DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

GEOLOGY OF THE MONTEREY SUBMARINE CANYON SYSTEM AND ADJACENT AREAS, OFFSHORE CENTRAL CALIFORNIA

Results of NOAA Sea Beam Survey
Descriptive Report for *Surveyor* Cruise

by

H. Gary Greene[1], William L. Stubblefield[2], and Albert E. Theberge, Jr.[3]

Open-File Report 89-221

This report is preliminary and has not been reviewed for conformity with U.S. Geological Survey editorial standards or with the North American Stratigraphic Code. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

[1] U.S. Geological Survey, Menlo Park, CA 94025

[2] National Oceanic and Atmospheric Administration, Seattle, WA

[3] National Oceanic and Atmospheric Administration, Rockville, MD

1989

TABLE OF CONTENTS

GEOLOGY OF THE MONTEREY SUBMARINE CANYON SYSTEM AND ADJACENT AREAS, OFFSHORE CENTRAL CALIFORNIA

Results of NOAA Sea Beam Survey
Descriptive Report for *Surveyor* Cruise

By

H. Gary Greene
U.S. Geological Survey, Menlo Park, CA

William L. Stubblefield
National Oceanic and Atmospheric Administration, Seattle, WA

Albert E. Theberge, Jr.
National Oceanic and Atmospheric Administration, Rockville, MD

INTRODUCTION

Extensive Sea Beam and Bathymetric Swath Survey System (BS^3) data covering the majority of the Monterey Submarine Canyon System and adjoining areas were collected offshore central California. Many discovered geomorphological features lead to significant new geologic conclusions about the formation and processes of submarine canyons in general and disclose unique sedimentary and tectonic features of the Monterey Canyon system (Figure 1). The highly detailed bathymetric maps constructed from the Sea Beam data indicate that the seafloor topographic pattern is influenced by sedimentary and tectonic processes; both remain active along the central California margin.

Submarine Physiography

Monterey Canyon dominates the submarine topography offshore central California, exhibiting much greater relief than do similar onshore features (Figure 1). The head of Monterey Canyon extends nearly to the coastline and drops off quite steeply within several hundred meters of the small fishing port of Moss Landing. In contrast, other canyons of the Monterey Canyon system, such as Soquel Canyon, heads far out on the continental shelf, in the northern part of Monterey Bay. Another canyon to the system, Ascension Canyon, is cut into the continental slope about 35 km northwest of Santa Cruz. Several of the eleven branches that compose the head of this canyon cut the distal edge of the continental shelf, but do not continue to the shoreline. The head of Carmel Canyon lies in Carmel Bay, 58 km south of the head of Monterey Canyon, only 30 m offshore of Monastery Beach. Both Carmel and Soquel Canyons steepen in gradient as they approach Monterey Canyon and Shepard and Dill (1966, p. 84) suggest that the intersections of these canyons may be represented by hanging valleys.

Near its head, Monterey Canyon meanders, and three such features, two oxbow-types and one incised, are well defined in the bathymetry (Plate 1). Within Monterey Bay, Monterey Canyon is joined by the tributary Soquel Canyon about 18 km seaward of Monterey Canyon's head at a depth of 915 m. Further offshore, along the upper part of the slope, approximately 30 km down canyon from the head of Monterey Canyon, Carmel Canyon joins Monterey Canyon in 1,900 m of water. Further offshore, along the lower slope and rise broad, flat-floored fan-valleys with locally eroded steep walls characterize the submarine canyon system. Near the base of the slope, at a depth of 3,290 m, Monterey Fan-Valley is joined by the lower submarine channels of Ascension Canyon. Monterey Canyon and its tributaries are generally characterized on the shelf and upper slope areas by "V"-shape cross-sections with steep walls and narrow floors.

Methodology

Data used in this study consist of recently acquired Sea Beam soundings in the form of bathymetric maps and 3.5 kHz seismic reflection profiles. These data were interpreted aboard NOAA's hydrographic ship *Surveyor* during a recent cruise in the Monterey Bay region (Figure 2). Data acquisition, characteristics and processing of Sea Beam data are discussed here. Standard techniques were used in the interpretation of the 3.5 kHz data.

A. Data Acquisition Methods

Data used in this interpretation of the Monterey Canyon system and adjacent regions were acquired under the auspices of the USGS-NOAA Joint Office for Mapping and Research in the Exclusive Economic Zone (EEZ) of the United States. The NOAA ships *Surveyor, Davidson,* and *Discoverer* conducted multi-beam swath mapping surveys on an intermittent basis from 1986 to the spring of 1988. The *Surveyor* and *Discoverer* conducted surveys with the 12 kHz Sea Beam system from the 600 m isobath on the east to longitude 124°W on the west, an area bounded on the north and south by latitudes 37°N and 36°N. The majority of Sea Beam work conducted in this area was done by the *Surveyor* in 1988. The NOAA ship *Davidson,* which is equipped with the 36 kHz mid-depth Bathymetric Swath Survey System (BS^3), surveyed the continental shelf and slope between the 150 m isobath and the 600 m isobath, from latitudes 37°N to 36°N.

Survey lines were generally run parallel to the prevailing bottom contours and controlled by Medium-Frequency (MF) radio-navigation systems that have nominal accuracies in the range of 10 to 20 m. Parts of inshore survey areas were positioned with Super High Frequency (SHF) radio-navigation systems with nominal accuracy of 5 to 10 m. MF navigation systems were calibrated both by SHF systems and the Global Positioning System (GPS) operated in the P-Code (Precision-Code) mode in the nearshore areas of the survey. Calibration and lane identification were accomplished exclusively with GPS in the offshore environment with the exception of a few occurrences of three range iteration for lane identification followed by GPS verification at the next available window.

Water mass sound velocity information was determined to better than 2 meters per second throughout the water column during all periods of surveying by taking over-the-side conductivity-temperature-depth (CTD) observations at regular intervals. Reference to expendable bathythermograph (XBT) temperature information taken on at least a daily basis indicates that the water mass retained essentially constant velocity characteristics during the survey operations. Errors in depth caused by erroneous sound velocity information are less than 0.25 percent of absolute depth. Errors in position of outer beam soundings are less than 10 m and this occurred because of velocity errors that generated incorrect ray travel paths.

All swath systems used were checked for gyro bias error (swath alignment), pitch bias error (fore and aft beam pointing error), and roll bias error on a period basis. These system errors are checked by running a specially designed pattern of reciprocal sounding lines on a NOAA developed "patch test". Swath alignment error was less than 0.5 degree, while roll bias and pitch bias errors were less than 0.25 degree during all survey operations.

Differences in the tidal elevations during the time of the survey were considered for the inshore survey areas. Predicted tide correctors were applied to BS^3 data. This, as well as adherence to the procedures and methods outlined above results in positioning errors of less than 50 m circular error of position and depth errors of less than 0.5 percent of water depth.

B. Data Characteristics

Multiple beam echo sounding systems are characterized by narrow fore and aft transmit pulses that are directed through relatively large angular zones athwartship. Hydrophone arrays receive the incoming echoes and algebraically resolve these echoes into multiple beams extending outward from vertical in a fan-shaped pattern.

In the case of Sea Beam, these beams are resolved into 16 (or less) individual 2.66 by 2.66 degree beams extending from vertical to 21.33 degrees. Functionally, this gives a total potential swath-width of 42.66 degrees, although this full swath is rarely attained. For full bottom coverage and a 10 percent overlap between individual swaths, as required on NOAA surveys, the functional swath width for survey planning purposes is approximately 0.6 times the water depth.

For BS^3 the beams are resolved into 22 (or less) individual 5 by 5 degree beams extending through approximately 105 degrees total swath width in the athwartships direction. Because outer beams are subject to depth errors exceeding 0.5 percent of water depth, only swaths of 70 degrees are used between the 150 m isobath and the 300 m isobath and swaths of 60 degrees are used between 300 m isobath and the 650 m isobath, which is the limit of BS^3 coverage. This functionally gives a swath width of approximately 1.0 times the water depth.

Sea Beam data were, depending upon ship speed and water depth, generally collected at a sample interval of 15 to 35 m in the along-track direction. The cross-track sampling interval is approximately 5 percent of water depth (i.e., 100 m in 2,000 m water depth, 200 m in 4,000 m water depth, etc). BS^3 data is generally collected at a sample interval of 10 to 20 m along track, which is also dependent upon ship speed and water depth. Because of wider individual beams (5 degrees for BS^3 versus 2.7 degrees for Sea Beam) BS^3 has a cross-track sampling interval of approximately 10 percent of water depth. Because of tangential spreading of the beam pattern, outer beams with both Sea Beam and BS^3 insonify a greater surface area than vertical beams at any given depth. This dictates a lower resolution for outer beams than near vertical beams with any constant angular beam width swath system.

The asymmetrical nature of Sea Beam and BS^3 data caused by higher density data in the along-track direction versus the cross-track direction and the variability of swath width with water depth presents the surveyor with a tradeoff during the data collection effort. Highest resolution is obtained by running survey lines perpendicular to the strike causing variability in swath width, which generates gaps in data coverage. For example, running a survey line upslope from a depth of 3,000 meters to a depth of 2,000 meters will cause a reduction in effective swath width form 1,800 m to 1,200 m. This effect is the primary reason for orienting large-area surveys parallel to the prevailing contour direction.

Caution is urged in interpreting the seemingly unprecedented detail attainable with swath-mapping systems. The ability to unambiguously define a seafloor feature is a complex inter-relationship between the size of the feature, orientation of the feature relative to the sound source, steepness of the feature, beam width, depth of water, and accuracy of navigation. As water depth increases, geometric spread of the beam pattern occurs. Thus, resolution is inversely proportional to water depth. On the other hand, efficiency of areal coverage is directly proportional to water depth.

As a rule of thumb, Sea Beam cannot unambiguously identify features that have horizontal dimensions less than 5% to 10% of water depth. Small conical features will appear relatively smeared out and truncated. Pinnacles equivalent to the Washington Monument would possible not be delineated at all in 3,000 meters of water and at best would show as small conical features with a much larger base and an attenuated height above the surrounding seafloor. Linear features such as small steep scarps or narrow depressions will appear as broader, less steep features on any contoured Sea Beam map or in any raw data or smoothed profile of the feature. For instance, it is a physical impossibility for Sea Beam to depict a vertical scarp. A vertical 150-meter scarp in 3,000 meters of water could only show as a 45 degree slope if sounding lines were run parallel to the feature while it could show as a 79 degree slope if sounding lines were run perpendicular to the scarp. The point of this discussion is that an attempt to over-interpret swath mapping data or draw inferences from the apparent micro-bathymetry can lead to major error. Sea Beam and BS^3 in the water depths surveyed are meso-scale tools. The maps produced from these systems are meant to be used for regional studies and to serve as guides for targeting anomalous areas that require further study by higher resolution (and higher cost) near bottom systems such as manned submersibles or towed and/or *in situ* instrument packages.

C. Data Processing

The major goals of data processing with swath data are the discovery and elimination of major errors induced by system malfunction or operator blunder. Other goals include, but are not necessarily limited to, the suppression of noise in the swath data, the reduction of data set size (by the selection of significant soundings for ease in developing gridded data sets), and the development of a digital gridded data set, which represents a sea-surface model for generation of graphic data sets including sounding plots, contour maps, three-dimensional plots, and profiles.

Shipboard post-acquisition data procession consists principally of plotting composite swath by swath contour mps of the survey area and the production of a digital data set of significant soundings. Significant soundings are defined as the maximum and minimum soundings within 250 m square areas for Sea Beam and within a variable dimension area based on water depth and other parameters for BS^3.

Swath contour maps are used to determine holidays caused by either swath underlap between adjacent lines or system malfunction and to identify artifacts in the data caused by erroneous soundings or peripheral system malfunctions. After "cleaning" the raw digital data based on inspection of the swath contour maps, the selection of significant soundings is accomplished by computer and output to magnetic media. The significant soundings are then plotted and checked against the contour sheets to assure that no holidays have been overlooked and that no apparent blunders have been carried through the data acquisition and processing stage.

When the ship staff is satisfied that a survey area has been adequately covered and that survey records are ready for forwarding, finished swath contour plots, plots of selected soundings, raw data tapes, selected sounding tapes, and supporting survey documentation (both digital and hard copy) are sent to a central processing facility. This facility inspects all survey records for completeness and adherence to proper procedures and then produces a gridded data set for the survey area by processing the selected sounding tape with a commercially available gridding and graphics package.

This gridded data set is used to produce a 1:50,000 contour map of the survey area. Selected soundings from the just processed survey are combined with selected soundings from previously verified adjacent surveys. On the updated version, this composite data set is gridded to produce a 1:100,000 scale contour map of a 1/2 degree of latitude by 1 degree of longitude "rectangle" as the standard product of the swath-mapping effort. Raw data tapes, selected sounding tapes, gridded data sets, and plot tapes are archived.

Geologic Setting

The geology of the Monterey Bay region is diverse and tectonically represented by allochthonous blocks carried into the region by the Pacific plate. One such structural block is the Salinian block (Figure 3). The Salinian block consists of continental crust composed of Cretaceous granitic and preintrusive metamorphic rocks. This basement rock is capped by upper Cretaceous to Holocene sedimentary rocks. Flanking the Salinian block are terranes composed of heterogeneous aggregation of Jurassic and Cretaceous rocks assigned to the Franciscan Formation, Great Valley sequence and the Coast Range Ophiolite. The northwest and southwest boundaries of this block are formed onshore by the San Andreas Fault Zone that extend from the Transverse Ranges northward over 800 km to Cape Menodocino, and the Sur-Nacimiento Fault Zones that extends offshore south of Point Sur and south eastward to the Transverse Ranges (Figures 2 and 3) (Page, 1970; Silver and others, 1971). The Salinian block is believed to be a mass of granitic basement displaced northward from the southern Sierra-Nevada Mountain Range, or further south, during Tertiary time by movement along the San Andreas Fault, with the Sur-Nacimiento Fault Zone representing a displaced segment of the boundary between granitic and Franciscan basement rocks (Hill and Dibblee, 1953, King, 1959; Page 1970; Howell, 1975; Ross, 1976). The Cretaceous granitic basement rocks of the Salinian block and overlying upper Cretaceous and Tertiary strata have been offset both horizontally and vertically by many faults that trend southeast from Monterey Bay through the Santa Lucia Range (Figure 4). The Sur-Nacimiento Fault Zone encompasses faults of various ages in a belt extending southeastward from Point Sur through the central and southern Coast Ranges of California (Page, 1970).

North of Monterey Bay, faults in the Salinian block trend northwest and offset granitic basement rocks and the overlying Tertiary strata (Jennings and Burnett, 1961; Clark, 1970; Brabb, 1970). The San Gregorio Fault, which extends onland for nearly 30 km northwest of Ano Nuevo Point, strikes N25°W and cuts across the regional structural grain.

The western boundary of the Salinian block is best seen in the structure contour map of the upper basement surface (Figure 5). Basement rocks east of the Sur Sliver consists mostly of Mesozoic crystalline basement rocks. Greene (1977) shows from seismic reflection data and geologic samples that exposures of this rock type are generally limited to the southwestern part of Monterey Bay, Carmel Bay, along the walls of the lower part of Monterey Canyon and along the eastern wall of Carmel Canyon (Figure 6). Seafloor samples in this area show the basement rocks to be composed of biotite granodiorite porphyry (Greene, 1977).

The geological character of the area west of the Sur Sliver is not as well known as the area to the east. Hence, the stratigraphy west of the sliver is based mostly on inferences from seismic reflection data with few or no lithologic control or correlation with onshore geology. Acoustic basement rocks in this area are thought to consist of lithified sedimentary and metamorphic rocks, and possibly basic intrusive and volcanic rocks as suggested from dredge samples collected in the area (Greene, 1977; Nagel, Mullens and Greene, 1986). Rocks forming acoustic basement appear on seismic reflection profiles to crop out in the head of Ascension Canyon, in Monterey Canyon, and possibly along the unnamed seaknolls on the slope west of Point Sur (Figure 5, Plate 2). Franciscan rocks appear to form the acoustic basement on the shelf west and south of Point Sur, west of the Sur-Nacimiento Fault, which can be correlated with Franciscan rock exposed onshore, and along the walls of the southern heads of Ascension Canyon.

Structure

Structure of the central California shelf and slope in the vicinity of Monterey Canyon is complex and is produced largely by post-Eocene tectonic events. Major structures include faults, folds, and fault-bounded basement ridges and associated sedimentary basins. Structure is variable in trend, and may record shifts in stress field associated with Pacific Plate movement since Oligocene 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, obliquely truncating structures in Monterey Bay (Figure 4). Structures west of the Palo Colorado-San Gregorio fault zone radiate westward from the fault zone, with a pivot point somewhere south of Point Sur. Faults further 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 (Figure 4).

Faults in the Monterey Bay area lie primarily within two major, essentially northwest-southeast-trending fault zones, the Palo Colorado-San Gregorio and Monterey Bay fault zones (Figure 4). Fault-plane solutions of eight earthquakes in the vicinity of these two fault zones indicate that the sense of fault displacement is similar to that on the San Andreas Fault; right-slip with rocks to the west being moved north in respect of rocks to the east (Greene and others, 1973). The Palo Colorado-San Gregorio fault zone is a narrow (approximately 3 km wide) feature defined by two or more faults. The length of this 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 that in turn join the San Andreas Fault northwest of the Golden Gate (Cooper, 1970). Also, rocks of Pt. Reyes are similar to rocks at Point Lobos, suggesting 180 km of displacement (Clark, and others, 1984). It also may join the Coast Range Fault to the south (Ross, 1976) and may continue into the Hosgri Fault (Silver, 1974; Graham and Dickinson, 1978).

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

The probable extension of the Sur-Nacimiento Fault Zone forms a third major fault that parallels the Palo Colorado-San Gregorio fault zone farther offshore along the southwestern edge of the Monterey Bay area. Several faults identified on the shelf between Point Sur and Cypress Point are aligned with faults onshore in the Sur-Nacimiento Fault Zone. Offshore and north of Point Sur, faults have been mapped that parallel the northwest trend of the Sur Fault Zone (Greene, 1977; McCulloch and Greene, in press). The westernmost of these faults may be the offshore trace of the Sur-Nacimiento Fault.

The Ascension Fault (Greene, 1977) lies about 5 km west of the Palo Colorado-San Gregorio Fault Zone, paralleling it for almost 70 km from Point Sur to the southernmost head of Ascension Canyon (Figure 4). Greene (1977) states that the youngest rocks displaced by this fault appear to be Miocene in age, based on the offset of acoustic reflectors of probable Miocene age, and the lack of offset reflectors in the overlying strata of Pliocene age.

Proceeding from west to east, in the Monterey Canyon region, the orientation of most faults seaward of the Palo Colorado-San Gregorio fault zone changes from northwest-southeast to nearly north-south. The southern ends of the most nearshore faults appear to converge at a common juncture south of Point Sur. Faults south of Point Sur generally trend northwest-southeast, but their northern ends appear to change abruptly to a nearly east-west orientation (Greene, 1977; McCulloch and Greene, in press).

Monterey Canyon is located mostly on the Salinian block, on the active strike-slip margin of California and has been displaced northward since its time of formation. Initially, this feature appears to have been formed subaerially, then later offset considerable distances by movements along the San Andreas and associated lateral faults (Greene, 1977). Monterey Canyon is old, as indicated by a deep gorge that extends just onshore from the canyon's head filled with ten-million-year-old (Miocene) sediments. According to Greene (1977) the canyon's long and complex tectonic history starts with a valley being cut subaerially along a fault in the granitic rocks of Salinian block. Approximately 21 million years ago this structural block was located several hundred kilometers south of its present location. Here, the margin was still being influenced by subduction and tectonic elevation, the result of the compressional processes associated with the collision of the North American and Pacific crustal plates, (Figure 7). Later, when the margin shifted from orthogonal collision to oblique strike-slip movement along the San Andreas fault, the Salinian block was ripped away from its parent mass and moved, along with the embryonic submarine canyon, northward. During its passage the Salinian block was repeatedly submerged beneath and elevated above or near sea level several times. When deeply submerged beneath sea level the canyon filled with sediments, but evidently was always able to preserve some type of physiographic depression due to differential compaction of sediments within the canyon. When it was elevated above or near sea level its expression as a depression focused erosive processes that could exhume the canyon and initiate another stage of canyon deepening. In this manner, Monterey Canyon formed steep walls by both eroding downward, through the action of turbidity flow, and building-upward, through sediment deposition (Greene, in press).

Offsets along offshore strike-slip faults, other than the San Andreas fault, displaced deeper parts of Monterey Canyon (Greene, 1977). These beheaded canyons have been moved to the north and appear today as Pioneer, Ascension and other submarine canyons primarily restricted to the continental slope (Figure 8). They do not cut into the continental shelf. Therefore, it appears that the older, headward part of Monterey Canyon focused erosional processes down the canyon to form off-shelf canyons that were regularly offset along active strike-slip faults.

Today Monterey Canyon is actively being excavated and exhumed. This activity continues to be tectonically controlled as fault rupture brought about by plate motion causes earthquakes that stimulate slumping and turbidity flows within the canyon. Continued movement along strike-slip faults are also displacing a segment of the deeper part of the canyon to the north (Greene, in press).

DESCRIPTION OF GEOMORPHOLOGY FROM SEA BEAM DATA

Interpretation of the NOAA composite maps and final raw Sea Beam bathymetric survey maps indicate a diverse and complex geomorphology for the Monterey Canyon system and adjoining region. Here a preliminary detailed description of the seafloor morphology is given and, where possible, supplemented with cited geology. This description is based on the general geologic sketch maps constructed as overlays to the bathymetric maps (Plates 1 through 4).

Examination of the Sea Beam data suggest that the region can be divided into four distinct geographic areas and four geomorphic provinces. The geographic areas are as follows:

1. Monterey Canyon—includes Soquel and Carmel Canyons
2. Ascension Canyon
3. Monterey Fan-Valley
4. Sur Canyon

The geomorphic provinces defined include the following:

1. Erosional, Canyon Cutting
2. Erosional, Slope Dissection
3. Erosional, Mass Wasting
4. Depositional, Aggradation

The majority of the region surveyed is influenced by the Monterey Canyon System, a composite submarine canyon system composed of six principal components. In order of importance these are:

1. Monterey Canyon
2. Monterey Fan-Valley
3. Carmel Canyon
4. Ascension Canyon
5. Ascension Fan-Valley
6. Soquel Canyon

Because of the complexity of the region each of the above features will be described independently starting with the Monterey Canyon system and discussing the other features in order of their geographic connection with Monterey Canyon. Following the discussion of Monterey Canyon is a description of the area north of Ascension Canyon, Sur Canyon, and its associated mass wasting fields, mass wasting at the base of the Sur-Platform Slope, Ascension Fan-Valley and the Monterey Fan-Valley meander.

Monterey Canyon

Monterey Canyon proper is an erosional feature, (located in an erosional, canyon cutting province) resulting from both canyon cutting and mass wasting.

The head of Monterey Canyon is deeply incised into Neogene and Quaternary rocks just offshore of Moss Landing (Figure 6). Generally, the canyon is sinuous, with a deeply incised axis in the floor of Monterey Bay and upper continental slope. Three distinct meanders, two of which were identified from previous work (Martin and Emery 1967, Greene 1977), are identified in the upper reaches of the canyon, each apparently resulting from different processes (Plate 1) as discussed below.

Between the coastline and the intersection with Soquel Canyon, the axis of Monterey Canyon, when compared to its lower segments, is relatively straight, except for a distinct "goose-neck" meander located halfway between Monterey Canyon head and Soquel Canyon intersection (Plate 1). Here, newly discovered from the Sea Beam data, is what appears to be an ancient (older) landslide that dammed the canyon axis ponding sediment immediately upstream from the slide. The bathymetry shows a mound projecting into the canyon from the north wall with a wide, flat to "U"-shaped floor up-canyon from the mound; this is an area where a "V"-shaped canyon profile would be expected because of the active sediment distribution to the canyon. Through an unknown amount of time canyon eroding processes broached and dissected this dam, which appears to consists of landslide deposits and ponded sediments. The goose-neck meander is an erosional feature formed by turbidity currents. These currents tended to turn southward at right angle to the previous axis, move around the nose of the slide and across the backside, or downstream side, of the slide to recapture the previously abandoned axis. Erosion of this slide is continuing today. In addition to this meander several previously mapped (Greene, 1977) slumps located on the wall of the canyon in this area are seen in the bathymetry.

A well-defined meander is incised into Neogene sedimentary and granitic basement rocks in the vicinity of the Soquel-Monterey Canyons intersection. Both the upstream and downstream legs of the meander trend northwest-southeast and have been interpreted as fault controlled (Greene, 1977). Furthermore, Greene (1977) reports that several faults of the Monterey Bay fault zone pass through the canyon and appear to have moved resistant basement rocks into the canyon axis during the past few million years. This tectonic process caused turbidity currents to swing northward around the granitic fault block and thence back southward to occupy the previous canyon axis. This path of least resistance for the turbidity currents along the fault zones and past the leading edge of this structural resistant block formed the meander.

Along the northern wall of Monterey Canyon, at the apex of the meander, and positioned between the faults of the Monterey Bay fault zone is a large slump mass (Plate 1). This feature possibly results from movement along faults of the fault zone. The canyon is steeply-walled along the downstream leg of the meander; along the northern wall of the upstream leg of Monterey Canyon Soquel Canyon debouches.

Soquel Canyon

Soquel Canyon is a short (9 km long), fairly straight canyon trending southwest downslope (Plate 1). It heads into the shelf, or northern floor of Monterey Bay, and is far removed from the shoreline. The canyon exhibits fairly steep relief and cuts through Pliocene sedimentary rocks of the Purisima Formation (Greene, 1977) (Figure 6). At its confluence with Monterey Canyon the mouth of Soquel Canyon appears to broaden by the slumping of canyon walls near the intersection with Monterey Canyon. Although apparently non-active, it is located in an erosional, canyon cutting province.

Middle Monterey Canyon

The area between the Monterey Canyon structural meander, near Soquel Canyon, and the confluence of Carmel Canyon is defined here as middle Monterey Canyon. In this location the character of Monterey Canyon changes from being relatively "V"-shaped in profile to a narrow, flat-floored "U"-shaped axis.

The downstream leg of the structural meander swings into another gently bowed meander (the third meander cutting the shelf) that exhibits prominent steep walls along the southern side of the canyon (Plate 1). This meander curves from a nearly northwest-southeast trend to an east-west trend. The meander begins upstream where the axis of the canyon is abruptly offset westward. This meander is abruptly terminated just upstream of the confluence of Carmel Canyon where the axis makes a right-angle turn to trend southward towards the mouth of Carmel Canyon. The change in direction of the axis is in the approximate location of Palo Colorado-San Gregorio fault zone (Greene and others, 1973; Greene, 1977). Immediately north of this site is a large (over 90 km^2) area of mass wasting composed of many slumps, exhibiting extensive headward erosion.

This mass wasting evidently supplies considerable sediment to the canyon as the canyon floor downstream of this location widens and flattens suggesting either a change in gradient with resultant deposition or a greater influx of sediment, or both. In addition, the walls of the canyon downstream from this extensive area of mass wasting show the effects of ongoing mass wasting processes that supply additional sediment for transportation down canyon.

Carmel Canyon

In comparison to Monterey Canyon, Carmel Canyon is relatively straight, yet is part of the erosional, canyon cutting province that Monterey Canyon is assigned. It has three heads. Two heads are found in Carmel Bay, one at the shoreline just opposite San Jose Creek, and the other offshore some distance (about 2 km) from the mouth of Carmel river; both cut Cretaceous granitic rocks (biotite granodiorite porphyry of the Monterey mass of Ross, 1976). These heads join together just outside of Carmel Bay and trend west from shore, for about 3 km to where the canyon makes a right-angle turn to the north. Here the canyon continues north, but another arm extends upslope to the south along trend with the north-south oriented segment and heads (the third head) about 3 km from the bend (Plate 1). The change in axial direction is believed to be fault controlled as faults of the Palo Colorado-San Gregorio fault zone pass through here (Greene and others, 1973; Greene, 1977). The north trending segment of the canyon is aligned with the fault zone and the head of the canyon appears to have been offset right-laterally along the fault zone. Near the mouth of the canyon the axis is also oriented in a general east-west direction and it is conceivable that this part and the head of the canyon at one time were aligned, but subsequently offset from each other a distance of 16.5 km by right-slip movement along the Palo Colorado-San Gregorio Fault Zone (Figure 9).

At the intersection with Monterey Canyon, Carmel Canyon changes from a northwest trend to a southerly trend and broadens into a rounded, gently dipping trough. No distinct hanging valley is seen in the bathymetry as proposed by previous workers (Shepard and Dill, 1966; Greene, 1977), but a steep rounded chute is defined (Plate 1). However, during recent Alvin dives in this area, it was reported that steep stair-step like cliffs or scarps existed in that a modified hanging valley-like geomorphology is present (Chris Harold, personal comm., 1988).

The upper east wall of Carmel Canyon is dissected by a few relatively straight dipping drainage channels and a few slumps. On the opposite wall, the western side of the canyon, steep cliffs extend to the crest of the bedrock ridge. The difference in morphology between the two walls of the canyon must be related to differing lithologies. The eastern wall is composed of the more resistant Cretaceous granitic rocks compared to Jurassic metamorphic rocks and Cretaceous sandstones that crop out along the western wall and constitute the bedrock ridge on the western side of the canyon (Greene, 1977). The backside (west) of this bedrock ridge is dissected by dendritic-like drainage channels.

Lower Monterey Canyon

West, or downstream, of the Palo Colorado-San Gregorio fault zone, and the associated area of mass wasting, the character of Monterey Canyon's profile changes; the floor flattens and the characteristic "V"-shaped profile disappears. Here aggregation as well as erosion appears to be active as indicated by the flat floor and slumping along the walls. Although this area is still in our erosional, canyon cutting province, it is transitional between erosional, canyon cutting and erosional,, mass wasting. The canyon generally trends southwest from the fault zone to the confluence of an unnamed canyon that enters the "main stream" from the south. This is some 18 km downstream of the Palo Colorado-San Gregorio fault zone (Plate 1). Steep canyon walls alternate with gentle slopes and the irregular toes of mass wasting fields. The mass wasting consisting of slumps and other landslide features are primarily concentrated along the northwest walls of the canyon and apparently result from erosional undermining of the slope by turbidity currents. Also, the southeastern wall along this stretch of canyon is dissected by the dendritic-like channels that cut the western slope of the ridge, which lies adjacent, to the west, of Carmel Canyon (Plate 1).

From the intersection of an unnamed canyon downstream the thalweg or main channel of the canyon bifurcates and fluvial-like braided drainage occurs here (depositional, aggradation province). Extensive mass wasting fields exist (erosional, mass wasting province) on both sides of the canyon in an area characterized by well-defined, large (one slide over 215 km^2 in area) individual slumps (Plate 1). Headward erosion appears active as headscarps of many slumps appear to be progressing upslope in a bow wave fashion.

Backing up a bit and looking at Monterey Canyon from the confluence of Carmel Canyon to the area of mass wasting just west of the confluence of the unnamed canyon, the axis is a gentle curve that swings from a southerly direction to a northwest trend that terminates approximately 18 km downstream (Plate 1). The floor of the canyon along this stretch broadens from about 0.75 km just below the intersection of Carmel Canyon to over 2 km wide at the downstream termination of the curve. Here a median bar has built-up in the center of the canyon floor, opposite and downstream of where several walls cut deeply into the mass wasting field north of the canyon, further undercutting the walls and causing slides to enter the active channel. Also, headward erosion along the upper parts of the mass wasting fields appear to be enlarging the area of instability thus generating new slumps and turbidity flows. The floor of the canyon here is in as depositional, aggradation province whereas the upper walls are in an erosional, mass wasting province.

Downstream from the median bar, the canyon floor broadens to nearly 3.5 km, trends nearly due west for over 21 km and is composed of fluvial-like braided drainage lines that slope off a higher northern floor (in a depositional, aggradation province). Continuation of the mass wasting from the east along the northern wall of the canyon appears to have supplied significant debris to the main channel, thereby building up the northern floor and causing the main channel to migrate southward and the canyon to constrict, narrowing the main channel floor. Downslope of this constriction the main channel of Monterey Canyon continues as a fan-valley depositional, aggradation province (Plate 1). Here the main channel turns to the south and the submarine flood plain widens considerably, initially to about 3 km. East of the bend and constriction of the channel a wide, gently northwest sloping platform is mapped; in a fluvial system the feature would be interpreted as a point bar. It is conceivable that turbidity flow results in fluvial-like deposition (Stubblefield and others, 1982; in press). Above these point bar deposits is a steeper yet sloping face, which may have been shaped by earlier erosion along a main channel that has progressively migrated westward in this location.

Ascension Canyon

Ascension Canyon is separated from Monterey Canyon to the south by a cone-shaped ridge extending from the shelf break westward for over 41 km (Plate 1). Surface topography of the ridge is smooth and principally undissected (depositional province). Greene (1977) states that the ridge is composed of Pliocene and Quaternary sedimentary rocks overlying metamorphic rocks of possibly the Franciscan Formation. The upper parts, or the base of the cone, is cut by faults of the Palo Colorado-San Gregorio and Ascension fault zones.

Ascension Canyon is a multi-headed, generally southwest trending system composed primarily of three major distributary channels (Plate 1). Our Sea Beam data discloses eleven heads, in contrast to nine heads previously reported by Greene (1977) and eight by Nagel, Mullins and Greene (1986). Beginning in the south, the southern main channel bifurcates upslope to form two arms that in turn separate into four individual (eight total) heads that nearly notch the distal edge of the shelf.

The southern set of four canyon heads are approximately equally spaced by a distance of about 1.8 km. The southern-most head in this set is unusual in that it initially trends southeast, then swings southwest, and then changes to a northwest trend. This box-like configuration appears to be the result of faulting as the Palo Colorado-San Gregorio fault zone aligns with the upper southwest trend of the head and the turn from southwest to northwest appears to occur in the area where the Ascension fault crosses the slope (Plate 1). The other heads of the southern set are relatively straight.

Separating the northern set of four canyon heads from the southern set are two small ridges. The northern head of the southern set is 3.6 km from the southern head of the northern set. Again distances between the three southern heads of the northern set are fairly equidistant at about 1.8 km apart and these heads are relatively straight compared to the northern-most head of this set. In contrast, the northern-most head of this set is offset about 2.7 km from the closest head to the south and exhibits an abrupt, almost right-angle, bend toward the southwest, approximately 1.8 km down slope from its headwall.

Scattered about the walls of the southern-most eight heads of Ascension Canyon, and especially along the northwest wall of the northern-most head, are landslides (Plate 1). Generally, the walls of the heads are steep and all have "V"-shaped profiles (all are located in an erosional, canyon cutting province). At the confluence of the two branches that connect these heads the channel widens to over 2.5 km and reduces in gradient. From here the channel is straight for over 19 km downslope and has a southwest trend. Extensive mass wasting occurs along the length of this straight channel exhibiting many slump and flow features. Like much of the mass wasting in the region, headward encroachment appears to be active.

Separating the most southerly main channel of Ascension Canyon from the other two main channels is a ridge of fairly smooth, undissected topography depositional province (Plate 1). Both sides of this ridge appear to be undercut by canyon erosive processes and mass wasting is disrupting the lower slopes of the ridge (erosional, canyon cutting province).

The center main channel of Ascension Canyon widens upslope to a set of two heads, one a well-defined feature that notches the distal edge of the shelf and the other, a smaller arm, that does not reach the shelf break. The southern arm of this set is separated from the northern-most head of the eight heads previously described by a southwest trending and dipping ridge that extends from the shelf break downslope for about 20 km to the intersection of the main channels (Plate 1). This arm is a relatively non-descript feature compared to most of the other heads in the system, it generally trends southwest with a slight southward curve. The major head of this set, however, cuts deeply into the upper slope sediments and trends southwest, generally with a straight axis for about 9 km where it makes a right-angle turn to a southeast trend and widens. Here, both heads exhibit "V"-shaped profiles.

The center main channel of Ascension Canyon widens to approximately 1.5 km just below the bend in the northern head and maintains this width for nearly 11 km downstream (Plate 1). Similar to that in the southern main channel, the mass wasting associated with the channel walls appears active along the entire length of the channel. Prominent mass failure in this area extends upslope to near the canyon heads.

Separating the central main channel from the northern main channel of Ascension Canyon is a topographic high dissected by dendritic-like drainage lines, slumps and other landslide features (Plate 1). Only one head is associated with the northern main channel and this head cuts further onto the shelf and exhibits greater bathymetric relief with steeper headwalls than the other heads of Ascension Canyon. Consequently, we believe that this head is the primary or principal active head of Ascension Canyon, because it cuts deeper and further into the shelf, thereby, intercepting the southward longshore transport of sediment before the other heads. We consider the other heads to be secondary and tertiary progressing from north to south. The main channel of the primary head is considerably narrower (less than 0.5 km wide) and generally straighter than the other heads and channels. Some mass wasting appears to be taking place along the northwestern wall of this primary channel. Similar to its southern neighbor, this northern head has a bend, which shifts the axial trend from southwest to south. This is, however, not as pronounced as the bend exhibited in the adjoining head.

As Normark (1969) has indicated, Ascension Canyon is now relatively inactive compared to its activity during the previous low stands of sea level. During the Pleistocene, when the shelf was exposed, all heads of Ascension Canyon were able to intercept longshore transported sediments as well as fucus terrestrial drainage,, and thus sediment transport down the canyon was quite active.

The confluence of the northern and central main channels of Ascension Canyon occur along the toe of the bathymetric high separating the two channels upslope (Plate 1). Here the combined channels widen downstream, from about 1.8 km to over 5.5 km, at the confluence of the southern main channel. Grade also reduces considerably and braided drainage lines are present. The combined northern and central main channels trend south to the intersection of the southern channel where they join the southern channel and continue downslope along a westerly trend. In this location, where the three channels merge, the canyon floor widens and continues to increase in width until 20 km downstream where it is about 7.5 km wide. Aggregation, as well as erosion, takes place along this extensive canyon floor (located in a transitional zone between erosion, aggradation and erosion, canyon cutting province).

Just south of the confluences of the Ascension Canyon main channels is a large area of mass wasting (erosional, mass wasting province). Here headward advancement of mass wasting will eventually meet the headward encroaching mass wasting field that exists on the southern side of the ridge that separates the Ascension drainage from that of Monterey Canyon. A topographical saddle now exists on the crest of the ridge and may have formed from a former channel. This saddle is aligned north-south.

One other channel associated with Ascension

Canyon system is worthy of mention. This is a fairly straight, southwest trending channel that lies north of, and is separated from, the northern channel by a south trending topographic ridge. The head of this channel appears to result from mass wasting as it's head is a squared shape bowl characteristic of erosion. This channel heads a little more than halfway up the upper slope and is about 18 km long, connecting with the main Ascension Canyon channel at the lower part of the broad canyon floor (Plate 1). A large mass wasting field (erosional, mass wasting province) composed of large slumps and flow features comprise the lower northern wall of this channel.

From the broad main channel floor of Ascension Canyon the axis changes, from a westerly direction to a southerly trend influenced by a gentle curve, and widens to nearly 20 km. This area appears to be either the apex of a proximal fan or a submarine depositional plain where sedimentation appears to predominate over erosion (depositional, aggradation province). Curving of the main channel is influenced by a domed high with low relief extending down from the north in a north-south orientation and thereby blocking further downslope transport to the south (Plate 1). We speculate that this high may represent an older fan levee deposit—as suggested by Normark (1969)—or the final resting spot of landslide debris that flowed down the slope from the north or northeast.

The main channel of Ascension Canyon once again starts to erode along the southern part of the fan or plain (erosional, canyon cutting province). Here a narrow (less than 0.25 km) straight channel is cut into the sedimentary deposits of the fan. The rejuvenation of erosion may be the result of a change in base, either by local tectonics, increase of erosion in Monterey Fan-Valley (Normark, 1969) or by change in base level of the fan or plain. The latter would occur along a prograding sediment wave front or from deposition of landslide materials. Normark (1969) suggests rejuvenation of erosion of the Ascension Fan-Valley resulted after sea level raise when the many Ascension Canyon heads were cut-off from sediment source and Monterey Fan-Valley was able to to cut-down faster than Ascension Fan-Valley, thus deepening of Ascension Fan-Valley started at its confluence and headed backward (headward).

Along the western edge and at the northern end of the fan or depositional plain are two anomalous triangular shaped areas of unusually oriented bathymetric contours (Plate 1). These areas slope upward toward the east and appear to represent the lower slope prior to dissection of the region by Monterey and Ascension Canyons erosion. Consequently, these areas are mapped as probable older slope deposits, remnants of non-dissected, depositional, aggradation province in a now predominantly erosional, mass wasting province. From where these deposits are separated by the drainage of Ascension Canyon, and extending eastward to the merging of the Ascension Canyon main channels, is a low area occupied by the wide main channel floor (Plate 1). This low area is bounded by extensive mass wasting (an erosional, mass wasting province) and we speculate that this low was once covered with slope deposits that failed some time in the past, moving downslope and cutting the gap between the two mapped areas of older slope deposits. This slide mass would have continued downslope trailing lateral debris deposits that subsequently influenced the drainage configuration. This material may have come to rest in the vicinity of the large meander of the Monterey Fan-Valley downstream thus possibly blocking the Monterey drainage to produce the meander (explained in more detail below).

The geomorphology of the continental slope north of Ascension Canyon is significantly different than to the south. Here the bottom morphology is no longer dominated by canyon erosion and mass wasting. Rather, dendritic-like drainage lines occur with many small, gentle relief channels dissecting the slope to form an erosional, slope dissection province (Plate 1). These are all slope channels that do not head anywhere close to the shelf break. A few landslides occur, the larger ones being located near the base of the slope. Most of the channels converge at the base of the slope along a wide (up to 6 km) depositional plain where the drainage lines become braided in style. This plain appears to be the upper limits of a proximal fan (depositional, aggradation province) that continues westward.

The dendritic-like bathymetry to the north is separated from canyon topography to the south by an unusually shaped ridge. This ridge is gently curved, extending from mid-slope southwesterly and eventually curving to the west near the base of the slope (Plate 1). The ridge is fairly narrow (averaging about 3 km in width) and is over 36.5 km long.

Sur Canyon

Sur Canyon is a major submarine canyon whose head lies 60 km south of the head of Monterey Canyon. It heads into the southern part of the Sur platform, approximately 5 km due south of Point Sur and the same distance from the shoreline. It is a multi-headed canyon.

The Sur platform is a generally flat-topped bedrock surface composed of principally metamorphic rocks of the Franciscan Formation and/or Sur Series. It projects out from the coastline from Point Sur with its upper flanks radiating out from the platform in a cone shape (Plates 2 and 3). The upper part of the cone is of smooth topography and relatively undissected compared to the lower part, except on the north and south where submarine canyons exist (Plate 2) and is considered a erosional, channel dissection province.

Sur Canyon is a sinuous canyon that generally trends west for over 50 km from its head to where the main channel sharply bends south and the floor broadens (Plate 2). There are three major distinct meanders, two near the head of the main channel and one 14.5 km farther downstream. The floor of the canyon averages about 0.25 km in width from the upper meanders to the bend where the channel widens considerably, to 0.75 km.

The origin of the meanders in the upper part of the channel is unknown. However, several northwest-southeast trending folds have been mapped in the area (McCulloch and Greene, in press) that indicate that the second meander may have been influenced by an anticlinal ridge bounded by synclines. The legs of the meander (trending northwest-southeast) may be aligned along the synclinal axes.

In the area of the upper meanders mass wasting is prominent (an erosional, mass wasting province). Along the northern wall of Sur Canyon in the location of the meanders, well-defined slumps and flow features are present. Headward advancement of mass wasting appears active along the upslope part of a mass wasting field (province).

Above, and to the west, of the mass wasting field and the upper meanders four very straight, south trending debris chutes are present located in an (erosional, channel dissection province) (Plate 2). One enters the head of the mass wasting field while the others enter the main channel of the canyon just below the downstream leg of the second meander. All extend up to near the top of the southern flank of the Sur platform. One chute (the third from east) appears to have been cut off by another chute (second from east); the head of the third chute being captured by the second.

Mass wasting also occurs along the eastern and southern sides of the canyon in the vicinity of the upper meanders (in an erosional, mass wasting province). Many slump scars have been mapped, especially along the southern side of the western trending downstream leg of the second meander. Above this leg of the meander is an area of subtle topographic relief that is interpreted by us to represent either incipient mass slope failure or "healed" relief of older submarine landslides, but still part of an erosional, mass wasting province. Headward advance of mass wasting may be occurring here.

Along the inside (east) curve of the first meander an elevated (raising above the floor of the meander), flat-surfaced canyon terrace is mapped (Plate 2). The presence of this feature suggests a westward migration of the channel within the curve. Headward of this curve erosional scarps are cut into the landslide debris. Steep cliff's exist along the cut banks of the meanders, in an erosional, canyon cutting province.

Downstream between the upper set of meanders and the lower meander, the channel winds sinuously through the steep-walled canyon (Plate 2). Several small slumps, one very well defined by its squared-off head, are mapped. The upper slopes of the canyon here may be unstable (in an erosional, mass wasting province), but the degree of mass failure is considerably less than near the upper meanders and downstream in the vicinity of the lower meander.

The lower meander of Sur Canyon is a spectacular example of a slump meander (Plate 2). Here a large slump (over 2.5 km^2 in area) dropped to the canyon floor from the northern wall of the canyon. This square-shaped block evidently completely blocked the canyon axis and the turbidity flows that keep the canyon swept clean were forced to erode around the slump mass. By doing so the channel mimicked the slump giving a distinct square-shape meander channel. Steep cliffs were eroded along the cut sides of the channel. The southern wall of the canyon appears to have extended nearly 1 km southward forming a steep bowl-shaped erosional cliff opposite the slump mass. Above this cliff an older landslide or incipient zone of mass wasting exists.

From the meander downstream to the bend an extensive area of mass wasting fans out from a point just above the lower meander to compose an erosional, mass wasting province (Plate 2). Here well defined slumps, flow features and subtle topographic relief that suggest older "healed" slides or incipient slumps are densely concentrated. Headward erosion along the upper slopes of the area of mass wasting appear active as indicated by gullying and gentle, arcuate bending of contours. The channel of Sur Canyon along this stretch is less sinuous than upstream and is cut deeply into the seafloor with walls comprised of steep cliffs.

Fault Zones Along the Flanks of Sur Platform

Previous geologic mapping in the region (Greene, 1977; McCulloch and Greene, in press) show several north-south trending faults or fault zones passing through the region in the vicinity of the Sur Canyon bend. Here, along the eastern side of the south trending channel of Sur Canyon are several north-south oriented cliffs that may be associated with faulting (Plate 2). These cliffs are somewhat distorted by landslides so no distinct structural relationship can be determined from the bathymetry alone. Also, terrace-like, flat triangular areas exist at several levels along the line of these cliffs suggesting that the active channel of the canyon may have pivoted from east to west many times in the past at the bend causing the westward migration to the channel. Nevertheless, the bend and cliffs still may be fault controlled.

Two inferred zones of faults, have been drawn on the geologic sketch map (Plate 2). One set crosses the channel near the bend and the other set is upslope of the first. The northern fault of the lower set extends north from just upstream (about 2 km) of the bend through a distinct linear swale into a star-shaped head of an unnamed canyon or gully. This fault, as mapped from the bathymetry, extends for over 50 km. The southern expression is the upper cliff along the eastern, upper wall of the south-trending main channel of Sur Canyon. Near the northern end, a distributary channel to a cross-shaped headed gully is aligned with the fault and a depression similar to a sag pond is present at the northern end of the swale. West of the swale a north-south oriented ridge supporting three flat-topped, probable bedrock, summit platforms may have been uplifted along this fault. This fault within the swale has been previously mapped (Greene, 1977). Greene (1977) and McCulloch and Greene (in press) show the ridge to be composed of metamorphic rocks, possibly dolomites of the Sur Series of Jurassic age, and Cretaceous sandstones (D. S. McCulloch, oral comm., 1988), based on dredge samples taken from the flanks of the ridge.

The second fault of the set is questionably inferred and is interpreted to extend northward from the bend to the western flank of the bedrock ridge previously described. Its bathymetric expression may be in the cliff that lies immediately east of the south trending main channel of Sur Canyon. The bend may have resulted from uplift along the eastern side of the fault. This fault may extend for over 40 km.

Between the two faults, from the bend to the bedrock ridge, large scale mass wasting is occurring, an erosional, mass wasting province (Plate 2). Two south flowing slumps are aligned with, and primarily restricted to, the area between the faults. The heads of these slumps lie along the tract of the upper (east) fault. A zone of mass wasting also extends upslope (east) from the fault zone. Failure of the slope in the fault zone probably removed support for the upslope deposits, thus causing upward propagation of mass wasting.

The second fault zone lies upslope (east) of the first, is composed of two faults and is not as well defined as the lower western fault zone (Plate 2). The lower (west) fault of this fault zone as mapped is 5.5 km upslope of the western fault zone and is primarily defined in the bathymetry by a steep, west-facing scarp associated with an unnamed seaknoll (here named "Surveyor knoll"). The fault trends northeast-southwest and appears to extend north to, and is aligned with, the unnamed canyon that debouches into the middle of Monterey Canyon. Based on bathymetry, (i.e., aligned topographic highs, notches in contours, heads of slumps), the fault is shown to extend south from "Surveyor knoll" crossing Sur Canyon 5.5 km upstream of the bend. The fault was previously mapped as a short fault associated with the seaknoll, east side up (Greene, 1977; McCulloch and Greene, in press).

Bottom currents appear to be strong in the area of the seaknoll and may flow north as suggested by a generally north-south elongated, tear-drop shaped depression (Plate 2). This depression wraps itself around the seaknoll from north to west; maximum width is over 1 km near the north end, with the narrow "front" end on the south. It is interpreted by us to be a current scour trough, however, due to carbonate rock outcrops in the general vicinity it could be the reflection of some type of karst topography.

The upslope (east) fault of the eastern fault zone, also previously mapped (Greene, 1977; McCulloch and Greene, in press), is defined in the bathymetry by a topographic saddle between "Surveyor knoll" and the upper slope. Continuation of this fault to the south shows it crossing the Sur Canyon about 7 km upstream from the bend. Throw on the fault is interpreted to be up to the west, making the seaknoll a horst. To the north, this eastern fault may extend to an area of mass wasting (in an erosional, mass wasting province) associated with the unnamed canyon to Monterey Canyon. In this vicinity the head of a small channel tributary to the unnamed canyon appears to be truncated along the trace of the fault.

Between the upper and lower faults of the eastern fault zone a series of topographic highs, perhaps bedrock highs, are concentrated along trend of the fault zone, south of the seaknoll. Further south, even Sur Canyon appears to be slightly offset by the fault zone.

Cross-Headed Gully and Mass Wasting

At the northern end of the bedrock ridge associated with the western fault zone, a cross-shaped head to a large gully is mapped, formed apparently from mass wasting in an erosional, mass wasting province. The star shape comes from the branching nature of the main channel, splitting into three distinct, equal length, evenly separated arms (Plate 2). The main channel and one head are aligned, oriented northwest, while another head extends northward and the third southeastward from the point where all arms intersect. The head of each arm is bowl shaped and gives the impression that headward erosion is active. Older landslides or incipient slides extend upslope, southward from the head of the southeastern trending arm.

Eastward of the cross-shaped gully head, and connected by an obscure gully is another fairly extensive area of mass wasting. This field (an erosional, mass wasting province) of mass wasting is composed of several well-defined slump scars, slump deposits and flow features. A bowl-shaped, steep relief topographic feature appears to represent an older, intermediate head of the unnamed canyon that was bypassed by headward advance of mass wasting (Plate 2). Here, the canyon floor is flat, about 1 km wide, and trends north towards Monterey Canyon.

From this bowl the Canyon axis steepens, narrows to less than 0.3 km and continues upslope, bending from a southeasterly to an easterly upstream trend. About 1/3 the way up from the intermediate head to where the canyon presently heads a 1 km by 1 km flat-floored platform exists and appears in the 3.5 kHz profiles to be a bedrock outcrop exposed by a landslide. The slope surrounding the canyon here shows evidence of mass failure with continued headward erosion. This narrow, fairly straight extension of the canyon may be a debris chute that grew from the bottom up, propagated by consistent and repeated upper slope failure.

A Major Mass Wasting Field

Downslope (east) of the western fault zone of the Sur Platform flanks, previously described, the lower mid-slope area remains a gently dipping cone-shaped feature (Plate 3). About 15 km below (west) of the bedrock ridge the base of the slope steepens and mass failure of the slope sediment is occurring (in an erosional, mass wasting province). This zone of mass wasting is an extensive field that ranges from the lower channel of the cross-shaped headed gully to just below (west) of the south-trending lower channel of Sur Canyon. This field covers an area of over 410 km^2. Within this field individual landslides range from less than 0.5 km^2 in area to over 11 sq. km. Areas of composite slumping cover areas as much as 55 km^2.

All types of landslides occur in this spectacular field (province) of mass wasting. Based on the sharpness of bent or curved isobaths, existence and steepness of rounded or squared scarps and bulging or hummocky topography, several different types of landslide features are mapped (Plate 3). Areas of gently curving, subtle contours are interpreted to represent older slides (of mature or old geomorphic age), which have "healed" in time, or incipient slides. The subtle contours can be produced in two ways: 1) by rounding initially sharp edges of landslide headscarps and lateral margins through sedimentation and/or erosion, or 2) by initial subsurface failure that gently lowers the seafloor slightly prior to eventual mass failure.

Sharply defined slumps are identified in the bathymetry by distinct rounded or squared contours, some indicating steep head scarps. These are youthful landslides and many occur near the base of the slope.

Slumps defined as mature are more difficult to identify in the bathymetry. However, these may appear as fairly rounded or squared contours, the degree of sharpness of the feature being intermediate between the subtly defined, older or incipient landslides and the well-defined youthful slides.

Aside from geomorphic age estimates of the landslides, origin or formational processes can be speculated based on the examination of the SeaBeam data. For example, in several cases slump morphology progresses retrogressively, from larger slumps at the base to smaller slumps up slope. The cause of failure of the lower, or earlier, slump is not known in most cases; however, many appear to occur from undermining by current scour in the primary channels of submarine canyons. The slumps further up slope most-likely failed from lack of support; support being removed when the lower slump failed. A cascade effect occurs, with the lower slump being the first and the oldest and the upper being the last and youngest.

Examples are seen where a large field of mass movement occurred, evidently as one event. This is the Sur submarine slide of Hess, Normark and Gutmacher (1979) and Normark and Gutmacher (1988) that exhibits a well-defined head scarp. Subsequently, the newly formed surface of the landslide was modified by the failure of its weakened subsurface materials producing many different smaller slumps and debris flows within the original mass.

In other places landslides appear to have failed high up on the slope with the resultant debris flowing straight down to the base of the slope. Once this event occurred a new generation of landslides began to fail downslope from the head of the first, propagating upslope along the path of the first slide.

An excellent example of upslope propagation of mass wasting is seen along the main downslope trend of the cross-headed gully (Plates 1 and 2). This gully is difficult to follow as no distinct channel is defined in the bathymetry, especially along the lower part of the slope. However, a line of upslope propagating landslides are seen and are used to interpret the general course and configuration of the gully. Evidently, sometime in the past (timing of landslide events cannot be determined from these data alone) a major failure occurred at the base of the slope, below (west of the cross-headed gully) where Monterey Fan-Valley cuts into the base of the slope. A landslide of considerable proportions (over 45 km^2 in area) broke away from the slope and apparently flowed out across the rise in a west to south direction (Plate 2). This landslide was most-likely generated from under cutting of the slope by erosion along the eastern wall of Monterey Fan-Valley and possibly through headward erosion of adjacent canyons, thus isolating the block from more shoreward material. A similar phenomenon is observed in east coast canyons (Stubblefield et al, in press).

After the landslide occurred, further mass wasting took place along the bowl-shaped headwall and in two places mass failures advanced upslope (in an erosional, mass wasting province). One failure zone is composed of small landslides (about 0.5 km^2 in area) clustered along the axis of the gully with the cross-shaped head (Plate 3). The other zones comprise larger landslides (up to 5.5 km^2 in areas) that propagate upslope to the bedrock ridge that lies between the western fault zone that cuts across the flank of the Sur platform.

It is unlikely that the cross-shaped headed gully formed from upslope propagation of mass wasting, as about 11 km of the 27 km gully appears to be unaffected by landslides. Certainly the head is formed by mass wasting and the lower parts of the drainage are at least modified, if not formed, by mass wasting. It, therefore, may be circumstantial that the gully formed as one long feature during one mass wasting event. More likely the gully simply connects two separate areas of mass wasting within an erosional, mass province; which formed first, or were the events simultaneous, is unknown.

Monterey Fan-Valley (in a depositional, aggradation province) in the vicinity of the northern base of the cone-shape flanks of the Sur platform is a wide (nearly 3 km), flat-floored feature with a cut bank (erosional scarp) along the eastern side of the main channel. The active channel or thalweg is generally located along the eastern wall where it is undercutting the base of the slope, in an erosional, canyon cutting province (Plate 3). In this locality a marine equivalent to a fluvial point bar has formed along the western side of the floor, which appears to lap-up onto the surface of a gently channelward dipping eroded landslide or levee deposit. An older erosional channel scarp is cut into a gentle relief topographic high or levee mound found west of the eroded landslide deposits.

The Meander of Monterey Fan-Valley

Just below the base of the continental slope, directly offshore (west) of the Sur platform a "horseshoe-shaped" or oxbow meander occurs in the upper part of Monterey Fan-Valley (Shepard and Dill, 1966; Normark, 1969). Northeast of this meander the floor of Monterey Fan-Valley is wide (3.5 km) trending generally southwest and is part of a depositional, aggradation province (Plate 4). The fan channel is essentionally an erosional, canyon cutting province incised into the fan, a depositional, aggradation province. Prior to entering the meander the fan-valley trends almost due south forming the upstream leg of the meander.

At the start of the upstream leg of the meander, at the bend, a modern point bar-like feature exists on the upslope (eastern) side of the active channel. This point bar or relic channel deposit is interpreted to extend from several kilometers upstream along the southwest trending part of the fan-valley to the south along most of the length of the south trending, upstream meander leg.

Immediately opposite the point bar, at the bend in the fan-valley, a 200 m cut bank scarp is found, in an erosional, canyon cutting province. In the upper part of the scarp a small landslide is present and upstream from this point the cliff splits into two with a lower eastward curved (paralleling the upstream channel axis), gently dipping 100 m scarp and an upper 150 m scarp that continues straight to terminate against landslides (Plate 4). The lower cliff appears to be cut into marine levee deposits or remnant channel material remaining from sedimentation when the channel was at or near grade. This deposit may also be the extension of the landslide deposits mapped upstream near the base of the large mass wasting bowl that lies at the base of the cross-headed gully. The channel deposits appear to cut into, and perhaps overlay, even older relic landslide debris.

From the bend marking the start of the meander, the upstream leg is remarkably straight and trends nearly due south for over 12.5 km where it sharply bends to the northwest (nearly a 110° bend). The active channel slips off a gentle, westerly dipping high along the eastern channel floor to occupy a thalweg that is located along the base of a 100 m erosional scarp located on the western side of the channel (Plate 4). Just below the bend that denotes the beginning of the upstream leg, on the western or cut bank side of the channel, a pronounced 0.5 km wide by 1 km long "re-entrant basin" with a 50 m headscarp and flat floor cuts into the neck of the meander. The level of the floor is at the same depth as the adjoining channel floor, but separated from the channel floor by a 40 m high bar across the narrow re-entrant's mouth. A short distance downstream from the re-entrant basin a landslide is also cutting into the neck of the meander.

This erosional activity is significant because the downstream channel of the oxbow meander lies less than 1.25 km due west and downslope of this area; the difference between the floor depths of the upstream and downstream legs of the meander, opposite the meander neck, is 130 m (upstream channel floor depth is 3,360 m and downstream channel floor depth is 3,490 m). A cutoff could occur here.

Farther along the western wall of the upstream leg of the meander, several landslides occur. The elongation of the slides appear to align with a relic or overbank flow channel that curves along the distal margin of the meander on the surface of the meander spur (Plate 4).

The surface of the meander spur exhibits topography that may suggest a general southward migration of the meander. In addition to the relic or overbank flow channel previously described, an arcuate overbank flow bar delineates the crest of the spur. Along the southern or downstream margin of the bar an elongated (scour?) depression is found. The bar extends from the neck of the meander westward out about 2/3 the way onto the spur flats. The few isobaths on the spur flat are curved and parallel to the proable advancing, southern curve of the meander channel.

The headward leg of the meander and the headward scarp of the spur are both 8 km long. The drop in depth of the active channel floor here is from 3,420 m to 3,460 m, a total of 40 m. The cut bank consists of a 150-100 m scarp on the upstream (south) curve and a 300 m scarp on the downstream (west) curve. These scarps are connected by a 50 m high scarplet that is cut into the toes of two landslides (Plate 4). The northern, or inside, wall of the channel is a 100 m high, very gently dipping headward slope of the meander curve. This slope steepens and increases to about 150 m in height opposite the downstream cut bank. This is a erosional, canyon cutting province.

At the location of the landslides mapped along the southern wall of the headward leg of the meander, an unusual topography composed of flat-floored depressions trend away from the meander in a southwest direction (Plate 4). The depressions all have concave downslope headward scarps ranging in height from 40 to 80 m. The floors of the depressions lie along a line of constant gradient (Figure 7). At the head of this trend, separated by about 3.5 km and parallel to the sides of the depressions, are two scarps. The eastern scarp is about 2 km long, 50 m high and dips toward the west while the western scarp is 4 km long, 100 m high, and dips toward the east. Continuation of the western scarp may be along the western margin of the first depression where a 100 m high, 4 km long scarp exists.

Alignment of the scarps and depressions suggest the presence of an old fan-valley channel, Monterey East Fan-Valley of Normark (1969), that sometime in the past was blocked and filled with sediment. Exhumation of this channel could presently be underway by mass wasting (this classified as an erosional, mass wasting province?), as suggested by the landslides at the head of this channel, near the meander, and the head scarps of the depressions. Slumping of the channel fill along the old channel floor may be producing the upslope scarps of the depressions. This process could be assisted during overflow periods or secondary channelization when density currents leave the meander channel and flow along the depressions (Normark, 1969). This overflow could either act as a modifier to the excavation of the old channel by the deposition of overflow materials, or may accelerate exhumation by having scarps and depressions act as plunge poles, similar to what has been observed onland.

Two other smaller depressions with associated scarps appear to be aligned in a similar fashion as the older filled channel just described. This may be another channel, perhaps older than the first, which has experienced a similar type of history. Or as Normark (1970) has observed, these depressions may be the result of erosion by channelized bottom currents into horizontally bedded fan sediments.

The downstream leg of the meander bends back into the meander spur trending northeast for a distance of about 7 km where the channel makes its closest approach to the upstream leg (Plate 4). In this stretch the cut bank along the western side of the channel ranges from a 300 m high steep cliff at the upstream curve to a gentle sloping 60 m high bank near the downstream end of the leg. The inside bank (southeast side) is a gently dipping 100 m bank that gives way to a flat 0.25 km wide channel terrace platform at the downstream bend or end of the leg. At the downstream edge of the terrace platform a landslide occurs in the meander spur deposits.

The final bend in the meander changes the trend of the channel from northeast to northwest, a 90 degree turn. An older point bar-like feature exists at this turn and bounds the channel on the southwest for about 8 km of the 15 km long stretch. The point bar is backed by a 100 m high erosional scarp.

The northeastern wall of the northwesterly trending channel is a 200 m high, steep erosional cliff that extends from the terrace platform at the last meander bend for about 5.5 km to where the cliff becomes a very gently dipping bank prone to landsliding. Above this cliff and bank is a flat, older channel terrace platform. The irregular and rolling nature of the bathymetry above this channel terrace platform suggests that some type of debris flow or slump material were deposited along the western margin of the terrace. The channel terrace was probably associated with an older channel before the meander formed.

At the end of the northwest trending channel the fan-valley takes another 90 degree turn to trend southwest (Plate 4). Here a point bar is again built out along the inside or southeastern margin of the channel. This bar continues back upstream around the bend to form the last 4 km of channel bank along the southeastern side of the northwesterly trending channel.

The confluence of Ascension Fan-Valley is at the bend, on the opposite side of the point bar deposit, and the southwesterly trend of the lower part of the fan-valley continues straight into the Monterey Fan-Valley of the same trend. From the confluence, trending southwesterly, the outside bank, or cut bank, is a steep 350 m high cliff that continues upstream along the northwestern wall of Ascension Fan-Valley.

Ascension Fan-Valley

Ascension Fan-Valley continues along a generally straight south trend from where it begins to cut into the seafloor, below the depositional plain that spreads out from the mouth of Ascension Canyon (Plates 1 and 4). The Fan-Valley extends for about 20 km as a narrow, "V"-shaped channel to a bend where the Fan-Valley changes direction to a southwesterly trend (Plate 4). The walls are cliffs ranging in height from 50 m near the head to 100 m at the bend. Along the eastern side of the Fan-Valley, a flat area extends from the top of the cliffed wall of the channel to the margins of what may be the edges of an old debris flow or levee deposit. This area may be an old channel terrace. It averages about 0.5 km in width, narrower upstream.

From the bend in Ascension Fan-Valley, the floor of the channel flattens and broadens (to about 0.25 km) along the southwesterly directed axis. The fan-valley extends another 12 km to where it intersects the Monterey Fan-Valley (Plate 4). Along this stretch a steep, 100 m high cliff bounds the northern side of the channel and a more gentle 100 m bank marks the southern side. Above the southern wall the older Ascension channel terrace broadens to over 3 km in width, continuing southwest to where it has been undercut by the older Monterey Fan-Valley channel adjacent to the northwesterly leg of the active Monterey channel, just below the meander. This terrace stands 100 m above the older Monterey channel terrace, a 100 m steep erosional scarp marks the boundary.

Five kilometers downstream from the erosional channel head, the Ascension Fan-Valley narrows and steepens in grade to a chute with a depression, or plunge pole, at the base of the chute (Plate 4). The floor of the channel is narrow, less than 0.2 km wide, with steep walls 100 m high. A "V"-shaped profile exists at the chute, but gives way to a "U"-shaped profile downstream. From the plunge pole the seavalley continues another 7 km downstream to its confluence with Monterey Fan-Valley. The walls are more gently dipping downstream, reducing in height from 200 m to 100 m. The fan-valley broadens to over 1 km wide at its confluence.

Meander Origin - A Hypothesis

Normark (1969) suggests that the Monterey Fan-Valley meander originated after sea level raise, when Ascension Canyon and Fan-Valley became less active because it was far removed from the coast, with Monterey Fan-Valley remaining active; Monterey Canyon continued to intercept longshore transported sediments. Consequently, Monterey Fan-Valley deepened faster than Ascension Fan-Valley, thereby, changing base level of Ascension Fan-Valley and precipitating headward erosion. According to Normark (1969) the meander resulted from piracy of the "lower" Ascension Fan-Valley by the old Monterey East Fan-Valley, perhaps through a break in the Monterey East Fan-Valley levee (Figure 10). Normark (1969) states that the mechanism for initiating the breach is not known, but it had to predate most of the down cutting within the Monterey Fan-Valley.

We speculate on an alternative origin for formation of the oxbow-type meander of Monterey Fan-Valley or formation of Normark's (1969) breached levee. Levee breach or initiation of meander formation could have occurred from a series of submarine slumps or debris flows that filled and blocked the pre-existing active channel, Monterey East Fan-Valley of Normark (1969). This is a reasonable speculation as the area upslope of the meander has a history of extensive mass failure of unconsolidated to semi-consolidated sedimentary rocks that overlie probable metamorphic rocks of the Franciscan Formation. These rocks are subject to seismic motion as two, apparently active, fault zones exist in the area of mass wasting. Examination of the Sea Beam bathymetry suggests the presence of at least three (including Monterey East Fan-Valley) older and now abandoned channels.

Prior to the formation of the meander the Monterey Fan-Valley continued along a straight southwesterly course parallel to the Ascension Fan-Valley (Normark, 1969) from where Monterey Canyon debouches onto the rise, at the slope base. Here the active channel turns from a generally perpendicular (westerly trend) across the slope to a course that runs along the rise, southwest, sub-parallel to the slope base. The two older, filled channels that extend southwesterly from the meander were probably the extension of this pre-meander fan-valley (Figure 11). The upper, or eastern, channel (channel 1, Figure 11) is probably the older of the two, as its physiographic expression is almost lost. Downslope migration of the earliest pre-meander channel to the lower or southern, better bathymetrically-defined channel (channel 2, Figure 11) may have been the result of slumps and debris flows pushing down onto the oldest channel from an unstable slope to the east.

Formation of the meander may have initiated when a slump mass or debris flow slid into the area, with the leading edge of the landslide coming to rest somewhere below, southwest, of the meander. This could have been one event that filled the active channel of the seavalley with debris and left a large northeast-southwest-trending mound or ridge of landslide materials along the western side of the pre-meander and present day fan-valley. Trend of the mound, or ridge, suggests that the landslide originating somewhere near the slope northeast of the mouth of Monterey Canyon, perhaps at the large mass wasting bowl we mapped near the mouth of Ascension Canyon. However, Normark (1969) refers to mound or ridge as a levee deposit and sees no indication of slumped materials in seismic-reflection profiles he collected in the region.

With landslide debris blocking and filling the pre-slide channel in the vicinity of the meander a new channel (channel 3) could have formed, probably in an area of low relief within the deposited landslide debris. This new channel appears to have formed just north of the present meander neck, occupying the area where the channel terrace deposits adjacent to the present northwesterly trending channel has been mapped. This newly-formed channel extended in a straight line for about 10 km where it again turned southeasterly, possibly to by-pass slide debris, and continued as a lower, but parallel, course to the blocked channels. Development of this channel could have occurred either from breaching of a levee as described by Normark (1969) or simply overflow produced by the filling of the channel by landslide debris.

Again, probably sometime in the recent past, another landslide from upslope flowed into the area of the meander and blocked the mouth of channel 3. This landslide may have originated at the mass wasting bowl mapped near the base of the slope about 20 km upstream from the meander. This second slide event, and perhaps other smaller events as well, produced a sharp bend in the active channel, shifting the course of the fan-valley to a south direction and thus forming the upstream leg of the meander.

Apparently, the meander migrated southwesterly along the old, now filled and buried, trends of the original channels (channel 1 and 2). The new active channel then sought its way around the edge or through areas of low relief of deposited landslide debris or levee deposits, swinging around on itself to eventually turn northwest, downslope, recapturing the former or lower channel, the southwesterly extension of channel 3. The meander front was easily able to erode the unconsolidated landslide or overflow deposits filling the older channels (channels 1 and 2, Figure 11). Supplied periodically with landslide material from upstream, the fan-valley deepened its base through erosion and extended the meander spur through aggregation.

Periodically, overflow would take place when the channel experienced a flood of debris from upstream as proposed by Normark (1969). Levees and overbank deposits were built-up along the leading edge of the meander and below the cut-bank of the downstream leg. Overflow material also continued down ("re-channelized") through the physiographic expression of the older filled and buried channels, continuing to fill the depressions with sediment (Normark, 1969).

Exhumation of the older channels, especially channel 2, may be occurring today. The flat floored depressions may represent the tops of slumps that have slid along the floor of the old channel (Figure 12). Arcuate scarps at the head, northeastern sides, of the depressions may be slump head scarps. The slumps are constrained by the walls of the old channels, mainly because they are composed of relatively unconsolidated materials compared to the walls and floor of the older channels.

Ascension Fan-Valley also may have been impacted by the first slide event. Debris from this event could have flowed westward to thinly (100-200 m) cover the older channel of the fan-valley and perhaps bent the mouth of the channel downslope in a northwesterly direction. The transition from a braided, generally aggradational sedimentary regime, near the mouth of Ascension Canyon to an erosional regime with a youthful "V"-shaped profile suggests a change in base level.

Normark (1969) states that the Ascension and Monterey Fan-Valleys were elevated above the fan surface with Monterey Fan-Valley lying higher up the slope. Breaching of Monterey East Fan-valley's western levee allowed the active channel to flow downslope and intercept Ascension Fan-Valley. Then downcutting occurred, entrenching the meander, and the rapid downcutting of Monterey Fan-Valley in relation to Ascension Fan-Valley caused the headward erosion along Ascension Fan-Valley. However, we suggest that this elevation of base could be the result of a sudden influx of landslide debris. Change in base in this region can also be attributed to tectonic processes. However, since both the Monterey Fan-Valley meander and the Ascension Fan-Valley are experiencing youthful downcutting in the same area, near where active mass wasting is occurring on the lower slope, we surmise that the change could be a depositional phenomenon. The straightness of the fan-valley is unusual as if structurally controlled, but our data does not allow us to determine the existence of a fault. However, structural control of the fan-valleys near the base of the slope should not be summarily dismissed.

An older channel course to Ascension Fan-Valley is indicated by the channel terrace that lies along the lower eastern margin of the modern fan-valley (Figure 11). Apparently, Ascension Fan-Valley entered into Monterey Fan-Valley some 5.5 km southeast, upstream in Monterey Fan-Valley, of its present day confluence.

The meander may be cut off in the future, leaving a cut-off oxbow-like meander. Near the neck of the meander, mass wasting and scour, as indicated by a landslide and a re-entrant scour-like basin, appears to be active. These processes have cut deeply into the neck, at least 1/3 through the neck's width. If mass wasting and scour were to progress unimpeded, eventually the meander cut-off will be complete and a channel configuration similar to that of channel 3 (Plate 1) would develop. However any sizable mass wasting event could block this process and the meander would continue to advance along the trend of the older channels 1 and 2.

ACKNOWLEDGMENTS

The authors wish to thank the officers and crew of the NOAA ship *Surveyor* who diligently helped in obtaining the data and took exemplary interest in the results of the cruise. Bonnie McGregor reviewed the manuscript, contributing substantial, constructive comments. Phyllis Swenson drafted the plates and, along with Brian Edwards and Florence Wong, expedited production of this report.

REFERENCES

Brabb, E.E. (compiler), 1970, Preliminary geologic map of the central Santa Cruz Mountains, California: U.S. Geol. Survey open-file map, scale 1:62,500.

Bailey, E. H., ed., 1966, Geology of northern California; Calif. Div. of Mines and Geology Bull. 190, 508p.

Clark, J.C., 1970, Geologic map of the Davenport area, Santa Cruz County, California, U.S. Geol. Survey open-file rept., 65 p, scale 1:24,000.

Clark, J. C., Brabb, E. E., Greene, H. G., and Ross, D. C., 1984, Geology of Point Reyes Peninsula and implications for San Gregario Fault history; *in* Crouch, J. E. and Bachman, S. B., eds., Tectonics and sedimentation along the California margin: Pacific Section SEPM, vol. 38, p. 67-86.

Cooper, A., 1971, Structure of the continental shelf west of San Francisco, California: U.S. Geol. Survey open-file rept., 65 p.

Graham, S.A., and Dickinson, W.R., 1978, Evidence for 115 kilometers of right slip on the San Gregorio-Hosgri Fault trend, Science, v. 199, p. 179-181.

Greene, H.G., Lee, W.H.K., McCulloch, D.S., and Brabb, E.E., 1973, Faults and earthquakes in the Monterey Bay region, California, U.S. Geological Survey, San Francisco Bay Region Environment and Resources Planning Study, Basic Data Contribution 58, 14 p.

Greene, H.G., 1977, Geology of the Monterey Bay Region, U.S. Geol. Survey open-file rept. No. 77-718, 347 p.

Greene, H.G., in press, Tectonic control in formation of submarine canyons; McGraw-Hill Science and Technology Yearbook.

Hess, G.R., Normark, W.R., and Gutmacher, C.E., 1979, Sur submarine slide, Monterey Fan, central California, Geol. Soc. Am. Abstracts with Programs, 11/3, 83-84.

Hill, M.L., and Dibblee, T.W., Jr., 1953, San Andreas, Garlock, and Big Pine faults, California—a study of the character, history, and tectonic significance of their displacements, Geol. Soc. America Bull., v. 64, no. 4, p. 443-458.

Howell, D.G., 1975, Hypothesis suggesting 700 kilometers of right slip in California along northwest oriented faults, Geology, v. 3, no. 2, p. 81-83.

Jennings, C.W., and Burnett, J.L., 1961, Geologic map of California, Olaf P. Jenkins, ed., San Francisco Sheet, Calif. Div. Mines and Geology, scale 1:250,000.

King, P.B., 1959, The evolution of North America, Princeton Univ. Press, Princeton, New Jersey, 189 p.

Martin, B.D., and Emery, K.O., 1967, Geology of Monterey Canyon, California: Am. Assoc. Petroleum Geologists Bull., v. 51, p. 2281-2304.

McCulloch, D.W., and Greene, H.G., in press, Geology of the central California Margin, Map 5A, Geology, *in* Greene, H. G., and Kennedy, M. P., eds., California Continental Margins Geologic Map Series, scale 1:250,000.

McGregor, B., Stubblefield, W.L., Ryan, W.B.F., and Twichell, D.C., 1982, Wilmington Submarine Canyon: A marine fluvial-like system, Geology, v. 10, p. 27-30.

Moore, G. W., 1982, Plate-tectonic map of the circum-Pacific region explanatory note; Tulsa, Okla; American Assocation of Petroleum Geologists, 14 p.

Nagel, D.K., Mullins, H.T., and Greene, H.G., 1986, Ascension submarine canyon, California—Evolution of a multi-head canyon system along a strike-slip continental margin, Marine Geology, v. 7, p. 285-310.

Normark, W. R., and Gutmacher, C. E., 1988, Sur submarine slide, Monterey Fan, central California: Sedimentology, v. 35, p. 629-647.

Normark, W.R., 1969, Growth patterns of deep sea fans; Ph.D. dissertation, University of California San Diego,, 165 p.

Normark, W.R., 1970, Channel piracy on Monterey deep-sea fan, Deep Sea Res., 17, 837-846.

Page, B.M., 1970, Sur-Nacimiento fault zone of California: Continental margin tectonics: Geol. Soc. America Bull., v. 81, no. 3, p. 667-690.

Ross, D.C., 1976, Reconnaissance geologic map of Pre-cenozoic basement rocks, Northern Santa Lucia Range, Monterey County, California, U.S. Geol. Survey, Misc. Field Studies Map, MF-750, scale 1:25,000.

Shepard, F.P., and Dill, R.F., 1966, Submarine canyons and other sea valleys: Rand McNally, Chicago, Ill., 381 p.

Silver, E. A., Curray, J.R., and Cooper, A.K., 1971, Tectonic development of the continental margin off central California: Geologic Society of Sacramento, Annual Field Trip Guidebook, p. 1-10.

Silver, E.A., 1974, Basin development along translational continental margins, *in* Dickinson, W.R., ed., Geologic interpretations from global tectonics with applications for California geology and petroleum exploration: San Joaquin Geological Society Short Course Notes.

Stubblefield, W.L., and McGregor, B. A., 1987, Geologic processes inferred from the morphology of submarine canyons, outer continental margin, mid-Atlantic bight of United States; EOS, Transactions, Amer. Geophysical Union, vol. 68, no. 44, p. 1315.

FIGURE CAPTIONS

Figure 1. Physiographic diagram of Monterey submarine canyon system and adjacent areas, (drawing from Tau Rho Alpha, after Greene, 1977).

Figure 2. Index map of California showing geomorphic and tectonic provinces, location of some major faults and general area of Sea Beam survey (modified from Bailey, 1966).

Figure 3. Location of Salinian block in relation to other Mesozoic basement terranes (modified from Silver, Curray, and Cooper, 1971).

Figure 4. Faults of the Monterey Bay region. Dots represent epicenters of selected earthquakes within the Palo Colorado-San Gregorio and Monterey Bay fault zones.

Figure 5. Contour map of basement surface in Monterey Bay region (from Greene, 1977).

Figure 6. Geologic sketch map of seafloor in Monterey Bay region based on bottom samples (from Martin and Emery, 1967; Greene, 1977).

Figure 7. Schematic diagram of Pacific crustal plates.

Figure 8. Physiographic diagram of a strike-slip margin showing offsets of canyons along faults. Submarine canyons that form across active faults are prone to be displaced along these faults. Canyons (PC = Pioneer Canyon; UN = unnamed canyon; AC = Ascension Canyon) were once connected to Monterey Canyon (MC). Solid lines are faults (af = Ascension fault; mb = Monterey Bay fault zone; mf = Monterey Canyon fault; PC-SG = Palo Colorado-San Gregorio fault zone), arrows show direction of movement. Large arrow indicates direction of Pacific Plate motion. PP = Pigeon Point; ANP = Ano Nuevo Point; PS = Point Sur; M = Monterey (from Greene, 1982).

Figure 9. Sketch map of Carmel Canyon showing (A) present day configuration in relation to faults of the Palo Colorado-San Gregorio fault zone and (B) pre-faulting configuration.

Figure 10. Model for the development of the Monterey Fan-Valley. 1) Originally the Ascension and Monterey East fan-valleys were parallel, active systems. 2) After capturing the lower Ascension Fan-Valley, the old foot of the Monterey East is beheaded and abandoned. 3) Incision of the new Monterey Fan-Valley leaves the old head of the Ascension Fan-Valley as a hanging valley. (After Normark, 1969).

Figure 11. Map showing locations of past, present, and proposed future channels of the Monterey Fan-Valley at the fan meander.

Figure 12. Cross-sections across (profiles A-A′ and B-B′) and along (profile C-C′) the older, filled Monterey Fan-Valley. Note how the lowest points of the depressions in the older Fan-Valley (profile C-C′) share a common dipping surface. This surface may be the old Fan-Valley floor and may represent the sole of the slumped fill. Location of profiles on Plate 4.

PLATE CAPTIONS

Plate 1. Preliminary seafloor geology and geomorphology map of the Monterey-Ascension Canyon system. Scale 1:100,000.

Plate 2. Preliminary seafloor geology and geomorphology map of the upper Sur slope. Scale 1:50,000.

Plate 3. Preliminary seafloor geology and geomorphology map of the map of the lower Sur slope. Scale 1:50,000.

Plate 4. Preliminary seafloor geology and geomorphology map of the map of the Monterey-Ascension fan-valley system and meander. Scale 1:50,000.

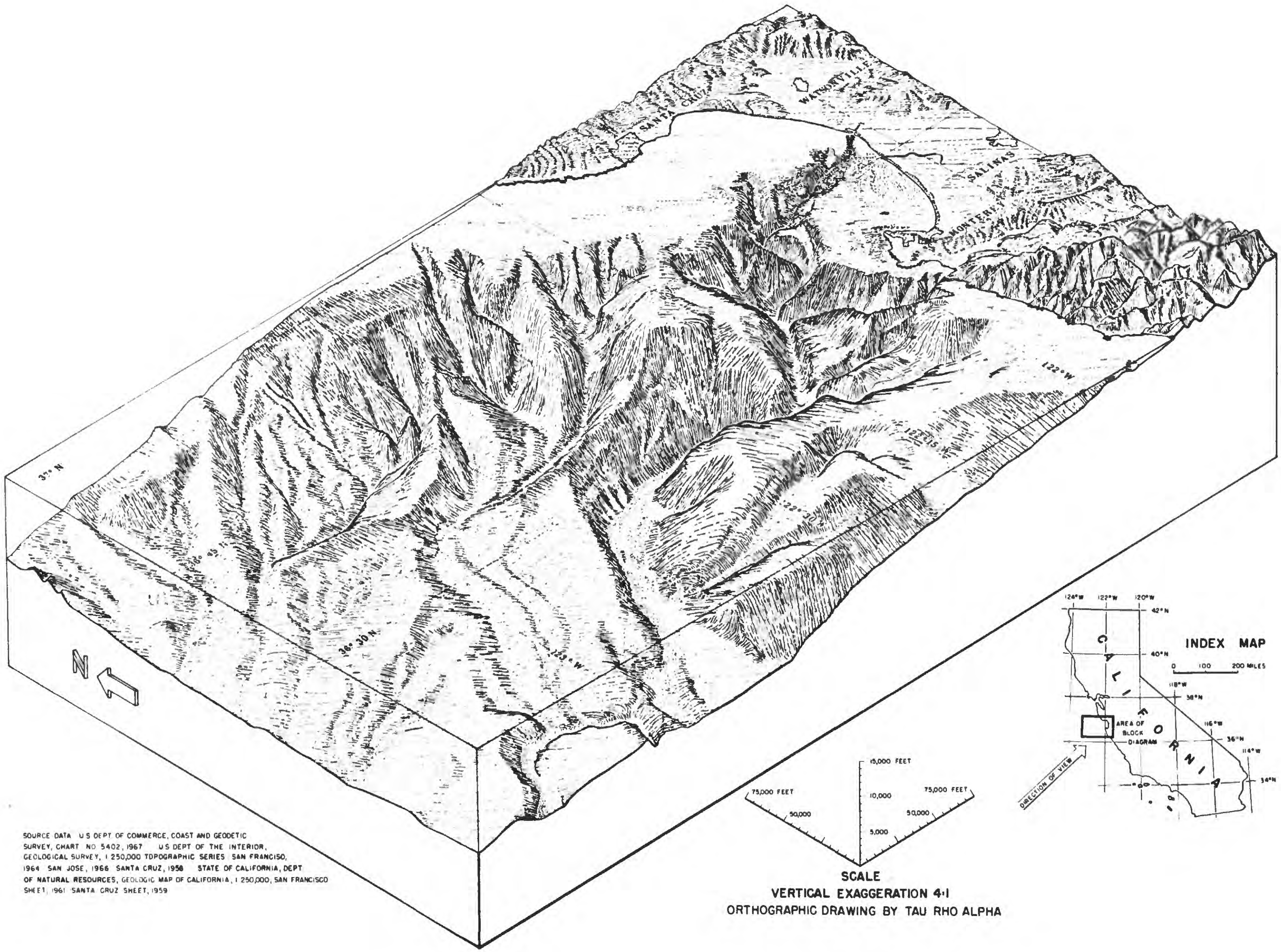

Figure 1. Physiographic diagram of Monterey submarine canyon system and adjacent areas, (drawing from Tau Rho Alpha, after Greene, 1977).

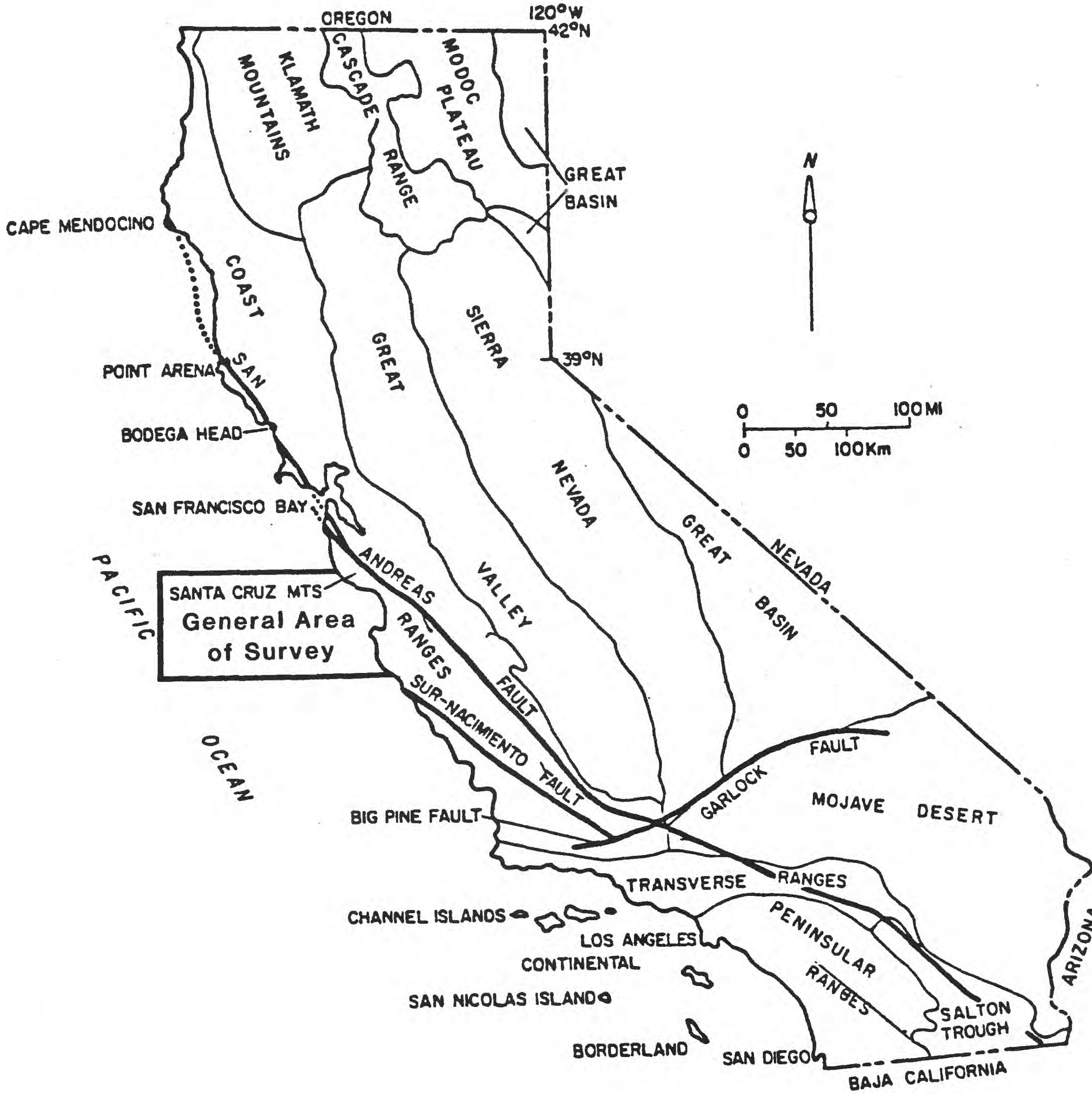

Figure 2. Index map of California showing geomorphic and tectonic provinces, location of some major faults and general area of Sea Beam survey (modified from Bailey, 1966).

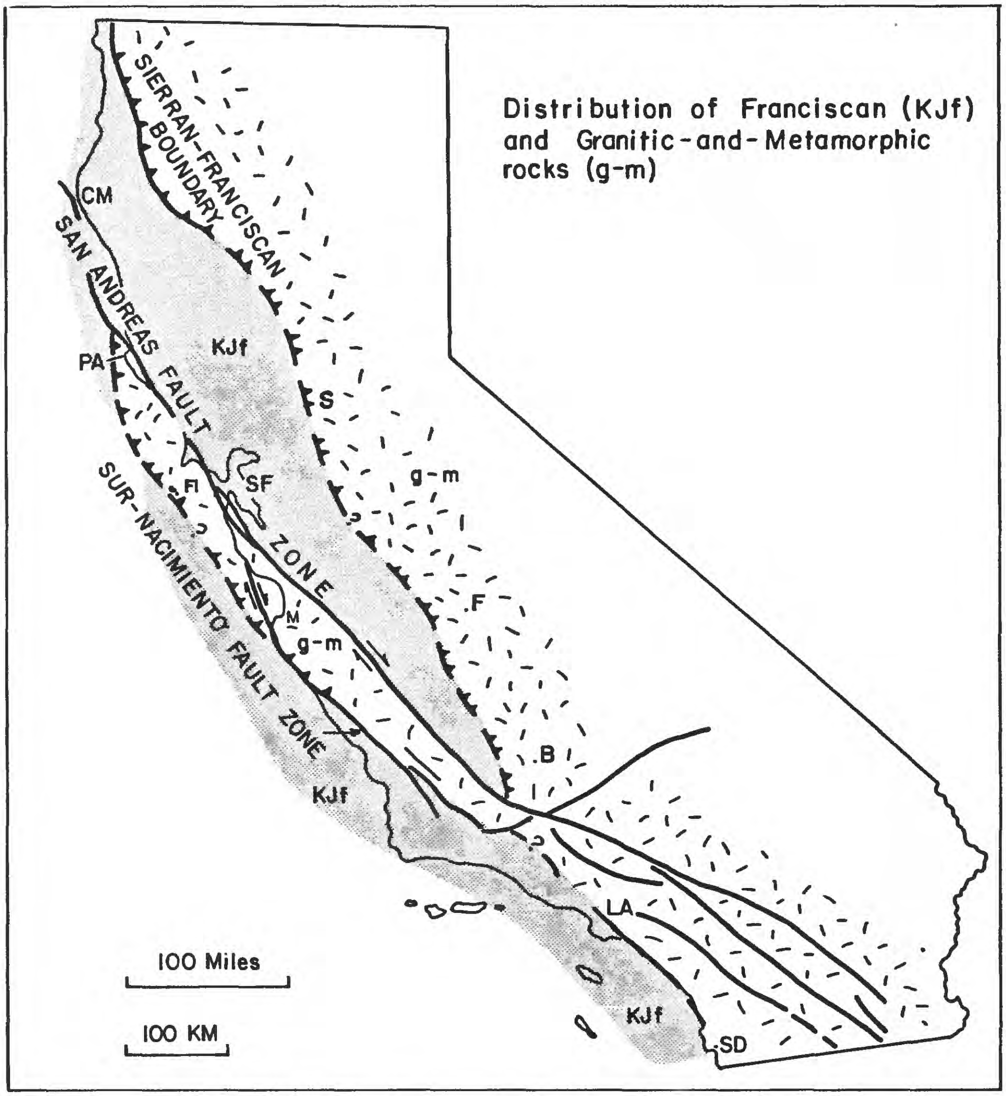

Figure 3. Location of Salinian block in relation to other Mesozoic basement terranes (modified from Silver, Curray, and Cooper, 1971).

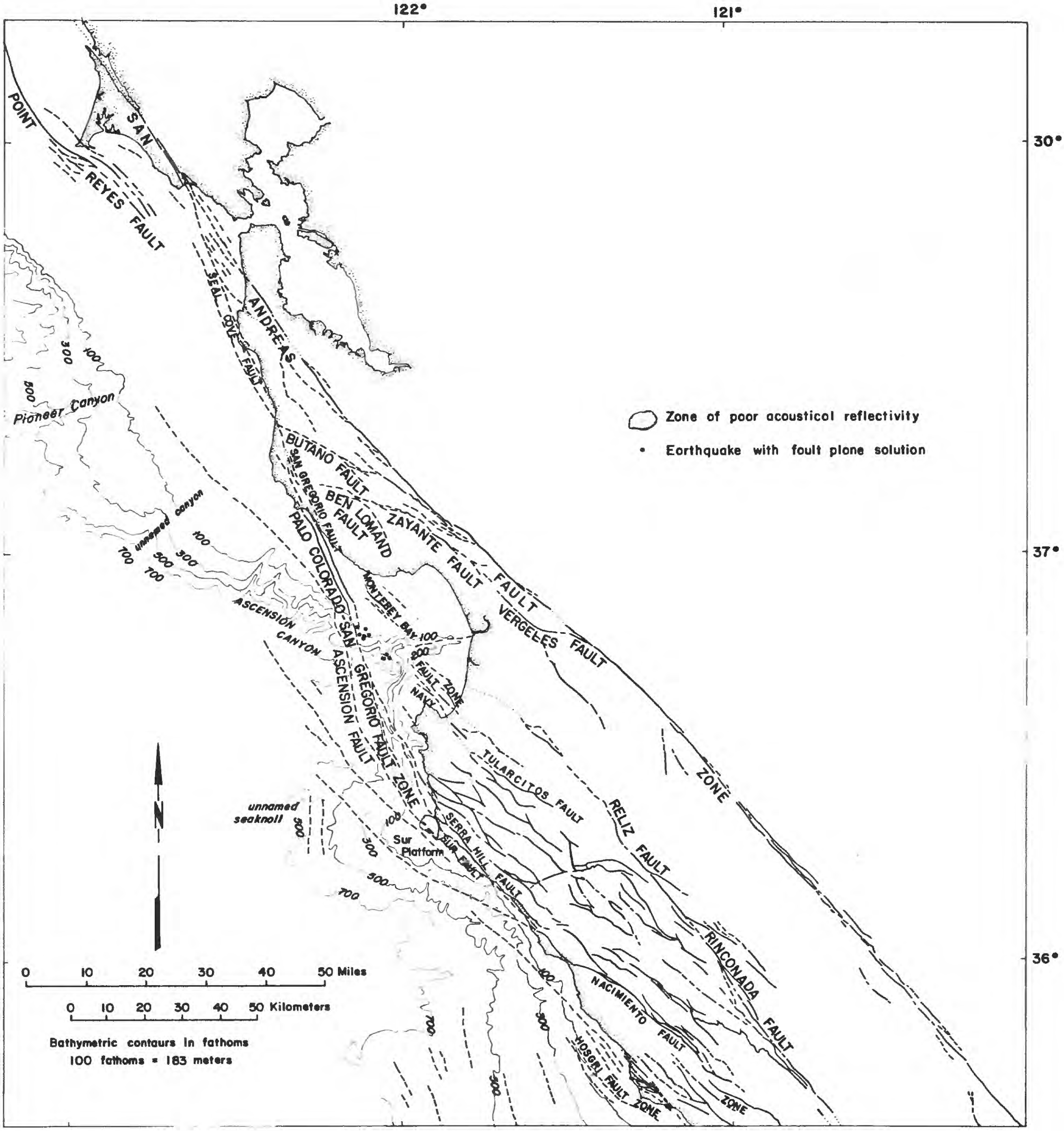

Figure 4. Faults of the Monterey Bay region. Dots represent epicenters of selected earthquakes within the Palo Colorado-San Gregorio and Monterey Bay fault zones.

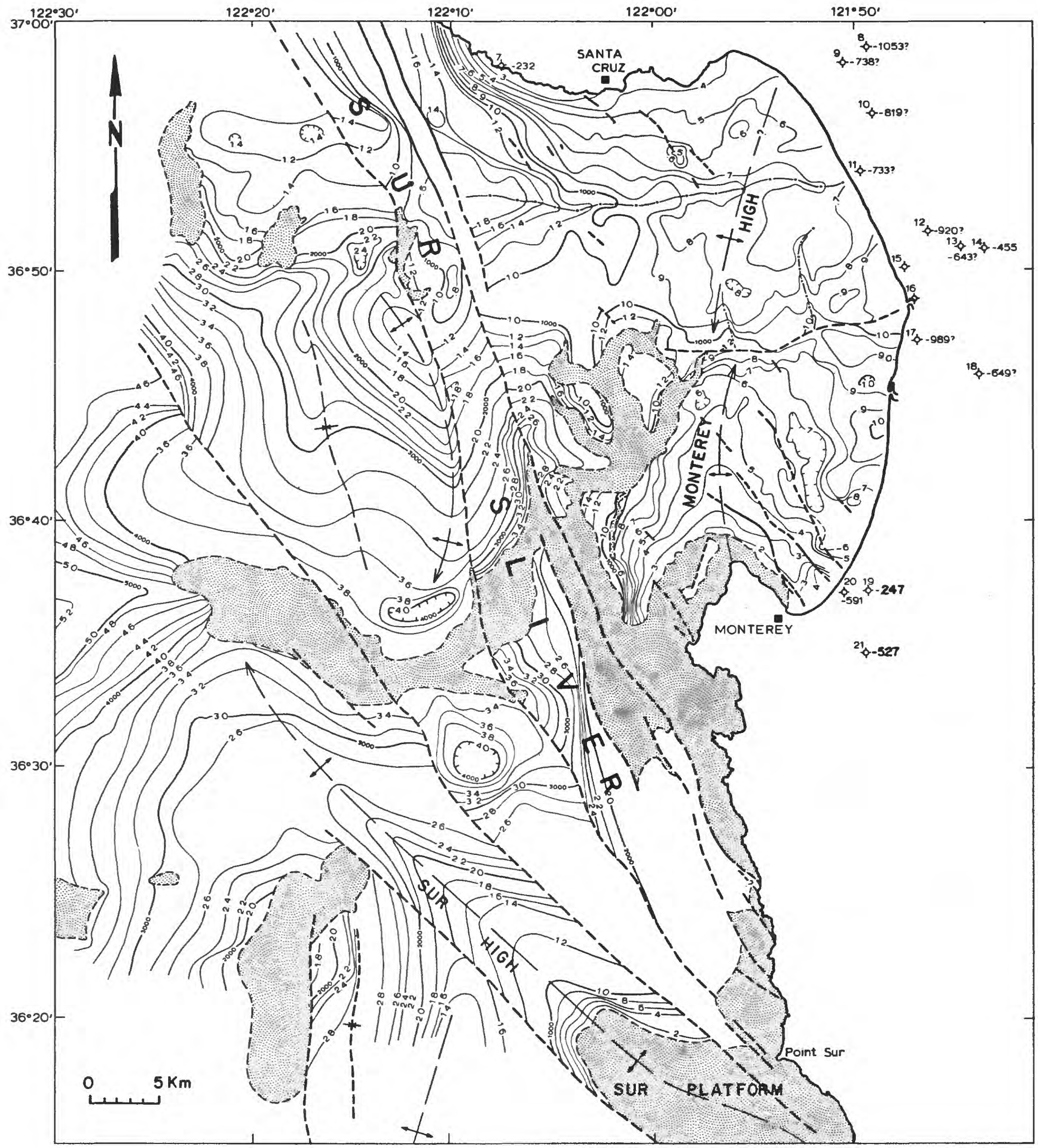

Figure 5. Contour map of basement surface in Monterey Bay region (from Greene, 1977).

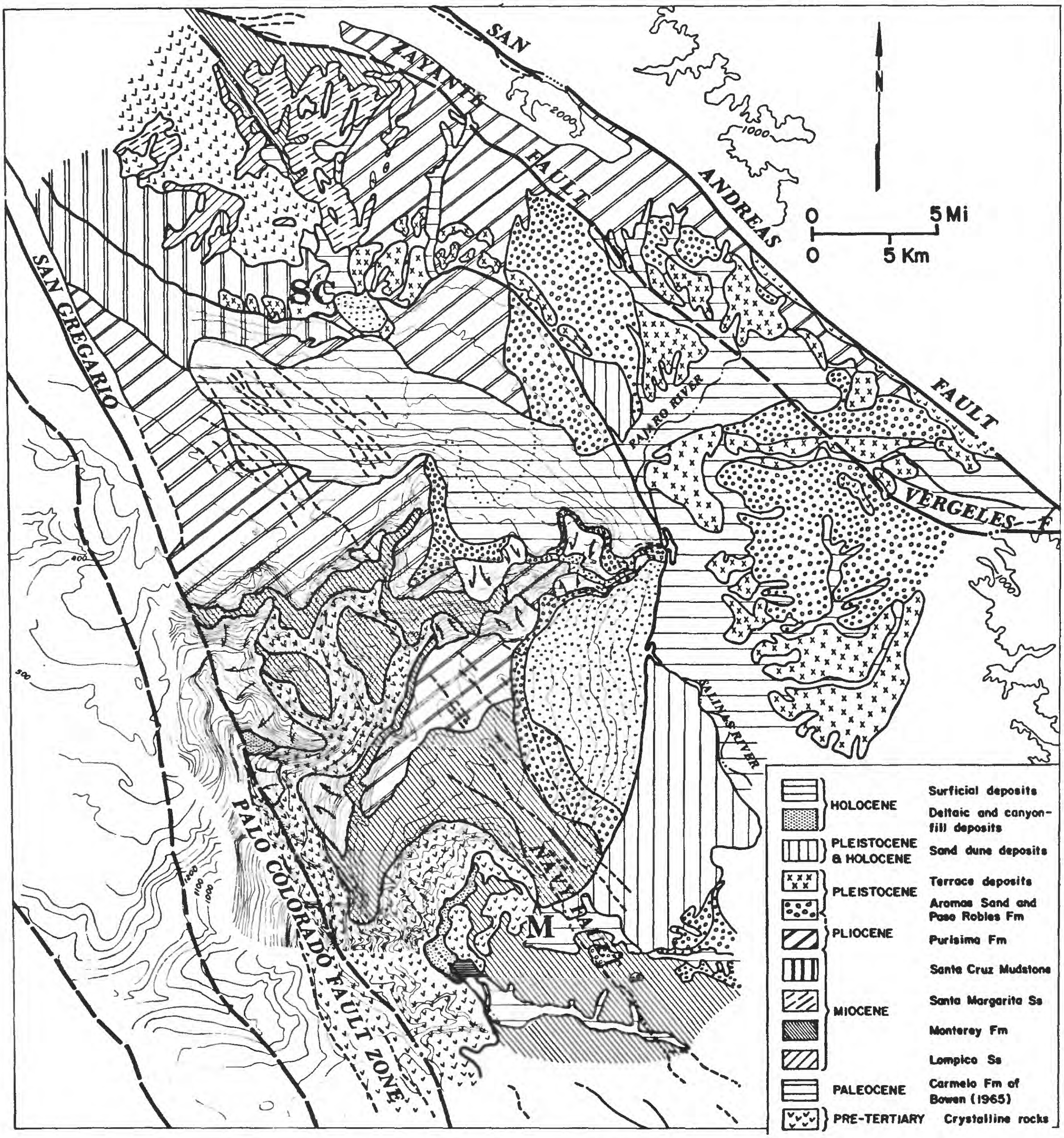

Figure 6. Geologic sketch map of seafloor in Monterey Bay region based on bottom samples (from Martin and Emery, 1967; Greene, 1977).

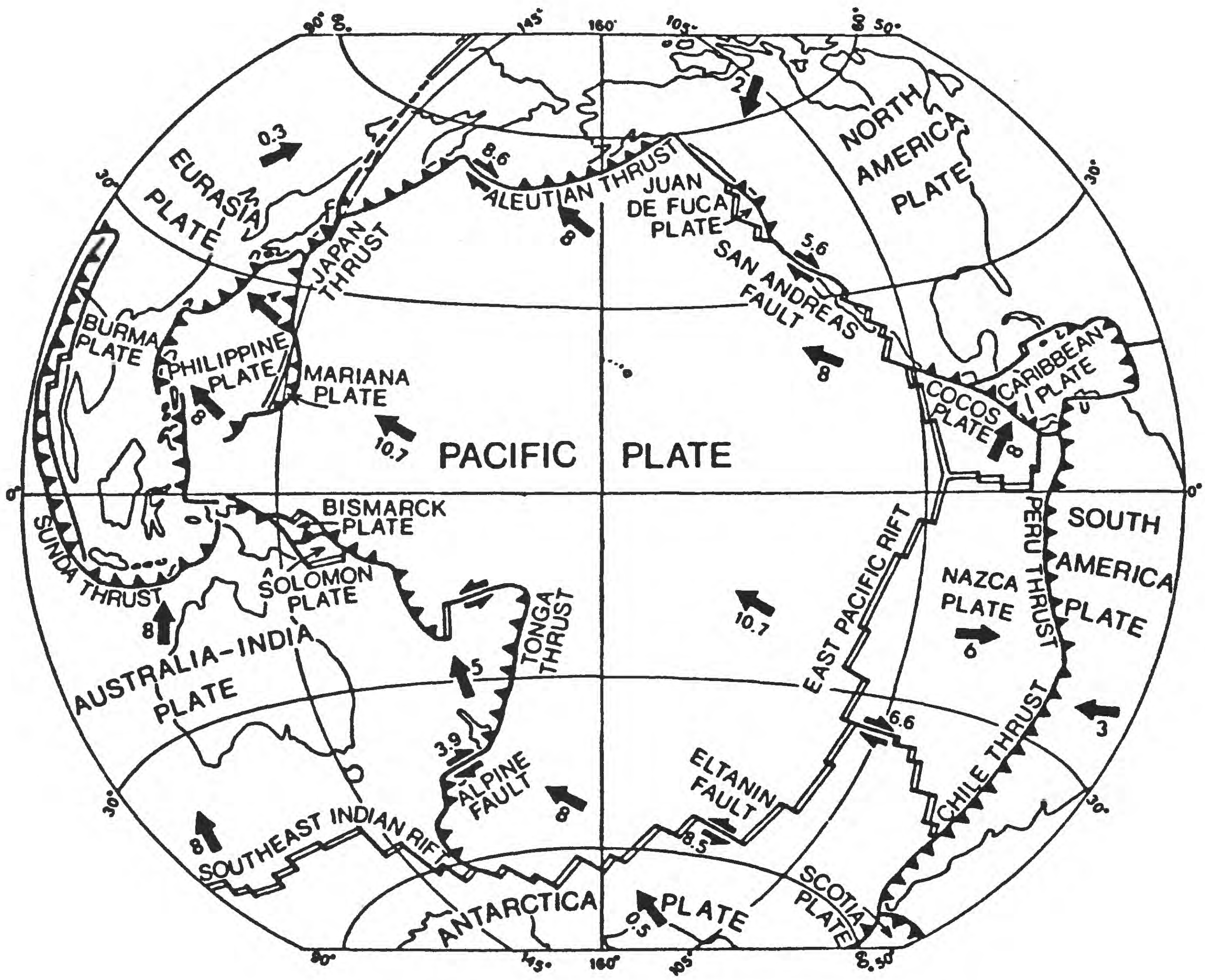

Figure 7. Schematic diagram of Pacific crustal plates.

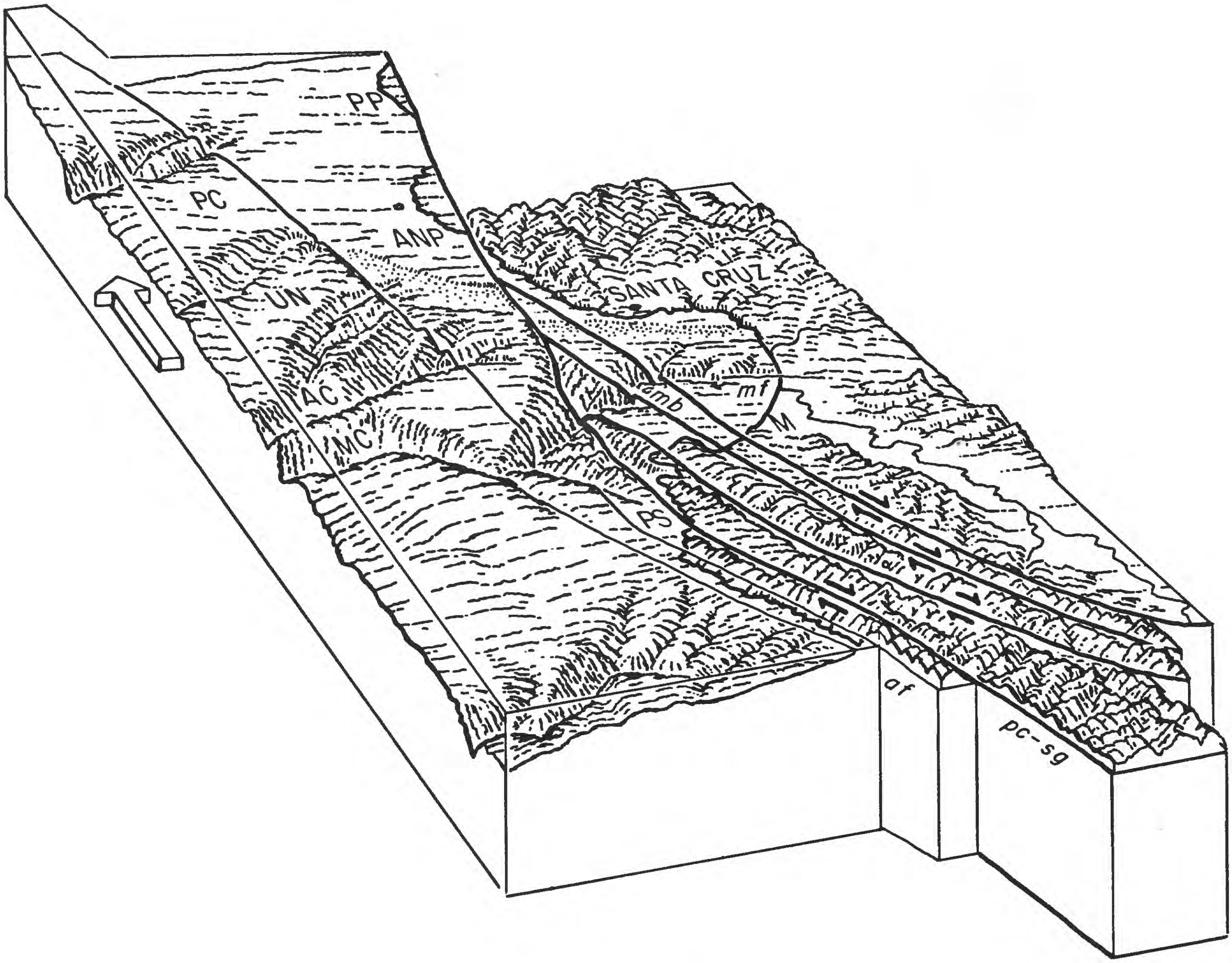

Figure 8. Physiographic diagram of a strike-slip margin showing offsets of canyons along faults. Submarine canyons that form across active faults are prone to be displaced along these faults. Canyons (PC = Pioneer Canyon; UN = unnamed canyon; AC = Ascension Canyon) were once connected to Monterey Canyon (MC). Solid lines are faults (af = Ascension fault; mb = Monterey Bay fault zone; mf = Monterey Canyon fault; PC-SG = Palo Colorado-San Gregorio fault zone), arrows show direction of movement. Large arrow indicates direction of Pacific Plate motion. PP = Pigeon Point; ANP = Ano Nuevo Point; PS = Point Sur; M = Monterey (from Greene, 1982).

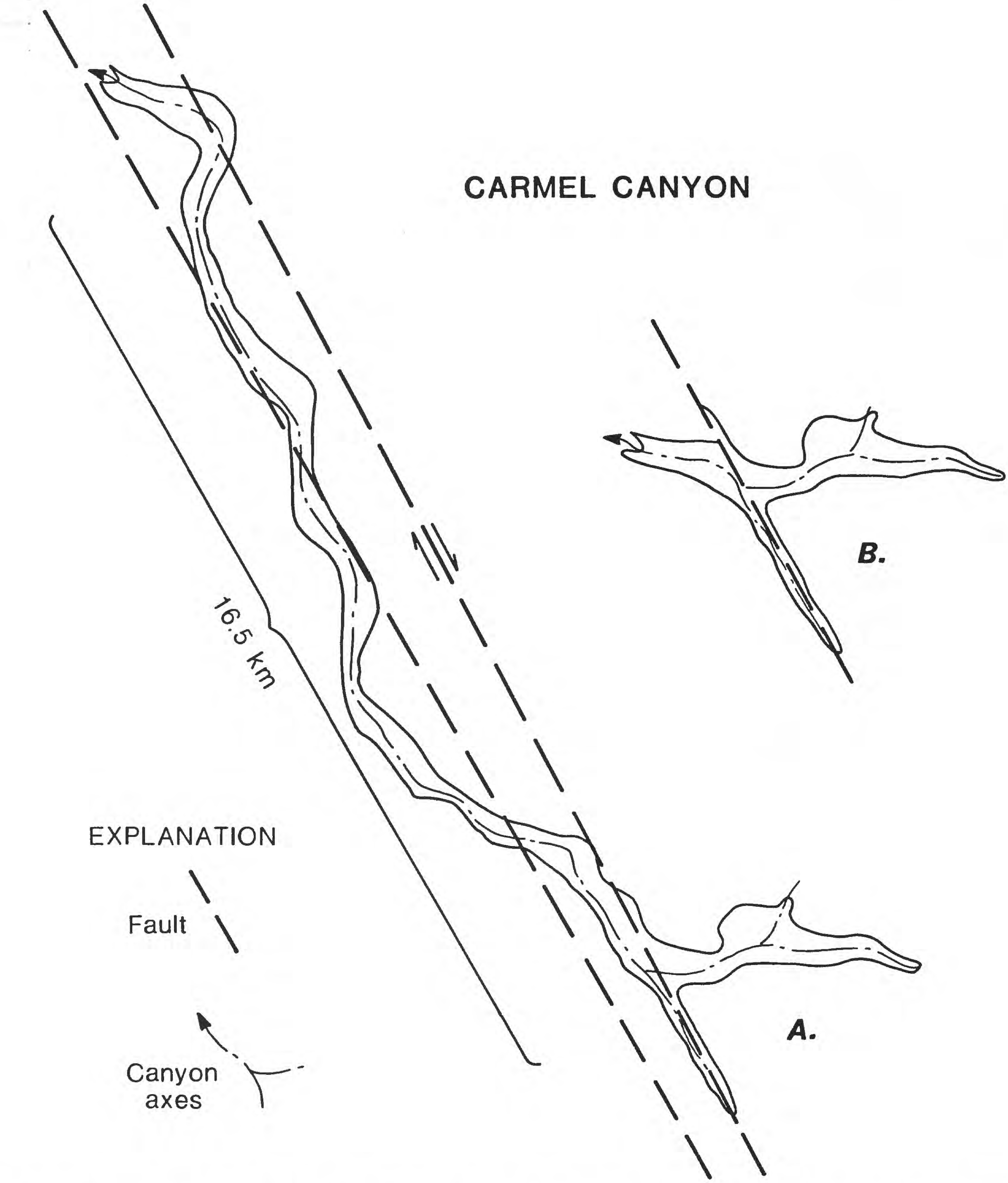

Figure 9. Sketch map of Carmel Canyon showing (A) present day configuration in relation to faults of the Palo Colorado-San Gregorio fault zone and (B) pre-faulting configuration.

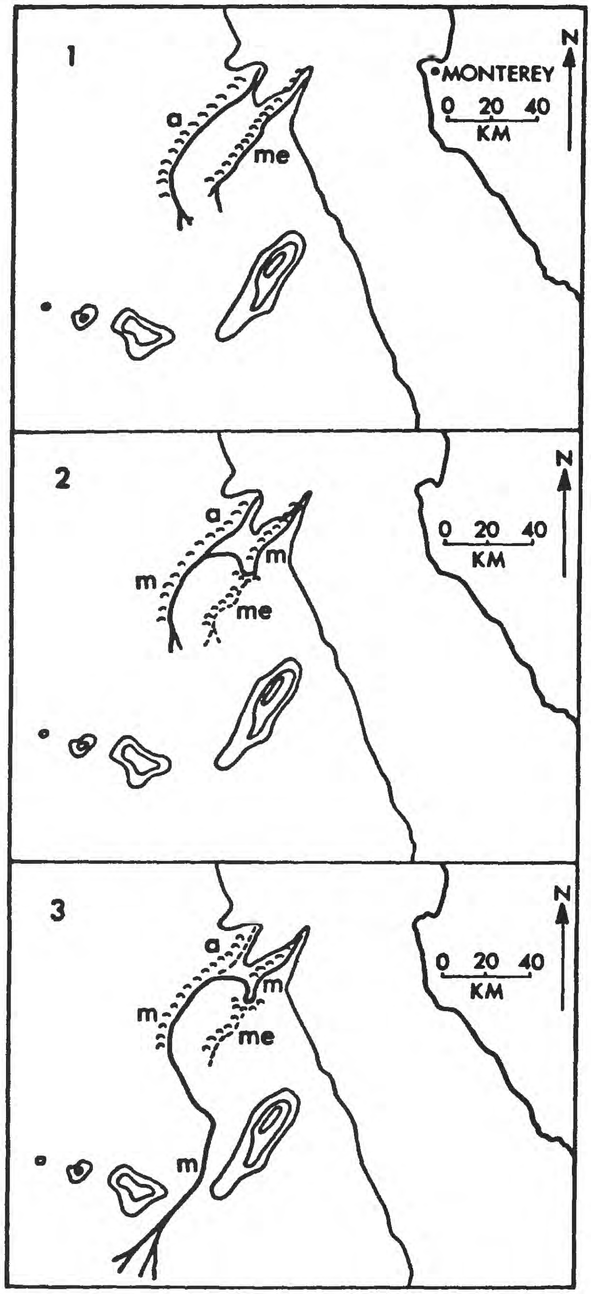

Figure 10. Model for the development of the Monterey Fan-Valley. 1) Originally the Ascension and Monterey East fan-valleys were parallel, active systems. 2) After capturing the lower Ascension Fan-Valley, the old foot of the Monterey East is beheaded and abandoned. 3) Incision of the new Monterey Fan-Valley leaves the old head of the Ascension Fan-Valley as a hanging valley. (After Normark, 1969).

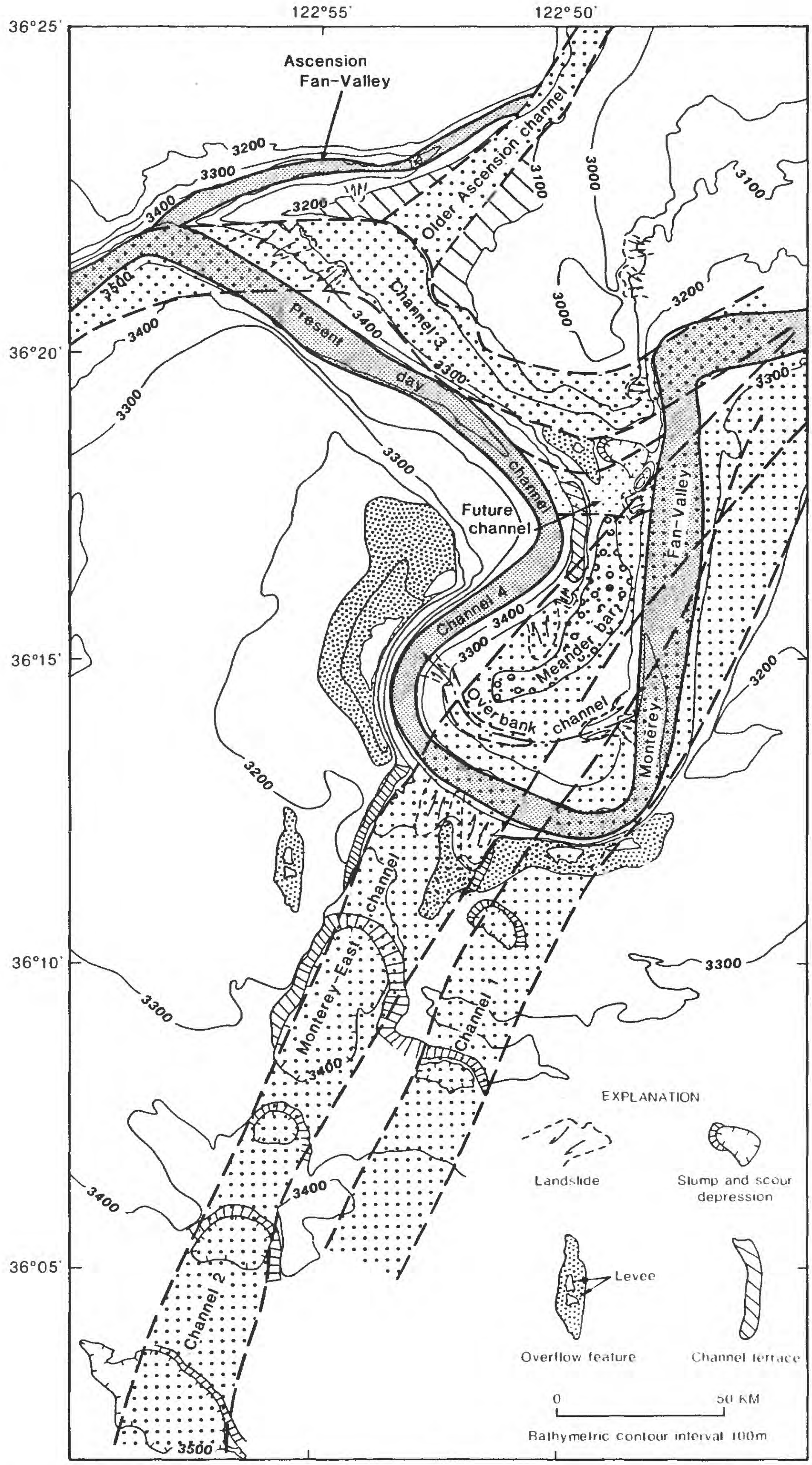

Figure 11. Map showing locations of past, present, and proposed future channels of the Monterey Fan-Valley at the fan meander.

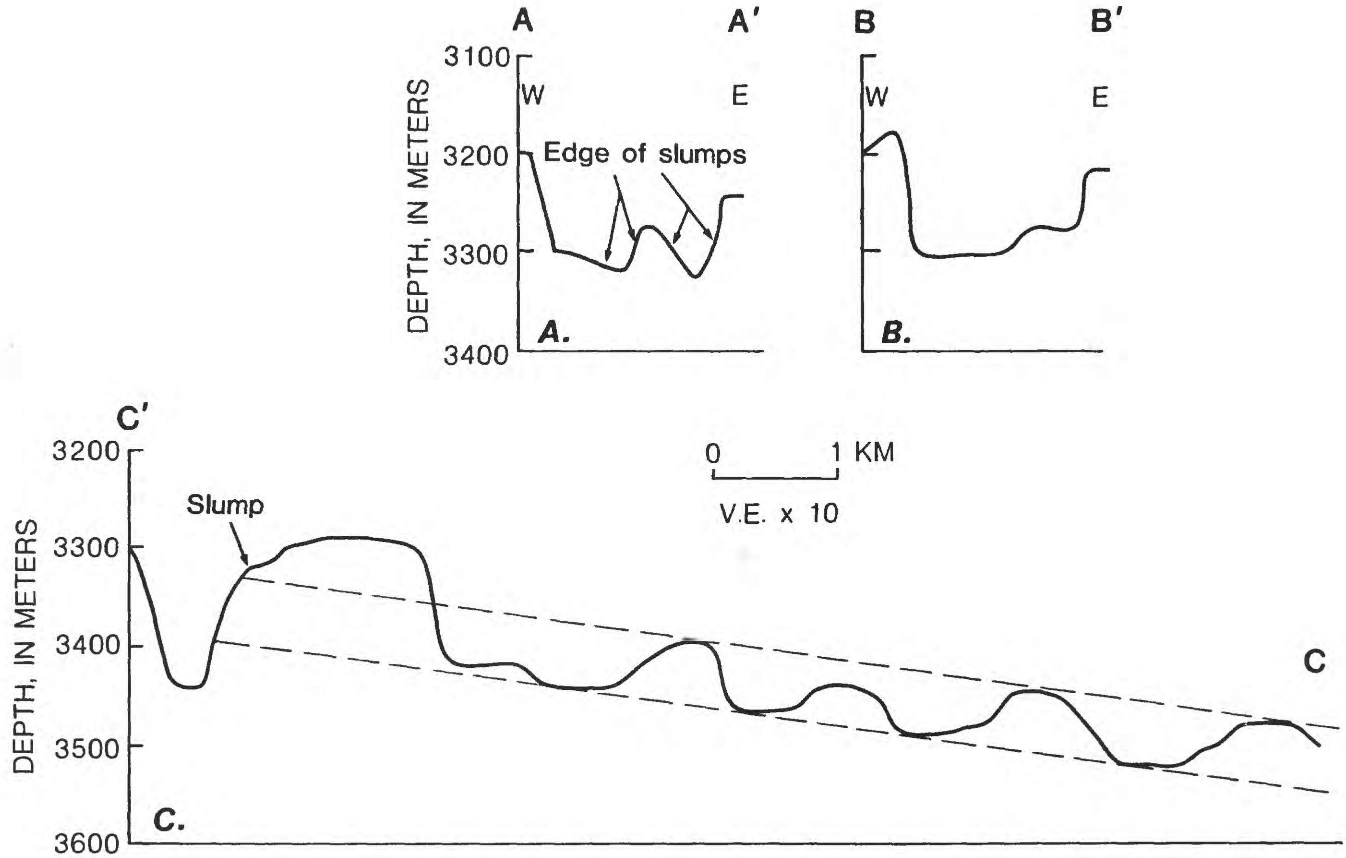

Figure 12. Cross-sections across (profiles A-A′ and B-B′) and along (profile C-C′) the older, filled Monterey Fan-Valley. Note how the lowest points of the depressions in the older Fan-Valley (profile C-C′) share a common dipping surface. This surface may be the old Fan-Valley floor and may represent the sole of the slumped fill. Location of profiles on Plate 4.