GEOLOGIC MAP OF THE MONTEREY AND SEASIDE 7.5-MINUTE QUADRANGLES, MONTEREY COUNTY, CALIFORNIA: A DIGITAL DATABASE

By

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INTRODUCTION

General Statement

The study area includes the Monterey Peninsula and part of the Carmel Valley area. Geologically, this region is situated within the complexly deformed Salinian block between the active San Andreas fault to the northeast and the San Gregorio fault zone to the southwest. It also is characterized by compressional tectonics related to the San Andreas fault system and includes many poorly understood subsidiary faults (Greene and others, 1988).

A series of high-angle faults trends northwestward across the quadrangles. Most of the faults in the area are discontinuous, with some less than 1 km long; however, the Tularcitos fault zone continues across the entire mapped area. These faults displace the Monterey Formation and locally offset Quaternary deposits.

Methods of Investigation

The geologic map in the database shows the combined distribution of the bedrock and Quaternary deposits in the Monterey and Seaside quadrangles with emphasis on Quaternary deformation. The data are updated from the previous mapping of Clark and others (1974), of Dupré (1990b), and of Rosenberg (1993). Although this map represents a joint effort, the individual contributions are as follows:

- Clark: Bedrock and fault mapping, field work from 1973 to 1974, 1984 to 1995;
- Dupré: Quaternary mapping, field work from 1980 to 1985; and
- Rosenberg: Fault mapping, landslide mapping, field work from 1988 to 1995.

The offshore geology is compiled from Galliher (1932); Dohrenwend (1971); Simpson (1972); Greene, Lee, McCulloch, and Brabb (1973); McCulloch and Greene (1989), and Gardner-Taggert, Greene, and Ledbetter (1993).

Previous Work

The geology of Carmel area was first described by Lawson (1893). Lawson mapped the geologic units near the mouth of the valley and demonstrated the influence of faulting on the topography. Beal (1915) and Galliher (1930) described the regional stratigraphy and geologic structure in the Monterey area. Because the focus of these early efforts was on bedrock mapping, the Quaternary geology of the region was largely uninterpreted.

Bowen (1965, 1969a, 1969b) mapped the Monterey and Seaside 7.5-minute quadrangles with emphasis on the Tertiary stratigraphy. Brown (1962) and Younse (1980) mapped the Rancho San Carlos and Laureles Grade/Robinson Canyon areas, respectively. Their work resulted in the refinement of the stratigraphy and structure of the Tertiary sedimentary rocks in Carmel Valley.

Preliminary geologic mapping (Clark and others, 1974) suggested that several faults in the study area were potentially active. Bryant (1985) reviewed published mapping, performed a limited reconnaissance of the area, and concluded that previously mapped faults were “not sufficiently active” to require zonation by the State Geologist. However, analysis of Quaternary mapping by Dupré (1990b), recent detailed mapping and trenching by geotechnical consultants, unpublished mapping by Clark (1984-1995), and investigation of geologic hazards of Carmel Valley by Rosenberg (1993) indicate that Holocene and late Pleistocene faulting has occurred, the extent and nature of which were previously unrecognized. Subsequent work by Rosenberg and Clark (1994) confirmed this movement along strike-slip and thrust faults in the study area.

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STRATIGRAPHY

General Statement

Resting nonconformably upon the schist and granodiorite of the Salinian basement is an incomplete stratigraphic section ranging in age from Paleocene to Holocene and having a composite thickness of as much as 1,920 m. Locally, the Paleocene rocks are intruded by Oligocene basaltic andesite.

Franciscan Complex, undifferentiated

Rocks that crop out on the sea floor west of the Carmel Canyon fault were tentatively assigned to the Franciscan Complex by McCulloch and Greene (1989) based on the presence of metamorphosed chert west of this fault (H.G. Greene, oral commun., 1996).

Schist of the Sierra de Salinas

A distinctive schist unit crops out on the east side of Laureles Grade and extends southeastward towards Arroyo Seco. This unit has been referred to as part of the “Sur Series” (Trask, 1926) and more recently as the “Schist of the Sierra de Salinas” (Ross, 1976). The schist is dusky blue to dusky yellowish-brown, and fine- to medium-grained. It consists of approximately 35–55 percent quartz, 30 percent plagioclase, and 15–25 percent biotite, with red garnet locally common (Herold, 1935). Prominent vein quartz and simple pegmatite are common in the schist. The appearance and chemical composition of the schist suggest derivation from graywacke (Ross, 1976). Although Cretaceous granitic rocks intrude the schist, the age of the schist is uncertain; estimates range from Paleozoic (Bowen and Gray, 1959) to Mesozoic (Ross, 1976).

Granodiorite of Cachagua

The Cachagua granodiorite represents a small part of the mapped area, cropping out near Laureles Grade. The Cachagua is a transitional unit between the Monterey mass and the adjoining quartz diorite to the southeast (Ross, 1976). Typically it is gray to light pink, medium- to coarse-grained, and is composed of approximately 34–45 percent plagioclase, 25–30 percent quartz, and 8–10 percent biotite, with subordinate amounts of orthoclase and microcline (Herold, 1935). However, it is a variable unit in both mineral content and texture, and this variability and local resemblance to the adjoining rocks make its differentiation difficult (Ross, 1976).

Porphyritic Granodiorite of Monterey

Two types of granitic rock crop out in the study area. Ross (1976) named these rocks the porphyritic granodiorite of Monterey, and the granodiorite of Cachagua. Porphyritic granodiorite crops out on the Monterey Peninsula and on the south side of Carmel Valley. In the Seaside area, exploratory wells reached granitic basement at nearly 600 m below sea level. Well logs and seismic refraction data reveal that granitic bedrock highs underlie the Carmel River alluvium.

The porphyritic granodiorite of Monterey is light gray to moderate pink and medium-grained with orthoclase phenocrysts ranging from 3 to 10 cm long. Although the Monterey unit is relatively homogenous and easily recognizable, there is a considerable range in the ratio of plagioclase to K-feldspar based largely on the irregular distribution of phenocrysts—in places the mass is not porphyritic (Ross, 1976). Numerous light-colored aplite dikes from 2 cm to 1 m wide intrude the granitic rock. Pegmatite dikes composed of coarse-grained quartz and feldspar are also common. The pegmatite dikes are typically about 10 cm wide. Radiometric dating indicates an age of 79.5 Ma for the porphyritic granodiorite of Monterey (R.W. Kistler, USGS, oral commun., 1995).

Carmelo Formation

Nonconformably overlying the granitic basement at Point Lobos and at the northern end of Carmel Bay are Paleocene marine sedimentary rocks known as the Carmelo Formation of Bowen (1965). The Carmelo consists mainly of thin- to thick-bedded and graded arkosic sandstone with interbedded siltstone and graded pebble and cobble conglomerate. Porphyritic granodiorite clasts predominate in the lower conglomerate beds on the north side of the Bay, whereas red, green, purple, and black siliceous clasts dominate higher in the section. The Carmelo rests depositionally upon and is locally faulted against the granodiorite. Estimates of thickness range from 220 m (Lawson, 1893) to 430 m (Herold, 1934). Mollusks and foraminifers indicate a Paleocene age for the Carmelo (Bowen, 1965). Clifton (1981) interpreted sedimentary structures and concluded that the Carmelo was laid down by turbidity currents in a submarine canyon. Paleocurrents were variable but suggest a westward flow (Nili-Esfahani, 1965).

Vaqueros(?) Sandstone

At Palo Corona Ranch, a thick-bedded, medium- to coarse-grained arkosic marine sandstone with granitic cobbles and few porphyry pebbles underlies Oligocene basaltic andesite. This sandstone may correlate with the Vaqueros Sandstone found to the south in the Santa Lucia Range.

Basaltic Andesite (Carmeloïte)

Thin flows and flow-breccias of basaltic andesite are discontinously exposed around Carmel Bay and to the east along Carmel Valley. These volcanic rocks have three structural relationships: unconformably overlying granodiorite, faulted against granodiorite, and intruding the Carmelo Formation. Termed carmeloïte by Lawson (1893), these volcanic rocks are fine grained with olivine phenocrysts that have been altered to distinctive reddish-brown iddingsite.

Bowen (1965) estimated the composition as 30–40 percent plagioclase feldspar, 20–30 percent augite, 15–20 percent olivine and pyroxene, 5–15 percent chlorite, 5–15 percent clay minerals, and 5 percent magnetite. Silica content is variable. X-ray spectroscopic analysis (USGS Branch of Analytical Laboratories, written commun., 1979) of samples from Arrowhead Point and from the north side of San Jose Creek canyon yields values of 53.10 and 50.33 percent, respectively; whereas R.B. Cole (written commun., 1995) reports silica contents of 61.14 and 61.48 percent for samples east of Arrowhead Point. Thus, compositionally these rocks range from basaltic andesite to andesite. Clark and others (1984) reported a K-Ar age of 27.0±0.8 Ma (Oligocene) for samples from Arrowhead Point and estimated a thickness of 20 m for the basaltic andesite.

Red Beds of Robinson Canyon

A clastic section as much as 260 m thick in the vicinity of Robinson Canyon nonconformably overlies the Salinian basement and underlies the Monterey Formation. The lower part of this section includes non-marine red beds consisting mostly of arkosic sandstone with common conglomerate and siltstone beds. Brown (1962) referred to this lower unit as the Robinson Canyon Member of the Chamisal Formation, which Bowen (1965) later defined.

The sandstone is moderate red on weathered surfaces and yellowish-gray where fresh, very thick bedded, very coarse to coarse grained, angular to subangular, and poorly sorted. The conglomerate consists of very thick beds of limited extent with well rounded cobbles composed of granodiorite, schist, and felsite. The siltstone consists of very dark red and dusky green, thin beds that are laterally continuous over tens to hundreds of meters. At the type locality in Robinson Canyon, the red beds are approximately 140 m thick (Bowen, 1965, p. 51). Although the age of these red beds is uncertain, stratigraphic position and regional correlation with similar units suggest that the red beds are middle Miocene (Younse, 1980).

Unnamed Sandstone

The red beds in Robinson Canyon are overlain conformably by marine sandstone. Bowen (1965) proposed the name "Los Tularcitos Member of the Chamisal Formation" for this sandstone. Clark and others (1974) used the name "marine sandstone" in their regional mapping to include the both the Los Tularcitos Member of the Chamisal Formation and the Los Laureles Sandstone Member of the Monterey Formation of Bowen (1965), because both sandstones are overlain conformably by the Monterey Formation and cannot be differentiated in the field. Pending further work on these units, the term "unnamed sandstone" is used in this report.

The sandstone consists of dark-yellowish-orange, very thick bedded, coarse- to fine-grained, angular to subangular, poorly to well-sorted arkosic sandstone, with common very thick cobble-boulder conglomerate beds in the lower part and rare siltstone beds in the upper part. Along Potrero Canyon, the red beds are absent, and the sandstone between the granitic basement and the Monterey Formation is as much as 175 m thick and contains late Luisian (middle Miocene) foraminifers in the upper part. Also locally common are 1 to 3 m-thick *Leptopecten andersoni* shell beds.

Monterey Formation

The Monterey Formation consists of as much as 900 m of siliceous and diatomaceous beds along Carmel Valley and on the Monterey Peninsula. Locally within the City of Monterey, the Monterey Formation rests directly on the granitic basement. North of the Chupines fault zone, the Monterey rarely crops out but is commonly penetrated in drill holes (see inset map on sheet 2).

Within the study area, there are three mappable units of the Monterey Formation. The lower unit, locally differentiated on the Monterey Peninsula, where it is as much as 30 m thick, is typically thin-bedded, yellowish-brown semi-siliceous mudstone with interbedded siltstone. Locally abundant are benthic foraminifers of the *Valvulinera californica* Zone diagnostic of upper bathyal (150–350 m) depths and of Luisian (middle Miocene) age (K. McDougall, written commun., 1987).

The middle unit (Aguajito Shale Member of Bowen, 1965) is as much as 600 m thick. It is thin-bedded and laminated, light brown to white porcelanite with very thin clay partings between the porcelanite beds and with thin interbeds of waxy-yellow to brown chert. This unit contains a few thin, dark-brown bentonite interbeds and rare thin pelletal and oölitic phosphorite interbeds in the lower part. Benthic foraminifers are diagnostic of outer neritic to upper bathyal depths during Luisian (middle Miocene) time to lower middle bathyal depths during Mohnian (middle to late Miocene) time (Younse, 1980).

The upper unit (Canyon del Rey diatomite Member of Bowen, 1965) is as much as 250 m thick. It is mainly very thick bedded and faintly laminated, very pale orange to white diatomite with thin interbeds and lenses of dark-brown chert and a few thick interbeds of light-gray vitric tuff. A sample collected near the base of this unit south of Canyon del Rey yielded benthic foraminifers diagnostic of upper (300–500 m) to upper middle bathyal (500–1,500 m) depths and of an early Mohnian (late Miocene) age (K. McDougall, written commun., 1994). Another sample from near the top of this unit east of Laureles Grade is diagnostic of inner neritic (50–100 m) depths and of a Mohnian (late Miocene) age (K. McDougall, written commun., 1994), indicating a shallowing of marine conditions during deposition of this upper unit.

Correlation with a dated Trapper Creek, Idaho section of a thick vitric tuff interbed about 60 m stratigraphically above the base of the diatomite unit that is exposed along Toro Road just east of the map area indicates an age of 10.83±0.03 Ma (A.M. Sarna-Wojcicki, writen commun., 1996). With a late Luisian age for the lowest beds, as sampled on the east side of Potrero Canyon, the Monterey Formation of this area spans a time interval from about 15 Ma to somewhat less than 10.83 Ma.

Santa Margarita Sandstone

Conformably overlying the upper diatomite of the Monterey Formation is a marine and brackish-marine, white, fine- to coarse-grained arkosic sandstone mapped as the Santa Margarita Sandstone. North of the Chupines fault zone, the Santa Margarita Sandstone is commonly found in the subsurface and crops out locally north of Canyon Del Rey. South of Canyon Del Rey, the Santa Margarita Sandstone is more extensively exposed along the Chupines fault zone.

Logs of water wells show that the Santa Margarita Sandstone is at least 99 m thick at Fort Ord, approximately 1.4 km north of the Seaside quadrangle (Oliver, 1994). Its conformable position above the Monterey diatomite together with megafossils collected from the Spreckels quadrangle to the east (Herold, 1935; Bowen, 1965) suggests a late Miocene age for the Santa Margarita.

Sedimentary Rocks

Dredge hauls offshore in Carmel Canyon recovered samples of greenish-gray siltstone and mudstone of possible Pliocene age. Also recovered from this area were samples of coarse-grained, arkosic marine sandstone of Tertiary(?) age (Greene, 1977).

Continental Deposits, undivided

Unconformably overlying the Santa Margarita Sandstone is a series of non-marine, semiconsolidated, fine-grained, oxidized sand and silt beds with common gravel beds. Previous workers (Beal, 1915; Herold, 1935) correlated these beds with the Paso Robles Formation of the southern Salinas Valley, a name also used in later mapping by Bowen (1965), and Clark and others (1974). Because of uncertainty of correlation with the type area to the south, Dupré (1990b) preferred not to use the name "Paso Robles" and called these beds "continental deposits." His usage is followed here.

Continental deposits are exposed in the foothills of the Laguna Seca area, and are mostly absent south of the Chupines fault zone. Herold (1935) estimated the continental deposits to be as much as 230 m thick in nearby San Benancio Gulch (in the Spreckels quadrangle adjoining the Seaside quadrangle). Two deep test holes near Laguna Seca revealed an even greater thickness of the continental deposits, 335 m, than exposed in outcrop (Staal, Gardner & Dunne, 1991). Stratigraphic position and regional correlation with similar units suggest that the continental deposits are Pleistocene and possibly Pliocene in part.

Sedimentary Deposits

Unconsolidated marine sediment; seismic characteristics suggest poorly bedded sands and gravels; Quaternary age (Greene, 1977).

Older Eolian Deposits

Exposed on the hilltops of Fort Ord is a series of Pleistocene eolian deposits largely equivalent to the Aromas Sand as mapped by Dupré and Tinsley (1980). The stratigraphic relationship of the older eolian deposits and the continental deposits is unclear. In some areas, the older eolian deposits appear to unconformably overlie the “Paso Robles” (Bowen, 1965); elsewhere, the two units may be in part facies equivalents (Dupré, 1990a).

The older eolian deposits consist of moderately well-sorted sand as much as 60 m thick that contains no intervening fluvial deposits. Several sequences of eolian deposits may be present, each separated by paleosols. The upper 3–6 m of each dune sequence is oxidized and relatively well indurated, and all primary sedimentary structures have been destroyed by weathering; the lower parts of each dune sequence may be relatively unconsolidated below the weathering zone.

Terrace Deposits, undivided

Elevated fluvial terraces are exposed mainly on the north side of the Carmel River on discontinuous topographic benches and as erosional remnants capping hilltops (equivalent to the “older alluvium” of Clark and others, 1974). These fluvial terrace deposits consist of weakly consolidated to semiconsolidated, moderately to poorly sorted, fine- to coarse-grained silty sand with pebble to cobble gravel. The terrace deposits are weakly to moderately cemented, and locally are strongly cemented with carbonate in the upper few meters; some are capped by moderately to fully well developed soils, some with duripans; expansive soils are locally present. Their thickness is highly variable, and is locally as much as 20 m. At least some of the fluvial terrace deposits in Carmel Valley correlate with the marine terrace deposits of Pleistocene age on the Monterey Peninsula (Williams, 1970, p. 52); however, discontinuous outcrops and intervening young faults make these correlations difficult.

Coastal Terrace Deposits

A series of uplifted coastal terraces crops out on the Monterey Peninsula and ranges in altitude from 10 m to 225 m. Coastal terrace deposits consist of semiconsolidated, moderately well sorted marine sand containing thin, discontinuous gravel-rich layers; some overlain by poorly sorted fluvial and colluvial silt, sand, and gravel. These terrace deposits are commonly well indurated in the upper part of the weathered zone; many are capped by maximally developed soils, some having duripans. The thickness of the coastal terrace deposits is variable, but generally less than 6 m.

Coastal dunes have mostly buried the marine terraces in the Fort Ord area, although evidence of buried terrace scarps still remains (Cooper, 1967). In addition, much of what was mapped as Miocene marine sandstone (Los Laureles Sandstone Member of Bowen, 1965) by Clark and others (1974) on the Monterey Peninsula actually consists of Quaternary coastal terrace deposits based on morphology, mineralogy, and stratigraphic relationships. However, differentiation between these two units is difficult, especially near Carmel-by-the-Sea.

The following age estimates for the coastal terraces are based on correlations with terraces in the Santa Cruz region (Dupré, 1991). Assuming that the ages for the Santa Cruz terraces estimated by Lajoie and others (1991) are correct, the “best-fit” constant-uplift rate is 0.18 mm/yr for the terraces on the Monterey Peninsula (table 1). Alternatively, if the ages of the Santa Cruz terraces are closer to those reported by Anderson and others (1990), then the uplift rates may be as much as 0.32 mm/yr. In either case, all of the coastal terrace deposits are Pleistocene.

The two lower coastal terraces probably formed during Sangamon highstands of sea level. The Lighthouse terrace (25 m altitude) is the more extensive of the two terraces and is tentatively correlated with the 124 ka Sangamon highstand and with the Highway 1 terrace in Santa Cruz, whereas the Ocean View terrace (10 m altitude) probably formed during the 102 ka highstand, correlative with the Davenport terrace in Santa Cruz. There appears to be no evidence of a 212 ka highstand preserved in the area; however, the Peninsula College terrace (60 m altitude) probably formed during the 319 ka highstand. Higher terraces, the Sylvan (75 m altitude) and the Monte Vista (130 m altitude) have estimated ages of 415 ka and 750 ka respectively. These latter terraces have been correlated by Dupré (1990a) with terraces near

Santa Cruz — the Sylvan terrace with the Western terrace and the Monte Vista terrace with the Wilder terrace.

The oldest Quaternary marine deposits are the Huckleberry terrace deposits, which are between 180–225 m altitude along the summit of the Monterey Peninsula. Assuming a constant uplift rate of 0.18 mm/yr, the Huckleberry terrace deposits are approximately 1.1–1.3 Ma. These deposits are the coastal equivalents of at least some of what Clark and others (1974) mapped as Paso Robles Formation along the crest of the Santa Lucia Range to the southeast (Dupré, 1990a). Table 1 summarizes the terminology and estimated ages of the terraces.

Table 1. Marine terrace terminology, Monterey Peninsula.

Age of deposits	Source of data		
	Williams (1970)	McKittrick (1988)	Dupré (1990a)
late Pleistocene (10 ka to 125 ka)	“25-foot level” (8 m)	“terrace 1” (9±2 m) 100 ka*	“Ocean View” (10 m) 102 ka§
late Pleistocene	“30 to 50-foot interval” (9 to 15 m)	----------------------------------	----------------------------------
late Pleistocene	“70-foot level” (21 m)	“terrace 2” (27±3 m) 120 ka*	“Lighthouse” (25 m) 124 ka§
middle Pleistocene (125 ka to 700 ka)	“160-foot level” (49 m)	----------------------------------	“College” (60 m) 319 ka§
middle Pleistocene	“225-foot level” (69 m)	“terrace 3” (66±5 m) 330 ka†	“Silvan” (75 m) 415 ka#
middle Pleistocene	“320-foot level” (98 m)	----------------------------------	----------------------------------
middle to early Pleistocene	“410-foot level” (125 m)	“terrace 4” (136±10 m) 700 ka†	“Monte Vista” (130 m) 750 ka#
early Pleistocene (700 ka to 1800 ka)	“550-foot level” (167 m)	----------------------------------	----------------------------------
early Pleistocene	“620-foot level” (189 m)	----------------------------------	“Huckleberry” (210 m) 1200 ka#

* indicates age based on soil-profile development.
† indicates age based on extrapolating 0.16 mm/yr rate of uplift inferred from lower terraces.
§ indicates age determination by altitude correlation to terraces in the Santa Cruz region (Dupré, 1991), the ages of which are estimated by Lajoie and others (1991). The Lighthouse terrace was estimated as 118 ka by Dupré (1990a); however, Dupré (written commun., 1996) considers this terrace to be 124 ka.
# indicates age based on extrapolating 0.18 mm/yr rate of uplift inferred from lower terraces.

Older Coastal Dunes

The late Pleistocene coastal dunes consist of weakly consolidated, well-sorted, fine- to medium-grained sand deposited in an extensive coastal dune field in the Fort Ord area. Thickness ranges from 2 to 25 m. Where a thin veneer of coastal dune deposits covers some of the coastal terrace deposits near Seaside, a subscript (e) follows the symbol of the coastal terrace overlain by these dune deposits. The older coastal dunes are locally divided into:

Younger dune deposits of middle(?) Wisconsinan age consist of weakly consolidated, well-sorted, fine- to medium-grained sand deposited in an extensive coastal dune field. Older dune deposits of early(?) Wisconsinan age consist of weakly to moderately consolidated, moderately well-sorted silt and sand deposited in extensive coastal dune fields. The upper 3–6 m is indurated by clay and iron oxide cementation in the weathered zone.

Landslide Deposits

Landslides in the study area are widespread and range from small, shallow debris flows to large, deep bedrock slides. Landslides form in all the geologic units, but are most common in the Monterey Formation. Additional landslides are probably present and are not shown on the map, especially in areas mapped as colluvium. Some landslides, or parts of them, may be very young and possibly moving.

Younger landslides have fresh scarps, disrupted drainages, closed depressions, and disturbed vegetation. Older landslides are modified by erosion, resulting in subdued scarps, reestablished vegetation, and new drainage paths. Soils have formed on the some of the older landslide deposits; however, most soils are poorly developed or absent because of high erosion rates and steep slopes.

Many of the younger slides are probably early Holocene as indicated by poorly to moderately defined scarps, hummocky topography, and well-developed drainages. From one landslide on the south side of Carmel Valley (sec. 25, T. 16 S., R. 1 E.), O'Rourke (1980) recorded a soft and wet slickensided clay slide plane at a depth of 17 m. Radiocarbon dating of a peat sample found on top of this slide indicates a minimum age of 9,600±160 yr B.P. for the landslide. This radiocarbon date supports the relatively young age suggested by the geomorphic features.

Radiocarbon dating of landslide material also confirms that some of the older, deep-seated landsliding occurred during the late Pleistocene. Charcoal fragments obtained from an 18-m-deep slide plane of the large landslide on the east side of Cañada de la Segunda have a radiocarbon age of 31,000 yr B.P.; however, the accuracy of this date is uncertain (A.S. Buangan, Wahler Associates, oral commun., 1991).

Samples of decayed plant matter from a slide plane in the large landslide complex on the Monterra Ranch south of State Highway 68 have radiocarbon ages of 12,780±90 and 13,000±110 yr B.P. (Rogers E. Johnson & Associates, 1986, p. 31). Ponded alluvium from the base of a closed depression on the upper part of this landslide yielded a radiocarbon age of 12,360±400 yr B.P. (Beta Analytic sample Beta-19986) (J.M. Nolan, written commun., 1987) and corroborates the age of this large landslide. Geomorphic features suggest that the smaller landslides within the older large landslide are more recently active.

Flandrian Dune Deposits of Cooper (1967)

The so-called "Flandrian" dune deposits described by Cooper (1967) consist of unconsolidated, well-sorted sand as much as 30 m thick, deposited in a belt of parabolic dunes up to 700 m wide. Their physical characteristics are similar to those of younger dune sand. Johnson (1993) noted a paleosol at the base of these dunes near Stilwell Hall, approximately 5 km north of the study area. Dating of charcoal in this paleosol gave ^{14}C ages of 2,130±80 (Lawrence Livermore National Lab sample CAMS-4806) and 1,800±60 yr B.P. (Lawrence Livermore National Lab sample CAMS-4807), indicating that these dune deposits are late Holocene age (Johnson, 1993).

Colluvium

Colluvial deposits are common in the hillside areas, especially in topographic swales. These deposits are up to tens of meters wide, hundreds of meters long, and are as much as 7 meters thick. Colluvium consists of a variable mixture of unconsolidated, heterogeneous deposits of moderately to poorly sorted silt, sand, and gravel, deposited by slope wash and mass movement. Some deposits have undergone minor fluvial reworking. Locally they include numerous landslides and small alluvial fans; contacts with alluvial deposits are generally gradational. Dating of the colluvium in the study area has yielded five ^{14}C ages ranging from 1,880 to 7,780 yr B.P. (Rogers E. Johnson & Associates, 1985; Rosenberg and Clark, 1994).

Older Flood-Plain Deposits

Older flood-plain deposits are stratigraphically between terrace deposits and younger flood-plain deposits and are Holocene age. Older flood-plain deposits consist of unconsolidated, relatively fine-grained, heterogeneous deposits of sand and silt, commonly including relatively thin layers of clay. The grain size of levee deposits decreases away from abandoned channel-fill deposits. The older flood-plain deposits are nearly flat to gently sloping and fill an irregularly shaped valley beneath the present-day Carmel River (Logan, 1983). Interpretation of well log data suggests that the older flood-plain deposits are typically less than 18 m thick in the study area, but locally may be as much as 40 m thick.

Younger Flood-Plain Deposits

Holocene age younger flood-plain deposits occur in and adjacent to the present Carmel River channel. These deposits consist of unconsolidated, relatively fine grained, heterogeneous deposits of sand and silt, commonly including relatively thin, discontinuous layers of clay. The gravel content is variable and is locally abundant within channel and lower point bar deposits. The thickness of the younger flood-plain deposits is generally less than 6 m. They typically are incised within older flood-plain deposits, except near the mouth of the Carmel River, where they occur as a veneer of levee deposits over older flood-plain deposits and are mapped separately as unit $Qyf_{(a)}$.

Alluvial Deposits

Alluvial deposits of variable thickness and composition fill the bottoms of the major hillside drainages. These deposits consist of unconsolidated, heterogeneous, moderately sorted silt and sand with discontinuous lenses of clay and silty clay, and locally include large amounts of gravel. They may include deposits equivalent to both the younger and older flood-plain deposits (Qyf and Qof, respectively) in areas where these were not differentiated. Their thickness is highly variable and may be more than 30 m near the coast.

Basin Deposits

Basin deposits consist of unconsolidated, plastic clay and silty clay containing much organic material, and locally contain interbedded thin layers of silt and silty sand. They are deposited in a variety of environments including estuaries, lagoons, tidal flats, marsh-filled sloughs, flood basins, and lakes. Their thickness is highly variable and may be as much as 30 m underlying some sloughs.

Dune Sand Deposits

The Holocene dune sand deposits consist of unconsolidated, well-sorted, fine- to medium-grained sand, deposited as a linear strip of coastal dunes near Spanish Bay and Cypress Point. These deposits are as much as 25 m thick and are possibly equivalent to the “Flandrian” dune deposits of Cooper (1976) to the north.

Marine Sand Deposits

Marine sand deposits include a variety of unconsolidated sediments ranging from gray coarse and medium sand within 0.5 km of the shore, to fine sand and dark grayish-green mud at 1 to 2 km offshore (Galliher, 1932). These deposits also include submerged offshore gravel bars.

Beach Sand Deposits

Beach sand deposits consist of unconsolidated, well-sorted, medium- to coarse-grained sand with local layers of pebbles and cobbles. Thin discontinuous lenses of silt are relatively common in back-beach areas. The thickness of the beach deposits is variable, in part due to seasonal changes in wave energy, and is commonly less than 6 m. Beach sand deposits may interfinger with either well-sorted dune sand or, where adjacent to coastal cliffs, poorly sorted colluvial deposits.

Artificial Fill

Artificial (man-made) fill is common throughout the study area. Fill consists of a highly variable mixture of sand, silt, clay, and gravel with varying amounts of organic material. Only the largest deposits are shown, and as a result areas of artificial fill are under-represented.

REGIONAL STRUCTURE

The Monterey and Seaside quadrangles are approximately 31–38 km southwest of the seismically active San Andreas fault and 6–11 km northeast of the San Gregorio fault zone. These two faults mark the northeastern and southwestern boundaries, respectively, of the Salinian block with its crystalline basement of granitic and regionally metamorphosed rocks.

The San Gregorio and Monterey Bay fault zones, both of which are seismically active, trend southeastward into the area where they are represented by the Carmel Canyon and Cypress Point faults. The Carmel Canyon fault, which strikes N. 30∞ W. along a tributary to Carmel Canyon, is a fault segment within the San Gregorio fault zone. The San Gregorio fault zone is at least 130 km long and may extend northwestward from Big Sur for about 190 km to join the San Andreas fault at Bolinas (Greene and others, 1973).

The Monterey Bay fault zone abuts the San Gregorio fault zone in the northwestern part of Monterey Bay and consists of a discontinuous series of en echelon faults that strike N. 40∞ W. Individual faults of the latter zone continue onshore into the Monterey/Seaside area. First-motion studies of earthquakes in Monterey Bay (Greene and others, 1973, p. 7) indicate that the offshore faults are nearly vertical and that right-lateral, strike-slip displacement is occurring along these northwest-trending faults.

Within the Salinian block, a series of high-angle faults trends northwestward across the quadrangles. Many of the faults in the region are discontinuous, with some less than 1 km long; however, the Tularcitos fault zone continues across the entire map area. These faults displace the Monterey Formation and locally offset Quaternary deposits.

The onshore and offshore faults that have the same general orientation appear genetically related. Where exposed, fault planes of the northwest-trending onshore faults are steeply dipping, and the more westerly orientation of fold axes, especially those truncated by the Tularcitos fault, strongly suggests right-lateral displacement. First-motion studies also indicate right-lateral movement at depth on most of the faults in the study area (Rosenberg and Clark, 1994).

FAULT GEOMETRY AND ACTIVITY

Ord Terrace Fault

The Ord Terrace fault is a northwest-striking, steeply southwest-dipping reverse fault that separates Monterey Formation from Pleistocene continental deposits in the subsurface. Beneath the city of Seaside, abrupt changes in the subsea elevation of the top of the Monterey define the Ord Terrace fault (see subsurface structure contour map on sheet 2). In addition, three water wells (Ord Village #1, Playa #4, and Monterey Sand "Metz") near the mapped trace of the fault reportedly produced hydrothermal ground water with temperatures as high as 28∞C. Although subsurface data are limited, the Ord Terrace fault extends 7 km southeastward into the Laguna Seca area, as implied by truncated fold axes and by offset subsurface structural contours on the Monterey Formation. The Ord Terrace fault appears to merge with the Chupines fault to the southeast.

The logs of two wells approximately 215 m apart, the Luzern test well #5 (well 14, sheet 2) and the now-abandoned Ord Village #1 (well 6, sheet 2), indicate that the Ord Terrace fault vertically offsets the Monterey Formation by 198 m. Logs from boreholes on opposite sides of the fault show approximately 180 m of offset of the continental deposits (Staal, Gardner & Dunne, 1990a, cross section C-C').

McCulloch and Greene (1989) show that the northern extension of the Ord Terrace fault cuts Pleistocene strata and offsets the sea floor. No indication of offset Holocene strata is evident from interpretation of well logs. However, most well logs do not differentiate strata ranging in age from Pleistocene older eolian deposits ("Aromas Sand") to Holocene dune deposits and thus are of little value in bracketing the latest time of movement.

Seaside Fault

The Seaside fault is a buried northwest-striking, steeply southwest-dipping reverse fault that separates Monterey Formation from Pleistocene continental deposits. South of the Seaside fault, the Monterey Formation is typically less than 30 m deep, whereas north of this fault the Monterey drops off to more than 200 m. In addition, hydrothermal waters from the East Monterey Hot Springs well (well 17, sheet 2) support the presence of a fault. Southeast of Del Rey Oaks, interpretation of well data suggests that the Seaside fault continues southeastward to connect with a northwest-striking splinter of the Chupines fault exposed in the foothills near the intersection of State Highway 68 and York Road.

The logs of two now-abandoned wells approximately 670 m apart, the East Tioga #8 test well (well 20, plate 2) and the "Tom Philips" (well 47, sheet 2), show that the Seaside fault vertically offsets the Monterey Formation by 133 m. These logs also show approximately 84 m of offset of Pleistocene continental deposits (Staal, Gardner & Dunne, 1990a, cross section B-B').

McCulloch and Greene (1989) show that the offshore extension of the Seaside fault does not appear to offset Quaternary strata or the sea floor. Because of the extensive cultural modification of the Seaside and Fort Ord areas, surficial evidence of Holocene faulting is lacking.

Chupines Fault

Several discontinuous northwest-striking faults extending from the Carmel Valley to the Seaside area comprise the Chupines fault. Near Laureles Grade, the Chupines fault places Monterey Formation on the north against older rocks (Monterey Formation, middle Miocene "Tularcitos sandstone", and granodiorite) on the south. A parallel branch of the fault also separates steeply dipping Pleistocene continental deposits from Monterey diatomite. On the south side of State Highway 68, part of the Chupines fault is concealed by alluvium. The fault emerges in the foothills and includes two short west- to northwest-striking branches that juxtapose Santa Margarita Sandstone and Pleistocene continental deposits against Monterey diatomite.

The Chupines fault continues northwestward for 5 km beneath the alluvium of Canyon del Rey toward Monterey Bay. Outcrops of steeply dipping Monterey diatomite delineate the trace of the Chupines fault along Canyon del Rey. The Monterey Formation is structurally high between the Chupines fault and the Seaside fault, where it was eroded during low stands of sea level. Hence, subsurface contours on the top of the Monterey Formation do not show significant displacement.

Estimates of minimum vertical displacement on faults within the Chupines fault zone range from about 200 m (Fiedler, 1944) to 300 m (Herold, 1935). Interpretation of well logs shows Pleistocene continental deposits offset by approximately 150 m (Staal, Gardner & Dunne, 1988a, cross section B-B').

Much of the late Quaternary displacement along the Chupines fault may be strike-slip. In a trench excavated across the fault (map locality 16, sheet 1), Vaughan and others (1991) found a vertical fault that “projects from two trench exposures to a right-deflected drainage, yielding a maximum horizontal slip rate of about 2 millimeters per year over the last 12,000 to 13,000 years.” Prominent saddles and linear drainages along the fault provide additional geomorphic evidence for strike-slip displacement. Alternatively, field mapping and interpretation of aerial photographs suggest that some of these features could be part of large landslides.

Stratigraphic evidence indicates post-Pleistocene movement on the Chupines fault, and other lines of evidence suggest Holocene activity. McCulloch and Greene (1989) show the offshore Chupines fault cutting Holocene strata and the sea floor. Four epicenters plot within 1 km of the surface trace and suggest that the Chupines fault is active (Rosenberg and Clark, 1994).

Navy Fault

The Navy fault is a northwest-striking, steeply southwest-dipping fault extending from Carmel Valley northwestward to Monterey Bay. Local shearing, structural discordances, and the discontinuity of westerly-trending fold axes delineate the Navy fault, although the trace is locally concealed by alluvium and landslide deposits. Its near alignment with the mapped Tularcitos fault to the southeast and the similarity in trend strongly suggest that these two faults are continuous.

The Navy fault is mapped northwestward from the mouth of Berwick Canyon and is characterized by locally sheared shale, truncated en echelon fold axes, and offset fluvial terrace deposits (map localities 21 and 22, sheet 1). Structural discordances in Monterey shale and truncated fold axes suggest that the Navy fault continues northwestward to join an offshore fault, although this part of the fault zone could not be traced on the ground or on aerial photographs through the Quaternary deposits. However, an artesian well 365 m west of the mapped trace of the Navy fault at the Naval Post Graduate School suggests the presence of a fault. This 335-m-deep well was drilled in 1882 and reportedly produced lukewarm, brackish water (Elmer Lagorio, local historian, written commun., 1994).

McCulloch and Greene (1989) mapped an offshore extension of the Navy fault as cutting Holocene strata and offsetting the sea floor. Galliher (1932) earlier mapped a small offshore channel trending N. 30∞ W. extending for approximately 8 km in nearly the same location. Galliher also noted elongate gravel bars (the “Italian Ledge” and “Portuguese Ledge” fishing grounds) along this channel. More recently, H.G. Greene (written commun., 1995) reports finding approximately 7 km offshore at a depth of between 85–89 m an anomalous carbonate-cemented conglomerate mound about 80 m long, 40 m wide, and 4 m high. He postulates that fluids migrating upward along an offshore extension of the Navy fault zone resulted in cementation of Pleistocene beach gravels and that late Pleistocene or Holocene deformation associated with this zone caused uplift and rifting of the mound. The Italian and Portuguese Ledges may have a similar origin.

Several lines of evidence support strike-slip movement along the Navy fault. Well-defined geomorphic features such as linear drainages, aligned benches, and saddles characteristic of strike-slip faults are common along the Navy fault. Also, the presence of northwest-trending thrust faults and en echelon fold axes is consistent with transpression developed along a right-lateral strike-slip fault. Seismologic evidence includes one fault plane solution that shows a combination of reverse and right-lateral motion (Rosenberg and Clark, 1994). Between two wells across the fault, the "Aguajito 1" well (well 70, sheet 2) and the "Saucito" wildcat well, the difference in elevation of granitic basement rock is only 60 m. This difference is small compared to other regional reverse faults, and suggests that much of the displacement on the Navy fault is strike-slip.

Several earthquakes that plot near the Navy fault indicate continuing Holocene activity (Rosenberg and Clark, 1994). Richter (1958) plotted two large earthquakes of magnitude 6.1 that occurred in 1926 as within the Monterey Bay fault zone, but alternatively these events may have been associated with movement along the San Gregorio fault zone.

Sylvan Thrust Fault

The Sylvan thrust fault consists of a zone of thrust faults that locally offset terrace deposits in the Monterey foothills. A 3-km-long thrust fault exposed on Sylvan Road offsets the 415 ka Sylvan coastal terrace against the Monterey Formation. The Sylvan thrust joins the Navy fault southeast of Flagg Hill. At that locality, the Sylvan thrust juxtaposes Pleistocene continental deposits against Monterey shale in 37-m-wide sheared and contorted zone. Nearby on Olmstead Road, Monterey shale is tightly folded and intensely faulted, and a fault offsets a middle Pleistocene fluvial terrace by 10 m (Wright and others, 1990). Road cuts near Devil Hill also reveal a parallel zone of thrust faults characterized by contorted and sheared zones of Monterey shale as much as 10 m wide.

Locally, faults with small vertical displacements near or associated with the Sylvan thrust fault offset terrace deposits and colluvium by 15–20 m (map locality 15, sheet 1). A road cut exposing the Sylvan thrust below La Mesa Elementary School reveals that a group of small thrust faults offsets coastal terrace deposits and colluvium against Monterey shale by 1–2 m. At this exposure, an organic-rich silt layer in faulted colluvium yielded a ^{14}C age of 4,890±90 yr B.P. indicating Holocene movement (map locality 6, sheet 1). Other indications of Quaternary movement include steeply dipping and possibly folded coastal terrace deposits along the Sylvan thrust (map localities 8 and 9, sheet 1).

During December 1975 and January 1976, a swarm of 21 small earthquakes occurred near the Sylvan thrust fault zone. Most of these earthquakes have first-motion solutions that indicate right-lateral motion on steeply southwest-dipping planes (Rosenberg and Clark, 1994), suggesting that the thrusting is genetically related to strike-slip motion on northwest-trending faults.

Tularcitos Fault

The Tularcitos fault zone extends from the southern part of the Seaside quadrangle southeastward into the Jamesburg area, where it splays into a zone of faults near Paloma Creek (Fiedler, 1944), a total distance of approximately 42 km. In upper Carmel Valley, the fault is buried beneath Quaternary alluvium and landslide deposits, but is locally delineated by upthrown granitic basement rock on the southwest and Tertiary sedimentary rock on the northeast. Geomorphic features such as deflected drainages and linear closed depressions, visible in the field and on aerial photographs, delineate this part of the Tularcitos fault. On Carmel Valley Road approximately 1 km east of Chupines Creek, two splays of the Tularcitos fault that dip 82∞ to 84∞ SW. offset colluvium and fluvial terrace deposits by 1 m against Monterey shale. At this exposure an offset organic silt horizon in the colluvium yielded a ^{14}C age of 7,780±160 yr B.P. (Rosenberg and Clark, 1994), indicating that the Tularcitos fault has Holocene movement.

A branch of the Tularcitos fault extends along the foothills south of the Carmel River near the southeastern boundary of the Seaside Quadrangle. This branch is marked by a zone of crushed granodiorite thrust over the unnamed sandstone of middle Miocene age and appears on aerial photographs as a series of topographic benches and saddles. A broad flat-lying terrace near the 500-foot contour in the NE. ¼ sec. 30, T. 16 S., R. 2 E. appears to be a result of uplift along the Tularcitos fault.

Near mid-Carmel Valley, alluvium conceals the main trace of the Tularcitos fault. This portion of the fault was located by plotting bedrock lithology as interpreted by Logan (1983) from water well logs. Water well logs and seismic refraction data also suggest a buried granitic bedrock high near the mouth of Juan de Matte Canyon. From Laureles Grade westward to Tomasini Canyon, a branch of the Tularcitos fault aligns with and cuts the edge of the broad fluvial terrace. On Rancho Fiesta Road, a fluvial terrace is tilted 18 degrees toward the Tularcitos fault (map locality 24, sheet 1).

Total post-Miocene vertical displacement of the Tularcitos fault is about 380 m (Fiedler, 1944, p. 237). Graham (1976, p. 151) postulated that at least 3.2 km and possibly as much as 16 km of right-lateral displacement may have taken place along the Tularcitos fault, based on the apparent offset of distinctive beds in the Monterey Formation. Other evidence of strike-slip displacement on the Tularcitos fault includes two earthquake focal mechanisms with right-reverse-oblique-slip movement. Offset Holocene colluvium and clustered epicenters indicate that the Tularcitos fault is active (Rosenberg and Clark, 1994).

Berwick Canyon Fault

The Berwick Canyon fault extends northwestward from the Carmel River about 5.5 km to just south of State Highway 68, and locally offsets Pleistocene terrace deposits. The main trace of the Berwick Canyon fault is defined by intensely fractured, steeply dipping Monterey shale in an area of otherwise gently folded beds. On topographic maps and aerial photographs, the fault appears as a series of aligned linear drainages and poorly developed topographic benches and saddles. The Berwick Canyon fault appears to have sheared and offset Pleistocene terrace deposits (map locality 23, sheet 1).

The dip of the fault is probably near-vertical to steeply dipping with a reverse sense of displacement, based on the geometry and relationship to nearby faults. The total amount of displacement is not known, although Younse (1980) shows approximately 100 m of vertical offset along the Berwick Canyon fault near Buckeye Canyon.

Offset terrace deposits demonstrate post-middle Pleistocene movement on the Berwick Canyon fault. Vaughan and others (1991) logged an exploratory trench across the projected fault trace and noted offset colluvial wedges. Radiocarbon dating of the colluvium indicated two or three episodes of movement during Holocene time.

Laureles Fault Zone

The Laureles fault zone extends discontinuously in a zone as much as 0.3 km wide for approximately 6.5 km along the foothills on the north side of Carmel Valley. Faults in the zone are northwest-striking and nearly vertical, separating Cretaceous granitic rock and Miocene marine sandstones. Steep to near-vertical dipping Monterey shale locally offset against Pleistocene terrace deposits characterizes the Laureles fault zone from Tomasini Canyon to Laureles Grade. An anomalously thick section of middle Miocene sandstone was encountered in a water well adjacent to the south side of the Laureles fault about 150 m west of Laureles Grade. Granite was not encountered to the total depth of 176 m, although it crops out nearby on the north side of the fault (R.R. Thorup, oral commun., 1992).

From Laureles Grade southeastward to Carmel Valley Village, the fault zone separates Salinian basement on the north from steeply dipping middle Miocene sandstone. Northeast of Carmel Valley Village, the Laureles fault zone continues eastward into a large landslide deposit and dies out. Fiedler (1944) showed the Laureles fault zone truncated by a cross-fault; but field evidence and analysis of aerial photographs do not support this interpretation.

Estimates of vertical displacement on the Laureles fault zone range from about 180 m (Fiedler, 1944) to 300 m (Herold, 1935). Clearly offset Quaternary deposits are limited along the Laureles fault zone, although we have interpreted a scarp east of Juan de Matte Canyon as tectonic in origin rather than the erosional edge of the terrace deposit, as mapped by Dupré (1990b). On a spur ridge approximately 120 m west of Juan de Matte Canyon, an en echelon segment of the Laureles fault offsets a small patch of Pleistocene fluvial terrace gravel (map locality 25, sheet 1). This limited exposure suggests that the latest movement on the Laureles fault zone is probably post middle(?) Pleistocene.

Snively Fault

Brown (1962) mapped a northwest-striking fault on the southwest side of Snivelys Ridge separating granite and sandstone. This fault appears to be the northern extension of the Piñon Peak fault of Trask (1926), which Bowen (1965) named the Snively fault. The combined length of these faults is approximately 4 km. The Snively fault has approximately 210 m of reverse throw, and separates Miocene sedimentary rock from granitic basement rock (Trask, 1926).

O'Rourke (1980) used exploratory borings and magnetometer data to extend the Snively fault north beneath the large landslide in the NE$^{1}/_{4}$ sec. 25, T. 16 S., R. 1 E. Rosenberg (1993) field checked 10-m-deep dozer excavations within the landslide area and found no Quaternary evidence for the concealed portion of the Snively fault mapped by O'Rourke (1980) and Clark and others (1974). On aerial photographs, the fault appears as a prominent linear feature flanked by several landslides. Within the study area, Quaternary landslide deposits are not offset by the Snively fault, suggesting that the fault is not active.

Hatton Canyon Fault Zone

A group of northwest-striking, near-vertical reverse faults that juxtapose Monterey shale against Pleistocene terrace deposits constitutes the Hatton Canyon fault zone. The Hatton Canyon fault zone extends from Carmel Valley Road northwest 11.5 km to Point Joe on the coast.

Along the north side of Carmel Valley Road, the fault is marked by intensely fractured, steeply dipping Monterey shale in an area of otherwise gently dipping beds. On Carmel Valley Road, the fault offsets landslide and terrace deposits (map locality 19, sheet 1). Along the projected trend of the fault is a possible hydrogeologic barrier at September Ranch (map locality 18, sheet 1). Ground water elevations on the south side of the fault were approximately 3 m higher than those on the north side of the fault (Oliver, 1991). Driller's logs for the wells along this barrier record a repeated section of shale, indicating reverse faulting.

North of the inactive Sierra Quarry, the fault has rotated terrace deposits (map locality 20, sheet 1). In a construction excavation, the fault clearly offset Monterey shale against a fluvial terrace deposit and landslide deposit (map locality 12, sheet 1). Colluvium overlying the fault thins abruptly on the upthrown side of the fault; however, the fault strand is obscure within the colluvium. Dating of this colluvium yielded a ^{14}C age of 2,080±40 yr B.P., suggesting Holocene movement.

About 1 km east of Hatton Canyon, gently folded fluvial terrace deposits above the mapped trace of the fault are cut by near-vertical clay-filled fractures that strike approximately N. 60∞ E. (map locality 11, sheet 1). The Hatton Canyon fault continues from State Highway 1 to Point Joe. Although exposures are poor in the densely vegetated canyons, discordant structural attitudes and prominent aligned linear drainages suggest faulting. The Hatton Canyon fault may continue offshore as a series of short en echelon faults mapped by H.G. Greene (oral commun., 1994).

The total displacement along the Hatton Canyon fault is unknown, but undivided terrace deposits of Pleistocene age located about 120 m south of map locality 12 are approximately 30 m lower in elevation. This difference in elevation suggests at least 30 m of vertical offset during or after Pleistocene time. Several earthquakes that align with the Hatton Canyon fault indicate recent activity (Rosenberg and Clark, 1994).

Cypress Point Fault

The Cypress Point fault extends for 3 km juxtaposing the Carmelo Formation with granodiorite at Pescadero Point and basaltic andesite with granodiorite at Carmel Point, with the northeast side relatively downthrown. Seismic profiles offshore indicate that a segment of the Cypress Point fault extends northwestward from Cypress Point for about 3 km as a single continuous fault (Greene and othes, 1973). A zone of discontinuous, en echelon faults continues for another 3 km to the southern wall of Monterey Canyon. The fault is identified in the seismic reflection profiles principally from juxtaposition of sediments of questionable Pleistocene age against granodiorite and from linear topographic expressions on the sea floor.

At Carmel Point ,vesicular basaltic-andesite flows and basaltic-andesite flow breccias are faulted against porphyritic granodiorite to the southwest in a 4 to 7-m-wide brecciated zone. In May 1993, severe beach erosion revealed a 60-m-long exposure of the fault striking N. 50∞ W., implying that the faults at Pescadero Point and Carmel Point are en echelon segments rather than continuous.

Field work by Clark (1989) on Palo Corona Ranch and along the canyon of San Jose Creek to the southeast failed to reveal any significant structural or stratigraphic discordances that would permit the extension of this fault southeastward to San Jose Creek canyon or beyond to the Blue Rock/Miller Creek fault zone 15 km to the southeast, as hypothesized by Ross (1976).

Exploratory drilling and seismic profiling suggest a vertical displacement of as much as 30 m for the Cypress Point fault (Staal, Gardner & Dunne, 1989). Right-lateral displacement is also possible, based on the relatively straight trend and en echelon character.

East of Carmel Point, the terrace platform (about 102 ka, according to Dupré, 1990a) appears to be more than 1 m higher above the basaltic andesite northeast of the fault than on the granodiorite to the southwest. suggesting late Quaternary movement on the Cypress Point fault. Alternatively, this elevation difference across the fault could result from deposition on an irregular platform surface. McCulloch and Greene (1989) show the offshore segment of the Cypress Point fault cutting Quaternary strata.

QUATERNARY DEFORMATION

General Statement

Several lines of geologic evidence indicate ongoing tectonic deformation in the study area. These include faulted, folded, and tilted Pleistocene terrace deposits; faulted Holocene colluvium; and earthquake epicenters that align with mapped fault traces.

Structural Framework

The Tularcitos/Navy fault is the dominant through-going fault in the study area. Microseismic data suggest that the Tularcitos/Navy fault extends to nearly 14 km depth. En echelon faults, such as the Laureles, appear to branch off at shallower depths.

Depth to basement increases northeastward across each block of the zone between the Chupines, Seaside, and Ord Terrace faults. One interpretation is that these faults are imbricated and splay off the Chupines or possibly the Navy fault . This is consistent with an uplifted block in a strike-slip fault zone in which sinuous faults splay from the main fault in “palm tree structure” (Sylvester, 1988, p. 1687).

Folding and Tilting

Two types of folds are common in the study area: (1) very tight and broken folds such as those occurring in the Monterey Formation next to fault zones, and (2) much broader, open folds that are as much as 8 km long. The broader fold axes are oblique to the trend of the through-going faults and trend mainly N. 65∞–85∞ W. Most of these major folds are subparallel to faults (N. 40∞–50∞ W. trend) and are truncated by faults, suggesting that folding was penecontemporaneous with strike-slip faulting.

The number and intensity of folds increase southward between the Chupines fault and the Hatton Canyon fault. This is especially evident in the zone between the Sylvan thrust and the Hatton Canyon fault. In this zone of deformation, isolated terrace remnants dip approximately 10 degrees. The distribution of earthquakes suggests that this deformation is caused by movement on these and related faults at depth, including an inferred blind thrust fault (Rosenberg and Clark, 1994).

Folding and tilting of Quaternary deposits is evident at several places. Northeast of the Chupines fault, outcrops of Pleistocene continental deposits dip as much as 20 degrees along the paired anticline and syncline south of Laguna Seca. Similarly, in the Seaside area, subsurface marker beds in the Pleistocene continental deposits dip almost 28 degrees along the anticline northeast of the Ord Terrace fault (Staal, Gardner & Dunne, 1990a, cross section C-C').

Younger terrace deposits are folded and faulted along the trace of the Sylvan thrust fault, although soft-sediment deformation is an alternate explanation locally. Gently folded and fractured terrace deposits are exposed above the mapped trace of the Hatton Canyon fault (map locality 11, sheet 1). These two examples imply post-middle Pleistocene deformation.

Tilted terrace deposits ranging in age from early to late Pleistocene are exposed in the Monterey and Carmel Valley hills. North of Huckleberry Hill (map locality 13, sheet 1), an early Pleistocene terrace is tilted approximately 13 degrees. On the north side of the Carmel River, the youngest and lowest fluvial terraces are tilted as much as 22 degrees (map localities 7, 8, and 11; sheet 1). Because these tilted terraces are adjacent to faults and untilted terraces are exposed elsewhere, the tilted terraces represent local deformation rather than regional uplift.

Quaternary Displacement Rates

Many of the faults in the study area cut Quaternary deposits, and the Tularcitos, Hatton Canyon, and Sylvan faults offset Holocene colluvium. The amount of displacement is easily measured; however, the absolute ages of most deposits are uncertain. A framework for determining the relative ages of the Quaternary deposits is outlined by Dupré (1990a). Dupré estimated ages of Monterey terraces by correlating these terraces with known sea level highstands and radiometrically dated terraces in Santa Cruz. Using this age framework, Quaternary vertical displacement rates range from 0.01 mm/yr (Cypress Point fault) to 0.41 mm/yr (Sylvan thrust fault) and average about 0.11 mm/yr (Rosenberg and Clark, 1994). This average rate is slightly lower than the 0.18 uplift rate for the Monterey area estimated by Dupré (1991). The lower rate probably reflects that fault displacements produce episodic uplift, whereas sea level curves represent long-term rates. The rugged topography in the study area also indicates relatively high long-term uplift rates.

Of the faults in the study area, the Sylvan thrust has the highest rate of uplift and the greatest number of recorded earthquakes. This high rate of uplift is related to transpression between the Hatton Canyon and Navy faults. The density of fold axes between these faults supports active folding as an explanation for the high uplift rate on the Sylvan thrust fault.

The vertical slip rate of the Navy fault is anomalously low at 0.02 mm/yr. This low rate corroborates the first-motion and geomorphic data indicating lateral displacement. Alternatively, the apparent lack of vertical displacement could result from stripping of Quaternary deposits during lower stands of sea level.

Quaternary horizontal displacement rates are difficult to calculate because of the absence of suitable markers. Local erosion rates are rapid; as a result, features that could be used for estimating horizontal displacement are lacking. The only estimate of horizontal displacement on local faults is the 2 mm/yr cited by Vaughan and others (1991) for the Chupines fault.

Alternatively, the lack of visible horizontal surface displacement can be explained using the strain partitioning model of Lettis and Hanson (1991). In their model, "oblique strain in the lower lithosphere may partition upward in the brittle crust into nearly pure strike-slip and dip-slip deformation, the dip-slip component being expressed as reverse faults and folds." This model accounts for the strike-slip sense of displacement indicated by focal-plane mechanisms and for the observed reverse stratigraphic displacement near the surface. The implication of this model is that short faults, such as the Sylvan thrust fault, are the upper crustal expressions of a seismic zone at depth.

Maximum Earthquakes

An important issue for planning purposes is assessing the largest size earthquake that is likely to occur along a fault. One approach is to determine the maximum earthquake (M_{max}) by using geologic and seismologic data. Calculating the maximum earthquake involves estimating fault characteristics and using empirical relationships to relate these characteristics to earthquake magnitude. Recent work by Wells and Coppersmith (1994) uses moment magnitude (M_w) rather than surface wave magnitude (M_s) to estimate maximum earthquake magnitudes. Using the regression equations of Wells and Coppersmith (1994), maximum earthquakes for local Quaternary faults are listed in table 2.

Table 2. Maximum earthquakes for local faults.

Fault and main type of movement	Dip (degrees)*	Fault length (km), Depth (km), Downdip width (km)*	Rupture area (km^2)†	Moment magnitude (M_w)§
Berwick Canyon (reverse)	85	5.5, 6, 8.0	22	5.5
Chupines (strike-slip)	85	30, 10, 13	200	6.3
Chupines (reverse)	85	30, 10, 13	200	6.4
Cypress Point (reverse)	85	12, 8, 11	64	6.0
Hatton Canyon (reverse)	80	11, 7, 9.5	52	5.9
Laureles (reverse)	75	6.5, 5, 6.9	22	5.5
Ord Terrace (reverse)	75	9.8, 6, 8.3	40	5.8
Seaside (reverse)	80	18, 6, 8.1	73	6.0
Sylvan thrust (reverse)	55	4.0, 6, 9.7	19	5.5
Tularcitos/Navy/Monterey Bay (strike-slip)	85	74, 13, 17	642	6.8
Tularcitos/Navy/Monterey Bay (reverse)	85	74, 13, 17	642	6.9

* Fault parameters from Rosenberg and Clark (1994) except for the Tularcitos/Navy/Monterey Bay fault zone length which is from Rosenberg (1993).

† Rupture area (RA) equals subsurface rupture length times downdip width. Assumes that surface rupture length is approximately 75 percent of subsurface length (Wells and Coppersmith, 1994) and that surface rupture length is one-half of mapped fault surface length.

§ For reverse faults $M_w = 4.33 + 0.90(\log(RA))$, for strike-slip faults $M_w = 3.98 + 1.02(\log(RA))$.

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