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Neogene folding and faulting in southern Monterey Bay

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Gardner-Taggart, Joan Marie, M.S.

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NEOGENE FOLDING AND FAULTING IN SOUTHERN MONTEREY BAY

A Thesis

Presented to San Jose State University

and

Moss Landing Marine Laboratories

In Partial Fulfillment

of the Requirements for the Degree

Master of Science in Marine Science

By

Joan Marie Gardner-Taggart

May, 1991

APPROVED FOR MOSS LANDING MARINE LABORATORIES

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ABSTRACT

NEOGENE FOLDING AND FAULTING IN SOUTHERN MONTEREY BAY

by Joan M. Gardner-Taggart

Structures in southern Monterey Bay reflect Neogene tectonic activity; folding and faulting are confined to strata of the Middle Miocene and younger. Structures strike almost perpendicular to one another and exhibit compressional tectonic characteristics such as thrust faulting, reverse faulting and asymmetrical folding. Shallow Mesozoic basement rocks outcrop at or near the surface in most of the region and form a decollement along which the Miocene Monterey Formation has decoupled and been folded. Wrench fault tectonics complicated by compression, gradual uplift of the basement rocks, and a change in plate convergence direction is responsible for the observed structures in southern Monterey Bay.

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ABSTRACT

Monterey Bay is located on an exotic terrain, the Salinian Block, that originated as part of a volcanic arc which has migrated northward along the San Andreas Fault zone. Strike-slip movement between the North American and Pacific plates started as subduction ceased 21 Ma, creating the San Andreas fault system. Clockwise rotation of the Pacific plate occurred between 3-5 Ma causing orthogonal convergence between the two plates. This plate rotation is responsible for the compressional nature of structures along the Central California Coast.

Structures in southern Monterey Bay reflect Neogene tectonic activity; folding and faulting are confined to strata of the Middle Miocene and younger. Structures strike almost perpendicular to one another and exhibit compressional tectonic characteristics such as thrust faulting, reverse faulting and asymmetrical folding. Shallow Mesozoic basement rocks outcrop at or near the surface in most of the region and form a decollement along which the Miocene Monterey Formation has decoupled and been folded. Wrench fault tectonics complicated by compression, gradual uplift of the basement rocks, and a change in plate convergence direction is responsible for the observed structures in southern Monterey Bay.

INTRODUCTION

Deformation of Miocene and Pliocene to Pleistocene sediments within a 60 km² area of the Monterey Bight between Ft. Ord and Monterey in southern Monterey Bay (Fig. 1) is indicative of Neogene tectonics associated with differential movement between the Pacific and North American plates. Few comprehensive structural geological studies have been done in the Monterey Bight. General studies of the onshore geology of Central California, including the Monterey Bay region, are fairly extensive and consist of work done by Clark (1930), Page (1966, 1970, 1981 and 1982), Dibblee and Clark (1973), Tinsley (1975), Graham (1976 and 1987), McKittrick (1987) and Dupre (1990). Detailed offshore structural geology studies in the bay have been done by Shepard and Emery (1941), Martin (1964), Curray (1965 and 1966), Martin and Emery (1967), Hoskins and Griffiths (1971), Greene et al. (1973), Greene (1977), Greene et al. (1989) and Greene (1990).

Detailed geophysical data was collected in the Monterey Bight area specifically to map the folds and faults and to determine the mechanism of folding and faulting. This analysis is used to determine the Neogene tectonic activity in the southern Monterey Bay region.

Fig. 1. Location map of the study area.

BACKGROUND GEOLOGY

Monterey Bay is located on the Central California coast approximately 115 km south of San Francisco. The bay is crescentic in shape and is one of the largest open embayments on the coast of California. Monterey Bay is best known for its submarine canyon which is comparable in size and depth to the Grand Canyon (Martin, 1964; Shepard and Dill, 1966).

Structure

Most of the geologic structure offshore and onshore in Central California reflects post-Eocene tectonic events. Subduction of the Farallon Plate beneath what is now Central California occurred prior to 29 Ma (Atwater, 1970; Atwater and Molnar, 1973). During the late Oligocene to early Miocene time, when the Mendocino triple junction migrated northward and subduction ceased (~21 Ma.), the San Andreas fault system developed in Central California (McKenzie and Parker, 1967; Morgan, 1968; Atwater, 1970; Atwater and Molnar, 1973) and relative motion between the Pacific and North American plates became strike-slip. Compressional tectonic features formed sometime around 5-3.5 Ma along the San Andreas fault system when clockwise rotation of the Pacific Plate occurred (Cox and Engebretson, 1985). This change in plate convergence direction is believed to have occurred rapidly (within 1 m.y. or less). The compression associated with this rapid change in convergence direction is present today and is recognized in the structural features of Pliocene and Pleistocene age along the San Andreas fault (Cox and Engebretson, 1985; Zoback et al., 1987). Some of the stress caused by this plate convergence is distributed along fault zones within the San Andreas fault system (Atwater, 1970; Johnson and Normark, 1974; Greene, 1977; Graham and Dickinson, 1978; Clark et al., 1984; Greene et al., 1973; and Greene, 1990).

Monterey Bay is located on a tectonically active granitic basement complex known as the Salinian block (Fig. 2) (Page, 1970; Greene, 1977). The San Andreas fault and the Sur-Nacimiento fault zone form the northeast and southwest boundaries respectively of the block which extends from the Transverse Ranges northward to Cape Mendocino (Page, 1970; Silver et al., 1971; Greene, 1977; Page and Engebretson, 1984). Cretaceous melange deposits of the Franciscan assemblage flank the Salinian block on both sides. The basement rocks

Fig. 2. Location of the Salinian block (modified from Greene, 1977 and Silver et al, 1971).

of the block are believed to have been formed as a continental volcanic arc and are underlain by Precambrian rocks (Page, 1966 and 1970; Ross and Brabb, 1972 and McCulloch, 1989). It is not clear how far the Salinian block has travelled since it formed. Graham (1976) and Page and Engebretson (1984) estimate that the block originated in the Sierran arc terrain, which is approximately 350 km southeast of its present position. In contrast, Kanter and Debiche (1985) suggest that the block may have migrated as much as 2600 km northward since its formation. Major right lateral strike slip movement along the San Andreas fault during the Tertiary is believed to be responsible for its displacement (Hill and Dibblee, 1953; Page, 1970; Greene, 1977).

Slivering of the granitic basement complex of the Salinian block and overlying Tertiary deposits has occurred along many northwest-southeast trending faults in the Monterey Bay area (Fig. 3). In addition, folds and fault-bounded geologic structures and basement highs associated with sedimentary basins also trend northwest-southeast in this region (Greene, 1977). Statistical analysis of Pliocene and younger geologic structures along coastal Central California by Zoback et al. (1987) suggest that the present direction of maximum principal stress is N 33° E.

Earthquakes

Monterey Bay is a tectonically active region which has experienced hundreds of earthquakes in the past 150 years (Cockerham et al., 1990). Historical accounts exist of earthquakes occurring in the region as early as 1836 (Griggs, 1973). Seismographs were not installed until 1934 so locations of earthquakes prior to this are not accurate (Griggs, 1973). The largest magnitude earthquakes documented in the Monterey Bay region occurred in 1926 and 1989. Two earthquakes of magnitude 6.1 occurred in 1926 (Steinbrugge, 1968) and were located by Richter (1958) in the Monterey Bay fault zone. Locations of the epicenters of these earthquakes is questionable since they occurred before seismographs were installed in the region.

Fig. 3. Geologic structure map of the Monterey Bay region (from Greene, 1990).

On October 17, 1989 the largest earthquake recorded in the Monterey Bay region occurred. This quake was the Loma Prieta earthquake which had a magnitude of 7.1. Damage caused by the quake was extensive in Moss Landing, Watsonville and Santa Cruz (Plaker and Galloway, 1989). Offshore slumping in the Monterey canyon caused by the quake was also extensive. Liquefaction of sediments both offshore and onshore was observed near Moss Landing (Greene et al., 1990).

First motion studies of quakes greater than magnitude 3.5 occurring in Monterey Bay after 1969 indicate that both thrust and strike-slip motion occurs along northwest trending faults (Greene, 1977; Cockerham et al., 1989). It is estimated that the Palo Colorado-San Gregorio fault zone is capable of producing earthquakes of magnitude 7.0 (Greene et al., 1973).

Faults

Two active fault zones exist offshore in the Monterey Bay. The Palo Colorado-San Gregorio fault zone and the Monterey Bay fault zone have been mapped and studied by Greene et al. (1973), Graham and Dickinson (1978), Greene (1977), Clark et al. (1984), Greene et al. (1987), and Greene (1990).

The Palo Colorado - San Gregorio Fault Zone. The San Gregorio fault zone is the longest fault zone on the Salinian block (Greene, 1977). This fault zone roughly parallels the coastline from Point Sal to just northwest of San Francisco Bay where it intersects the San Andreas Fault. The fault strikes almost due north-south and is thought to have up to 115 km of right-lateral offset since the Miocene (Graham and Dickinson, 1978). Clark et al. (1984) have suggested that at least 180 km of total offset exists based on the similarity of rocks found at Point Lobos and Point Reyes. Displacement along this fault may account for Pacific-North America plate slip that doesn't occur along the San Andreas Fault zone (Greene, 1977; Weldon and Humphries, 1986; DeMets et al., 1987).

In the Monterey Bay region, the San Gregorio fault zone is referred to as the Palo Colorado - San Gregorio fault zone by Greene et al. (1973) and Greene (1977) due to its connection with the Palo Colorado fault in the Santa Lucia Range between Carmel and Point

Sur. Graham and Dickinson (1978) advocate that the onland expression of this fault occurs along the Sur fault zone at Point Sur and connects further south with the San Simeon - Hosgri fault. This connection has not been mapped and no clear evidence has been presented to support this theory.

The Palo Colorado - San Gregorio fault zone trends N 25° W from its onland expression near Point Sur, as a series of faults in a zone approximately 3 km wide in Monterey Bay (Greene et al., 1973; Greene, 1977). It connects onland, in the northern part of the bay, with the San Gregorio fault and a thrust fault near Año Nuevo Point (Clark, 1970; Greene et al., 1973; Greene, 1977) (Fig. 3.).

The Palo Colorado - San Gregorio fault zone is seismically active. Fault-plane solutions for 5 earthquakes, ranging in magnitude from 1.0 to 4.4, indicate that the faults in this zone have nearly vertical fault planes, exhibits some reverse and thrust movements and undergoes right-lateral strike slip movement similar to the San Andreas Fault (Greene et al., 1973 and 1989; Greene, 1977 and 1990; Yang, 1991).

The Monterey Bay Fault Zone. The Monterey Bay fault zone lies east of the Palo Colorado - San Gregorio fault zone (Fig. 3). Faulting in this area has been identified from high resolution seismic records (Greene et al., 1973; Greene, 1977). A 10-15 km wide zone of en echelon faults with an approximate N 50° W trend exists here. The Monterey canyon is used by Greene et al. (1973) to divide the fault zone into north and south segments. Faulting within the canyon that connects the two regions has not been identified and has been inferred by Greene et al. (1973) and Greene (1977).

First motion studies and fault plane solutions for eight earthquakes of magnitude 0.9 - 4.7 occurring in the Monterey Bay fault zone north of the Monterey canyon indicate that right lateral strike-slip motion along vertical fault planes has occurred in this area (Greene et al., 1973; Greene, 1977). The motion here is similar to what has been observed on the Palo Colorado - San Gregorio fault zone which, in the north, truncates the western boundary of this fault zone. Only two epicenters are located south of the Monterey Canyon. They also

exhibit a right lateral strike slip motion. The low number of epicenters in this region could be due to the lack of seismic instrumentation in the area, rather than an absence of seismic activity.

The North Monterey Bay Fault Zone. Faulting along many of the faults in the north Monterey Bay fault zone appears to be downthrown on the northeast or landward side (Greene et al., 1973; Greene, 1977). The faults and folds in this region range in length from 1.6 km to 9.6 km. Most of the faults in this region extend to within 6 meters of the surface and displace Pliocene deposits (Greene et al., 1973; Greene, 1977). A few of the faults appear to displace Pleistocene and Holocene deposits.

The South Monterey Bay Fault Zone. The South Monterey Bay fault zone consists of en echelon folds and faults of >1.5 km in length. Offshore in this region, faults extend to within 6 meters of the ocean floor and displace Pliocene, Pleistocene and Holocene deposits. Faults in this region also displace Cretaceous granites and Tertiary deposits and are covered by as much as 100 meters of sediment (Greene et al., 1973).

Greene et al. (1973) and Greene (1977) have mapped three of the more continuous faults in the south Monterey Bay fault zone between Monterey and Fort Ord. These represent offshore extensions of onshore faults identified by Clark et al. (1984). Two of the faults are 9 km in length, strike approximately N 40° W, and appear to be the offshore expression of the Navy - Tularcitos fault and the Chupines fault. Both the onshore and offshore expressions of these faults exhibit Mesozoic granite in fault contact with Tertiary sedimentary rocks on the northeast block (Clark et al., 1984; Greene, 1977).

Folds

Folding of Tertiary sediments in Monterey Bay is extensive and varied. The North and South Monterey Bay fault zones exhibit the greatest concentration of anticlines and synclines in the region. Many of the folds in this area are highly compressed, fractured and asymmetrical (Greene, 1977).

Stratigraphy

Stratigraphy of Monterey Bay east of the Palo Colorado-San Gregorio fault zone consists of Mesozoic granitic rocks unconformably overlain by Tertiary and Quaternary sediments. Northern and southern Monterey Bay display similar stratigraphy (Fig. 4.).

Mesozoic Sequence. Mesozoic granodiorite forms the crystalline basement sequence found throughout the bay. These basement rocks are unconformably overlain by as much as one kilometer of sediment in northwest Monterey Bay and outcrop onland in the Santa Cruz Mountains, the Monterey Peninsula, the Gabilan Range, the Sierra de Salinas and the Santa Lucia Range (Greene, 1977). These granodiorites also outcrop offshore in southern Monterey Bay. Greene (1977) recognized a basement high, named the Monterey High, that extends northeastward from the city of Monterey to Aptos. This basement high is erosionally bisected by the Monterey Submarine Canyon. Micro-paleontologic evidence by Greene (1977), coupled with the recognition of arched marine terraces in the Aptos area (Alexander 1953), suggests that the Monterey High has undergone episodes of uplift from the early Miocene to Holocene time

Middle Miocene. The middle Miocene Monterey Formation unconformably overlies the Mesozoic granodiorite in Monterey Bay. The Monterey Formation is a marine, interbedded, organic mudstone, diatomaceous-siliceous shale and siltstone. The thickness of this formation varies from approximately 640 meters near the Salinas River to 50 meters in the Monterey Bight area (Greene, 1977). Most of the compressional features observed in the Monterey Bay fault zone are confined to the Monterey Formation.

Upper Miocene to Pliocene. In northern Monterey Bay, the upper Miocene to Pliocene Santa Margarita Sandstone, Santa Cruz Mudstone and Purisima Formation unconformably overlie the Monterey Formation. In southern Monterey Bay, only the Purisima Formation unconformably overlies the Monterey Formation. This change in stratigraphy represents a time transgressive sequence with several facies changes occurring from north to south in the bay (Greene, 1977).

NORTHERN MONTEREY BAY REGION

AGE		SEQUENCE	FORMATION	LITHOLOGY	THICK- NESS (meters)	DESCRIPTION
QUATERNARY	Holocene	Upper Pliocene to Holocene	Surficial deposits		40	Recently deposited marine sand and mud.
					240	Submarine landslide and slump material.
	Pleistocene		Aromas Sand		50	Gravel, sand, and mud; some broken consolidated material.
					300	Well sorted, cross-bedded, quartzose sand; nonmarine, eolian. Fluvial locally at base.
	Deltaic material		+ 40		Sand and mud; marine, deltaic.	
TERTIARY	Pliocene	Upper Miocene to Pliocene	Purisima Formation		670+	Greenish-gray, semi-consolidated to consolidated sandstone, siltstone, and shale; marine, generally fossiliferous.
			Santa Cruz Mudstone of Clark (1946)		200+	Siliceous, organic mudstone; marine.
			Santa Margarita (?) Sandstone		370?	Bedded arkosic sandstone(?)
	Miocene	Middle Miocene	Monterey Formation		550	Light olive-gray, rhythmically bedded, organic mudstone, diatomaceous and siliceous shale and siltstone; marine.
MEZOZOIC OR OLDER			Granitic rocks (crystalline basement)	X X X X X X X X X X X X X X X X X X X X		Probably predominantly granodiorite.

SOUTHERN MONTEREY BAY REGION

AGE	SEQUENCE	FORMATION	LITHOLOGY	THICK- NESS (meters)	DESCRIPTION
QUATERNARY	Pleistocene to Holocene upper Pleistocene to Holocene	Surficial deposits Deltaic deposits Aromas Sand Paso Robles Formation		40?	Recently deposited marine sand and mud
				240	Submarine landslide and slump material
				50	Gravel, sand, and mud; some broken consolidated material
				120	Sand and mud deposited by outwash from Salinas River; marine, deltaic
				120	Well sorted, cross-bedded, quartzose sand; nonmarine, eolian
TERTIARY	Pliocene to Pleistocene middle to Pliocene	Purisima Formation	60	Poorly bedded, sand, gravel, and clay; nonmarine	
		Monterey Formation	210	Greenish-gray, semi-consolidated to consolidated sandstone, siltstone and shale; marine, fossiliferous	
			640	Light olive-gray, rhythmically bedded, organic mudstone, diatomaceous and siliceous shale and siltstone; marine Base of unit locally contains coarse-grained, white, granitic or arkosic sandstone	
MESOZOIC OR OLDER		Granitic rocks (Crystalline basement)	XXXXXX XXXXXX XXXXXX XXXXXX		Predominantly porphyritic biotite granodiorite

Fig. 4. Stratigraphy of the Monterey Bay (from Greene, 1977).

The Santa Margarita Sandstone is an arkosic sandstone with a maximum thickness of 370 meters near Soquel Canyon (Greene, 1977). This unit is believed to extend southward where it grades laterally into the upper Monterey Formation.

The Santa Cruz Mudstone is a siliceous marine mudstone which has an average thickness of 200 meters. In the extreme northern and northwestern parts of the bay the Santa Cruz mudstone outcrops on the seafloor. The maximum thickness here is estimated to be greater than 200 meters (Greene, 1977).

The Purisima Formation is found in both the northern and southern parts of the bay. It consists of sandstone, siltstone, and shale which are semi-consolidated to consolidated. It unconformably overlies the Monterey Formation in the south bay and conformably overlies the Santa Cruz Mudstone in the north bay (Greene, 1977). The thickness of the Purisima Formation ranges from zero in the Monterey Bight area to 600 meters in the northwestern part of the bay.

Upper Pliocene, Pleistocene and Holocene. Quaternary sediments in Monterey Bay are represented by the Aromas Sands, deltaic deposits and surficial deposits. The Aromas Sands are nonmarine eolian material that unconformably overlie the upper Miocene to Pliocene formations in the bay. This formation is most extensive nearshore and can be as thick as 255 meters. Deltaic deposits consist of fluvial, brackish and salt water muds and sands and are concentrated at the mouth of the Salinas and Pajaro Rivers. Surficial deposits comprise canyon fill and submarine landslide and slump materials. These deposits are confined to the Canyon.

METHODS

The data used in this study were collected on Moss Landing Marine Laboratories cruises numbered PS 1-87-MB and PS 1-89-MB aboard the R.V. *Point Sur* in 1987 and 1989. Side scan sonar and Uniboom data were collected on both cruises. Cruise PS 1-87-MB was undertaken in cooperation with the U.S. Geological Survey.

Navigation

Precision positioning was obtained with the use of a Motorola Falcon Miniranger aboard the *Pt. Sur*. The ship's position was calculated and recorded every twenty seconds on a Grid Systems laptop computer. This recorded data was later processed and plotted by the U. S. Geological Survey. Positional accuracy of the system is 2 meters. An average ship speed over ground of 4.0 - 4.5 knots was maintained while collecting data on both *Pt. Sur* cruises. The original track line numbers from both cruises were reassigned to prevent duplication of line numbers (Fig. 5.). Table I in the Appendix contains a list of the original line numbers and the reassigned line numbers.

Side Scan Sonar Data

Side scan sonar data were collected on cruise PS 1-87-MB with the EG&G Mark 1B system. Data from cruise PS 1-89-MB was collected with the EG&G 960 system. Both systems produce "plan view" photo-like images of sea floor topography. Transducers mounted on both sides of a 5 foot long towfish emit a 100 Khz frequency acoustic signal that is reflected off the seafloor. The towfish receives and amplifies the reflected signal and transmits it back to the towing vessel. Differing intensities of this reflected acoustic signal produce images of the seafloor similar to those produced by aerial photography. Topographic features such as seamounts and ridges produce an acoustic shadow or dark image on the records. These shadows are created by blockage of the acoustic signal. Outcrops of granite and sand ripples are good acoustic reflectors that produce dark images while poor reflectors such as depressions, fine grained sands and muds produce lighter images. The resultant images produced by the differing intensities of acoustic backscatter provide a detailed representation of the surveyed area. A total swath width of 500 meters (250 meters per side)

Fig. 5. Location and reassigned line numbers of ships track in study area.

was used on cruise PS 1-87-MB. A swath of 400 meters (200 meters per side) was used on cruise PS 1-89-MB. Survey lines were laid out so that a minimum of 40 meters (10%) of overlap was achieved between adjacent survey lines. Records from both cruises were microfilmed and photographically reproduced onto mylar by the U.S. Geological Survey. These mylar reproductions were used to construct a photographic mosaic of the study area.

Seismic Reflection Data

Single-channel seismic reflection data was collected on both cruises with a single-plate EG&G Uniboom sound source. A sweep of 1/4 second was used with a maximum power output of 200 joules on cruise PS 1-87-MB. A sweep of 1/2 second with a maximum power output of 200 joules was used on cruise PS 1-89-MB. Operating frequencies for both cruises were between 400 Hz and 8 KHz. A filter was attached to the triggering and recording device on the ship to eliminate noise or erroneous signals. Resolution of this system is about 2 meters. Sub-bottom penetration averaged about 90 meters in both surveys.

Line drawing interpretations were constructed for each of the seismic lines and can be found in the Appendix. These hand drawings are the means by which the seismic lines are interpreted geologically and contain the geologic bias of the interpreter. Reproductions of untouched original profiles are also provided in the Appendix so the reader can compare the author's interpretation with the "raw" data. The guidelines used to determine the existence of geologic structures in the data are the same as those used by Greene (1977) and are as follows:

Well Defined Faults and Folds - These are identified by the observation of clearly displaced seismic reflectors, an abrupt change in the direction of the dip of the reflectors, discontinuous reflectors or a marked change in the clarity of the seismic reflectors.

Inferred Faults and Folds - These are identified by reflectors that appear to be bent but not completely broken, in the case of faults, and/or a change in reflector strength that can be correlated with identifiable folds and faults on adjacent lines.

Sense of motion was determined on all the faults in this study. Marker beds or groups of reflectors that could be identified on both sides of the fault were the best indicator of motion. Folding caused by reverse drag was also observed on some faults and served as a good indicator of direction of motion. Formations of differing ages in vertical contact with one another were primarily used to determine sense of motion.

Depth to the reflectors was calculated using an average seismic velocity of 1.89 km/s. This velocity is characteristic of the highly folded and fractured Monterey Formation found in southern Monterey Bay (Yang, 1991). Vertical exaggerations in the profiles from the 1987 and 1989 cruises are 6:1 and 4:1. Dips were calculated where two or more seismic profile cross.

Both the side scan sonar fish and the Uniboom sled were towed and operated simultaneously. Towing configurations for both cruises were essentially the same as illustrated on Figure 6.

Geologic Map

A seafloor geologic map of the study area was constructed from observations and examination of differing intensities of backscatter on the side scan images. Seismic image characteristic changes, such as the absence or existence of bedded strata in the subsurface, combined with sediment samples documented from coring and dredging done by Greene (1977) and Martin (1964) were also used to construct this map.

Bathymetric Map

Detailed bathymetric data of the study area was obtained from the Naval Postgraduate School. Soundings were collected in Loran arcs at 200 meter intervals and recorded by computer every 20 seconds (Fig. 7). Miniranger navigational information collected during the sounding surveys were used to position the soundings. The soundings were converted from fathoms to meters, plotted and then hand contoured by the author.

Fig. 6. Towing configuration of Sonar fish, Uniboom sled and hydrophone streamers.

Fig. 7. Bathymetric chart with sounding arcs.

RESULTS

A total of seventeen faults ranging in length from 200 meters to 1500 meters were observed on the high resolution Uniboom seismic records (Plate 1). These faults cut formations of Miocene to Recent age. Identification of the maximum depth of faulting observed on the seismic records was controlled by an average signal penetration depth of 150 meters on cruise PS 1-87-MB and 250 meters on cruise PS 1-89-MB. Four of the seventeen faults were also located on the side scan sonar maps (Plates 2 and 2a). Eleven folds ranging in length from 200-2000 meters were also observed and mapped.

Faults

Sections of the seismic lines used to map the faults in the study area are shown and discussed in the following pages. Fault numbers are arbitrary and correspond to the faults mapped on Plate 1. Thrust and reverse faults are numbered from F1-F16. Only one normal fault exists and it is numbered N1. Northeast striking faults are numbered in ascending order from north to south. Northwest striking features are numbered in ascending order from south to north. Faults covered by less than one meter of alluvium are assumed to be exposed on the seafloor.

Fault F1. Fault F1 is a high angle reverse fault with a strike of N 65° E (Figs. 8 and 9). The southeastern block of the fault is upthrown approximately 8 meters and displaces the Monterey Formation. This fault is approximately 700 meters in length. Fault F1 is buried under 8 meters of Quaternary to Recent alluvium and is truncated by an erosional unconformity.

Fault F2. Fault F2 is a vertical fault with a strike of N 40° E (Fig. 9). The southeastern block of the fault is downthrown by 5 meters and displaces the Monterey Formation. The fault is 240 meters in length and is buried under approximately 6 meters of Quaternary to Recent alluvium. This fault is also truncated by an erosional unconformity.

Fault F3. Fault F3 is parallel to fault F2 and is a vertical fault with a strike of N 40° E (Fig. 9). The southeastern block of the fault is upthrown by approximately 6 meters

Fig. 8. Uniboom profile of fault F1. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation, Q - Unconsolidated Quaternary to Recent sediments.

Fig. 9. Uniboom profile of faults F1, F2 and F3. Uninterpreted (top) , interpreted (bottom), Tm - Miocene Monterey Formation, Q - Quaternary - Recent unconsolidated sediments.

and displacement occurs within the Monterey formation. This fault is 240 meters in length and is buried under approximately 6 meters of Quaternary to Recent alluvium. An erosional unconformity truncates this fault.

Fault N1. Fault N1 is a high angle normal fault with a strike of N 25° E (Figs. 10, 11, 12). The southeastern block of the fault is downthrown a minimum of 8 meters in Fig. 10. This displacement increases to greater than 35 meters in Fig. 12 (the seismic line in Fig. 10 is 1 km north of the line in Fig. 12). These displacements are minimum throw estimates since good marker beds on both sides of the fault are difficult to identify. This fault displaces Monterey Formation at depth and is exposed, at its southern end, on the seafloor. The fault is approximately 1050 meters in length.

Fault F4. Fault F4 is a vertical fault whose strike can not be determined because it is located on only one seismic line (Fig. 11). The southeast block is upthrown by approximately 2 meters. This fault displaces Monterey Formation and is buried under approximately 2 meters of Quaternary to Recent sediments.

Fault F5. Fault F5 is a vertical fault with a strike of N 45° E (Figs. 13 and 14). The southeastern block of the fault is upthrown about 5 meters and displacement occurs within the Monterey Formation. This fault is about 75 meters in length and is exposed on the seafloor where it is covered by less than one meter of alluvium.

Fault F6. Fault F6 is a vertical fault with a strike of N 55° E (Figs. 15 and 16). The southeastern block of the fault is upthrown by approximately 21 meters. Displacement occurs within the Monterey Formation at depth. This fault is exposed on the seafloor where it is covered by less than one meter of alluvium. This fault is 180 meters in length.

Fault F7. Fault F7 is a vertical fault with a strike of N 55° E (Figs. 15 and 16). The southeastern block of the fault is downthrown approximately 6 meters and displacement occurs within the Monterey Formation. This fault is exposed on the seafloor in Miocene Monterey Formation. Fault F7 is approximately 50 meters in length.

Fig. 10. Uniboom profile of fault N1. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 11. Uniboom profile of faults N1 and F4. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 12. Uniboom profile of fault N1. Uninterpreted (top), interpreted (bottom), gr - Mesozoic granodiorite, Tm - Miocene Monterey Formation.

Fig. 13. Uniboom profile of fault F5. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 14. Uniboom profile of fault F5. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 15. Uniboom profile of faults F6, F14, F7 and F8. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 16. Uniboom profile of faults F6, F7, F8 and F14. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fault F8. Fault F8 parallels faults F6 and F7. It is a vertical fault with a strike of N 55° E (Figs. 15 and 16). The southeastern block of the fault is downthrown 9 meters. Displacement occurs within the Monterey Formation. This fault is exposed on the seafloor in Miocene Monterey Formation. Fault F8 is 50 meters in length.

Fault F9. Fault F9 is a thrust fault with a strike of N 55° E and a dip of 30° to the southeast (Figs. 17, 18, and 19). The northwestern block is downthrown 9 meters. Displacement occurs within the Monterey Formation. This fault is exposed on the seafloor in Quaternary to Recent sediments. Fault F9 is 350 meters in length.

Fault F10. Fault F10 is a thrust fault with a dip of approximately 35° to the southeast and a strike of N 65° E (Figs. 18, 19, 20, and 21). The northwest block is downthrown 12 meters at depth in the Monterey Formation. This fault is exposed on the seafloor in the Monterey Formation. Fault F10 can also be identified on side scan sonar images (Fig. 22, Plate 2 and Plate 2a). Fault F10 is 820 meters in length.

Fault F11. Fault F11 is a thrust fault with a dip of 40° to the southeast and a strike of N 73° E (Figs. 20 and 21). The northwestern block is downthrown 9 meters. This fault displaces the Monterey Formation and is exposed on the seafloor. Fault F11 can also be identified in side scan sonar images (Fig. 23, Plate 2 and Plate 2a). Fault F11 is 600 meters in length.

Fault F12. Fault F12 is a thrust fault with a dip of 40° to the northeast and a strike of N 25° W (Figs. 24, 25, and 26). The southwest block is downthrown approximately 9.4 meters in Figure 24 and approximately 4 meters in Figure 26 (the seismic line in Fig. 24 is 1 km west of the line in Fig. 26). This fault displaces Monterey Formation and is exposed on the seafloor. Fault F12 can be identified on side scan sonar images (Fig. 27, Plate 2 and Plate 2a). Fault F12 is 1.45 km in length.

Fault F13. Fault F13 is a thrust fault with a dip of 40° (Fig. 28). The strike of this fault could not be determined since the fault could not be identified on adjacent seismic lines. Nine meters of offset occur on this fault which does not appear on the seafloor.

Fig. 17. Uniboom profile of fault F9. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 18. Uniboom profile of faults F9 and F10. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 19. Uniboom profile of faults F9 and F10. Uninterpreted (top), interpreted (bottom), gr - Mesozoic granodiorite, Tm - Miocene Monterey Formation.

Fig. 20. Uniboom profile of faults F10 and F11. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 21. Uniboom profile of faults F10 and F11. Uninterpreted (top), interpreted (bottom), gr - Mesozoic granodiorite, Tm - Miocene Monterey Formation.

Fig. 22. Side scan sonar image of fault F10. Tm - Miocene Monterey Formation, Q - Quaternary to Recent sediments.

Fig. 23. Side scan sonar image of fault F11. Tm - Miocene Monterey Formation, Q - Quaternary to Recent alluvium, U - upthrown block, D - downthrown block.

Fig. 24. Uniboom profile of fault F12. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation, Q - Quaternary to Recent alluvium.

Fig. 25. Uniboom profile of faults F12 and F14. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 26. Uniboom profile of fault F12. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 27. Side scan sonar image of fault F12. gr - Mesozoic granodiorite, Tm - Miocene Monterey Formation, Q - Quaternary to Recent sediments, U - upthrown block, D - downthrown block.

Fig. 28. Uniboom profile of faults F13, F14 and F15. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fault F14. Fault F14 is a thrust fault with a dip of 5-10° to the northeast and a strike of N 36° W (Figs. 25, 28, and 29). The southwest block of the fault is downthrown approximately 6 meters. This fault displaces the Monterey Formation at depth and on the seafloor. Fault F14 is 2.5 km in length. Side scan sonar images of this fault are shown in Fig. 30, Plate 2 and Plate 2a.

Fault F15. Fault F15 is a thrust fault with a dip of 40° to the northeast and a strike of N 34° W (Figs. 28 and 29). The southwest block is downthrown at least 11 meters (Fig. 26). This fault displaces the Monterey Formation at depth and on the seafloor. Fault F15 is 1.1 km in length.

Fault F16. Fault F16 is a thrust fault with a dip of 5-10° to the northeast and a strike of N 50° W (Figs. 31 and 32). The southwest block is downthrown at least 20 meters (Fig. 31). This fault displaces Monterey Formation at depth and is buried under 3 meters of Quaternary to Recent alluvium. Fault F16 is 900 meters in length.

Folds

Folding in the study area is confined to the Monterey Formation. Five of the folds are broad and symmetrical anticlines and synclines. These folds have strikes ranging from N 30° E to N 40° E. Figure 33 is an example of one of these folds. Folds of this type occur mostly in the northern-most part of the study area where less faulting occurs. These anticlines and synclines appear to be truncated by a Quaternary erosional event.

In contrast, six anticlines (Fig. 34) and synclines occur in the study area. These folds strike almost due east-west and are not truncated. All six of these folds are asymmetrical in shape and occur in the highly deformed strata of the southern-most part of the study area.

Surface Geology

Plate 3 is a map of the surface geology of the study area. Three stratigraphic units have been identified: Mesozoic granodiorite (gr), Miocene Monterey Formation (Tm) and

Fig. 29. Uniboom profile of faults F14 and F15. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 30. Side scan sonar image of fault F14. Tm - Miocene Monterey Formation, Q - Quaternary to Recent alluvium, U - upthrown block, D - downthrown block.

Fig. 31. Uniboom profile of fault F16. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 32. Uniboom profile of fault F16. Uninterpreted (top), interpreted (bottom), Tm - Miocene Monterey Formation.

Fig. 33. Uniboom profile of a symmetrical anticline. Tm - Miocene Monterey Formation.

Fig. 34. Uniboom profile of asymmetrical anticline and syncline. Tm - Miocene Monterey Formation.

Quaternary-Recent alluvium (Q). These units were mapped on the basis of changes in backscatter intensities observed on the side-scanning sonar maps, subsurface bedding pattern changes on the seismic images and correlation with sediment samples taken by Martin (1964) and Greene (1977).

In the side scan sonar images the Mesozoic granodiorite appears as a dark granular mass that is confined to the southwest corner of the study area. The Miocene Monterey Formation appears on the side scan as alternating bands of light and dark that represent the bedding planes. These bedding planes are folded and compressed in the southeastern part of the study area. The Quaternary-Recent alluvium is light colored to white on the side scan with little or no texture. This alluvium covers most of the northern part of the study area.

The Mesozoic granodiorite appears in the seismic records as a chaotic mass of reflectors with no discernible bedding pattern. In contrast, the Miocene Monterey Formation appears as evenly stacked strong reflectors representing bedding within the formation. Quaternary to Recent alluvium appears as a zone void of reflectors.

DISCUSSION

The folds and faults in this study follow two general trends: (1) faults F1 - F11 plus five of the folds strike in a northeast direction and (2) faults F12 - F16 plus six folds strike in a northwest or east-west direction. The structures striking in a northeast direction have not been previously mapped.

The northwest to east-west striking features are parallel to, or contiguous with, those mapped by Greene et al. (1973) and Greene (1977). Faults F7 and F8 were once joined and formed a northeast striking fault. This fault was split and the two halves were displaced approximately 400 meters by right lateral strike-slip movement along fault F14. Figure 35 is a map of both offshore and onshore faults previously mapped in the Monterey region. Several northeast striking thrust faults and folds onshore parallel those mapped in this study.

Wrench fault strain ellipsoids illustrating the orientation of structures predicted from a laboratory based model developed by Wilcox et al. 1973, and the structures actually mapped in this study for both the Palo Colorado-San Gregorio fault zone and the Monterey Bay fault zone have been constructed in Figure 36. In the Palo Colorado-San Gregorio ellipse, four thrust faults (F12, F14, F15 and F16), four folds and the normal fault mapped in this study closely parallel the model predicted structures caused by right lateral strike-slip wrench faulting in a N 25° W direction. Ten of the faults (F1-F3 and F5-F11) mapped in this study also parallel the antithetic strike-slip fault axis, but do not exhibit strike-slip movement. In comparison, the strain ellipse for the Monterey Bay fault zone, oriented in a N 50° W direction, has ten faults (F1-F3 and F5-F11), three of which are thrust faults (F9-F11), parallel to the model predicted thrusts caused by right lateral strike-slip movement. In addition, two folds and the normal fault closely approximate what is expected. Three thrust faults (F12, F14, and F15) parallel the synthetic strike-slip axis. Fault F16 parallels the wrench fault axis. Only fault F14 exhibits strike-slip motion. The structures mapped in this study best approximate the orientation and sense of motion predicted by the wrench fault system model oriented in the direction of the Monterey Bay fault zone.

Fig. 35. Fault map of the Monterey Bay region (From Dibblee, et al., 1973 and Greene et al., 1987). CPF - Cypress Point Fault, CCF - Carmel Canyon Fault, CF - Chupines Fault, BCF - Berwick Canyon Fault, gd - Mesozoic granodiorite, T - Tertiary Monterey Formation, QT - Tertiary to Quaternary undifferentiated sediments, Q - Quaternary alluvium. Teeth represent upthrown block of thrust faults.

Palo Colorado-San Gregorio Fault Zone

Monterey Bay Fault Zone

Fig. 36. Strain ellipses for the Palo Colorado-San Gregorio Fault Zone and the Monterey Bay Fault Zone. (modified from Wilcox et al., 1973).

CONCLUSIONS

Two different orientations of geologic structures onshore and offshore in the area studied suggest a complex tectonic history for the southern Monterey Bay. First motion studies of earthquakes in this region support the theory that right lateral strike-slip motion is occurring (Greene et al., 1973). Greene et al. (1988) suggest that transpression caused by wrench tectonics has caused elongation and distortion of the Salinian Block.

The orientation of the folds and faults mapped in this study closely approximate the orientation of structures predicted from a wrench fault system strain ellipse model, developed by Wilcox et al. (1973), oriented in the direction of faulting observed in the Monterey Bay fault zone (Fig. 36). The slight departure in orientation of the mapped structures from the model predicted structures can be accounted for in a couple of different ways. The model developed by Wilcox et al. (1973) assumed that the material undergoing strain was homogeneous. The Monterey Formation in the study area is heterogeneous. Therefore a slight difference in orientation of the mapped structures from the model predicted structures would be expected. In addition, Wilcox et al. (1973) believe that any amount of convergence or divergence between blocks delineated by the strike-slip faults in the wrench fault system will cause compression or extension within the system and cause the development of structures in the region to differ slightly from what the model predicts. The dominance of compressive structures such as reverse and thrust faults, suggest that convergence among blocks delineated by basement controlled faults in the region is occurring.

The compressive tectonic environment represented here appears to be controlled by movement of the basement complex. The basement rocks in the study area are shallow (0-360 meters) and have undergone episodic uplift from the early Miocene to the Holocene (Alexander, 1953; Greene, 1977). This shallow basement complex acts as a decollement or "backstop" along which the Monterey Formation can easily slide. Decoupling of the Monterey Formation from the basement combined with gradual episodic uplift has caused compression in the immediate study area. This compression in combination with the rapid change in plate

direction throughout the Miocene has caused rotation of the fault blocks delineated by the northwest striking strike-slip faults in the region (Cox and Engebretson, 1985).

Evidence of compression caused by rotation of the blocks delineated by strike-slip faults is apparent in the study area. Faults F12, F14, F15 and F16 all strike in the direction of strike-slip motion predicted from first motion studies of earthquakes in the area. If these faults are basement-controlled it is likely that rotation is occurring between the blocks delineated by these faults. Three faults mapped by Greene et al. (1973) and Greene (1977) are basement-controlled and are contiguous with faults F12, F14 and F16 mapped in this study (Plate 1). Fault F14 is slightly offset and displays an opposite sense of motion from the fault mapped by Greene. These two faults, however, are believed to be contiguous. The thrust motion in Fault F14 occurs along breaks in the bedding plane which is the result of strike-slip movement along the deeper basement-controlled fault mapped by Greene. The vertical sense of motion observed by Greene on his fault is probably strike-slip in nature which explains the apparent opposite sense of motion along its shallower counterpart mapped in this study.

It is also interesting to note how the magnitude of deformation observed within the study area is dependent on the proximity of the basement complex. The Monterey Formation is more tightly folded in the southern part of the study area where the basement is shallow. The amount of faulting is greatest where the basement is exposed both on land and on the seafloor near the city of Monterey. This further supports the theory that basement-controlled faulting and decoupling along the basement surface are primarily responsible for the structures observed in this part of Monterey Bay.

The structures mapped in this study formed during the Miocene and Pliocene. During the late Miocene, right lateral strike-slip along northwest striking faults in the Monterey Bay fault zone is believed to have contributed to the present shape of the granitic Monterey Peninsula (Greene, 1977). The strike-slip motion along these faults was probably confined to the Mesozoic basement rocks during this period of time. Rapid compression between the Pacific and North American plates began sometime between 3-5 Ma (Cox and Engebretson, 1985).

Formation of the northeast striking structures developed during this time period as right-lateral motion continued along northwest striking faults. Sea level regressed sometime in the late Pliocene or early Pleistocene leaving much of Monterey Bay emergent (Greene, 1977). This period of emergence is represented by an erosional unconformity in the northern part of the study area. This unconformity truncates the observed structures which indicate that the development of the structures had ceased. Uplift along the Monterey High, which extends from the city of Monterey to the city of Soquel, occurred sometime after the Pliocene which explains the absence of an unconformity and of Pliocene and Pleistocene deposits in the southern part of the study area. The absence of seafloor displacement along the northeast striking structures here indicate that these structures probably ceased development at the same time as the northeast striking structures in the northern part of the study area did. Active seismicity in the Monterey Bay fault zone suggests that the northwest striking faults are the only faults presently active in the study area.

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APPENDIX

The following appendix contains a table of the original navigation track line numbers and the reassigned track line numbers used for this study. In addition, line drawings of all the Uniboom seismic lines used to construct the structure map of the study area are included in the following pages. See the methods section for criterion for fault placement in the line drawings and for seismic wave velocities used to determine depth of penetration.

Table I
Original and Reassigned Track Line Numbers

Cruise #PS 1-87-MB		Cruise #PS 1-89-MB	
Original Line Number	Line Number for this Study	Original Line Number	Line Number for this Study
17	20	2	1
10	21	4	2
16	22	6	3
11	23	3	4
12	24	5	5
15	25	17	6
13	26	7	7
14	27	10	8
19	28	8	9
20	29	18	10
37	30	9	11
21	31		
36	32		
35	33		
22	35		
33	36		
24	37		
23	38		
32	39		
25	40		
31	41		
26	42		
30	43		
29	44		
27	45		

NW

SE

63

Dip Correction

Vertical Exaggeration 6X

NW

SE

64

Dip Correction

Vertical Exaggeration 6X

NW

SE

65

Dip Correction

Vertical Exaggeration 6X

NW

SE

66

Vertical Exaggeration 6X

NW

SE

67

Dip Correction

Vertical Exaggeration 6X

NW

SE

68

Dip Correction

Vertical Exaggeration 6X

NW

SE

69

Dip Correction

Vertical Exaggeration 6X

NW

SE

70

Dip Correction

Vertical Exaggeration 6X

NW

SE

71

Dip Correction

Vertical Exaggeration 6X

NW

SE

72

Vertical Exaggeration 6X

NW

SE

73

Vertical Exaggeration 6X

NW

SE

74

Vertical Exaggeration 6X

NW

SE

75

Dip Correction

Vertical Exaggeration 6X

NE

SW

NE

SW

NE

NE

78

SW

NE

79

ks

SW

NE

NE

Tracks
0

Depth (meters)
14
89
33

80

acks

Depth (meters)

acks

cks
0

SW

Vertical Exaggeration 4X

NE

81

Dip Correction

Exaggeration 4X

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Oversize maps and charts are filmed in sections in the following manner:

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Black and white photographic prints (17" x 23") are available for an additional charge.

University Microfilms International

36° 40' 00"

36° 39' 00"

36° 38' 00"

STRUCTURE MAP

MAP

PLATE 1

121° 52' 00"

121° 50' 00"

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36° 40'00"

SIDE

36° 39'00"

36° 38'00"

SIDE SCAN SONAR MAP

MAP

PLATE 2

Cruise #PS 1-89-MB

36° 38'00"

36° 37'00"

36° 36'00"

121° 56'00"

Map Scale 1:20,000

121° 54'00"

Monterey

F12

F14

F

F14

F10

F11

Monterey

Seaside

Along T

0
N

° 54'00"

121° 52'00"

Seaside

Along Track Scale
0 500
Meters

Cross Track Scale
0
500
M
e
t
e
r
s

Thrust Fault

Up

121° 52'00"

121° 50'00"

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SID

36° 40'00"

36° 39'00"

36° 38'00"

SIDE SCAN SONAR MAP

R MAP

PLATE 2A

Cruise #PS 1-87-MB

36° 38'00"

36° 37'00"

36° 36'00"

121° 56'00"

Map Scale 1:20,000

121° 54'00"

Monterey

F12

F14

F

PLEASE NOTE:

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36° 40'00"

36° 39'00"

36° 38'00"

Quaternary alluvium

GEOLOGY MAP

AP

PLATE 3

36° 38'00"

36° 37'00"

36° 36'00"

121° 56'00"

121° 54'00"

Quaternary alluvium

Miocene Monterey Formation
<6 meters from the seafloor

Miocene Monterey Formation
outcropping on the seafloor

Mesozoic granodiorite
<6 meters from the seafloor

Mesozoic granodiorite
outcropping on the seafloor

— — — Limits of study area

Map Scale 1:20,000

Monterey