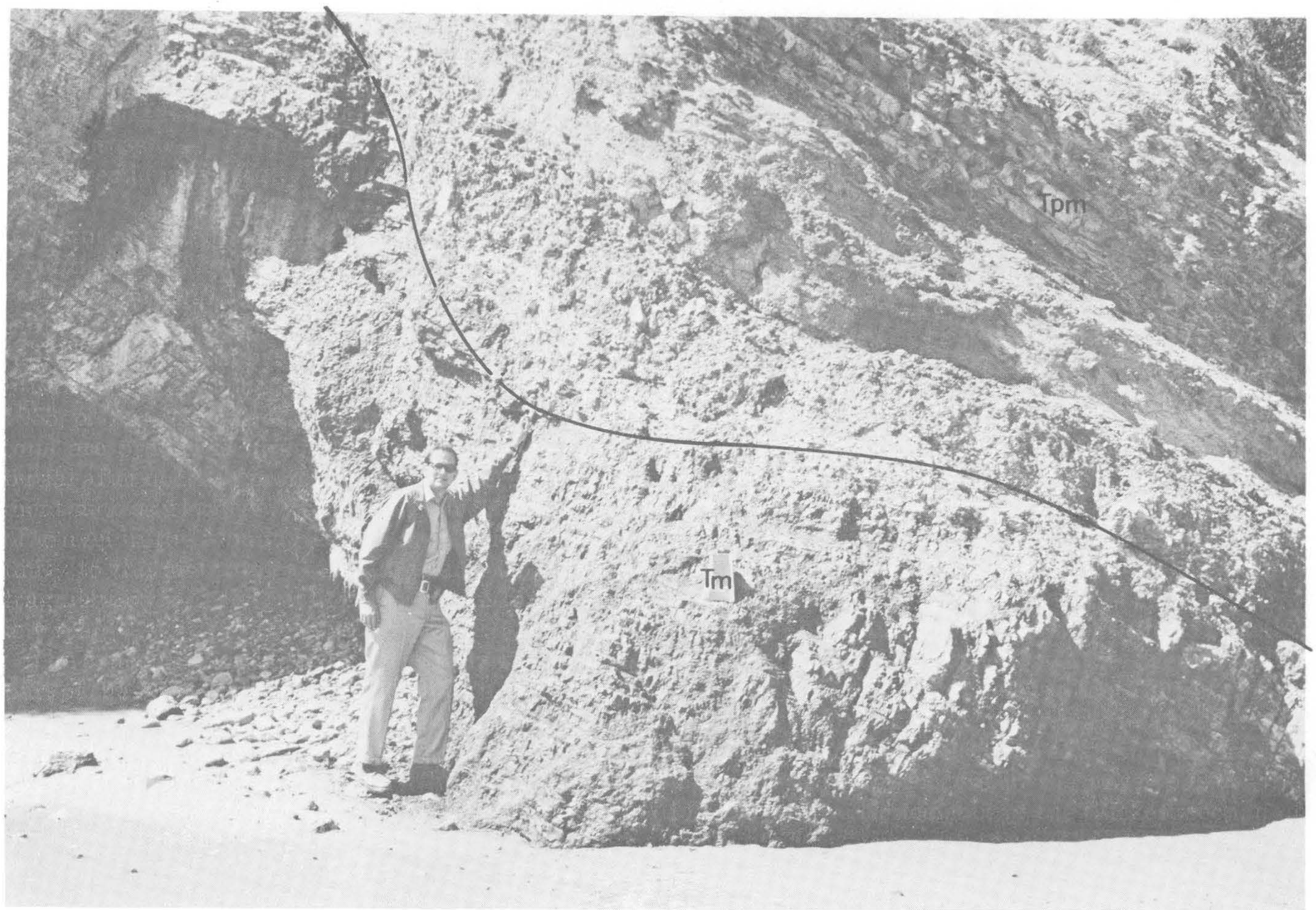

FIGURE 12.—Thick basal conglomerate bed of the mudstone member of the Purisima Formation (Tpm) resting unconformably upon siliceous beds of the Monterey Formation (Tm) about 640 m east of Año Nuevo Point.

stone members are in fault contact, their stratigraphic relationship is uncertain.

The sandstone member consists of well-sorted fine-grained lithic sandstone that is typically thick to very thick bedded and locally crossbedded. The sandstone is olive gray where fresh but weathers pale yellowish brown to grayish orange. Small, irregular carbonate concretions are scattered in the sandstone and locally form thin discontinuous interbeds. Other carbonate concretions are elongate as much as 1 to 1.5 m parallel to the bedding.

As much as 110 m of the sandstone member is discontinuously exposed between the Green Oaks fault to the west and the San Gregorio fault to the east, but this sea cliff section is folded and locally faulted. Neither the base nor the top of this member is exposed. It probably rests unconformably upon the Pigeon Point Formation because lithologically similar beds of the Purisima are unconformable upon the Pigeon Point above 2 km to the north. It is unconformably overlain by Pleistocene terrace deposits.

A few cetacean bones and vertebrae are enclosed within the carbonate concretions of this member. Mollusks are more common and locally abundant in the sea cliff exposures southeast of Año Nuevo Creek, where they are concentrated in lenses as much as 10 cm thick. Mollusks and irregular echinoids are also abundant in sandstone beds of the Purisima along Año Nuevo Creek about 60 m south of the northern boundary of the quadrangle (USGS loc. M5154).

The sandstone member of the Purisima is separated into two faunally distinct sections by an unnamed fault that cuts the sea cliff about 600 m west of the mouth of Año Nuevo Creek (pl. 1). The fauna from the section west of the fault (Arnold's loc. 139, 1908a) was believed by Branner, Newsom, and Arnold (1909, p. 6) to be similar to that of the type Purisima to the north.

The eastern sandstone section that is truncated by the San Gregorio fault to the east is more fossiliferous. Because Branner, Newsom, and Arnold (1909) believed that its fauna (Arnold's loc. 140, 1908a) was younger and similar to that of the lower part of the type Merced Formation, they incorrectly mapped these eastern beds as "Merced."

From a locality (USGS loc. M5154) about 1 km north of the mouth of Año Nuevo Creek that is probably on strike with the eastern sandstone section, the writer collected *Dendraster gibbsi* (Rémond). This echinoid species is reported by Touring (1959, p. 185) to be common in one bed in the upper part of the upper Pliocene San Gregorio Member of the Purisima Formation of Cummings, Touring, and Brabb (1962). This species has not been reported from the type Merced Formation but occurs in the Etchegoin Formation (W. O. Addicott, written commun., 1969).

These correlations suggest that the sandstone member is, at least in part, of late Pliocene age in the provincial megainvertebrate chronology and is correlative with both the Purisima and Merced Formations in their type areas.

QUATERNARY DEPOSITS

MARINE TERRACE DEPOSITS

Five prominent emergent marine terraces indent the seaward slope of Ben Lomond Mountain between Santa Cruz and Año Nuevo Point. Each terrace consists of remnants of a wave-cut platform and sea cliff, which are cut into the crystalline and Tertiary sedimentary rocks of the mountain. The elevations of the inner edges of the platform surfaces from lowest to highest are: 27 to 38 m, 80 to 111 m, 116 to 135 m, 167 to 197 m, and approximately 255 to 260 m (modified from Bradley, 1965, fig. 13–1).

These surfaces are overlain by a thin, discontinuous cover of marine and nonmarine sediments (pls. 1–2). The terrace deposits consist typically of massive to locally crossbedded, moderate-yellowish-brown, well sorted, fine to medium sand. Locally at the base of the sand is a thin pebble and cobble gravel bed that contains rounded clasts of mudstone, silicic volcanic rocks, granitic rocks, and black and red chert. Adjacent to the emergent sea cliffs, these deposits commonly include semiconsolidated, poorly sorted, sandy granule conglomerate composed mainly of mudstone clasts.

These deposits are best preserved on the lowest emergent platform, where they are generally from 1.5 to 6 m thick and reach a maximum thickness of about 24 m along the coast above Greyhound Rock in the Año Nuevo quadrangle. The upper terraces have been deeply dissected and their surficial deposits largely removed by subsequent erosion. From 3 to 4 m of sand is preserved only locally on remnants of the highest emergent marine terrace.

Where the platform surfaces bevel the Santa Cruz Mudstone or the Purisima Formation, the bedrock surface is commonly pitted by molluscan borings. Fossil shells are preserved, however, only in the deposits on the lowest emergent terrace of the coastal area. Mollusks are locally abundant at the base of these deposits near Point Santa Cruz and north and east of Año Nuevo Point, where Arnold (1908a, p. 355-356) records 32 gastropods and pelecypods. Addicott (1966) lists 101 larger invertebrate taxa, mainly mollusks, 27 taxa of foraminifers, and 18 species of ostracodes from these two areas and assigns a late Pleistocene age to these fossil assemblages.

Mollusks from this lowest terrace yield uranium-series dates of 68,000 to 100,000 years (Bradley and Addicott, 1968) and amino-acid dates of 130,000± 50,000 years (Lajoie and others, 1975). Presumably all of the terraces are of Pleistocene age. Lajoie, Weber, and Tinsley (1972, p. 107) postulate that the highest terrace "would be between 700,000 and 800,000 years old," whereas Bradley and Griggs (1976, p. 444) estimate the age of this oldest platform to be 1,000,000 to 1,200,000 years.

Bradley (1965) believes that these terraces were cut by wave erosion when sea level was rising and that the marine sediments were laid down as beach deposits when sea level was falling. These marine sediments were then locally covered by a relatively thin veneer of fluvial and colluvial sediments. This sequence of erosion and deposition must have been repeated at least five times during uplift of the Ben Lomond Mountain area.

The lowest and thus youngest emergent terrace was probably cut by the high stand of the sea during the Sangamon Interglaciation of the mid-continent. Addicott's (1966) analysis of the mulluscan assemblage from this terrace suggests that the late Pleistocene marine climate in the area was cool temperate compared to the modern temperate climate.

RIVER TERRACE DEPOSITS

Along the San Lorenzo River, terraces are locally mantled by weakly consolidated sandy pebble to cobble gravel and pebbly fine to medium sand. The topographically highest terrace deposit on the east slope of Ben Lomond Mountain is exposed along the Felton-Empire Road at an approximate elevation of 275 to 290 m. These deposits are more numerous along the river to the south where they occur locally at elevations of 120 to 145 m, 92 to 100 m, 62 to 80 m, and possibly from 43 to 49 m. These gravels and sands were laid down by the river when the region was lower during Pleistocene time.

LANDSLIDE MATERIAL

Landslide conditions are widespread in the area. Although all of the mapped rock units have been affected locally, landslides are most commonly developed in the northern and western parts of the area where steeper slopes are underlain by one of the mudstone units. The highly fractured rocks of the Monterey Formation and of the Santa Cruz Mudstone have been most susceptible to landsliding, and extensive creep of these strata has resulted in unreliable structural attitudes on slopes and along narrow ridges.

Only the larger definite landslide deposits that could be readily mapped in the field are shown on plates 1 and 2. A preliminary landslide map of Santa Cruz County based on photointerpretation by Cooper-Clark and Associates (1975) covers most of the area of the present report and should be consulted for land-use planning.

ALLUVIUM

Alluvial deposits of Holocene age are discontinuously distributed along the valley bottoms of the larger streams and consist of unconsolidated moderately sorted silt, sand, and gravel derived from the drainage areas of the respective streams. This alluvium is a meter to several meters thick but is locally thicker near the coast. A well drilled along the San Lorenzo River near the northern limit of the city of Santa Cruz is reported to have penetrated 29 m of gravel (Alexander, 1953, p. 20).

Some of the thicker coastal deposits may be as old as late Pleistocene, for detrital wood fragments from 15 m below the surface of alluvial fill in the valley of Año Nuevo Creek yield a radiocarbon date of 10,200± 300 years B.P. (Wright, 1971).

Soil and colluvium have not been mapped but cover much of the area and hinder precise mapping of the bedrock geology.

STRUCTURE

The Santa Cruz Mountains are traversed by two major active faults, the San Andreas fault to the northeast and the San Gregorio fault to the southwest (fig. 1). The San Andreas fault, forming the northeastern boundary of the Salinian block, passes 5 km northeast of the mapped area. To the west within the area, the San Gregorio fault has juxtaposed two major tectonic blocks with markedly different stratigraphies.

The tectonic block between the San Gregorio and San Andreas faults is broken into two smaller blocks with interdependent histories by the northwest-trending Zayante fault. South of the Zayante fault, crystalline rocks of the Salinian block are extensively exposed or occur at shallow depths below a thin cover of Tertiary strata that are folded into broad open structures. North of this fault, the basement is not exposed and is deeply buried under a very thick section of Tertiary strata that are more strongly deformed and locally overturned.

SAN GREGORIO FAULT

The onshore trace of the San Gregorio fault was originally mapped by Branner, Newsom, and Arnold (1909) as a single fracture extending from the coast about 3 km east of Año Nuevo Point northwestward for 27 km to coastal exposures near San Gregorio (fig. 1).

Recent onshore and offshore mapping has demonstrated that the fault as traced by these early workers is part of a wider zone of deformation that includes numerous shorter subparallel faults (Brown, 1972). East of Año Nuevo Point, this zone is about 3 km wide and includes at least five northwest-trending faults from the Año Nuevo fault on the west to minor faults at Greyhound Rock to the east (pl. 1).

The Año Nuevo fault is well exposed in the sea cliff abut 430 m east of the point, where it strikes N. 40° W. and 38° NE. (fig. 13). The lowest emergent marine terrace is displaced about 5.2 m by this fault, and siliceous beds of the Monterey Formation are thrust over unconsolidated marine terrace sand and gravel. In the sea cliff west of this fault, phosphatic mudstone beds of the Vaqueros(?) Formation are highly sheared for a distance of about 17 m, but this shearing does not appear to have affected the overlying terrace deposits.

About 500 m east of the Año Nuevo fault, the Green Oaks fault is poorly exposed above the beach, where it has juxtaposed nodular beds of the mudstone member of the Purisima Formation against beds of the sandstone member. Dips in the sandstone beds steepen westward toward the fault, suggesting that the east side is relatively downthrown. This fault probably continues northwestward 2.2 km to sea cliff exposures north of Año Nuevo Point, where a gouge zone separates slightly overturned siltstone of the Vaqueros(?) to the south from steeply dipping beds of the Pigeon Point Formation to the north.

About 700 m farther to the east, a nearly vertical fault has dropped Quaternary alluvium down against sandstone beds of the Purisima to the west and separates two faunally distinct Purisima sections. Charcoal from a deformed bed of this alluvium has yielded a carbon-14 age of 9,510±140 years B.P. (Weber and Lajoie, 974). This fault strikes N. 30° W. across the lowest terrace, where it has produced an alinement of topographic scarps.

The major change in stratigraphy occurs across the main strand of the San Gregorio fault (fig. 14). This fault intersects the coasts east of Año Nuevo Creek at a notch in the sea cliff that trends N. 15° W. There, fossiliferous sandstone beds of the Purisima are faulted against the Santa Cruz Mudstone. In sea cliff exposures west of the fault, the Purisima is cut by numerous minor high-angle faults, whereas for 150 m southeast of the fault the Santa Cruz is highly fractured. The lowest emergent terrace appears to be vertically offset about 5 m by this fault (W. C. Bradley, written commun., 1970).

In the sea cliffs east of Greyhound Rock, the Santa Cruz Mudstone and terrace deposits are vertically displaced a total of 10.5 m by three closely spaced northwest-trending faults (W. C. Bradley, written commun., 1970). The easternmost fault appears to offset the upper surface of the Pleistocene terrace deposits (Hall and others, 1974). These faults at Greyhound Rock may mark the eastern boundary of the San Gregorio fault zone.

Seismic profiling south of the Año Nuevo coast has delineated two northwest-trending parallel faults that bound a deformed zone (Greene and others, 1973). The eastern offshore fault is alined with the main strand of the San Gregorio fault, whereas the western fault trends toward the Green Oaks fault. Greene, Lee, McCulloch, and Brabb (1973) have traced the San Gregorio fault zone southward across Monterey Bay and postulate that it continues onshore near Point Sur in the Santa Lucia Range as the Serra Hill and Palo Colorado faults. These workers also suggest that this fault zone trends northward from San Gregorio to join the onland Seal Cove fault in San Mateo County and then continues offshore to

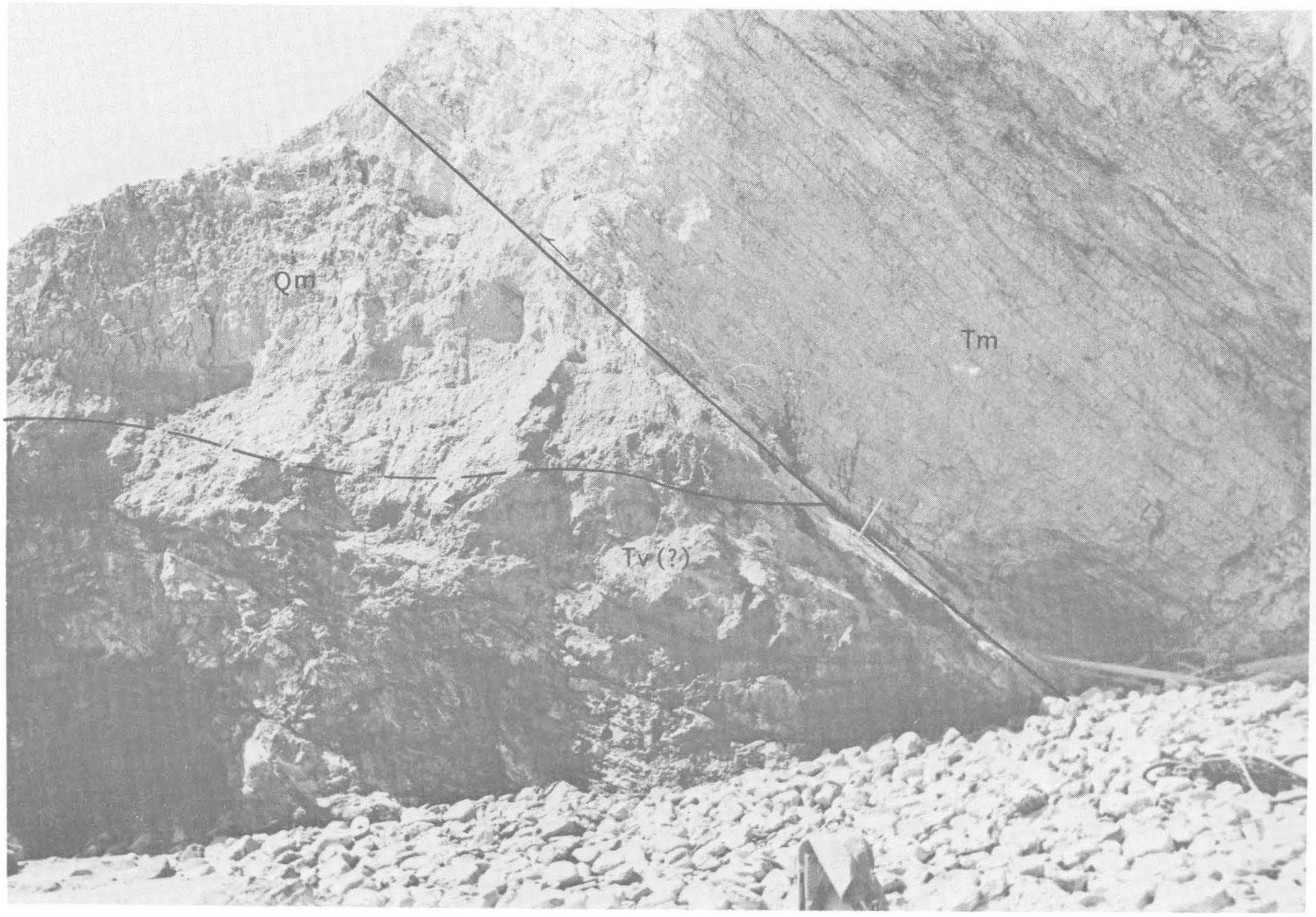

FIGURE 13.—Año Nuevo fault has thrust siliceous beds of the Monterey Formation (Tm) over sheared mudstone beds of the Vaqueros(?) Formation (Tv?) and over unconsolidated marine terrace deposits (Qm) about 430 m east of Año Nuevo Point.

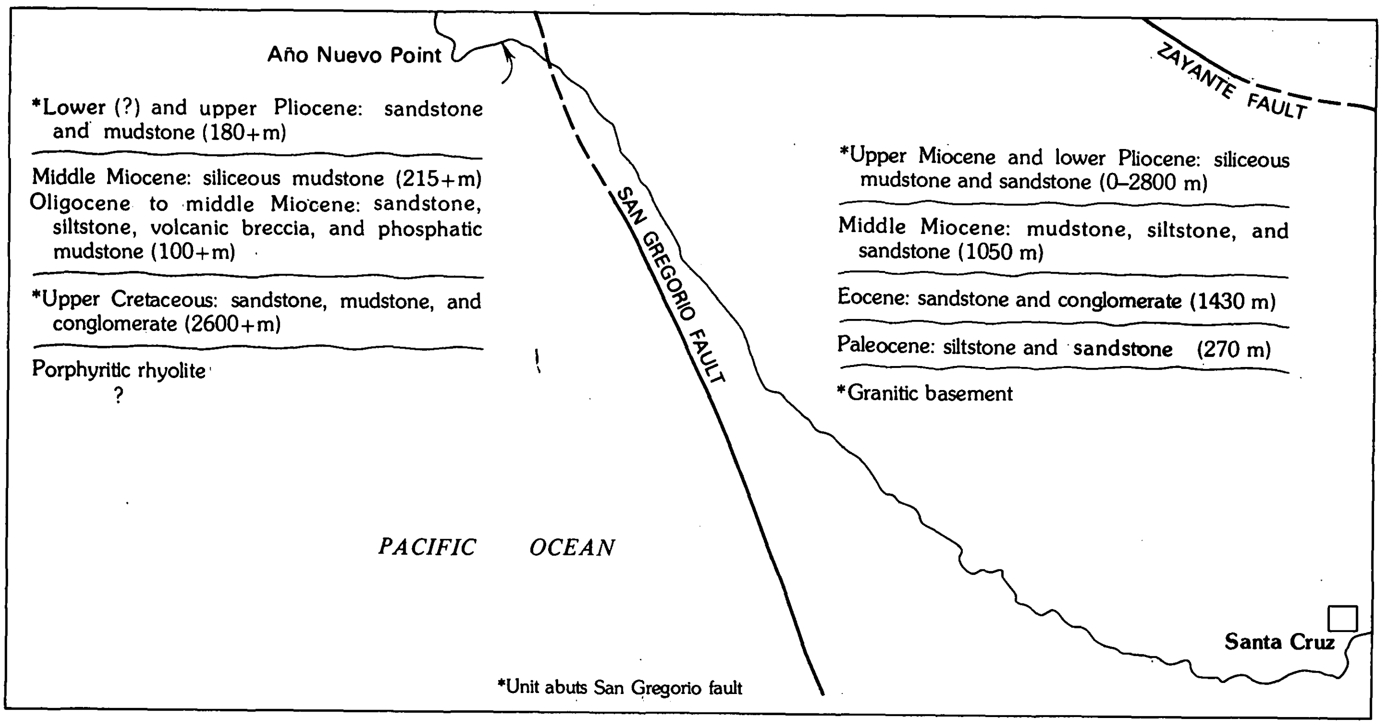

FIGURE 14.—Contrasting stratigraphic sections across the San Gregorio fault in the central Santa Cruz Mountains. Offshore trace of San Gregorio fault from Greene, Lee, McCulloch, and Brabb (1973).

join the San Andreas fault north of the Golden Gate near Bolinas in Marin County (see Jennings, 1975, for a recent compilation of these faults). If these postulated extensions of the San Gregorio fault zone are correct, this zone would be a major branch of the San Andreas fault with an overall length of at least 200 km.

The San Gregorio is an active fault zone. The topographic expression of probable fault breaks and anomalous stream patterns along this fault zone in San Mateo County are cited by Brown (1972) as evidence for active faulting. The deformation of Holocene beds east of Año Nuevo Point confirms recent movement. Recent earthquake epicenters cluster near this zone in Monterey Bay and are scattered along this zone northward into the area of the present report and beyond (Greene and others, 1973, pl. 2). A magnitude 4.6 earthquake of May 22, 1963, appears to have been associated with the onshore San Gregorio fault zone in the Santa Cruz Mountains (Bolt and others, 1968, p. 1738). Fault-plane solutions for this and recent Monterey Bay earthquakes along this zone are interpreted as showing nearly vertical faults with right-lateral strike-slip motion (Bolt and others, 1968; Greene and others, 1973). The more west-trending, oblique orientation of minor fold axes within the Monterey Formation near Año Nuevo Point is also consistent with right-lateral movement.

The marked contrast in the stratigraphic sections across the San Gregorio fault in the Santa Cruz Mountains (fig. 14) suggests past large-scale lateral displacement. Upper Cretaceous strata are notably absent in the block to the east of the fault, and the thick Santa Cruz Mudstone section that abuts the fault to the east is represented by an unconformity in the block to the west. Although Monterey strata of middle Miocene age are mapped in both blocks, these rocks differ in lithology fauna and bathymetry.

Hill and Dibblee (1953, pl. 1) included the San Gregorio fault with faults that have or possibly might have a substantial strike-slip component of displacement. Matching pairs of offset geologic features, Graham and Dickinson (1978) have recently postulated about 115 km of post-early Miocene right slip along this fault zone. But the past history of this fault is still to be worked out.

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 east boundary of the Santa Cruz 30-minute quadrangle. Because of the dense vegetation and deep weathering in the area, this fault is poorly exposed, and its trace is mapped largely from structural and stratigraphic discordances of adjacent beds.

Where the Zayante fault is exposed along Bear Creek Road about 0.7 km north of the mapped area, the Butano Sandstone and Vaqueros Sandstone are separated by a 6-m-wide, nearly vertical shear zone. Although the throughgoing strand of this fault is confined to a narrow zone, branching lineaments in the vicinity of Newell Creek occupy a zone as wide as 2 km. Only locally is the Zayante fault expressed topographically. East of Zayante Canyon, Mountain Charlie Gulch flows southward until it reaches the fault and then turns abruptly westward to follow the fault to Zayante Creek. The relatively straight course of this fault across the canyons and ridges of the area indicates that the fault plane is nearly vertical.

Along Mountain Charlie Gulch, the Zayante Sandstone and the lower sandstone member of the Butano are juxtaposed by the fault, indicating about 1.2 km of dip separation with the north side relatively downthrown. Model studies of the gravity field across the area suggest that the crystalline basement is displaced approximately 2 km by this fault (Clark and Rietman, 1973, p. 12–14).

The Zayante fault can be mapped southeastward from the area for about 17 km to the vicinity of Corralitos, where it becomes covered by Quaternary sediments. A gravity investigation (Clark and Rietman, 1973) demonstrates the continuity of this fault beneath this cover into the Vergeles fault at the northern margin of the Gabilan Range, about 44 km southeast of the area. The Vergeles fault in turn continues southeastward into the San Andreas fault south of San Juan Bautista.

The Zayante fault has been mapped northwest from the town of Boulder Creek to its juncture with the Ben Lomond fault (fig. 1). Because the suggested amount and sense of displacement along a fault on the north flank of Ben Lomond Mountain are of the same order of magnitude as that along the Zayante fault to the east, Clark and Rietman (1973) believe that the northwestern part of the Ben Lomond fault of earlier mappers is the westward continuation of the Zayante fault. The Zayante-Vergeles fault, including this western segment, is 82 km long.

The Oligocene (Zemorrian) shallowing that is recorded by the upper part of the Rices Mudstone Member of the San Lorenzo Formation along Newell and Love Creeks probably denotes initial movement along the Zayante fault. Continued uplift along this fault resulted in emergence of the crystalline basement to the south, in deposition of the terrestrial Zayante Sandstone along and north of the fault, and in restriction of marine conditions to an embayment to the north. Allen (1946) reports a remarkably similar history along the Vergeles segment of the fault in the San Juan Bautista quadrangle to the southeast.

The Zayante fault ceased to be an important structural feature by early Miocene (Saucesian) time. The fine clastic deposition of the Lambert Shale north of the fault suggests that the uplifted block to the south had been reduced to a lowland, which was subsequently transgressed by the middle Miocene seas with deposition of the Monterey Formation. Two small patches of Monterey Formation that are preserved as tectonic slivers along the fault provide evidence for post-Miocene displacement. This movement may have occurred in post-early Pliocene time, for the Purisima Formation is offset along this fracture to the east of the area.

Some segments of the Zayante fault may be active. Recent movement east of Corralitos is suggested by a scarp of probable Holocene age and a deformed late Pleistocene surface alined with this fault (Hall and others, 1974). These workers also postulate that the Zayante fault east of Corralitos may be connected to the San Andreas by a diffuse system of possible fault breaks, which they define as the Corralitos fault complex. They suggest late Pleistocene and possible Holocene activity along this fault complex.

Griggs (1973) plots numerous earthquake epicenters in the central Santa Cruz Mountains between the western segment of the Zayante fault and the Butano fault to the north. It is not known, however, which fault or faults may have produced this activity.

MINOR FAULTS

The Ben Lomond and Bean Creek faults are relatively minor dislocations that displace middle Miocene (Luisian) strata. As originally defined, the Ben Lomond fault was an arcuate fracture that extended west of Boulder Creek (Branner and others, 1909). The name "Ben Lomond" is now restricted to the fault that trends southeastward from near Boulder Creek, through the community of Ben Lomond, to the vicinity of Felton.

Near Boulder Creek, this fault has brought the Monterey Formation into contact with the granitic rocks of Ben Lomond Mountain and to the south has locally juxtaposed the Monterey and Lompico Sandstone, suggesting a dip separation of less than 200 m. Model studies of the gravity field in the Felton area suggest that the crystalline basement is vertically offset less than 350 m by the Ben Lomond fault (Clark and Rietman, 1973, pl. 1). The youngest strata clearly displaced by this fault are of the Monterey Formation of middle Miocene (Luisian) age. The Quaternary alluvium along the San Lorenzo River does not appear to be affected.

Movement on the Bean Creek fault has deformed the Monterey strata near Mount Hermon. Chevron drag folds in strata on the south side of this fracture indicate that this side is relatively upthrown. As the beds on both sides of the fault yield similar foraminifers diagnostic of Luisian age, dip separation appears to be minor. East of the mapped trace of the Bean Creek fault, the Santa Margarita Sandstone is not displaced.

Numerous small faults occur in isolated exposures of the area, but only those that could be traced beyond a single exposure or that are inferred to juxtapose different rock units have been mapped in the present study.

FOLDS

South of the Zayante fault, the Tertiary strata and crystalline basement are deformed into three broad, northwest-trending structures—the Scotts Valley syncline, the Ben Lomond high, and the Davenport syncline (fig. 1). These structures record several periods of deformation.

The Scotts Valley syncline extends from Boulder Creek eastward through Scotts Valley. This fold appears to die out farther east in the Laurel quadrangle, where beds of the Purisima Formation rest on shallow crystalline basement. The Monterey strata are more strongly folded along this structure than the overlying beds of the upper Miocene to Pliocene sequence, documenting late middle or early late Miocene deformation. Downwarp of the Scotts Valley syncline probably continued during deposition of the Santa Margarita Sandstone, for the thickest sandstone section coincides with the axis of this structure. Gently folding of the Purisima Formation along this syncline records post-early Pliocene deformation.

The crystalline rocks of Ben Lomond Mountain are exposed along a northwest-trending anticline that is herein referred to as the Ben Lomond structural high. Beds of the middle Miocene and upper Miocene to Pliocene sequences rest nonconformably upon these rocks and generally dip to the northeast and southwest away from the core of the mountain.

The Ben Lomond structural high appears to have been delineated by middle Miocene time. On the east flank, the middle Miocene sequence coarsens toward the west, and on both flanks of the mountain, the Monterey Formation contains thick sandstone interbeds. These facies changes and marked differences in the middle Miocene faunas on opposite sides of the mountain suggest that the Ben Lomond high had formed by middle Miocene (Relizian) time.

This high was probably later uplifted along the Ben Lomond fault before deposition of the Santa Margarita Sandstone, which subsequently transgressed this crystalline complex. The unconformable relationship of the Purisima Formation to the underlying Santa Cruz Mudstone in the sea cliffs west of Point Santa Cruz records positive movement along the Ben Lomond axis in latest Miocene time.

The emergent wave-cut terraces on the western slope of Ben Lomond Mountain have been uplifted and tilted in a seaward direction, documenting that uplift has continued into Quaternary time (Bradley and Griggs, 1976).

West of Ben Lomond Mountain, the Santa Cruz Mudstone is broadly folded along the Davenport syncline, which trends westward into the San Gregorio fault north of the mapped area (fig. 1). As the emergent terraces appear to be undeformed by this structure, folding did not continue into the Quaternary.

The opening folding south of the Zayante fault contrasts with the tight folding to the north. Along the north limb of the San Lorenzo syncline, which can be traced 16 km to the northwest (fig. 1), the Vaqueros Sandstone and Lambert Shale are locally overturned. This overturned section is poorly exposed in the northeastern part of the area but well exposed to the east along Mountain Charlie Gulch.

The Glenwood syncline, along which the Purisima Formation is folded, can be traced for 20 km to the east to the vicinity of Corralitos. After the Eocene to lower Miocene sequence was deformed into the San Lorenzo syncline during middle or late Miocene time, beds of the upper Miocene to Pliocene sequence unconformably overlapped this older structure, and they were subsequently synclinally folded in post-early Pliocene time with the axis of folding to the south of the earlier axis.

The two periods of deformation recorded by the synclinal downwarps north of the Zayante fault probably coincide with the late middle or early late Miocene and post-early Plicoene deformations of the Scotts Valley syncline. These northern synclines are separated from the Scotts Valley syncline by an unnamed anticline, along the axis of which the Zayante Sandstone is exposed.

The contrast in the intensity of folding north and south of the Zayante fault probably results not from a difference in the type of basement underlying the two areas but rather from a difference in the thickness of the overlying sedimentary sections. To the south where the sedimentary section is much thinner, the rigidity of the relatively shallow crystalline basement has resulted in less intense deformation of the overlying strata.

FOSSIL LOCALITIES

[M are megafossil localities; Mf microfossil locality; LSJU are Stanford University localities. Localities are shown on plates 1 and 2]

USGS Cenozoic localities (Menlo Park register)

M1035 Sand pit on east side of intersection of Glen Canyon Road and Redwood Drive, SW¼ sec. 31, T. 10 S., R. 1 W., Felton quadrangle. Santa Margarita Sandstone, upper Miocene. Collected by J. C. Clark and C. A. Repenning, 1962, 1963, and 1964.

M1036 Slope at north edge of clearing, west of Bean Creek, sec. 13, T. 10 S., R. 2 W., Felton quadrangle. Upper part of Santa Margarita Sandstone, upper Miocene. Same stratigraphic position as M1037; same locality as M5053. Collected by J. C. Clark and C. A. Repenning, 1963.

M1037 Cut at sharp curve of abandoned dirt road, about 30 m east of Bean Creek Road, Felton quadrangle. Upper part of Santa Margarita Sandstone, upper Miocene. Same stratigraphic position as M1036; same locality as M5052. Collected by J. C. Clark and C. A. Repenning, 1963.

M1038 High vertical cut in sand pit on west side of old Highway 17 in Scotts Valley, elevation about 215 m, Felton quadrangle. Upper part of Santa Margarita Sandstone, upper Miocene. Collected by J. C. Clark, 1960.

M1039 Kaiser sand pit, south of Bean Creek, Felton quadrangle. Lower part of Santa Margarita Sandstone, upper Miocene. Collected by C. A. Repenning,, 1963.

M1105 Cut on east side of Nelson Road, NE¼ sec. 13, T. 10 S., R. 2 W., Felton quadrangle. Upper part of Santa Margarita Sandstone, upper Miocene. Collected by J. C. Clark and C. A. Repenning, 1964.

M1106 Palisades on east side of Branciforte Drive in De Laveaga Park, NW¼ sec. 7, T. 10 S., R. 1 W., Santa Cruz quadrangle. Santa Margarita Sandstone, upper Miocene. Collected by C. A. Repenning, 1964.

M1107 Large exposure at rifle range on west side of Peasley Gulch canyon, elevation 24 m, Santa Cruz quadrangle. Santa Margarita Sandstone, upper Miocene. Collected by J. C. Clark, 1963.

M1108 Cliff on east side of Moore Creek canyon, below Western Drive in Santa Cruz, elevation 55 m, sec. 15, T. 11 S., R. 2 W., Santa Cruz quadrangle. Upper part of Santa Margarita Sandstone, upper Miocene. Collected by J. C. Clark and C. A. Repenning, 1964.

M1109 Glauconitic bed in sea cliff below intersection of Delacoste Avenue and West Cliff Drive in Santa Cruz, SE¼ sec. 23, T. 11 S., R. 2 W., Santa Cruz quadrangle. Base of Purisima Formation, upper Miocene. Collected by J. C. Clark and C. A. Repenning, 1963.

M4667 Cut on northeast side of abandoned section of Smith Grade, 10 m northwest of new road and 30 m east of fork of Majors Creek, S½ sec. 29, T. 10 S., R. 2 W., Felton quadrangle. Lower part of Locatelli Formation, Paleocene. Same locality as LSJU 3401A. Collected by J. C. Clark, 1960.

M4668 North side of deep cut along Smih Grade, approximately 300 m southwest of where Smith Grade joins Empire Grade, Felton quadrangle. Lower part of Locatelli Formation, Paleocene. Collected by J. C. Clark, 1960.

M4669 Bed in unnamed westward-flowing tributary to San Lorenzo River, about 530 m east of where tributary joins river, in Henry Cowell Redwoods State Park, Felton quadrangle. Lower part of Locatelli Formation, Paleocene. Collected by J. C. Clark, 1960.

M5049 Molluscan bioherm on hillside, approximately 150 m west of Zayante Road, elevation of 245 m, SW¼ sec. 30, T. 9 S., R. 1 W., Felton quadrangle. Above basalt flows within Vaqueros Sandstone, Oligocene. Collected by J. C. Clark, 1960.

M5050 Molluscan bioherm just east of Zayante Road and west of Zayante Creek, SW¼ sec. 30, T. 9 S., R. 1 W., Felton quadrangle. Above basalt flows within Vaqueros Sandstone, Oligocene. Collected by J. C. Clark, 1960.

M5052 Cut at sharp curve of abandoned dirt road, about 30 m east of Bean Creek Road, Felton quadrangle. Upper part of Santa Margarita Sandstone, upper Miocene. Same stratigraphic position of M5053, same locality as M1037. Collected by J. C. Clark, 1961.

M5053 Slope at north edge of clearing, west of Bean Creek, sec. 13, T. 10 S., R. 2 W., Felton quadrangle. Upper part of Santa Margarita Sandstone, upper Miocene. Same stratigraphic position as M5052, same locality as M1036. Collected by J. C. Clark, 1961.

M5054 Bed or unnamed tributary to Laguna Creek, about 125 m east of Smith Grade, elevation about 195 m, NW¼ sec. 31, T. 10 S., R. 2 W., Davenport quadrangle. Sandstone interbed in Monterey Formation, middle Miocene. Collected by J. C. Clark, 1962.

M5055 Bed of Majors Creek, below U-curve in Smith Grade, Felton quadrangle. Lompico Sandstone, middle Miocene. Collected by J. C. Clark, 1962.

M5056 East bank of Laguna Creek, about 90 m upstream from city water reservoir, SW¼ sec. 30, T. 10 S., R. 2 W., Davenport quadrangle. Lower part of Monterey Formation, middle Miocene. Collected by J. C. Clark, 1962.

M5057 Near base of large exposure on northeast side of straight stretch of Smith Grade, Davenport quadrangle. Monterey Formation, middle Miocene. Collected by J. C. Clark, 1962.

M5058 East bank of Laguna Creek, elevation about 125 m Davenport quadrangle. Lompico Sandstone, middle Miocene. Collected by J. C. Clark, 1962.

M5060 Concretion in west bank above Majors Creek, 30 m N. 60° W. of where Majors Creek forks, Felton quadrangle. Lompico Sandstone, middle Miocene. Collected by J. C. Clark, 1962.

M5061 Near base of high cliffs on west rim of Majors Creek canyon, elevation about 150 m, Felton quadrangle. Lompico Sandstone, middle Miocene. Collected by J. C. Clark, 1962.

M5062 Cliffs on west side of Majors Creek canyon, elevation 185 m, Santa Cruz quadrangle. Lompico Sandstone, middle Miocene. Same stratigraphic position as M5061. Collected by J. C. Clark, 1962.

M5063 Cut on west side of abandoned logging road on west side of Majors Creek canyon, elevation 170 m, Santa Cruz quadrangle. Lompico Sandstone, middle Miocene. Approximately same stratigraphic position as M5061 and M5062. Collected by J. C. Clark, 1962.

M5064 West bank of Baldwin Creek across stream from small clearing at end of logging road, elevation 140 m, Santa Cruz quadrangle. Near base of Lompico Sandstone, middle Miocene. Collected by J. C. Clark, 1962.

M5065 North bank of Gold Gulch, about 90 m upstream from where stream passes under Highway 9, Felton quadrangle. Lower part of Locatelli Formation, Paleocene. Collected by J. C. Clark, 1962.

M5066 Bed in Gold Gulch, approximate elevation 160 m, Felton quadrangle. Lower part of Locatelli Formation, Paleocene. Collected by J. C. Clark, 1962.

M5067 Bed of Laguna Creek, about 215 m downstream from M5058, elevation about 115 m, Davenport quadrangle. Lompico Sandstone, middle Miocene. Collected by J. C. Clark, 1963.

M5068 Southeast bank of Baldwin Creek canyon, below clearing, elevation 150 m, Santa Cruz quadrangle. Lompico Sandstone, middle Miocene. Collected by J. C. Clark, 1963.

M5069 Southeast bank of Baldwin Creek canyon, 30 m west of M5068, elevation 140 m, Santa Cruz quadrangle. Lompico Sandstone, middle Miocene. About 6 m stratigraphically below M5068. Collected by J. C. Clark, 1963.

M5086 *Astrodapsis* bed in high cut near top of Kaiser sand pit on east side of Zayante Road, elevation 170 m, Felton quadrangle. Santa Margarita Sandstone, upper Miocene. Same stratigraphic position as M5155. Collected by J. C. Clark, 1961.

M5112 *Astrodapsis* bed in cliff beneath water fall along unnamed tributary to Zayante Creek, about 280 m east of Zayante Creek, NW¼ sec. 30, T. 9 S., R. 1 W., Felton quadrangle. Santa Margarita Sandstone, upper Miocene. Collected by J. C. Clark, 1960.

M5154 Bank of Año Nuevo Creek, 10 m below small dam on creek, Año Nuevo quadrangle. Sandstone member of Purisima Formation, Pliocene. Collected by J. C. Clark, 1968.

M5155 *Astrodapsis* bed on ridge known as "sand dollar hill," NE¼ sec. 1, T. 10 S., R. 2 W., Felton quadrangle. Santa Margarita Sandstone, upper Miocene. Same stratigraphic position as M5086; same locality as LSJU 3995. Collected by J. C. Clark, 1960.

Mf2187 Wave-cut below sea cliff below intersection of Delacosta Avenue and West Cliff Drive in Santa Cruz, SE¼ sec. 23, T. 11 S., R. 2 W., Santa Cruz quadrangle. Santa Cruz Mudstone, upper Miocene. About 3 m stratigraphically below unconformity with overlying Purisima Formation. Collected by J. C. Clark, 1963.

Mf3675 North side of unimproved road in new subdivision, elevation 120 m, NW¼ NW¼ sec. 6, T. 11 S., R. 1 W., Felton quadrangle. Tuffaceous siltstone bed of Purisima Formation, lower Pliocene. About 18 m above contact with Santa Margarita Sandstone. Collected by J. C. Clark, 1976.

Mf3676 Cut on east side of parking lot, 30 m south of Water Street in Santa Cruz, SW¼ sec. 7, T. 11 S., R. 1 W., Santa Cruz quadrangle. Diatomaceous siltstone bed of Purisima Formation, lower Pliocene. About 6 to 9 m above contact with Santa Cruz Mudstone. Collected by J. C. Clark, 1976.

Mf3677 Cut on north side of Highland Avenue just north of sharp curve in Santa Cruz, NW¼ sec. 13, T. 11 S., R. 2 W., Santa Cruz quadrangle. Diatomaceous siltstone bed of Purisima Formation, upper Miocene. About 6 to 9 m above contact with Santa Cruz Mudstone. Collected by J. C. Clark, 1976.

Mf3678 Cut on west side of hill behind Callaway house, east of Glen Canyon Road, about 2½ km south of Scotts Valley, Felton quadrangle. Tuffaceous siltstone bed of Purisima Formation, lower Pliocene. About 1 m above beds of Santa Cruz Mudstone, which here is not differentiated from Purisima because of map scale, and about 4.5 m above contact with Santa Margarita Sandstone. Collected by J. C. Clark, 1976.

California University of Paleontology (Berkeley) localities (UCMP)

V4004 Santa Cruz Aggregates sand pit, north of Bean Creek, SE¼ sec. 14, T. 10 S., R. 2 W., Felton quadrangle. Lower part of Santa Margarita Sandstone, upper Miocene.

V5244 Santa Cruz Aggregates sand pit, north of Bean Creek, SE¼ sec. 14, T. 10 S., R. 2 W., Felton quadrangle. Santa Margarita Sandstone, upper Miocene. About 60 m above base, and 25 m below top; about 46 m stratigraphically above V4004.

V5555 Graham sand pit east of Nelson Road, Felton quadrangle. Lower part of Santa Margarita Sandstone, upper Miocene.

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