ABSTRACT

The tectonic and structural evolution of the Monterey Bay region of central California is complex and diverse. Onshore and offshore geologic investigations during the past two decades indicate that the region has been subjected to at least two different types of tectonic forces; to a pre-Neogene orthogonal converging plate (subduction) and a Neogene-Quaternary obliquely converging plate (transform) tectonic influence. Present-day structural fabric, however, appears to have formed during the transition from a subducting regime to transform regime and since has been modified by both strike-slip and thrust movement.

Monterey Bay region is part of an exotic allochthonous structural feature known as the Salinian block or Salinia tectonostratigraphic terrane. This block is proposed to have originated as part of a volcanic arc a considerable distance south of its present location, somewhere between the Transverse Range (being the displaced segment of the southern Sierra-Nevada Mountain Range) and the latitude of Central America. It consists of Cretaceous granodiorite basement with an incomplete cover of Tertiary strata. Paleogene rocks are scarce, evidently stripped from the block during a time of emergence in the Oligocene time.

The Salinian block is presently located on the Pacific plate at the Pacific and North American plates' active tectonic boundary. This boundary shifted to a transform margin approximately 21 Ma when the Mendocino triple-junction passed through the Monterey Bay region. Since that time the Salinian block has been moving northward along the San Andreas fault zone and basin and ridge topography was generated within the strike-slip Faults of the San Andreas fault system. Sometime between 5 and 3.5 Ma, due to the shift in the direction of Pacific plate motion and the development of a more orthogonal convergence between the Pacific and North American plates, compressional forces became more pronounced in the region. The 1979 Loma Prieta earthquake and recently reprocesses multichannel seismic-reflection data offshore indicate that the the Monterey Bay region is presently being subjected to both strike-slip (wrench) and thrust (compressional) type tectonic forces.

INTRODUCTION

The coastal region of central California from Monterey Bay to San Francisco, encompasses a geologically complex part of the continental margin of North America, the California Coast Ranges Province (Fig. 1). Interest and knowledge of the geology of this region has increased significantly over the past two decades due to detailed mapping and the recasting of the Tertiary tectonic history of the area in light of plate tectonic concepts (McKenzie and Parker, 1967; Morgan, 1968; Atwater, 1970; Atwater and Molnar, 1973; McWilliams and Howell, 1982; Howell et al., 1985a; McCulloch, 1987). The purpose of this paper is to review the structure and tectonics of the region, with emphasis on the Monterey Bay area.

Monterey Bay is a nearly crescentic bay that lies along the central California coast approximately 115 km south of San Francisco (Fig. 1). It was named by the Spanish explorer Sebastian Vizcaino who in 1602-1603 voyaged up the coast of California to as far as Cape Mendocino, and named many prominent land features with the familiar names we know and use today. The bay measures 37 km across its mouth between Point Santa Cruz and Point Pinos. The towns of Santa Cruz and Monterey are located on the bay's north and south shores, and Moss Landing is positioned approximately in the middle of the east shore (Fig. 1).

Topography is varied along the coast between San Francisco and Point Sur. Steep cliffs with flat-topped terraces interspersed with sandy pocket beaches, including the half crescent-shaped embayment of Half Moon Bay, are characteristic of the coastal region from San Francisco to Soquel Point. From Soquel Point southward almost to Moss Landing, cliffs fronted by sandy beaches are prevalent. Broad sandy beaches backed by large dune fields stretch southward in an unbroken line from Moss Landing to the rocky headland of the Monterey Peninsula, and from this point southward to Point Sur steep, rocky cliffs predominate.

Low to high relief mountain ranges and broad, flat-floored valleys are prevalent farther inland. The Santa Cruz and Gabilan mountain ranges dominate the topography in the northern and central half of the region. Two major rivers enter Monterey Bay from these highlands through well defined valleys. The San Lorenzo River enters Monterey Bay
at the town of Santa Cruz, and the Pajaro River empties into the bay 6 km north of Moss Landing (Fig. 1). Elkhorn Slough, an old river estuary that today is occupied only by tidal salt marshes, extends inland from Moss Landing for more than 10 km. The broad, extensive Salinas Valley and the northern Santa Lucia Range are the dominant topographic features in the southern half of the region, where the Salinas River is the major drainage system and empties into Monterey Bay 8 km south of Moss Landing. South of Monterey, the west flank of the Santa Lucia Range drops abruptly into the ocean. The valley of the Carmel River, which empties into the Pacific Ocean in Carmel Bay, and the Little Sur River, which enters the ocean 6.5 km north of Point Sur, are dominant topographic features in the southern part of the region (Fig. 1).

Figure 1. Generalized regional index map of the central California coastal region showing locations of major cultural and geomorphic features.
Figure 2. Submarine physiographic diagram generated from SeaBeam data collected by NOAA. Diagram courtesy of NOAA, National Ocean Services, Rockville, Maryland.
**SUBMARINE PHYSIOGRAPHY**

The undersea topography of the Monterey Bay region is as diverse and even more spectacular than that onshore. The submarine Ascension-Monterey Canyon system that comprises Monterey submarine canyon, fan-valley, and fan dominates the submarine topography, exhibiting much greater relief than similar features onshore (Fig. 2; see Greene, this volume). Monterey Canyon was first described by Davidson (1897), who noted that

"... at Monterey Bay there is a complete breaking down of the Coast Ranges from 25 miles [40 km]; with the mountains receding well inland. Into this broad and deep bight heads the finest of submerged valleys."

Monterey Canyon cuts deeply into the flat shelf of Monterey Bay, heads less than 2 km seaward of the mouth of Elkhorn Slough, extends westward for over 90 km, and bisects the bay along its trend (Fig. 2). It is one of the world’s widest, deepest, and longest submarine canyons; its overall dimensions are comparable to those of the Grand Canyon of the Colorado River (Martin, 1964; Shepard and Dill, 1966).

Other canyons of the system, Ascension (named for Fray Ascension, a Spanish priest who accompanied the Vizcaino expedition), Año Nuevo and Cabrillo Canyons, cut into the continental slope about 35 km northwest of Santa Cruz. Several of the eleven branches that compose the headward parts of these canyons cut the distal edge of the continental shelf, but do not continue to the shoreline. These canyons converge at a depth of about 2,200 m and connect with Monterey Canyon at a depth of 3,290 m. Monterey Canyon is joined directly with two smaller canyons, Soquel and Carmel Canyons (Fig. 1). Soquel Canyon heads far out on the continental shelf, in the northern part of Monterey Bay. The head of Carmel Canyon lies in Carmel Bay, 58 km south of the head of Monterey Canyon, only 30 m offshore. Both Carmel and Soquel Canyons steepen in gradient as they approach Monterey Canyon.

Further north along the coast, between Año Nuevo Point and San Francisco, two other submarine canyons are present (Fig. 2). One canyon, located off Pescadero Point, is unnamed and is restricted to the continental slope (Fig. 1). North of this canyon, offshore and west of Half Moon Bay, Pioneer Canyon is located. This canyon also does not cut the continental shelf, but is restricted to the slope where it generally trends in a straight line between Pioneer and Guide Seamounts, two volcanic seamounts located at the base of the continental slope.

**TECTONIC SETTING**

The geology of the coastal central California region is diverse and tectonically defined by allochthonous blocks or tectonostratigraphic terranes of Coney et al. (1990), Jones (1983) and Howell et al. (1983, 1985a). McWilliams and Howell (1982) describe two major tectonic components for the coastal central California region, the Sur-Obispo composite terrane and the Salinian terrane (Fig. 3). These two terranes make up the Santa Lucia-Orograpa allochthon. The Sur-Obispo composite terrane is composed of the Stanley Mountain and San Simeon terranes which lie west of the Sur-Nacimiento and the San Gregorio fault zones (Fig. 3). The Stanley Mountain terrane is composed of a Middle Jurassic ophiolite overlying thick Upper Jurassic to Upper Cretaceous forearc basin strata that resemble, and are coeval with, the Great Valley sequence. Lying structurally beneath the Stanley Mountain terrane is the San Simeon terrane, a Franciscan melange formed approximately 72 Ma.

The Monterey Bay region is located on the major structural element known as the Salinian block of Page (1970), or Salinia terrane of Howell et al. (1985a, b). The Salinian block consists of continental crust composed principally of Cretaceous granitic rocks and metamorphic rocks of indeterminate age, it is flanked on either side by a heterogeneous aggregation of Jurassic and Cretaceous eugeosynclinal rocks assigned to the Franciscan assemblage. The northeast and southwest boundaries of this block are formed by the San Andreas and Sur-Nacimiento fault zones, and it extends from the Transverse Ranges northward almost 800 km to Cape Mendocino (Page, 1970; Silver et al., 1971). It was initially proposed that the Salinian block was a mass of Sierran granitic basement displaced northward during...
Figure 4. Paleolatitude of the Salinian and Stanley Mountain terranes as a function of time, compared with paleolatitude of "target area" on North America for present-day position, 35°-39° north latitude. Stippled path represents the two terranes after suturing. The North American and Salinian/Stanley Mountain tracks intersect at ~50 Myr BP.

- Data from Sur-Obispo terrane.
- Paleomagnetic data from Salinian terrane.

Arrows in lower right give northward velocity in cm/yr for reference. The dashed and solid lines represent alternative paleolatitudes for the Stanley Mountain terrane depending on the choice of magnetic polarity. (After McWilliams and Howell, 1982.)

Tertiary time by movement along the San Andreas fault, with the Sur-Nacimiento fault zone representing a displaced segment of the boundary between Sierran and Franciscan basement rocks (Hill and Dibblee, 1953; King, 1959; Page, 1970). However, McWilliams and Howell (1982), based on paleomagnetic data from upper Cretaceous strata on the Salinian block, proposed that this exotic terrane was displaced from a location 2,500 km to the south. They show that the Stanley Mountain and Salinian terranes collided in Cretaceous time (~72 Ma), in the latitude of Central America, to form a new amalgamated terrane that then moved northward (Fig. 4). Accretion of the Sur-Obispo composite terrane to North America occurred in late Paleocene to early Eocene time (McWilliams and Howell, 1982).

Tectonic Blocks of the Salinian Terrane

Beginning with Lawson in 1914, many geologists have described the structure of the Coast Ranges in terms of orographic or tectonic blocks (Clark and Rietman, 1973). Likewise the Salinian block in the Monterey Bay region was described by Clark (1930) as comprising a series of smaller, elongate, northwest-trending, uplifted blocks and basins. The basins—Santa Cruz basin (La Honda basin of Clark and Rietman, 1973 and Stanley, this volume), Salinas graben, and Santa Lucia basin—are separated from each other by faults and by structural highs known as the Ben Lomond, Gabilian, and Toro Mountain blocks (Fig. 5a). The most northerly

Figure 5. Historical development of subdivision of the Salinian terrane in the Monterey Bay region into tectonics, "orographic" blocks (modified after Greene, 1977).
basin delineated in this region by Clark (1930) is the Santa Cruz basin (La Honda basin), a synclinorium in a thick sequence of Tertiary sedimentary rocks located between the central Santa Cruz Mountains and the northern Gabilan Range. This basin (described in greater detail by Stanley, this volume) is separated from the Ben Lomond block to the southwest by the Ben Lomond fault. Evidence from gravity data tends to confirm Clark’s (1930) belief that the Santa Cruz basin (La Honda basin) extended southeastward to the San Juan Bautista area during early Tertiary time (Clark and Rietman, 1973). The largest structural depression of the region, variously termed the Salinas graben (Clark, 1930), Salinas trough (Starke and Howard, 1968), and King City flexure (Fairborn, 1963), extends from Monterey Bay down the Salinas Valley to King City, and is bounded on the northeast and southwest by the Gabilan and Toro Mountain blocks. Southwest of the Toro Mountain block is an irregular area named the Santa Lucia basin by Clark (1930).

Martin and Emery (1967) divided that part of the Salinian block underlying the Monterey Bay area into three tectonic blocks: the Gabilian stable area, the Monterey semi-stable area, and the Monterey graben (Fig. 5b). The Gabilian stable area is bounded on the northeast by the San Andreas fault zone, and is separated from the Monterey graben and Monterey semi-stable area to the southwest by the Gabilian-King City fault of Martin and Emery (1967). The Monterey graben and Monterey semi-stable area, in turn, are separated from the central Franciscan area to the west by the Carmel Canyon fault (later extended and named the Palo Colorado-San Gregorio fault zone by Greene et al., 1973), and the San Gregorio-Hosgri fault zone by Graham (1978), and from each other by the so-called Monterey fault located in lower Monterey Canyon (Martin and Emery, 1967).

Based on their petrologic analysis of basement rocks, Ross and Brabb (1972) have divided the Salinian block in the Monterey Bay region into four tectonic sub-blocks: the Zayante-Vergeles block, Ben Lomond block, Gabilian block, and the Monterey block (Fig. 5c). The Zayante-Vergeles block is bounded on the northeast by the San Andreas fault, and is separated from the Ben Lomond and Gabilian blocks to the southwest by the Zayante-Vergeles fault. The Ben Lomond and Gabilian blocks, in turn, are separated from each other by the Santa Cruz fault of Ross and Brabb (1972), which since has been dropped because no evidence of it has been found. The Monterey block is bounded on the southwest by the seaward projection of the Sur-Nacimiento fault zone, and is separated from the Ben Lomond and Gabilian blocks to the northeast by the northwestward extension of the King City fault. Clark and Rietman (1973) consider the Ben Lomond and Gabilian blocks of Clark (1930) to be a single block, terming it the Ben Lomond-Gabilian block. This block separates the Santa Cruz basin of Clark (1930) from the Santa Lucia basin (Fig. 5).

The "orographic" and "tectonic" blocks of the various authors mentioned above were redefined by Greene (1977) on the basis of subsurface geophysical (seismic-reflection) data collected in Monterey Bay. Four blocks—the Ben Lomond, Monterey, Salinas, and Santa Lucia—appear to have had a major influence on the Tertiary stratigraphy of the offshore area east of the Palo Colorado-San Gregorio fault zone (Fig. 5d).

The southern edge of the uplifted Ben Lomond block abruptly plunges to the southwest in northern Monterey Bay (Fig. 5d). Strata of the Monterey block to the south lap onto and wedge out against this basement high. The Monterey block forms a relatively flat, shallow basin that extends from the Zayante fault westward to the Palo Colorado-San Gregorio fault zone offshore, where the block may be truncated (Figs. 5d and 6). In the southwestern part of Monterey Bay the northern edge of the uplifted Santa Lucia block, which forms the northern Santa Lucia Range and the Monterey Peninsula, is separated from the Monterey block to the north by Monterey Canyon. To the east, faults within the Monterey Bay fault zone mark the boundary between the Santa Lucia and Salinas blocks. The Salinas block contains sediments of the Salinas basin that lap onto the Monterey high (Fig. 5d). The Monterey high separates the Monterey and Salinas blocks (Fig. 6).

Regional structure and stratigraphy are different and less well understood west of the Palo Colorado-San Gregorio fault zone than to the east. Identification of tectonic blocks west of the Palo Colorado-San Gregorio fault zone is difficult because of the absence of data, and because true and acoustical basement are not correlative. However, a discrete zone of complexly deformed rocks termed the Sur Sliver by Greene (1977), lying between the Palo Colorado-San Gregorio fault and the Ascension fault of Greene (1977), separates the contrasting tectonic regimes of the Monterey Bay area and the continental slope (Figs. 6 and 5d). Because of right-lower and compression (thrusting) along the Ascension Fault and faults within the Palo Colorado-San Gregorio and Monterey Bay fault zones, differing structural units are juxtaposed on either side of the Sur Sliver, which is characterized by neither positive nor negative displacement.

Assuming acoustical basement west of the Palo Colorado-San Gregorio fault zone to either directly represent true basement or to indirectly express basement relief, three tectonic blocks were delineated along the continental slope seaward of the Monterey Bay area (Greene, 1977). These are the Ascension high, the Monterey low (Monterey basin), and the Sur high (Figs. 5d and 6). The Ascension high is an acoustical basement dome supporting the submarine upland between the Ascension and Monterey submarine canyon systems (Greene, 1977; Nagel et al., 1986). It is bounded both on the east and west by faults that appear to displace only Miocene and older strata. To the southeast these same faults bound the Monterey basin, which is bisected by the lower Monterey Canyon. The Sur high lies in fault contact along the southwest side of the Monterey basin. This is an acoustical basement high extending northwestward from Point Sur.

Tectonic Movement

The central California coastal region records a complex late Cenozoic sedimentary history. Tectonic uplift and depression have produced a succession of regressive and transgressive sedimentary units (Fig. 7), while contemporaneous right-lower along faults of the San Andreas system has
Figure 6. Offshore basement contour map of the Monterey Bay region, central California (after Greene, 1977; Greene and Clark, 1979).

EXPLANATION

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FAULT
Solid where well defined; dashed where approximately located or poorly defined; queried where questionable located or obscure

BASEMENT RIDGE CREST
Arrow indicates direction of plunge

BASEMENT TROUGH AXIS
Arrow indicates direction of plunge

PALEODRAINAGE LINES

CONTACT-BASEMENT EXPOSURE

BASEMENT CONTOUR
Two digit numbers (4.0) represent seismic two-way travel time in seconds. Four digit numbers (4000) represent depth in meters based on an assumed seismic velocity of 2 kilometers per second

EXPLORATORY OIL AND GAS WELLS
Single to two digit numbers are well numbers. Three digit numbers are depth in meters below sea level to surface of basement rocks

Figure 7. Generalized stratigraphic cross section showing transgressive-regressive relationships of Neogene sedimentary units in the onland regions adjacent to Monterey Bay (after Greene and Clark, 1979).
offset major structural and lithologic elements (Hill and Dibblee, 1953; King, 1959; Hamilton, 1969; Page, 1970; Suppe, 1970). In addition, diastrophism resulting in the deformation or removal of some sedimentary units has produced three regional and several local unconformities within the upper Tertiary rocks (Fig. 7). In the Monterey Bay offshore area mainly the Neogene history is recorded in the sedimentary rocks, whereas onshore the Neogene and locally the Paleogene histories are recorded. paleogene units appear to have been present offshore, but were extensively eroded by pre-middle Miocene erosion, possible being preserved in small wedges on the Monterey shelf and in the deeper parts of offshore sedimentary basins.

During Late Cretaceous and early Tertiary time, subduction and underthrusting of an oceanic (Farallon) plate occurred along the continental margin off central and southern California (Atwater, 1970; Atwater and Molnar, 1973). Monterey Bay at this time was located in the north part of the southern California Continental Borderland, near the present location of the Transverse Ranges. Subduction ceased in the Monterey Bay in early Tertiary time (~21 Ma), coincident with the northward migration through the region of the Mendocino triple junction and the local subduction of the Farallon plate. Thereafter the relative motion between the Pacific and North American plates was expressed as strike-slip along the San Andreas fault system; in the Monterey Bay region this system is composed of parallel to subparallel faults located between Ascension fault offshore and the Hayward-Calaveras fault zone onshore (Fig. 8) (McKenzie and Parker, 1967; Morgan, 1968; Atwater, 1970; Atwater and Molnar, 1973). Although the boundary between these two rigid plates was commonly portrayed as a single through-going transform fault, several workers think that some motion was taken up on other faults of the system (Atwater, 1970; Johnson and Normark, 1974; Graham, 1976; Greene, 1977; Greene and Clark, 1979). Movement on the San Andreas fault itself only accounts for about 40 percent of the relative plate motion (Plafker and Galloway, 1989).

Cox and Engebretson (1985), based on shifts in the alignments of volcanic centers along the Hawaiian hotspot trace, proposed that many of the compressional features formed parallel to the San Andreas fault in the last 5-3 M.y. result from a shift in Pacific plate motion with an increase in plate convergence continuing from the Pliocene to Pleistocene time. Pollitz (1986), however, based on correlations of computed hotspot tracks within the Pacific and the Nazca hotspot, places the time of plate motion change at between 5 and 3.2 Ma. He suggests, based on work by Epp (1978), that the slip rate along the San Andreas fault decreased by about 22 mm/yr since 3.2 Myr ago. This is also the time that the divergence within the Gulf of California started (Mammerickx, 1980). Both Cox and Engebretson (1985) and Pollitz (1986) relate the shift in plate motion to plate torque brought about from slab detachments within the western Pacific.

Johnson and Normark (1974) and Howell (1976) have suggested that slivering and northwestward extension of the Salinian block occurred along faults west of the San Andreas during Neogene time. However, Howell (1975) and Clarke et al. (1975) argue for a Late Cretaceous episode of slivering south of the Monterey Bay region in order to create the borderland physiography inferred for Late Cretaceous and Paleogene rocks of west central California. The style of faulting observed in the Monterey Bay offshore area suggests that the Salinian block in this region has a history of tectonic "slivering" that continues into the present (Greene, 1977). Elongation of the block appears to be resulting from strike-slip along faults inside the block that are within the San Andreas fault system, such as the Palo Colorado-San Gregorio and Hayward fault zones (Greene et al., 1973; Greene, 1977; Greene and Clark, 1979; Clark et al., 1984). Also, stresses built up in the San Andreas fault system are released along faults within the Monterey Bay fault zone, considered part of the San Andreas fault system. Burford (1971) noted that a sequence of fault creep and small earthquakes on the San Andreas fault near Pinnacles National Monument abruptly ceased with a magnitude 4.3 earthquake (August 3, 1970) in Monterey Bay, probably within the Monterey Bay fault zone.

One probable effect of slivering the Salinian block is to produce a serrated, rather than a straight, western boundary for the block. Fragmentation of this margin as the Salinian block moves northward along the San Andreas fault seems likely; in this case fragments and slivers of basement rocks may have been pushed ahead of the main block or shoved out alongside the block, where they exist as isolated pods west of the Sur-Nacimiento and Palo Colorado-San Gregorio fault zones (Greene, 1977).

The recent 1989 7.1 magnitude Loma Prieta earthquake exhibited both horizontal (right-lateral slip) and vertical (thrust) motion (Plafker and Galloway, 1989; see Earthquakes below). Although the San Andreas fault is primarily a straight, right-slip fault zone, a prominent bend in the fault at the location of the epicenter and slight convergence in relative plate motion favor both horizontal and vertical offsets (Donna Eberhart-Phillips, written comm., 1989). The Salinian block, being carried along by the Pacific plate, was thrust up onto the North American plate, as well as pushed right-laterally to the north. Reprocessed multi-channel seismic-reflection profiles collected by the USGS in 1983 along the western margin of the Salinian block also show evidence of thrusting along this margin (Fig. 9). Several lines across the southern offshore extension of the Palo Colorado-San Gregorio fault zone exhibit thrust faults verging to the east that may be the result of the shift in plate motion proposed to have occurred 8-3 Ma (Cox and Engebretson, 1985; Pollitz, 1986). Plafker and Galloway (1989) state that compression associated with oblique convergence between the Pacific and North American plates, which is perpendicular to the San Andreas fault, caused uplift of the mountains and deformation of younger rocks within the Santa Cruz Mountains. McLaughlin (1974) indicates that thrust faults that bound the northeastern margin of the southern Santa Cruz Mountains are active with the mountain side moving upward and northeastward relative to the valley side.
Therefore, it appears that there may be a series of inclined fault surfaces along which the Santa Cruz Mountains, and perhaps the Gabilan and Santa Lucia Ranges, are being thrusted. The Salinian block is not only being elongated and pulled apart by northward transcurrent fault movement, but is also being sheared by thrust movement resulting from compression and pushed further eastward onto the North American plate.

Figure 8. Fault map of the central coastal region of California.
Figure 9. Preliminary interpretation of multichannel seismic-reflection profile across the Palo Colorado-San Gregorio fault zone near Santa Cruz showing thrust faults. See Figure 1 for location. U.S. Geological Survey unpublished data.

STRUCTURE

The structure of the Monterey Bay region is complex and is produced largely by post-Miocene tectonic events. Major structures in the Monterey Bay region include faults, folds, and fault-bounded basement ridges associated with sedimentary basins (compressed horsts and grabens). The structural grain of the region is variable in trend, and may chronicle shifts in stress field or changes in the Pacific-American plate boundary since Miocene time. Structural trend is generally northwest-southeast for the region as a whole. However, the Palo Colorado-San Gregorio fault zone trends more north-south than other major faults in the region, obliquely truncating structures in Monterey Bay (Fig. 8). Structures west of the Palo Colorado-San Gregorio fault zone fan out westward away from the fault zone, with a pivot point somewhere south of Point Sur. Faults farthest west are oriented more nearly east-west than structures nearer the fault zone. South and west of the pivot point, structures are oriented nearly north-south. The two major fault zones present along the coastal region of central California, the San Andreas and the Palo Colorado-San Gregorio fault zones of the San Andreas fault system, appear to control structural development of the basins and ranges, although recent (last 3 m.y.) plate convergence has imprinted compressional structural features onto strike-slip features (Cox and Englebreton, 1985). Faults in the Monterey Bay region lie primarily within two major, northwest-trending, converging fault zones, the Palo Colorado-San Gregorio and Monterey Bay fault zones (Fig. 10). The probable offshore extension of the Sur-Nacimiento fault zone may connect with, and become part of the Palo Colorado-San Gregorio fault zone or, as proposed by McCulloch (1989), could have been displaced along the Palo Colorado-San Gregorio fault zone and now be represented by a fault (the Ascension fault of Greene, 1977) located along the edge of the continental shelf north of Monterey Canyon.

Faults

San Andreas Fault Zone

The San Andreas fault zone is the longest, most continuous fault zone in California, extending from the Salton Sea at the extreme southern end of the state for nearly 1,300 km to Cape Mendocino in the north. It is part of a seismically active system, a transform fault system (the San Andreas fault system) that marks the boundary between the Pacific and North American plates. Relative plate motion along this right-lateral strike-slip boundary is 5.6 cm/yr (Circum-Pacific Map Project, 1985). Since its inception (~30 Ma), over 300 km of displacement has occurred (Plafker and Galloway, 1989). The San Andreas fault system not only includes the San Andreas fault zone, but many other faults that lie up to 50 km away from the San Andreas fault zone; for example the Palo Colorado-San Gregorio, Monterey Bay and Hayward-Calaveras fault zones are all considered part of this system of faults.

In the Monterey Bay region the San Andreas fault zone is composed of several faults in addition to the San Andreas, including the Sargent, Butano, and Zayante-Vergeles faults (Fig. 10). All of these faults generally trend parallel or sub-parallel (oriented northwest-southeast) to the San Andreas fault. An exception occurs where the Zayante fault swings westward and becomes east-west trending near Scotts Valley. In this area faulting is complex with the Ben Lomond fault extending away to the south from its intersec-
Figure 10. Structural sketch map of the Monterey Bay region showing locations of faults, folds and major physiographic features. Outline of submarine canyon shown in broad, gray lines; Monterey canyon axis shown by broad, gray, dashed line.
tion with the Zayante fault. The Ben Lomond fault is an arcuate fault that marks the eastern face of Ben Lomond Mountain. It appears to be quiet seismically and may not be an active fault within the San Andreas fault system.

**Palo Colorado - San Gregorio Fault Zone**

The Palo Colorado-San Gregorio fault zone is a narrow (approximately 3 km wide) feature defined by at least two arcuate faults (Fig. 10). It appears to merge to the south with the Serra Hill and Palo Colorado faults onshore (Trask, 1926; Jennings and Strand, 1958; Gilbert, 1971), and to the north with the San Gregorio fault zone, composed of the Coastways and Frijoles (thrust) strands (Weber, 1980, Griggs and Weber, 1990). The length of this fault zone, including its onland segments, is at least 125 km; however, its total length may be considerably greater, for it appears to join faults at Half Moon Bay (Seal Cove fault) that in turn join the San Andreas fault northwest of the Golden Gate (Cooper, 1971). It may also join the Coast Ridge fault to the south of the Monterey Bay region (Ross, 1976).

The Palo Colorado fault onshore, south of Monterey Bay, has been described as a southeast-trending thrust that parallels the coast for approximately 2 km, ultimately bending to the east, with Mesozoic quartz diorite thrust over Cretaceous sandstone (Trask, 1926). According to Trask (1926), the fault plane probably dips 70°NE, with separation of about 1,000 m.

Offshore, south of Monterey Bay, the Palo Colorado-San Gregorio fault zone consists of two faults that trend northwestward from the Big Sur coast. This fault zone trends northwest across the Carmel-Sur coastline and one of the faults trends N25°W down the axis of the western tributary of Carmel Canyon, and may have controlled the location of this canyon. Faults in the zone here appear to be continuous for more than 26 km, and bound a zone of deformed, steeply dipping rocks. Onshore, near Point Sur, one of the faults in this fault zone dips 50°-60°N. Mesozoic granodiorite northeast of this fault is thrust over upper Miocene sandstone. Gilbert (1971) estimates that vertical separation on the fault is at least 300 m.

Continuations of the offshore Palo Colorado-San Gregorio fault zone to the north on the northern Santa Cruz shelf show evidence of relatively recent displacement (Fig. 10; Greene, 1977). The easternmost fault lies directly on the trend with the main strand of the San Gregorio fault (Coastways strand of Weber, 1980), which, as mapped by Clark (1970), has juxtaposed Pliocene strata of the Purisima Formation to the west against the upper Miocene Santa Cruz Mudstone. The westernmost fault lies on trend with a fault on Año Nuevo Point, where the Miocene Monterey Formation is thrust (northeast side up) over Pleistocene marine terrace deposits; alternatively, it may connect to the Frijoles strand (Clark, 1970; Weber, 1980). Recently re-processed multi-channel seismic-reflection data across the Palo Colorado-San Gregorio fault zone shows high-angle reverse faults with the east block upthrown (Fig. 9).

Silver (1977) first proposed 80 to 90 km of right-lateral offset on the offshore San Gregorio fault. Others followed with estimates of differing amounts of offset; Greene (1977), based on proposed offset of submarine canyons, proposed 70 km as did Howell and Vedder (1978); Graham and Dickinson (1978) proposed 115 km based on matching pairs of onland geologic features. However, Clark et al. (1984), matching up the lithologies of the Point Reyes area with the Point Lobos area (Fig. 1) and making a detailed biostratigraphic analysis of the region proposed that 150 km of right-slip has occurred along the Palo Colorado-San Gregorio fault zone since late Miocene time.

**Monterey Bay Fault Zone**

The Monterey Bay fault zone is located in Monterey Bay between the cities of Monterey and Santa Cruz and forms a diffuse zone, 10 to 15 km wide, of short, en echelon, northwest-trending faults (Fig. 10). This zone may comprise the offshore extensions of northwest-trending faults in the Salinas Valley and the Sierra de Salinas to the southeast. To the north, this zone appears to terminate against the Palo Colorado-San Gregorio fault zone.

Most faults in the Monterey Bay fault zone displace late Tertiary and Pleistocene sediments. North of Monterey Canyon, faults rise to within 6 m of the ocean floor; most displace upper Pliocene strata, some displace Pleistocene deposits, and a few may displace Holocene deposits (Greene et al., 1973; Greene, 1977). South of Monterey Canyon, most faults close to shore near Monterey also rise to within 6 m of the ocean floor and cut Pleistocene deposits. Some cut Holocene deposits as well. Farther offshore in southern Monterey Bay, faults appear to be older because they displace upper Tertiary and older strata and are covered by about 100 m of Quaternary sediment. A few faults cut only Cretaceous granites and strata of early to middle Tertiary age.

Previous mapping has demonstrated the onshore continuity of many of the offshore faults of the Monterey Bay fault zone (Clark and others, 1974). Three relatively continuous faults in southern Monterey Bay appear to extend onshore between the southern part of Fort Ord and Monterey; two are about 9 km long and the third is approximately 3 km (Fig. 10). One of the 9-km-long faults may be the offshore extension of the Chupines fault, which appears to enter the bay north of Monterey near Seaside. Seismic-reflection profiles from the offshore area and geophysical data on land indicate that the two 9-km-long faults exhibit the same sense of separation as the Chupines and Tularcitos-Navy faults on land (Greene et al., 1973; Greene, 1977). These faults have Tertiary sedimentary rocks downthrown on the northeast against Mesozoic granite on the southwest. However, high-resolution seismic-reflection profiles across the nearshore part of the southernmost fault offshore show drag folds indicating the opposite sense of displacement, i.e., northeast side upthrown. This drag folding could be the result of recent fault motion, which might differ from the predominant displacement, or may indicate that the fault has a component of strike slip (Greene, 1977).
On land, the Chupines fault trends northwestward from the Sierra de Salinas and extends beneath an area of alluvial deposits several kilometers wide near the coast. The fault is well defined in the mountains of the Sierra de Salinas, where the Miocene Monterey Formation locally lies in fault contact with lower Pleistocene Aromas Sand (Jennings and Strand, 1958; Bowen, 1969; California State Dept. of Water Resources, 1970), and with granitic basement rocks at depth (Clark and others, 1974). Sieck (1964) has interpreted gravity data to indicate that the Chupines fault lies beneath the alluvium at the foot of the mountains, and has suggested that dip-slip movement along the fault may have displaced the Monterey Formation near Canyon del Rey. The fault exhibits a vertical separation of about 300 m, upthrown to the southwest. The Chupines fault is more than 26 km long if it is an onland continuation of one of the more continuous faults in the Monterey Bay fault zone.

The Navy fault, a southwest-dipping reverse fault where exposed, is a second major onshore fault that may be continuous with faults offshore in southern Monterey Bay. The Navy fault has been mapped in a northerly direction across Carmel Valley and the Meadow Tract area of the Monterey Peninsula. It then passes beneath alluvium at the base of the mountains, and finally trends out to sea near the U.S. Navy Postgraduate School (Clark et al., 1974). The Navy fault may represent the northwestward continuation of the Tularcitos fault. If the Tularcitos-Navy fault continues into Monterey Bay and joins the southernmost of the relatively continuous faults offshore, its length would be more than 42 km.

The northeastern boundary of the Monterey Bay fault zone in southern Monterey Bay is gradational and is formed by a relatively continuous fault and several discontinuous en echelon faults (Fig. 10). This boundary may be the offshore extension of the King City fault (also called Gabilian fault) (Clark, 1930; Reed, 1933). This continuous offshore fault is aligned with the inferred trace of the King City fault as projected from the northern base of the Sierra de Salinas to the ocean just south of the town of Marina.

On land, the King City fault is a high-angle reverse fault along which granitic rocks of the Sierra de Salinas are uplifted to form the south-western border of the Salinas Valley (Reed, 1925, 1933; Clark, 1930; Sieck, 1964). Vertical separation along this fault decreases to the north, toward Monterey Bay, where it may die out. The King City fault is presumed to extend beneath the southwest margin of the Salinas Valley (Figs. 8 and 10) at least as far southeastward as the area west of Greenfield (Clark, 1930; Reed, 1933; Schombel, 1943; D.L. Durham, oral commun., 1972). Gravity data from the southern margin of the Salinas Valley suggest about 2,500 m of vertical separation (Fairborn, 1963), whereas gravity data from the west end of the Sierra de Salinas indicate between 900 and 1,200 m of separation (Sieck, 1964). If the King City fault and faults forming the northeast boundary of the Monterey Bay fault zone are continuous, the vertical separation decreases to about 240 m offshore (Greene, 1977).

The Reliz fault was first mapped as a branch of the King City fault (Schombel, 1943); however, Durham (1970) terminates the Reliz fault about 4 km south of the King City fault near Olsen Ranch (Fig. 10). Other workers, including Gribi (1967), Walrond et al. (1967), Tinsley (1975), and Graham (1978), believe that the Reliz fault extends northwestward along the northern base of Sierra de Salinas into the King City fault, and refer to both faults as the Reliz fault. Dibblee (1972) concurred with the latter interpretation on the basis of the linearity and near alignment of the steep front of the Sierra de Salinas with the Reliz fault south of Olsen Ranch. Dibblee (1972) also considers the Reliz fault to be part of a system including the Rinconada fault, which extends for more than 110 km farther to the southeast.

Continuation of the King City fault beneath the alluvial cover of the lower Salinas Valley near the Monterey coast is inferred from water well data. These data also suggest that the fault has a probable post-Pleistocene vertical separation of 30 m, south side up, near the town of Marina about 3 km from the coast (California State Dept. of Water Resources, 1970, Sheet 5 of Pl. 2). Movement along the fault has juxtaposed the Miocene Monterey Formation, on the southwest, with the upper Pliocene to lower Pleistocene Paso Robles Formation (see Figure 11 for stratigraphic relationship). Farther southeast, at Fort Ord, the Paso Robles Formation southwest of the fault occurs in the subsurface at an elevation of 30 m above sea level. The Paso Robles is not encountered near the surface to the northeast, across the fault, but deposits northeast of the fault occur at a depth of more than 160 m below sea level (Greene, 1977). The northwest limit of the Monterey Bay fault zone in southern Monterey Bay is formed by a series of parallel faults that trend northwestward from Cypress Point (Fig. 10). Three of these faults displace the sea floor by 1 to 5 m; two show relative uplift on the southwest and the other shows relative uplift on the northeast (Greene et al., 1973; Greene, 1977). The most continuous fault in this boundary zone may connect with the onland Cypress Point fault that extends southeastward from Cypress Point across Carmel Bay to connect with a fault just north of the mouth of Carmel River (Bowen, 1969; Clark et al., 1974).

**Monterey Canyon Fault**

Deep penetration (160 k) seismic-reflection profiles provide evidence for the Monterey Canyon fault (Monterey fault of Martin, 1964), previously inferred to lie beneath, and parallel to, the headward axis of Monterey Canyon (Martin, 1964; Greene, 1970, 1977). Cretaceous granites forming the basement complex occur at shallower depths on the south side of the canyon than on the north; the apparent vertical separation is approximately 60 to 150 m, south side up, and increases in amount farther offshore.

The Monterey Canyon fault is approximately 10 km long and follows the axis of the canyon from the easternmost meander to the mouth of Elkhorn Slough (Fig. 10). The fault may extend onshore, and could be responsible for the trough in basement rocks beneath Elkhorn Slough (Starke and Howard, 1968). Shallow reflectors are poorly defined in the seismic-reflection profiles, and it is difficult to determine the
youngest strata cut by the Monterey Canyon fault. However, this fault probably does not extend up to the base of the modern canyon fill (Greene, 1977). The fault is not active today and probably records an earlier stress field as its orientation is nearly perpendicular to present-day structural trend; it most likely was associated with a pre-transform west to east subduction stress field.

Ascension Fault

Offshore, the Ascension fault (questionable Sur-Nacimiento fault of McCulloch, 1987, 1989) generally extends northward for over 180 km from the Palo Colorado-San Gregorio fault zone, where it appears to be truncated near the southernmost head of Cabrillo Canyon (Fig. 8). However, continuation of this fault to the south for 60 km, where it may tie into the Sur thrust fault zone, has been proposed by Greene (1977) and is questionably mapped by McCulloch and Greene (in press). Seismic reflection data collected by the U.S. Geological Survey to the north indicate the fault to be a thrust, west over east (McCulloch and Greene, in press), and recently reprocessed USGS multichannel seismic-reflection profiles suggest the fault exhibits both strike-slip and thrust movement (Fig. 9). The youngest rocks displaced by this fault appear to be Miocene, based on the offset of reflectors of probable Miocene age and the lack of offset of reflectors in the overlying strata of probable Pliocene age, in seismic-reflection profiles (Greene, 1977).

Sur-Nacimiento Fault Zone

Several faults identified on the shelf between Point Sur and Cypress Point are aligned with faults onshore in the Sur-Nacimiento fault zone, a major structural feature in the southern Monterey Bay region (Fig. 8). This zone is a belt of faults of various kinds and ages that extends onshore for about 300 km southeastward from the Sur fault zone (Page, 1970) and includes the Sur thrust zone, the Nacimiento fault, and several smaller faults.

Other Offshore Faults

Two other faults extend N50°W from the Point Sur shelf. These linear faults are the northeastern and southwestern margins of the basement ridge that forms the Sur platform (Figs. 6 and 8). The northeastern fault is at least 80 km long; it passes about 11 km seaward of Point Sur and probably continues to the south, paralleling the southern Sur coast. To the north McCulloch and Greene (in press) show this fault connecting to a thrust fault that swings eastward to merge near Guide Seamount with a paleo-subduction zone of McCulloch (1989), a remnant shear zone or thrust representing a former convergent boundary (Fig. 12).

A third fault is located along the east side of Surveyor sea knoll on the continental slope due west of Point Sur (Fig. 10). This fault is oriented NE-SW, as are structures to the south. It appears to be about 60 km long but may extend a greater distance to the south (Greene et al., 1989). This fault has a distinct seafloor expression as shown by SeaBeam data (Fig. 2). The southern ends of the most nearshore faults appear to approach a common juncture south of Point Sur. McCulloch (1989) and McCulloch and Greene (in press) show that faults seaward of the Sur coast trend north-west-southeast until they approach Point Sur, where their trend appears to change abruptly to a nearly east-west orientation. Along the base of the continental slope McCulloch (1987; 1989) has mapped the paleo-subduction zone (Fig. 12).

Folds

Bedding of Tertiary sedimentary rocks is generally flat-lying or homoclinal in the Monterey Bay region. The most complex structures occur in the Monterey Bay fault zone, where Tertiary rocks have been severely contorted and compressed into tight synclinal and anticlinal folds (Greene, 1977). Most well-defined folds lie offshore and onshore in the southern Santa Cruz Mountains. Onshore, synclinal basins of Eocene age rocks have been mapped between the San Andreas and Zzyante faults (Fig. 10). In this area several north-west-southeast oriented anticlines and synclines are mapped (Brabb, 1989).

East of Palo Colorado Fault Zone

Between Ben Lomond and the San Andreas faults in the southern Santa Cruz Mountains several major northwest-southeast oriented folds are mapped (Fig 10). Less
continuous folds are exposed along the western flank of Ben Lomond Mountain near Año Nuevo Point (Brabb, 1989).

Anticlines and synclines in the Monterey Bay fault zone are short and have orientations that appear to range from about N70°W to N80°W (Fig. 10). Major folds near shore, in the Monterey bight area, have orientations that parallel faulting (N50°W); some folds extend onshore and join folds mapped in the subsurface by Clark et al. (1974). Folding and shearing within the northern part of the Palo Colorado-San Gregorio fault zone have severely distorted the sedimentary strata between the two major faults of the zone. Most folds within this zone have flank dips greater than 35 degrees. These folds may have formed by compressional forces associated with strike-slip along faults within the Monterey Bay fault zone, or they may represent the recent (last 8-3 m.y.) plate convergence compressional event.

The only other folded structures east of the Palo Colorado-San Gregorio fault zone are located in northern Monterey Bay. Five short, discontinuous folds in gently dipping Pliocene strata of the Purisima Formation are located between the head of Soquel Canyon and the Capitola-Aptos coastline (Fig. 10). In addition, several discontinuous folds occur in Miocene marine strata and upper Tertiary to Quaternary deltaic deposits offshore from Santa Cruz. These structures are oriented approximately N80°W.

West of the Palo Colorado-San Gregorio Fault Zone

West of the Palo Colorado-San Gregorio fault zone, Tertiary sedimentary rocks are strongly folded along the northwest part of the Point Sur shelf and slope, between faults fanning outward from the Sur platform (Figs. 6 and 10). Orientation of these folds ranges from east-west to about N80°W. These folds appear to be the result of motion along nearby faults, and are limited in occurrence to areas of shallow basement. In addition, a faulted syncline has been mapped in the area between Monterey Canyon and the Sur platform. The only other significant folds in this area are a large syncline located on the slope between Monterey and Ascension Canyons, and an anticline folded between the converging thrust fault and paleo-subduction zone southeast of Guide Seamount (Fig. 12). A small north-south syncline lies just west of Surveyor Seamount.

Sedimentary Basins and Basement Ridges

Several basins and basement ridges have been identified in the submerged continental borderland of central California (Curray, 1965, 1966; Hoskins and Griffiths, 1971; Silver et al., 1971; Silver, 1974; McCulloch et al., 1977, 1980; Howell et al., 1980; Nagel and Mullins, 1983; McCulloch, 1987, 1989; see Fig. 13). The Santa Cruz and Pigeon Point highs are individual basement ridges delineated by Hoskins
Figure 13. Map showing generalized boundaries of central California continental shelf, slope and coastal basins and offshore exploratory drill holes (modified after McCulloch, 1989).
and Griffiths (1971) and Silver et al. (1971). The outer ridge (Santa Cruz high) lies northwest of Monterey Bay and south of the Farallon Islands (Fig. 14). This ridge was first proposed by Silver et al. (1971) to be composed of rocks of the Franciscan assemblage, and has been mapped as three distinct segments that are believed to be continuous at depth. Greene (1977), based on offshore seismic-reflection data, proposed that the offshore Palo Colorado-San Gregorio fault zone marks the boundary between Franciscan and the granitic rocks of the Salinian block in the Monterey Bay region where this ridge is truncated and speculated that Franciscan rocks crop out in Ascension Canyon. Mullins and Nagel (1981) confirmed from dredge samples that Franciscan rocks are exposed in the lower headward parts of Ascension Canyon and represent basement rocks of the southern Santa Cruz high. Shoreward of the Santa Cruz high is another ridge (Pigeon Point high) composed of granitic rocks that crop out as quartz diorite in the Farallon Islands (Silver et al., 1971).

The Santa Cruz and Pigeon Point highs bound a major sedimentary basin seaward and northwest of Monterey Bay which is described by Hoskins and Griffiths (1971) as follows:

"The outer Santa Cruz basin extends northwest from Monterey for 80 miles [130 km] to about 37°30' N lat., where it appears to merge with the continental slope. It is a shallow, post-Miocene syncline which encompasses approximately 1,400 sq. mi. [3,630 km²] of Miocene and younger marine beds."

These authors note that the basin axis plunges continuously toward the northwest and that structural trends within the basin generally parallel this axis (Fig. 14). They conclude that the basement of the basin is granite, although basement rocks are not exposed on either Pigeon Point and Santa Cruz high. The extreme southeast end of the outer Santa Cruz basin of Hoskins and Griffiths (1971) appears as a synclinal sedimentary basin in deep penetration seismic-reflection profiles collected along the continental slope between Ascension and Monterey Canyons (Greene, 1977; Nagel and Mullins, 1983). Tertiary sediments have an aggregate thickness of more than 2,000 m in this basin. This sedimentary sequence thins abruptly to the south and west where the sequence laps onto the basement ridges. For a complete, detailed description of this basin see Heck et al. (this volume).

A smaller basin exists southwest of Monterey Bay and is a fault bounded basement depression termed the Monterey low by Greene (1977), or Monterey basin (Figs. 6 and 13). This basin trends northwest-southeast and is bounded to the north by the Ascension high of Greene (1977), to the south by the eastern faulted flank of the Pt. Sur high, and to the east by the Ascension fault (Fig. 10). Monterey Canyon bisects the basin and exposes the metamorphic basement rocks here. The Sur high is a northwest-plunging basement ridge that appears to be the buried seaward extension of the Sur platform.

No significant sedimentary basins are present within Monterey Bay proper (Fig. 6). A relatively flat-topped granitic basement complex supports a late Tertiary sedimentary cover of less than 1,000 m (Greene, 1977). A subtle basement ridge, the Monterey high, trends northward from the Monterey Peninsula to the Soquel-Aptos area and probably limits the seaward extension of the onland Salinas basin (Fig. 6 and 13).

EARTHQUAKES

Earthquakes in the Monterey Bay region reflect the tectonic movement and deformation that is presently occurring along the Pacific-North American plates' boundary. By studying earthquakes and their associated effects such as surface rupturing and aftershocks tectonic forces actively deforming the region can be determined. The Monterey Bay region is a very active seismic area and in 1989 was subjected to an earthquake that resulted from release of tectonic stress built up between the Pacific and North American plates.

The largest recorded earthquakes in the Monterey Bay region occurred in 1926 and 1989. Steinbrugge (1968) has described the 1926 earthquakes as follows:

"1926, October 22, 4:35 A.M. Center on the continental shelf off Monterey Bay. Intensity VIII at Santa Cruz, where many chimneys were thrown down: VII at Capitola, Monterey, Salinas and Soquel. Felt from Healdsburg to Lompoc (a distance of 250 miles [450 km]) and east to the Sierra, an area of nearly 100,000 square miles [180,000 km²]. Another shock one hour later was similar to the first in almost every respect."

Detection of earthquakes and determination of their locations and focal depths (hypocenters) in the Monterey Bay region has been difficult because the area lies largely outside of the network of permanently located seismo-
Figure 15. Map showing faults, earthquakes, and fault plane solutions in the Monterey Bay region. Heavy dotted line shows approximate locations of aftershocks from the October 17, 1989 Loma Prieta earthquake; mainshock shown with large circle and leaded first motion ball. Epicenter data from 1926 to 1986 with the exception of 1989 earthquake mainshock (see Figure 17 for aftershock distribution). (After Cockerham et al., in press.)
graphic stations. Nevertheless, refinement and expansion of the California Seismographic Network (CALNET) has resulted in more accurate location and analysis of earthquakes in the region.

First motion studies of magnitude 3.5 and greater earthquakes occurring between 1969 and 1976 were interpreted by Greene et al. (1973) indicate that right-lateral strike-slip was occurring on northwest-trending faults in the bay (Greene et al., 1974). Analyses of seismic events that occurred in the Monterey Bay region between 1 January 1969 and 30 April 1986 (Fig. 15) indicate that the fault planes within the Palo Colorado-San Gregorio and Monterey Bay fault zones vary from nearly vertical to high-angle reverse and that strike-slip movement as well as thrust motion has occurred along these northeast or northwest trending faults (Cockerham et al., in press). Recent re-processing of multi-channel seismic-reflection profiles in the area of the southern Monterey Bay fault zone (Fig. 16) and high-resolution seismic-reflection profiles and side-scan sonographs indicate that the zone may be a thrust.

The two large earthquakes (magnitude 6.1) that occurred in 1926 also have been located within the Monterey Bay fault zone by Richter (1958). However, the locations of these epicenters probably are not known with sufficient accuracy for certain assignment to a specific fault zone. These were the largest earthquakes recorded in the region until 1989.

On October 17, 1989 the 7.1 M Loma Prieta earthquake occurred along the San Andreas fault within the Santa Cruz Mountains (37°02'N' N latitude, 121°53'W longitude), approximately 15 km east-northeast of the city of Santa Cruz and about 95 km southeast of San Francisco (Fig. 17). Although this earthquake was not of a great magnitude the destruction and damage in the Monterey Bay region was similar to that which occurred during the great San Francisco earthquake of 1906 (Lawson et al., 1908). The initial fault rupture (focal point) occurred at a depth of 18.5 km and propagated along strike for nearly 40 km. In contrast the 1906 earthquake rupture length was about 450 km. During the 1989 event, a subsurface area of over 300 km² ruptured along a fault plane striking N50°W ± 8° and dipping 70° ± 10° to the southwest; direction of slip was 130° ± 15° (Plafker and Galloway, 1989).

Plafker and Galloway (1989), from whom most of the following description is taken, describe the area of rupture accompanying the 1989 earthquake as being along a locked

Figure 16. Preliminary interpretation of multichannel seismic-reflection profile across the southern part of the Monterey Bay fault zone showing thrust faults.
segment of the San Andreas fault that last ruptured in 1906. In contrast, south of this area accumulated elastic strain is absent and numerous small earthquakes occur, indicating continuous movement on that segment of the San Andreas fault. The 1989 Loma Prieta earthquake occurred in a seismic gap that existed between Los Gatos and Watsonville (Fig. 18). After the initial event a complex pattern of aftershocks began that appear to have resulted from movement on multiple branching faults, including vertical segments of the San Andreas and Sargent faults (Plafker and Galloway, 1989). A subparallel cluster of secondary aftershocks triggered by a 5.0 magnitude event 33 hours after the main shock is believed by Plafker and Galloway (1989) to be associated with possible movement along the Zayante fault, even though no clear evidence of surface rupture was found.

Accurate geodetic measurements made shortly after the Loma Prieta earthquake and reported by Plafker and Galloway (1989) established that over 2 m of northward (right-lateral) horizontal movement and nearly 1.5 m of vertical displacement on the upthrown (southwest) block resulted from the earthquake (Fig. 19). These data suggest that a broad area of uplift occurred with about +0.5 m on the southwest block and about -0.2 m of subsidence on the northeast block (Fig. 20). No surface ruptures were identified; however, local cracks and crack sets were found along the trace of the San Andreas fault (Plafker and Galloway, 1989). Plafker and Galloway (1989) describe a combination of extension and left-laterally or right-laterally offset cracks along Summit Road, just south of Hwy 17 (see road log, this volume; Canby, 1990). They appear to have formed by movement along the fault at depth. Older, local slump cracks also opened up along the San Andreas fault; many of these cracks follow the trend of bedding, and are interpreted by Plafker and Galloway (1989) to be concentrated over weaker shale beds. Severe shaking along ridge tops occurred and Plafker and Galloway (1989) speculate that this may have caused cracking when the tops spread laterally as the slopes moved outward and downward toward the valleys below under the influence of gravity. Severe shaking of the ridges can also be explained by the enhancement of seismic waves travelling upward from the focal point by reflecting off the air-earth interface.

Seismic intensities in the Monterey Bay region resulting from the Loma Prieta earthquake were very high, rang-
Figure 18. Map showing location of earthquakes occurring from 1 May 1986 to 16 October 1989. The epicenters are well located, but the magnitudes are preliminary. Note lack of activity (seismic gap) in area where October 17, 1989 occurred. Inset cross sections show seismicity along San Andreas fault from north of San Francisco to south of San Juan Bautista. A, Background seismicity recorded during 20-year period before October 17, 1989 earthquake. On Loma Prieta segment, what little seismicity has occurred has effectively outlined a U-shaped area (Loma Prieta Gap) that has been virtually aseismic over the past 20 years. B, Aftershocks and mainshock (largest circle) mostly completely filled former quiet zone of Loma Prieta Gap. Data provided by the Branch of Seismology, U.S. Geological Survey (modified after Plafker and Galloway, 1989; Cockerham et al., in press).
In general, seismicity of the Monterey Bay region indicates that both compressional and strike-slip motion is occurring along the plate boundary there. Recurrent earthquakes, although not rupturing the ground surface, cause significant uplift in the coastal mountains and stimulate erosion through landslides. In the valleys and coastal areas liquefaction and associated subsidence accelerates erosion locally. One tectonic event such as the 1989 Loma Prieta earthquake can significantly alter the geology.

CONCLUSIONS

The geologic structure and active seismicity of the Monterey Bay region indicate that the central California coast has been, and is today, subjected to complex tectonic processes. The region was subjected to nearly orthogonal collision and subduction until about 21 Ma when a trans-
form margin formed. Transtensional and transpressional structures resulted from widespread transcurrent movement along faults of the San Andreas fault system and these structures were either overprinted or altered and deformed during and after a shift in the stress field. Change in direction of the Pacific plate in relation to the North American plate some 5-3 Ma produced a more orthogonal convergence that initiated formation of compressional structures parallel to the San Andreas fault. The 1989 Loma Prieta earthquake exhibited the complex deformation that is occurring along this central California boundary. Both thrusting and strike-slip displacement occurred indicating that the structural pattern of the region is the result of both transform movement and compression between the two plates.

The sedimentary basins, both onshore and offshore, including the Outer Santa Cruz basin (see Heck et al., this volume), were formed along the California margin during the transition period between subduction and transformation. These basins were then enlarged, elongated, filled and deformed during the transform movement, and transported on the Pacific plate to their present location. During their evolution many of these basins underwent a depositional and thermal history that favored the generation and concentration of hydrocarbons. Today, onshore seeps of tar sands are present along the coast between Santa Cruz and Davenport (see Phillips, this volume). Offshore, the concentration of shallow hydrocarbons, including natural seepage of thermogenic hydrocarbons into the oceanic water column, near the southern terminus of the outer Santa Cruz basin is reported by Mullins and Nagel (this volume). Several oil fields have been developed in the region including the Half Moon Bay, La Honda and Moody Gulch fields (see Wright, Stanley, and Gribi, this volume). All of these fields are located along structures that resulted from Neogene and Quaternary tectonic movement.

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