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STRUCTURE OF THE CONTINENTAL SHELF WEST OF SAN FRANCISCO, CALIFORNIA

By

Alan Cooper

Open-file report

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This report is preliminary
and has not been edited or
reviewed for conformity with
Geological Survey standards

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ABSTRACT

The continental shelf west of San Francisco, California is divided into two structural provinces along the offshore extension of the Seal Cove fault, the Farallon and Golden Gate platforms. The Farallon platform lies west of the Seal Cove fault and is characterized by a thick sequence of Tertiary sediments with a maximum thickness of 3.5 km. These sediments are bounded at the edge of the continental shelf by a ridge of Cretaceous granitic rock which crops out at the Farallon Islands. The granitic basement is vertically displaced along the eastern flank of the granitic ridge and along two high angle reverse faults located near Point Reyes. The Point Reyes fault trends east-west and has possibly offset the granitic basement 1500 meters since late Pliocene time. Two northwest trending anticlines lie south of the Point Reyes fault. The eastern boundary of the Tertiary basin is delineated by a structural high composed of deformed basin sediments. This structural high is truncated at the Seal Cove fault. On the Golden Gate platform, the San Andreas fault zone is marked by a near surface graben, showing a maximum vertical displacement of 20 meters, and by a wider linear depression observed to a depth of 700 meters. The Pilarcitos fault continues offshore and joins the San Andreas fault south of Bolinas.

The development of the present Tertiary basin under the continental shelf commenced in late Miocene time with the initial uplift of the Farallon ridge and the compression of the eastern basin margin.

Strike-slip faulting on the Seal Cove fault in Pliocene time truncated middle Tertiary sediments at the fault and thus formed a distinct structural boundary between the Farallon and Golden Gate platforms. Surface extensional features observed within the San Andreas fault zone are suggestive of strike-slip faulting in late Tertiary time. The compressional high angle reverse faulting at Point Reyes occurred during the late Pliocene orogenic period of the California Coast Ranges.

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CHAPTER I

INTRODUCTION

The Gulf of the Farallones includes that part of the California continental shelf which lies west of San Francisco, extends north to Point Reyes, and reaches south to Half Moon Bay (Fig. 1). In this area, the shelf is a flat, shallow platform which deepens to the northwest and extends 40 km west from San Francisco to the Farallon Islands. The earliest investigations of this portion of the California continental margin are reported by Hanna (1952), Chesterman (1952), and Uchupi and Emery (1963) from bottom samples collected in the Gulf of the Farallones and on the continental slope. Curray (1965, 1966) published a seismic reflection profile which crosses the shelf and extends to the base of the continental slope. This study was part of a more comprehensive investigation of the structure of the central California continental margin. Recent geologic and geophysical information obtained by the Shell Oil Company in its exploration of the continental shelf is summarized by Hoskins and Griffiths (1971).

The Farallon Islands are the exposed portion of a buried ridge which is described by Hanna (1951). Curray (1965) indicates that the ridge parallels the edge of the continental shelf. The presence of granitic rocks, quartz diorite, on the Farallon Islands (Hanna, 1951) and granitic debris on the sea floor north and south of the islands (Hanna, 1952 and Chesterman, 1952) indicates that the

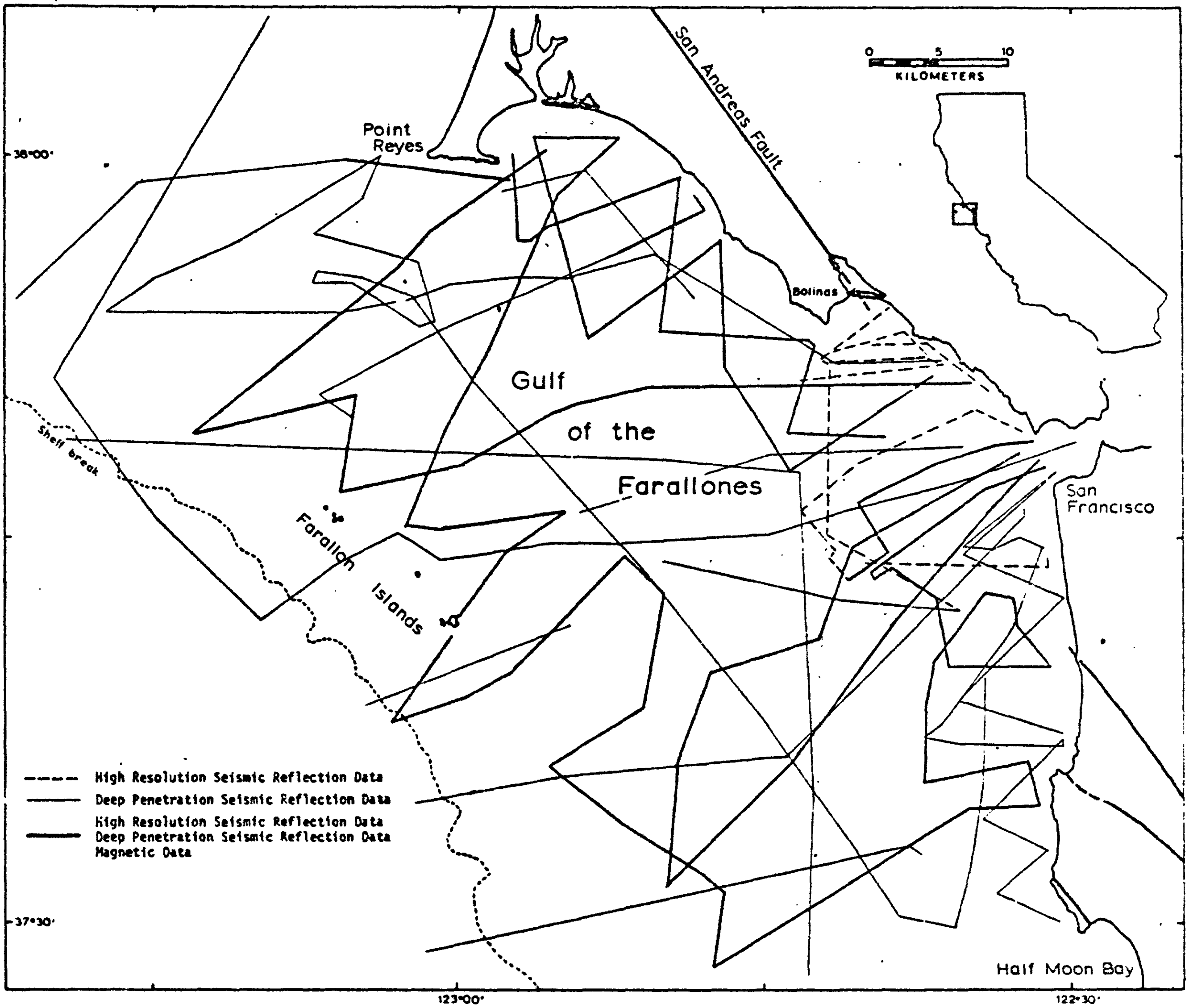

Figure 1.--Map of the Gulf of the Farallones study area with the location of ships tracks used in the investigation.

ridge is granitic. Similar granitic rocks are found at Point Reyes (Galloway, 1966) and on Montara Mountain (Darrow, 1963). Ages determined for these rocks by the potassium argon method are 89.5 million years, 83.9 million years, and 91.6 million years, respectively (Curtis and others, 1958).

A thick accumulation of sediments east of the Farallon Islands is indicated in the seismic reflection record of Curray (1965), and in two structure cross sections by Hoskins and Griffiths (1971). Within the Gulf of the Farallones, Orlin (1962) documents a gravity calibration range established by the U.S. Coast and Geodetic Survey from bottom gravity meter data. A general interpretation of the gravity data is made by Jones (1963). From his interpretation of the gravity information,Griscom (1966) estimates the minimum depth to the basement surface as 4 km. West of Point Reyes, Hoskins and Griffiths (1971) show a northwest trending sedimentary basin filled with 3 km of Tertiary sediments.

The geology of the Point Reyes peninsula has been mapped and described by Anderson (1902),Dickerson (1922), Weaver (1949), and Galloway (1966). Investigation of the Pliocene basins along the San Andreas fault, on the Point Reyes peninsula,and south of San Francisco, is reported by Higgins (1961), Glen (1959), Hall (1966) and Addicott (1969). A partial collection of papers concerning the history of lateral displacements along the San Andreas fault is compiled and summarized by Dickinson and Grantz (1968). Darrow (1963) and Dibblee (1966) discuss the Pilarcitos fault and its possible origins.

The present investigation of the Gulf of the Farallones was undertaken by the author early in 1970. The primary objective was to examine the regional and local structures of the continental shelf and their relationship to shelf development during Tertiary time. The recent emphasis upon the importance of the San Andreas fault, in the San Francisco area, has raised numerous questions concerning the offshore portion of the fault between Mussel Rock and Bolinas. Continuation of other important land structures into the offshore area has not previously been examined. The study of these and other problems concerning the structural transition from land to the offshore areas of the continental shelf are important objectives of this investigation.

The area was studied, on two separate cruises, aboard the U.S. Geological Survey R/V POLARIS using three continuous seismic reflection profiling systems and a proton precision magnetometer. Other seismic reflection records and gravity data were generously made available for this study by Joseph Curray of Scripps Institution of Oceanography, and David S. McCulloch and Stephen C. Wolf of the U.S. Geological Survey. The additional data increased the total track length to 750 nautical miles. Figure 1 shows the combined cruise tracks of the various surveys utilized in this study.

The three continuous seismic reflection profiling systems used included: 1) a 9000 joule arcer system with a four source array and fashioned after a system described by Rusnak (1967); returning signals were fed into a bandpass filter of 25 to 98 hertz and the records were presented at a 1 second sweep rate, 2) a 33,000 joule arcer system with a dual source array; a similar filter was used and the records were made at 1 and 2 second sweep rates, 3) a short pulse, 600 joule high resolution arcer system using a 50 tip, 12 joules per tip, stinger source; bandpass filter settings were 100 to 515 hertz and a 1/4 second sweep rate was utilized for presentation of the records. Most reflection profiles were recorded at an approximate vertical exaggeration of 6 to 1. An average ship speed of 6 knots was maintained using radar for navigation. The gravity lines were also run using radar navigation and the maximum error is believed to be $\pm$ 3 mgal. A resolution of $\pm$ 2 gamma was easily maintained by the proton precession magnetometer.

The low frequency seismic reflection profiles generally showed a maximum penetration of 1.0 seconds two-way travel time for the 9000 joule system and 1.8 seconds for the 33,000 joule system. The greatest penetration was seen in areas of thick flat lying sediments, such as northeast of the Farallon Islands. In areas where hard rock was buried at shallow depths, near the coastline from Montara Mountain to Bolinas, the deep penetration records were generally discontinuous and showed poor resolution of buried structures. The short pulse length of the high resolution system allowed a discrimination of structures about 2 to 3 meters thick, within approximately 200 meters of the sea floor. These records were particularly useful in detecting small faults and in resolving complex structures from the area near the San Andreas fault. Gravity information was used primarily for delineating basement faults with vertical displacements which could not be observed in the reflection profiles. The magnetic data was useful in detecting susceptibility changes at fault boundaries.

CHAPTER II

REGIONAL STRUCTURAL FRAMEWORK

Compton (1966) and Page (1970) indicate that the continental shelf off San Francisco lies within the boundaries of the Salinian block which extends from the Transverse Ranges, 375 km south, to Point Arena, 140 km north. Basement in this block consists of granitic and high grade metamorphic rocks. Page (1970) suggests that the offshore extension of the Sur-Nacimiento fault, which lies on the continental slope west of the Farallon Islands, is the approximate boundary between the sialic rocks of the Salinian block and the eugeosynclinal type rocks of the Franciscan assemblage. The eastern-most contact of granitic rocks and the Franciscan Formation is generally the San Andreas fault; however, locally the Pilarcitos fault forms the boundary (Fig. 2) (Darrow, 1963). The distribution of granitic rocks around the Gulf of the Farallones and the widely accepted concept of Salinia suggest that the basement rocks under the Gulf of the Farallones are granitic.

Structures on land generally follow the northwesterly regional trend characterized by the strike of the San Andreas fault. Two important faults, the Seal Cove fault and the Pilarcitos fault, are mapped west of the San Andreas fault near Montara Mountain. Darrow (1963) indicates that the contact between granitic rocks of Montara Mountain and the ubiquitous Franciscan Formation occurs at the Pilarcitos fault. The emplacement of the Franciscan Formation west of the

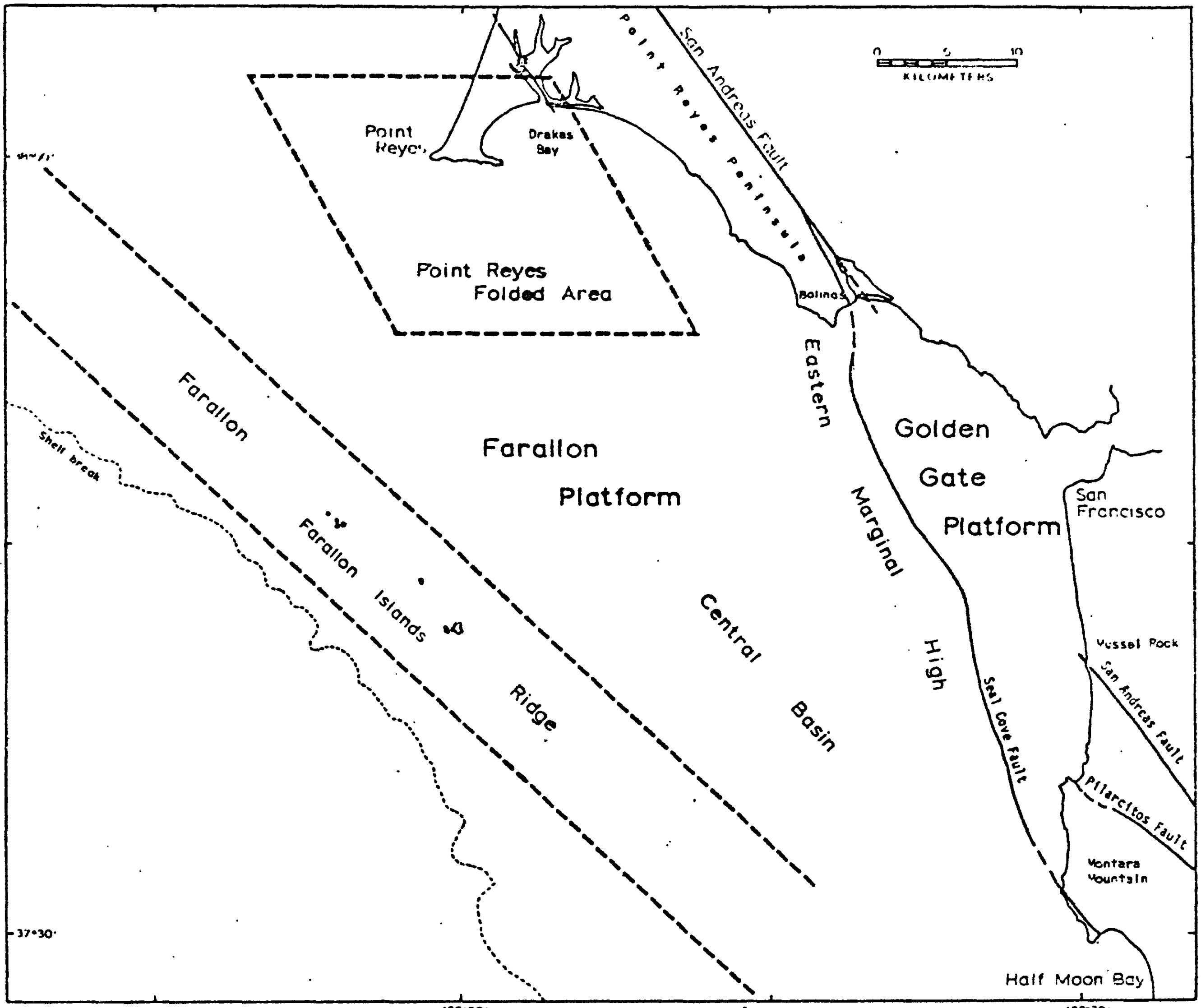

Figure 2.--Index map of the structural provinces described in the text. The two platform areas are separated by the offshore extension of the Seal Cove fault. A division of the Farallon platform into four smaller regions is also made.

San Andreas fault has been explained by thrusting along the Pilarcitos fault (Darrow, 1963) and alternatively by right lateral movement along the same fault (Dibblee, 1966). Several authors including Page (1966), Dibblee (1966), and Hoskins and Griffiths (1971) have speculated on the possible offshore joining of the Pilarcitos fault and the San Andreas fault, southeast of Bolinas. The Seal Cove fault lies west of Montara Mountain and parallels the present coastline. It is a high angle, northeasterly dipping, normal fault which appears to have juxtaposed rock types of different ages and lithologies (Glen, 1959). Thirteen meters of displacement of Quaternary terrace deposits is reported on the fault by Jack (1969).

Hill and Dibblee (1953) have suggested that the San Andreas fault has shown large right lateral displacement since early Tertiary time. On the Point Reyes peninsula, middle Miocene rocks are juxtaposed against Jurassic-Cretaceous rocks along a vertical contact at the San Andreas fault (Galloway, 1966). Darrow (1963) reports a similar juxtaposition of different rock types across the fault south of San Francisco. Pliocene rocks with similar lithologies and faunas, observed in outcrop across the San Andreas fault at Bolinas and near Mussel Rock, have led Gluskoter (1969) and Higgins (1961) to speculate that these rocks have been horizontally displaced at the fault. Generally it has been assumed that the San Andreas fault extends offshore from Mussel Rock to Bolinas, based on the reports of ground displacements on the Point Reyes peninsula and south of San Francisco during the 1906 earthquake (Gilbert, 1908). However, the seaward trace of the San Andreas fault has not been previously investigated.

The dominant structure of Point Reyes is an offshore fault which is mapped by Hoskins and Griffiths (1971) and is assumed to control the morphology of the southern coastline (Galloway, personal communication). A steep northeast gravity gradient is present across the southern face of Point Reyes (Orlin, 1962). The axis of the Drakes Bay syncline (Fig. 2) lies east of Point Reyes and parallels the trend of the San Andreas fault. Middle Miocene and lower Pliocene rocks on the Point Reyes peninsula indicate small northwesterly trending folds; however, the regional dip is to the west (Galloway, 1966). Along the coast from Bolinas to Drakes Bay, Wahrhaftig reports an elevated marine terrace which suggests the uplift of the southern Point Reyes peninsula.

CHAPTER III

GENERAL STRUCTURAL OVERVIEW

The important structural features of the continental shelf, within the Gulf of the Farallones, can be divided into two structurally distinct areas, the Farallon platform and the Golden Gate platform (Fig. 2). A separation of the two regions along the offshore extension of the Seal Cove fault is chosen to isolate those structures locally affected by the San Andreas fault system from structures associated with regional stress. The abrupt structural transition between the Farallon platform and the Golden Gate platform is suggested in the seismic reflection profiles which cross the Seal Cove fault. Consequently, the two platform areas will be considered separately.

The Farallon platform is characterized by a thick sequence of Tertiary sediments overlying a granitic or high grade metamorphic basement. The platform is divided into four regions, each with characteristic structure and type of deformation. These regions include: (1) Farallon ridge, (2) central basin, (3) Point Reyes folded area, and (4) eastern marginal high (Fig. 2). An overview of structures within the Farallon platform can be seen in the contour map of Figure 3. Contours in units of two-way travel time have been drawn on a strong reflector that could be located in most seismic records. It is inferred to be a chert layer of early late Miocene age (Galloway, personal communication) as exposed in an outcrop on the beach of the Point Reyes peninsula east of Drakes Bay (Fig. 3). Structures illustrated on the upper Miocene(?) surface are generally similar to those observed in the overlying sediments; however, such a relationship with the older sediments is uncertain. An orthographic diagram of the same surface is shown in Figure 4.

The dominant structural trend within the post upper Miocene(?) sequence (Fig. 3) on the Farallon platform is northwest, and is similar to the regional trends observed onshore. The eastern marginal high, and those structures south of Point Reyes, deviate from the strike of the San Andreas fault. These fluctuations appear to be local variations from a regional northwesterly trend. The central basin is a single depression near Pillar Point that bifurcates northward and forms two distinct troughs, the eastern trough and the western trough. The eastern trough parallels the eastern marginal high and continues toward Drakes Bay. A syncline, which has been mapped onshore by Galloway (1966) as the Drakes Bay syncline, may be the continuation of the eastern trough; however, this is a speculative correlation since the eastern trough is shown ending at the Point Reyes fault (Fig. 3).

The western trough forms the most pronounced depression on the Farallon platform. It deepens northward and passes between the Farallon ridge and the Point Reyes folded area. The deepest part of the central basin lies along the axis of the western trough. Near Point Reyes, the central fault and the Point Reyes fault form the boundary for two broad anticlines. The contours of Figure 3 indicate that large vertical displacements have occurred on these two faults.

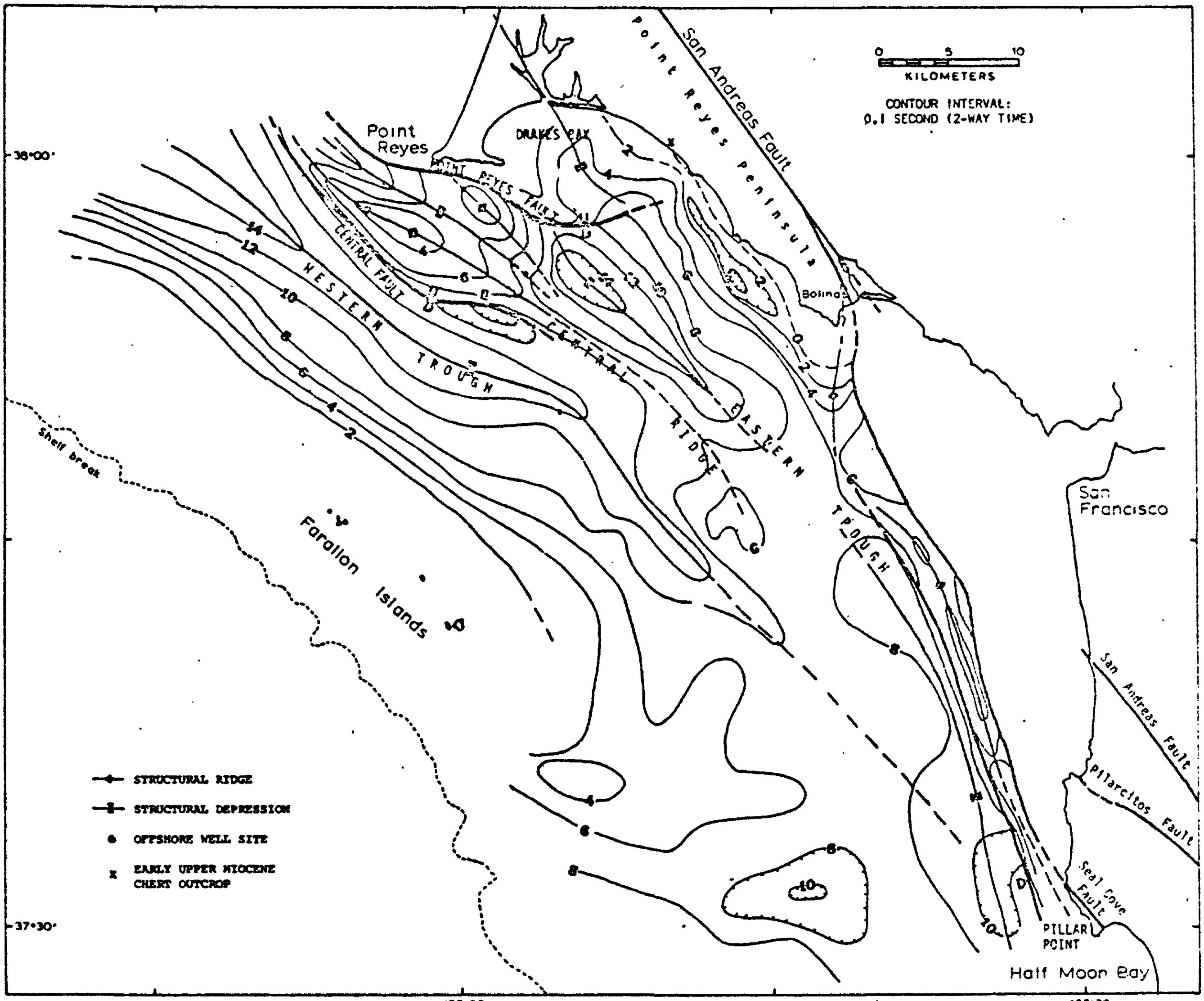

Figure 3.--Structure contour map on a distinctive reflecting horizon inferred to be chert of early late Miocene age from an outcrop in the beach on the Point Reyes peninsula (X). This surface indicates the major structural features which have developed since the initial uplift of the western margin in late Miocene time. The surface terminates at the Seal Cove fault and cannot be observed east of the fault.

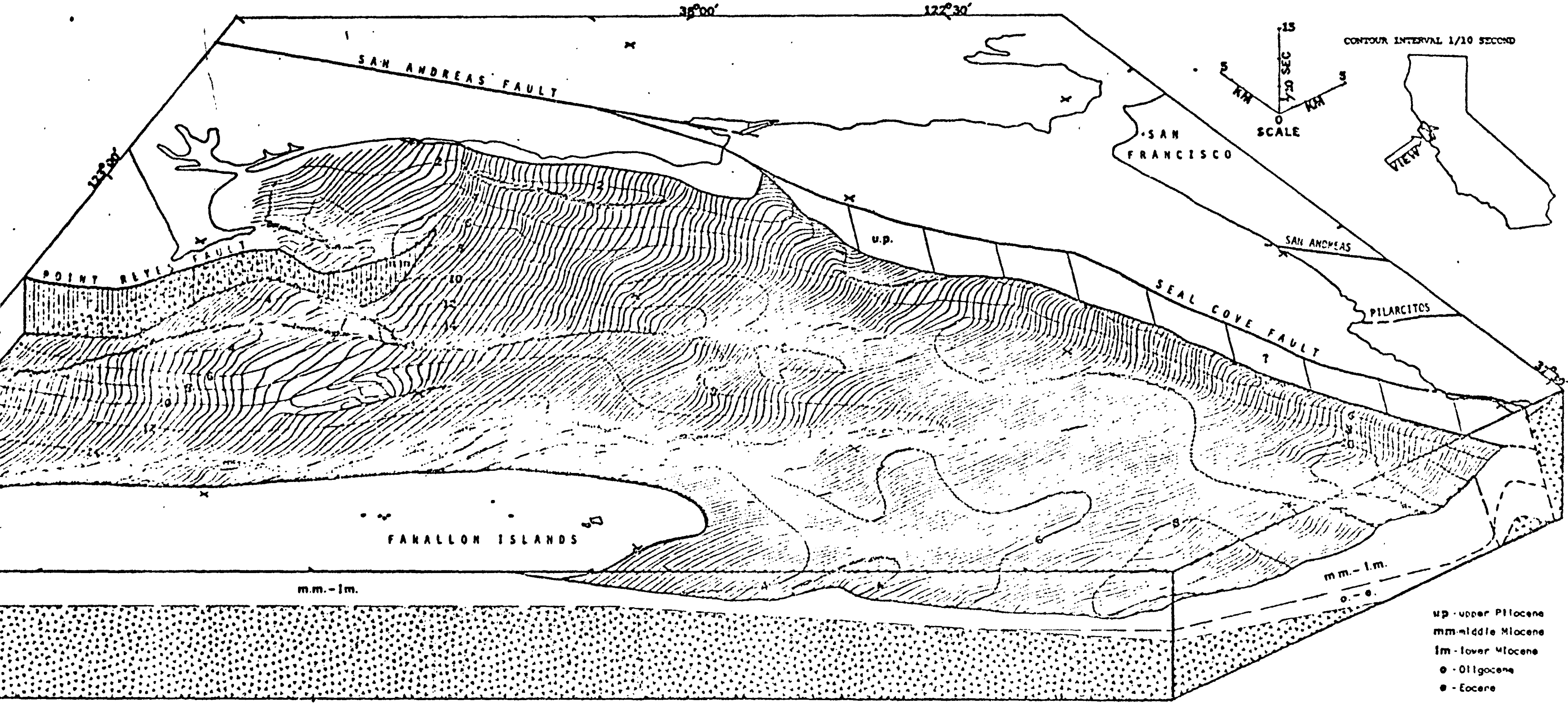

Figure 4.--An orthographic projection of the upper Miocene surface described in the caption of Figure 3. The southern cross section is adapted from Hoskins and Griffiths (1971). The Point Reyes fault shows a steeply dipping fault scarp, across which the upper Miocene surface has been displaced. Horizontal and vertical displacement is assumed at the Seal Cove fault.

The eastern marginal high is composed of complexly folded sedimentary rocks which are truncated on the east side by the offshore extension of the Seal Cove fault. The upper Miocene(?) reflector terminates at this point and cannot be followed onto the Golden Gate platform. Near Bolinas, the eastern marginal high emerges onto the Point Reyes peninsula, and the Seal Cove fault joins the San Andreas fault.

The Golden Gate platform is located east of the Seal Cove fault and extends to the present coastline. It contains three major faults, the Seal Cove fault, the Pilarcitos fault, and the San Andreas fault. In addition, there are numerous smaller faults which have sheared sediments presumed to be of late Tertiary age. The San Andreas fault crosses the Golden Gate platform as a depressed zone with possible en echelon faults; the recent(?) trace of the San Andreas fault is shown in Figure 2. The Pilarcitos fault subparallels the Seal Cove fault offshore and it is inferred to be the offshore contact between the granitic basement of the Salinian block and the Franciscan Formation. Near Bolinas, the Pilarcitos fault joins the recent(?) trace of the San Andreas fault.

CHAPTER IV

FARALLON PLATFORM

I. INTRODUCTION

The discussion of the Farallon platform will include only the area located west of the structural transition at the Seal Cove Fault; the area east of the fault will be discussed later. This division is made to isolate the structural histories of the Farallon and Golden Gate platforms, since the juxtaposition of the platforms may have occurred subsequent to the original deposition. The four areas of structural interest within the Farallon platform are: 1) the Farallon ridge, 2) the central basin, 3) the Point Reyes folded area, and 4) the eastern marginal high.

II. FARALLON RIDGE

The western margin of the Farallon platform and the present edge of the continental shelf is delineated by a 5 km wide ridge which is exposed at the Farallon Islands. The ridge can be seen in the line drawings of the seismic reflection profiles (Fig. 5) where it constitutes the high area which forms the western edge of the central sedimentary basin. The basement ridge is continuous for 50 km northwest to Cordell Bank, at which point the ridge apparently ends. Southeast of the Farallon Islands, the continental shelf broadens and the granitic ridge beomes difficult to trace under a cover of sediments. However, it is inferred to continue along a similar trend throughout the area.

<u>Descriptive.</u>

The only rock type sampled on the Farallon Islands is biotite quartz diorite which has been dated by the potassium argon method as 89.5 m.y.

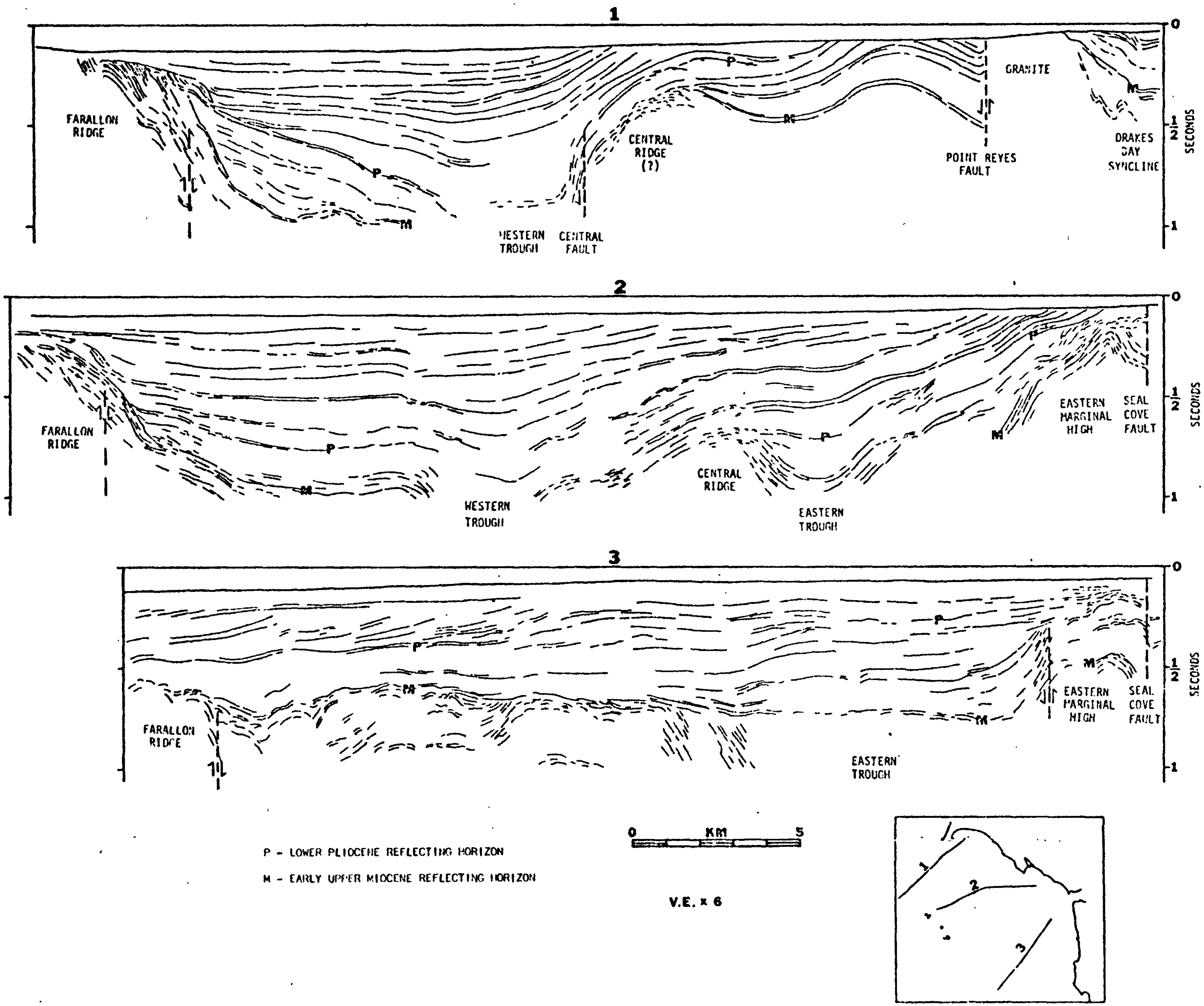

Figure 5.--Line drawings of three seismic reflection profile records made across the Gulf of the Farallones. Upper Miocene (M) and lower Pliocene (P) horizons are indicated.

(Curtis and others, 1958). Curtis and others (1958) place the age of intrusion as upper Cretaceous, and they correlate the intrusions with the orogeny of the same age in the Santa Lucia Mountains to the south. No trace of a Paleocene conglomerate, which is associated with the granites at Point Reyes and at Montara Mountain, has been reported on the Farallon Islands. Hanna (1951) found many small, rounded pebbles characteristic of the Franciscan formation scattered around the islands. He believes that they were not derived from a local conglomerate, but that they were carried to the island by the indigenous wildlife.

The upper Miocene (?) surface (Fig. 3) can be seen along the flank of the granitic ridge in profiles 1 and 2 Figure 5. The present dip of this surface into the basin decreases from 19° in the north (profile 1) to 8° in the south (profile 2), as the basin widens and becomes shallower. The onlap of younger sediments over the upper Miocene (?) surface is characteristic of the northern and central Farallon ridge (Fig. 5). Near the Farallon Islands the upper part of the Miocene section appears to have been eroded and subsequently covered by these younger sediments.

It is difficult to distinguish the internal structure of the sediments beneath the upper Miocene along the ridge flank in profiles 1 and 2 (Figure 5) since the reflectors dip steeply into the central basin. However, in these two lines and others not illustrated, the reflectors suggest a simpler internal structure and a more conformable relationship to the granitic surface than in the other sections of the Farallon platform. Some evidence of folding within the pre-upper Miocene section is suggested in the reflection profiles near the crest of the ridge, north of the Farallon Islands. Curray (pers. comm.) also reports the presence of folded sediments along the eastern edge of the ridge in the same locality. Gravity information and some reflection profiles suggest that the folding occurs locally over an irregular and faulted basement surface.

Faulting

Gravity information from Orlin (1962) and a U. S. Geological Survey investigation indicates a steep easterly gradient along the landward edge of the Farallon ridge near the Farallon Islands. Jones (1963) interprets the gradient as being indicative of a large boundary fault. Confirmation of large steeply dipping faults, which have displaced the basement surface, is suggested in a single reflection profile. This profile penetrated to the granitic basement at the eastern base of the Farallon ridge. Other reflection profiles do not indicate a good basement reflector in the areas where the granitic ridge dips steeply into the central basin. Local high angle faulting of the basement can be seen in some reflection profiles across the southern portion of the ridge. In the vicinity of profile 3 (Fig. 5), the eastern edge of the granitic ridge is faulted with the basin side dropped about 100 meters and 600 meters, respectively, on two separate faults.

Ridge Development

A distinct hiatus is present in the early Tertiary geologic record along the crest of the Farallon ridge. The oldest sediments reported in this area are found along the crest of the ridge to the north of the Farallon Islands. These deposits consist of shales of early Miocene age (Uchupi and Emery, 1963). Pre-Miocene Tertiary sediments are reported from the central part of the basin (Hoskins and Griffiths, 1971); however, they are not found in outcrop along either flank of the Farallon ridge (Hanna, 1951 and Uchupi and Emery, 1963). The apparent absence of pre-Miocene sediments suggests that either the ridge was tectonically positive during early Tertiary, or that the geologic section had been eroded prior to Miocene time. Throughout early and middle Miocene time, the ridge was probably covered by the same thick sequence of shales, mudstones, and cherts that is present on the Point Reyes peninsula.

The end of the middle Miocene was marked by a period of diastrophism which initiated the uplift of the ridge along high angle normal faults. The age for the initial uplift is suggested by the onlap of younger sediments over the upper Miocene(?) reflecting horizon. This late middle Miocene uplift, along the western margin of the Farallon platform, marked the first in a series of episodic events which formed the present central basin.

III. POINT REYES FOLDED AREA

Descriptive

The dominant structural feature of the Point Reyes folded area is an east-west trending high angle fault adjacent to the southern coastline of Point Reyes. Since this fault is responsible for the morphology of Point Reyes, it is referred to as the Point Reyes fault. The two northwest trending anticlines and the northern portion of the eastern trough (Fig. 3) are bordered on one side by the Point Reyes fault and on the other by a second prominent high angle fault, the central fault (Fig. 3). The eastern trough and the Drakes Bay syncline may have been continuous at one time; however, the two axes are presently offset about

5 km in a right lateral sense. This apparent offset is the only evidence for possible horizontal displacement along the Point Reyes fault.

The subsurface vertical displacement on the Point Reyes fault increases westward from the axis of the Drakes Bay syncline. In the vicinity of Point Reyes, the granitic basement appears on the sea floor to the north of the Point Reyes fault, whereas on the basin side, the granite is buried to a minimum depth of over 1400 meters. The thickness of sediment cover is inferred from the total depth of an offshore well drilled at the crest of the central ridge (Fig. 3) at a distance of 3 km from the Point Reyes fault. Vertical displacement decreases to about 500 meters at the northern end of the eastern trough, and disappears approximately 3 km from the present shoreline, based on the displacement of the upper Miocene (?) surface (Fig. 3). The granitic basement is not observed in the seismic reflection profiles at the junction of the axis of the Drakes Bay syncline and the Point Reyes fault. The vertical offset at this point is inferred from the bend in the contours of the upper Miocene (?) structure map (Fig. 3). Offshore gravity readings, parallel to the coast from Drakes Bay to Bolinas, indicate that the basement is probably not offset at the eastern extremity of the fault (3 km offshore). However, the fault does appear to mark an increase in the southward inclination of the basement surface.

Profile 1 of Figure 5 is a cross section of the central fault, the two anticlines, and the Point Reyes fault. Granitic basement rock at the Point Reyes fault is juxtaposed against layered and folded sediments of the older central basin sequence. The dip of the two fault planes cannot be directly measured from the reflection profile information. However, the abrupt truncation of reflectors at the Point Reyes fault, and the steep apparent dips at the central fault are indicative of steeply dipping fault planes. The steep gravity gradients measured across both faults are also suggestive of nearly vertical faults with possible reverse fault displacement. Adjacent to the Point Reyes fault, the sediments appear to thin toward the west and show onlap of the central ridge. The deepest reflectors at the crest of the central ridge in this area are discontinuous and suggest an irregular surface which may represent an older unconformity. This acoustic condition appears at the crest of the ridge along its entire length (profiles 1 and 2, Fig. 5). Consequently, the southeasterly continuation of the central ridge, as a structural high, is based upon the similarity of reflectors along the crest of the high, the regional structural trend, and the continuous onlap of sediments from the eastern trough.

Structural Development near Point Reyes

Large vertical displacements on the Point Reyes fault and the central fault are suggested by the seismic reflection profiles, gravity information, and offshore well data. Folding within this area is probably a result of vertical and strike slip faulting. Hoskins and Griffiths (1971) report that faulting near Point Reyes occurred in Pleistocene time. Other evidence indicates that some structures in the Point Reyes folded area developed prior to late Tertiary time, and that faulting on the Point Reyes fault may have commenced in late Pliocene time and extended into Pleistocene time.

The central fault, central ridge, and eastern trough (profile 1,

Fig. 5) were initially formed prior to the late Pliocene Orogenic period but may have undergone repeated deformation during this time. The broken character of the acoustic reflectors at the top of the central ridge, and the eastward thickening of sediments above the upper Miocene (?) horizon, suggest that the central ridge was high during part of late Miocene time. The onlap sequence is younger than early late Miocene, and it has been folded into a smaller anticline, east of the central ridge, presumably while the Point Reyes fault was active. From these assumptions, the central ridge must have been uplifted in middle Miocene time and have remained positive into late Miocene time. Subsidence of the central ridge during Pliocene time is indicated by the sediment cover over the crest of the central ridge (profiles 1 and 2, Fig. 5). In the Point Reyes area, the late Tertiary faulting caused the ridge to be uplifted with the subsequent erosion of a portion of the Pliocene section (profile 1, Fig. 5). The truncation of reflectors at the sea floor is indicated in high resoltuion reflection profiles (not illustrated) over the central ridge. This truncation is evidence that the most recent uplift of the ridge occurred during or after the deposition of the Pliocene section.

The eastern trough is believed to be the offshore extension of the Drakes Bay syncline, which has been right laterally offset and vertically displaced by the Point Reyes fault. The trough is an older structure which was active during the same period as the central ridge. The eastward thickening of upper Miocene to lower Pliocene sediments from the central ridge into the eastern trough can also be observed in the isopach map of Figure 6. The map indicates possible right lateral offset of the eastern trough at the Point Reyes Fault, that horizontal displacement may

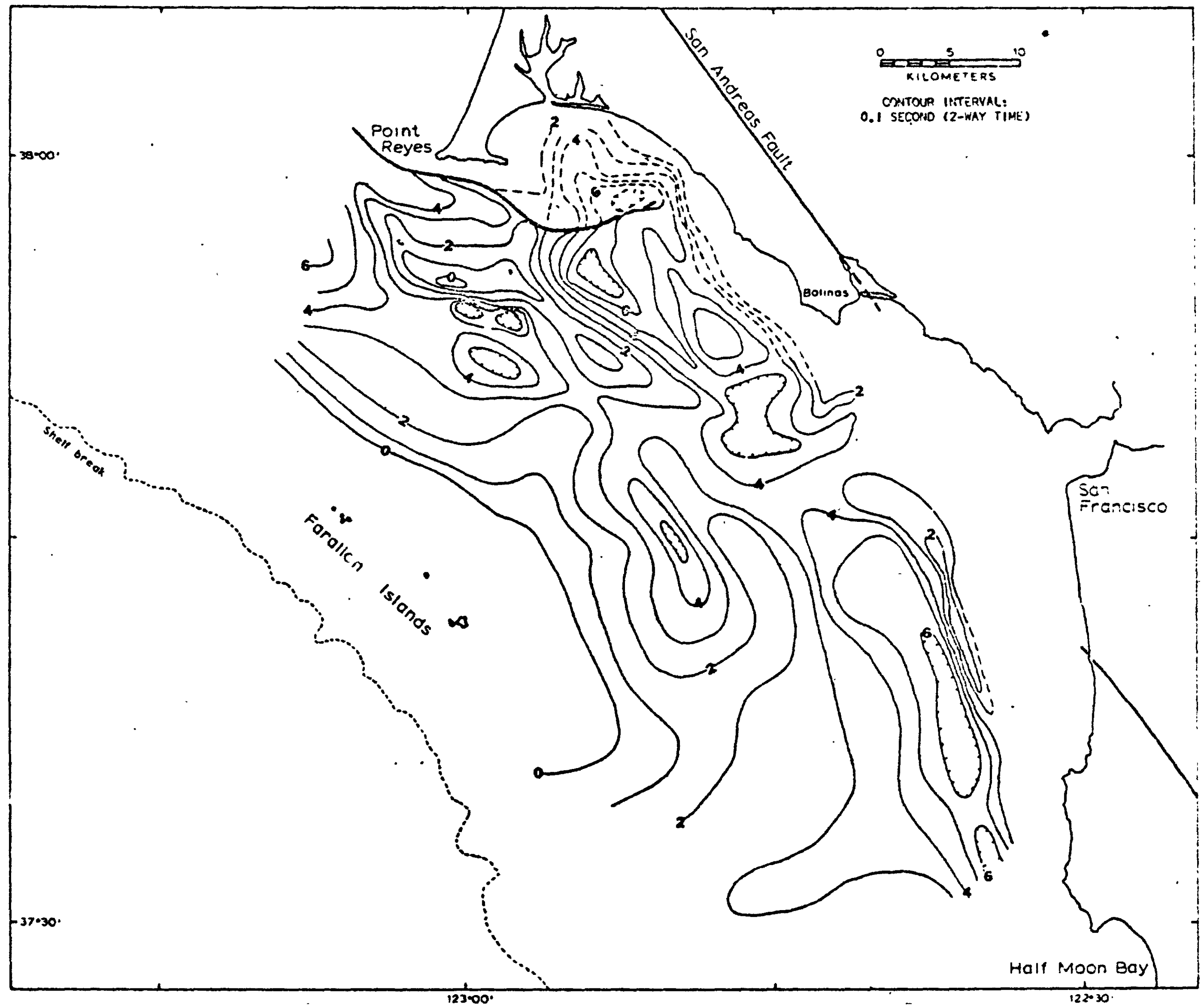

Figure 6.--Isopach map of upper Miocene to lower Pliocene sediments, compiled using the reflecting horizons of Figure 3 and Figure 7. The thickness is expressed in units of two way travel time. Contours are dashed where the upper horizon is missing, and the thickness is inferred from the projection of dips.

have occurred subsequent to early Pliocene time. Since sediments younger than early Pliocene are missing north of the Point Reyes fault, the total displacement cannot be determined, and an age for the horizontal movement is uncertain. The earliest limiting age from this line of evidence is late Pliocene.

The exact time at which vertical movement commenced on the Point Reyes fault is uncertain, on the basis of available information. However, truncation of reflectors inferred to be of Plio-Pleistocene age, at the Point Reyes fault trace, indicates that the Point Reyes fault has been active into Pleistocene time. Since a fault scarp is not observed at the sea floor, the possibility for recent vertical displacement cannot be established. If the fault is a Pleistocene feature, as suggested by Hoskins and Griffiths (1971), a minimum of 1500 meters of vertically displaced sediments must have been eroded from Point Reyes since Pleistocene time. This large sediment volume, which is no longer present at Point Reyes, may have been carried into the Central basin along an older subsidiary trough which trends south from Drakes Bay. Figure 7, a structure map constructed on a lower Pliocene reflecting horizon, indicates a southward thickening of sediments younger than lower Pliocene within this trough. Hoskins and Griffiths (1971) show a thick, approximately 1000 meter, sequence of upper Pliocene to recent sediments within the western trough, southwest of Point Reyes. They also report that only a thin veneer of Pleistocene sediments is present. As a result of this investigation, it is suggested that the thick sequence of upper Pliocene sediments within the western trough, and probably the subsidary trough (Fig. 7), were eroded from the Point Reyes area following vertical

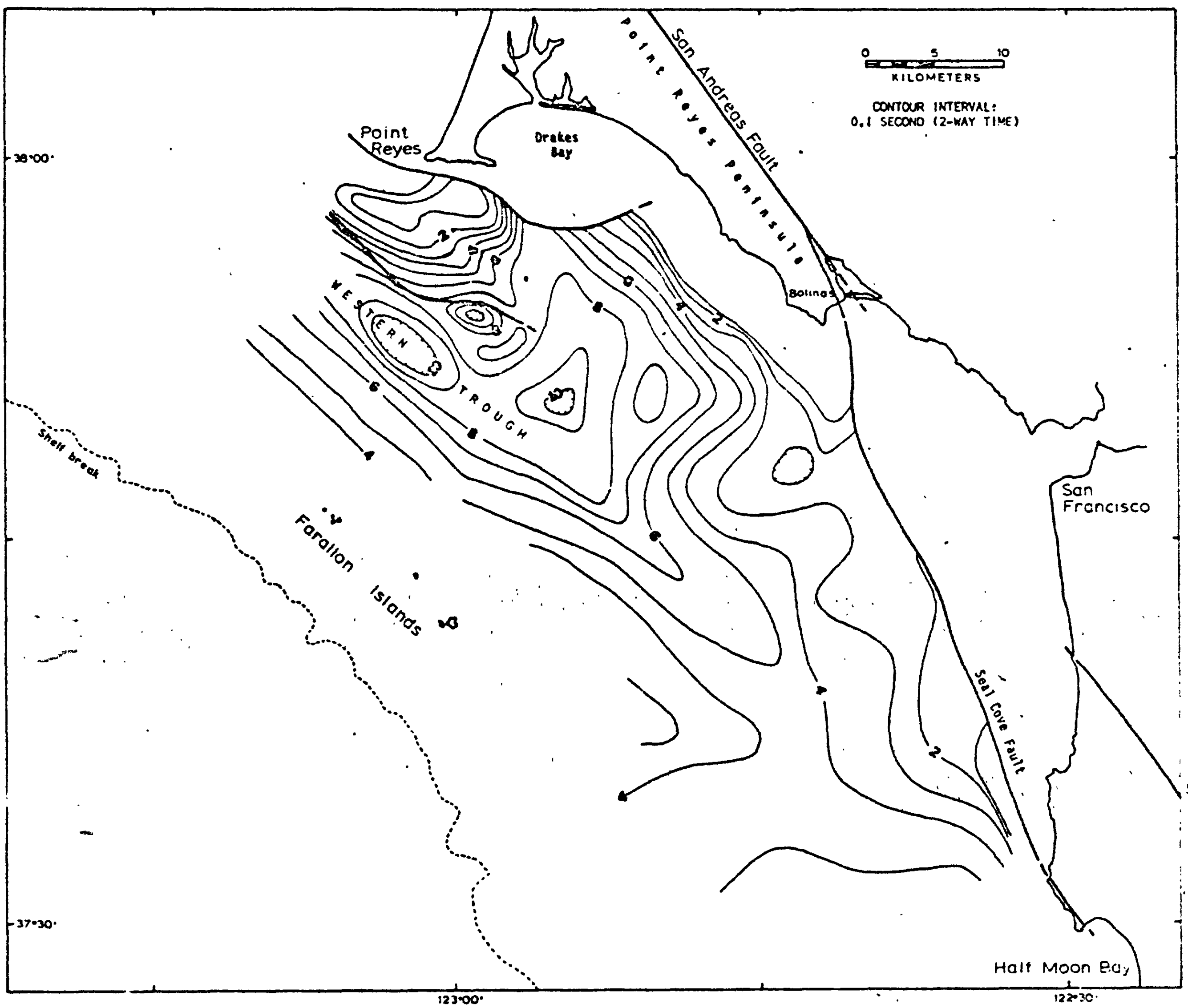

Figure 7.--Structure contour map on a reflecting horizon inferred to be of early Pliocene age from the projection of this surface onto the Point Reyes peninsula near Drakes Bay.

displacement on the Point Reyes fault in late Pliocene to Pleistocene time. Thus; faulting probably commenced in late Pliocene time, and the bulk of the sediments at Point Reyes may have been eroded before Pleistocene time, leaving only a small sediment supply available for Pleistocene depostion.

IV. CENTRAL BASIN

Descriptive

A thick accumulation of Tertiary sediments within the central basin makes it difficult to outline the granitic basement surface in the seismic reflection profiles. Figure 8 is a basement contour map based on gravity profiles, selected seismic reflection profiles which penetrated to basement, and well information. When seismic reflection information is used, the depths are computed using a velocity gradient of 1.0 km/sec/km for sediments above the upper Miocene(?) reflector, and a velocity of 3.5 km/sec for all other sediments overlying the acoustic basement (Hamilton, 1969). The gravity information is taken from unpublished sea gravimeter profiles run by the U. S. Geological Survey in 1968. Following Thompson and Talwani (1964), a northeasterly regional gradient of 0.6 mgal/km is removed, and the residual anomalies are subsequently used for the depth determinations. The assumed densities are: (1) 2.7 gm/cm^3 for the granitic basement, (2) 2.5 gm/cm^3 for pre-Miocene(?) sediments, (3) 2.4 gm/cm^3 for early and middle Miocene(?) sediments, and (4) 2.0 gm/cm^3 for the post-upper Miocene(?) section (Thompson and Talwani, 1964 and Greve, 1962).

The basement surface (Fig. 8) indicates that the central basin parallels the Farallon ridge, and deepens northward. Along the east flank

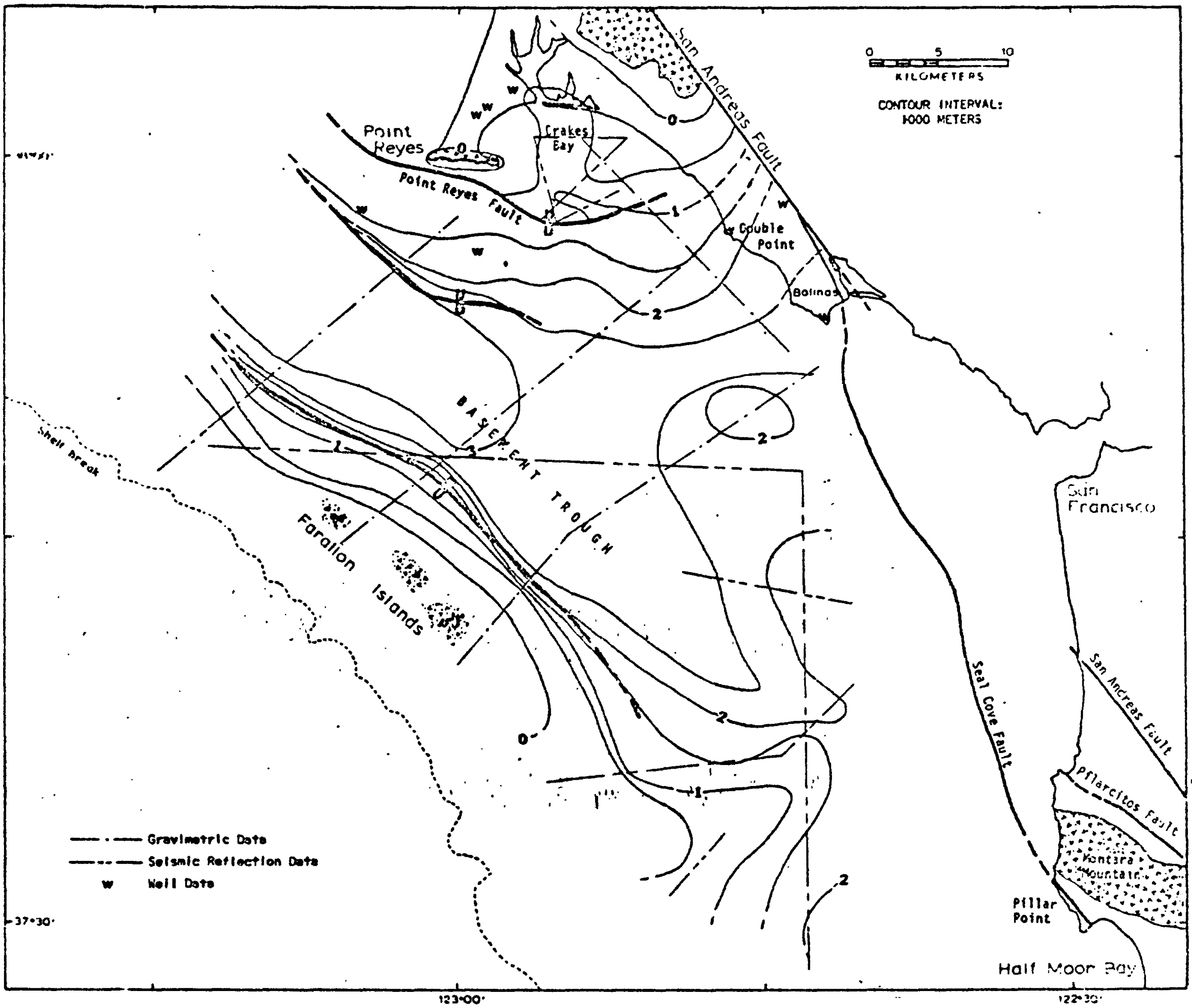

Figure 8.--Structure contour map on the granitic basement surface constructed from gravity data, seismic reflection data, and onshore and offshore well data. Control lines are shown. Stippled areas are outcrops of granitic rocks.

of the Farallon ridge, a steep gravity gradient of 6 mgal/km suggests a nearly vertical slope of the basement surface. An eastward extension of the Farallon ridge forms a subsurface high which constricts the basement trough near Pillar Point. The Drakes Bay syncline appears as a distinct basement depression north of the Point Reyes fault; south of the fault, the structure is too deeply buried to be observed. The axis of the basement trough (Fig. 8) and the axis of the overlying western trough (Fig. 3) both show a local westerly bend south of the central fault. The structures north of Point Reyes appear to resume their original northwest trend (Hoskins and Griffiths, 1971 and Silver and others, 1971). Within the Point Reyes folded area, the structures follow the trend of the western trough axis (Fig. 3). The strike of the inferred basement surface also changes from west to northwest in this area (Fig. 8). Local alignment of structures at the bend suggests that the faulting at Point Reyes may have displaced the basement trough.

The structures within the shallow subsurface portion of the central basin are illustrated in profiles 1, 2, and 3 of Figure 5. The western trough, adjacent to the Farallon ridge, widens southeastward from Point Reyes as the sediments above the upper Miocene(?) reflector become thinner. The central ridge separating the western and eastern troughs can be seen in profiles 1 and 2 (Fig. 5). In the southern crossing, profile 3 (Fig. 5), the ridge appears to merge with a broader area of deformed sediments. The upper Miocene(?) marker horizon is mapped along the top of these contorted reflectors; however, the surface may not be continuous in this area. Since the deformed sediments are below the early upper Miocene(?) horizon, profile 3 (Fig. 5), and they are in contact with the Farallon ridge, it is assumed that they represent the upper part of the middle Miocene sequence. These beds are probably contemporaneous with the sediments on the east flank of the Farallon ridge, profiles 1 and 2 (Fig. 5). The western trough does not appear as a distinct feature in profile 3 (Fig. 5), and the deformed sediments of this area are covered by younger westerly prograding sediments.

Sediment Distribution

The presence of lower Tertiary sediments within the central basin is reported by Hoskins and Griffiths (1971) in their structure cross sections near Point Reyes and Pillar Point. They consider the central basin to be the seaward extension of the Purisima trough which appears on land to the southeast in the Santa Cruz Mountains. Onshore, the Purisima trough contains more than 3000 meters of pre-Miocene, Tertiary sediments (Cummings and others, 1962). Hoskins and Griffiths (1971) show 1100 meters of Eocene and Oligocene marine shales and sandstones and diabase sills at Pillar Point. These pre-Miocene sediments are assumed to thin northeastward from Pillar Point along the eastern edge of the basin, since they do not appear under the Point Reyes peninsula at Drakes Bay (Galloway, personal communication). A well drilled 12 km south of Drakes Bay at Double Point (Fig. 8) revealed a section consisting of 1525 meters of Miocene sandstone, shale, and basalt, 450 meters of Paleocene conglomerate, and granitic basement.

The exposure of pre-Miocene rocks on the Point Reyes peninsula is limited to a small outcrop of Paleocene conglomerate overlying granitic rocks at the west end of Point Reyes. This small remnant may be part of the sequence of pre-Miocene, Tertiary rocks shown by Hoskins and Griffiths (1971) southwest of the Point Reyes fault. They indicate 800 meters of Eocene rocks in the western trough, and suggest that the thickness increases to 6100 meters near Point Arena, 140 km to the north. The limited information on the distribution of the lower Tertiary rocks suggests that these rocks are confined to the deeper parts of the central basin, and they pinch out near the base of the Farallon ridge. Lower Tertiary rocks are found in the eastern trough. They probably are not present east of the Seal Cove fault since the observed gravity anomalies in this area can be explained by an accumulation of late Tertiary rocks. In the vicinity of the Point Reyes peninsula, rapid northerly thinning at the eastward extension of the Point Reyes fault would account for the absence of the lower Tertiary rocks north of Drakes Bay.

Sediments believed to be of early and middle Miocene age are generally not observed within the reflection profiles across the central basin, due to the thick cover of younger sediments. However, these older sediments are seen beneath the early upper Miocene(?) reflector in the southern basin (profile 3, Fig. 5) and along the flanks of the Farallon ridge (profiles 1 and 2, Fig. 5). The observed gravity information is taken from gravity lines across the central basin (Fig. 8). The observed data may be explained using a two dimensional model in which the deepest parts of the central basin are filled with pre-Miocene age sediments, 2.5 gm/cm^3, that are overlain by a relatively constant thickness, about 1 km, of early and middle Miocene sediments, 2.4 gm/cm^3. Such a model would agree with the sediment thickness reported by Hoskins and Griffiths (1971) in a cross section west of Point Reyes. The upper Miocene(?) reflector is seen in the reflection profiles throughout most of the central basin (Fig. 3). A younger horizon inferred to be of early Pliocene(?) age (Fig. 7) is not as continuous as the upper Miocene(?) reflector. However, this marker probably delineates an approximate time boundary within the lower Pliocene section. A one kilometer accumulation of post-lower Pliocene(?) sediments occurs within a depression trending south from Drakes Bay (Fig. 7). Pliocene sediments thicken toward the northwest in the western trough, reaching a maximum thickness of 1 km south of Point Reyes. The correlation of sediments younger than early Pliocene age from the central basin with rocks onshore is not possible; these younger sediments either terminate offshore at the sea floor or cannot be followed across offshore faults.

Development of the Central Basin

The pre-Tertiary history of the central basin is unknown since the oldest rocks assumed to be present are granitic rocks of upper Cretaceous age,which form the basement complex. Lower Tertiary rocks overlying the basement are present in the central basin and onshore; however, pre-lower Miocene sediments have not been reported from the Farallon ridge. It is possible that either the ridge was above sea level during early Tertiary time or that the section was removed by erosion before early Miocene time. During early and middle Miocene time, the present central basin may have been part of a more extensive basin. A period of diastrophism at the end of middle Miocene time initiated the uplift of the

Farallon ridge and the central ridge. The pre-middle Miocene section was probably deformed, uplifted, and eroded at this time. It has subsequently been buried too deeply to be observed in the reflection profiles except in the southern basin. The discontinuity of the upper Miocene(?) surface in the southern basin is evidence that parts of the central basin were emergent in early Pliocene time. The central ridge may also have been exposed during the same period. Late Tertiary events included the submergence of the high areas uplifted in early Pliocene time, the filling of the eastern trough, faulting along the Farallon ridge, and subsidence of the western trough. Displacement of the western trough was probably the result of local faulting in the Point Reyes area during the late Pliocene orogenic period. The subsidence of the southern Farallon ridge in Pliocene time is suggested by the presence of westerly prograding sediments which cover the eroded granitic ridge crest (profile 3, Fig. 5).

V. EASTERN MARGINAL HIGH

Between Half Moon Bay and Bolinas, the sediments along the eastern margin of the Farallon platform are folded into an anticlinal structural high which appears to be faulted along its western flank. The offshore extension of the Seal Cove fault delineates the eastern edge of this marginal high from Pillar Point to Bolinas. Buried reflectors terminate along the western side of the Seal Cove fault (profile 4, Fig. 9), and thus make it impossible to follow the upper Miocene(?) reflector onto the Golden Gate platform.

Descriptive

The structural transition from flat lying basin sediments to the

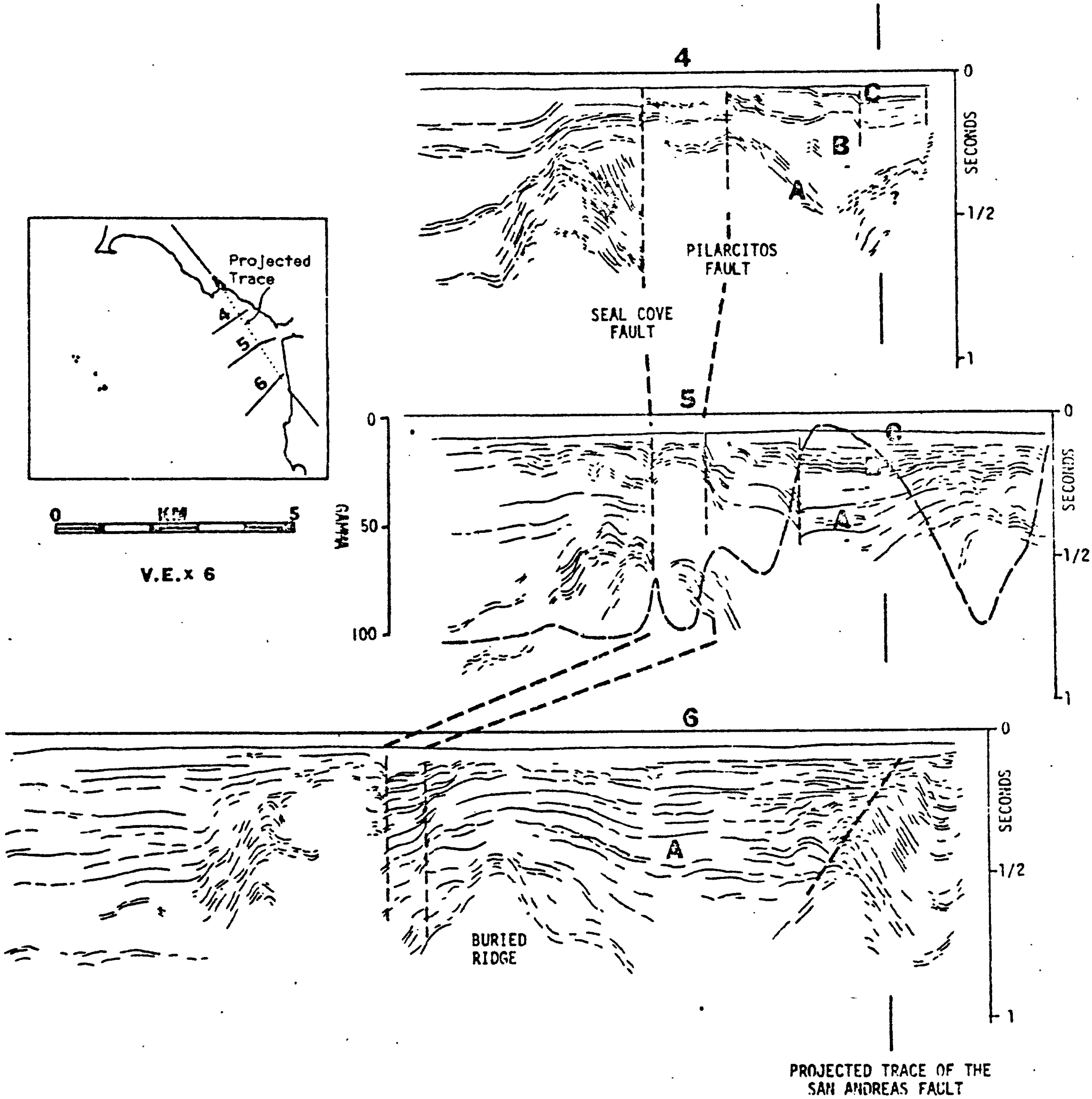

Figure 9.-- Line drawings of three seismic reflection records across the Golden Gate platform. Note that the structural breaks associated with the Seal Cove and Pilarcitos faults are more distinctive than the San Andreas fault, which is characterized by a confined depression. The projected trace of the San Andreas fault has no structural significance and is only used in the alignment of the profiles. The letters A, B, and C identify acoustic units described in the text.

folded and faulted sediments of the eastern marginal high is shown in profiles 2 thru 6 of Figures 5 and 9. The eastern marginal high has been eroded to varying depths along its length, and has subsequently been covered by younger sediments (profiles 2 and 3, Fig. 5). Above the unconformity, the oldest sediments are probably of early Pliocene age, since the reflector which is used to construct the early Pliocene structure contour map (Fig. 7) overlies the unconformity. These Pliocene sediments appear to onlap the upper Miocene(?) reflector along the western flank of the marginal high (profile 2, Fig. 3). The apparent dip of reflectors along this flank increases with depth (profile 4, Fig. 9) and is indicative of more than one onlap sequence. Approaching Pillar Point, the apparent dips steepen toward the central basin, not illustrated, suggesting a high angle fault with the basin side downthrown. This fault is assumed to continue northwest along the western flank of the marginal high, and parallel to the Seal Cove fault. Hoskins and Griffiths (1971) indicate two high angle northeasterly dipping faults at Pillar Point; however, they do not show the tightly folded structures between these faults that form the eastern marginal high. High resolution reflection profiles across the Seal Cove fault indicate displacement near the sea floor. This strongly suggests current uplift west of the fault near Pillar Point.

Near Bolinas, the axis of the eastern marginal high appears to continue onshore as an anticline which has been mapped by Douglas (1943). Galloway (1966) and Gluskoter (1969) do not show an anticline at this location, and their structural data in the Bolinas vicinity are insufficient to delineate the anticline. The proximity of the axis of the eastern marginal high to the onshore continuation of the Seal Cove fault near Bolinas, about 0.5 km, makes it difficult to distinguish the anticline as an independent structure. North of Bolinas, the strata generally dip to the west suggesting that the eastern portion of the offshore high is missing.

Evidence for the current uplift of the southern portion of the Point Reyes peninsula has been reported by Wahrhaftig (1970). He indicates that a small plateau west of Bolinas, 40 to 75 meters above present sea level, is a remnant of a more extensive wave cut bench. Equivalent benches which can be followed north from Bolinas decrease in elevation and pass below sea level at Drakes Bay. Wahrhaftig (1970) believes that the tilting of these terraces is a result of the uplift and warping of the southern Point Reyes peninsula. Gilbert (1908, pp. 81-87) reports that during the 1906 San Francisco earthquake, a reef west of the town of Bolinas was uplifted about 30 cm, but that over the following year the reef subsided to its original lower elevation. He also states that the east side of the San Andreas fault, in Bolinas Lagoon, subsided 30 cm during the earthquake. The work of Wahrhaftig (1969) and Gilbert (1908) suggests that the northern portion of the eastern marginal high is currently being uplifted.

Development of the Eastern Marginal High

Several structural features observed along the eastern margin of the Farallon platform suggest that the uplift of the eastern marginal high may be related to downwarping of the adjacent eastern trough. Those features which suggest this interpretation include: (1) a linear, parallel trend of both the marginal high and the trough, (2) a general decrease in the dip of reflectors on the west flank of the marginal high as the trough shallows to the north, and (3) an apparent widening of both the marginal high and the trough north from Pillar Point. The three observations suggest more than a fortuitous structural relationship. Two plausible mechanisms for the formation of the system would include block faulting in the basement which has uplifted the ridge relative to the trough, or horizontal compression which has uplifted the eastern portion of an older and wider trough. The second model employing local horizontal compression appears to be the better interpretation.

Vertical block faulting of the basement does not appear likely, since the eastern marginal high is not associated with a positive gravity anomaly (Fig. 10). The Bouguer gravity map indicates that the marginal high is underlain by a linear negative gravity trough, -22 mgal Bouguer anomaly. A compressional model for current deformation is in agreement with the observations of Burford (1968). He reports that present crustal strain in the central Coast Ranges, measured from U. S. Coast and Geodetic Survey triangulation data, indicate a regional northeast-southwest compression. Right lateral, simple shear occurs only with a 30 km wide band centered over the San Andreas fault. This lateral shear could produce local compression at a bend, or discontinuity, within an active strike-slip fault zone. If similar regional and local compressive stresses were present during the initial deformation, they would provide a mechanism for the formation of the marginal high: extension and opening of a local trough near a bend in an active lateral

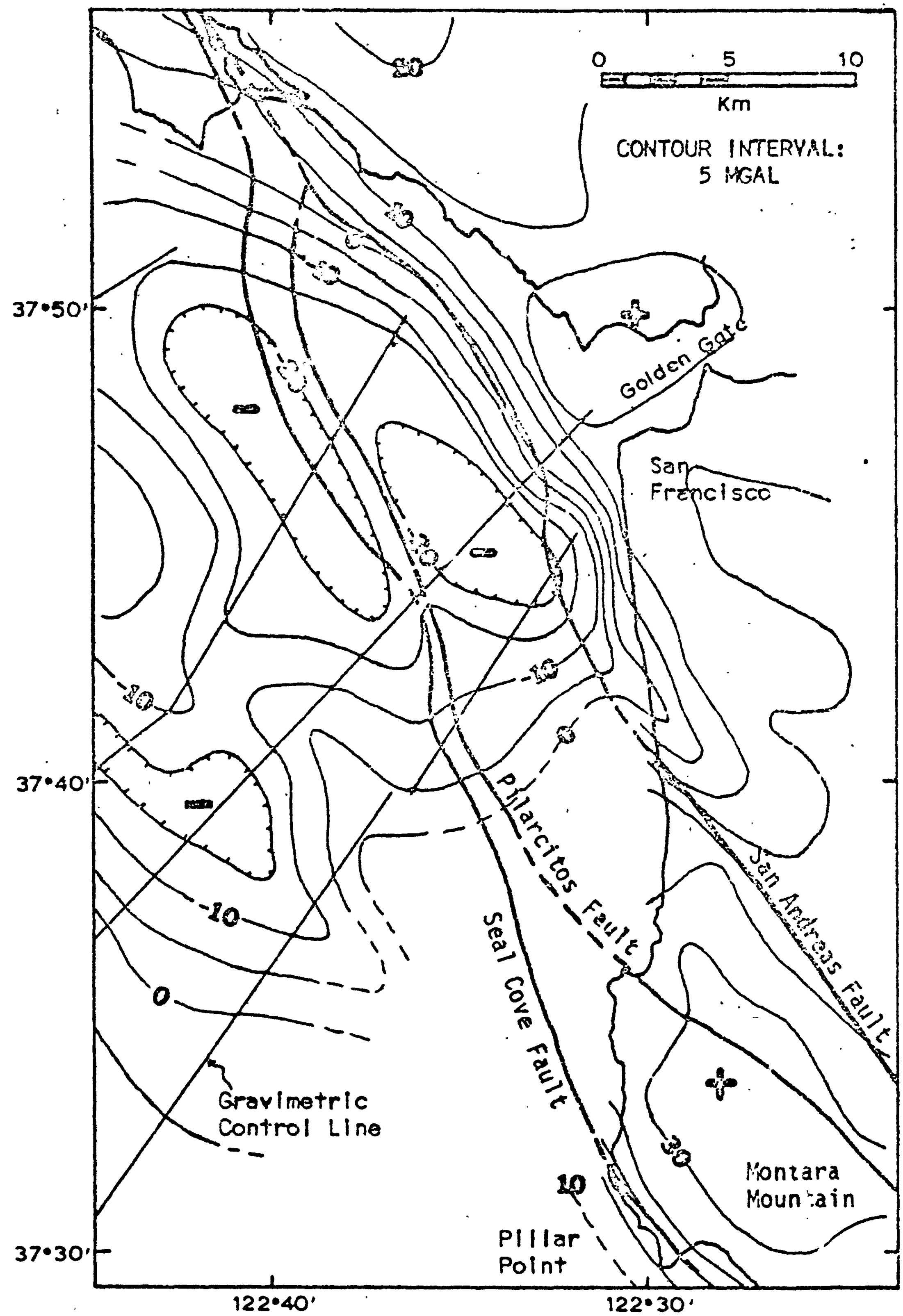

Figure 10.--Offshore Bouguer gravity map of the Golden Gate platform modified from Chapman and Bishop(1968). The two large negative anomalies west of the Golden Gate probably represent thick accumulations of sediments. The most recent trace of the San Andreas fault is mapped offshore.

fault, presumed to be the Seal Cove fault or Pilarcitos fault, with a subsequent filling of the trough, and the compression of these sediments into a ridge paralleling the axis of the fault.

A more intense local compression of the marginal high near Pillar Point is suggested by the tighter folding which may result from thrusting of the Montara Mountain block. Darrow (1963) indicates that Montara Mountain has been thrust up along an east-west fault on the northeastern side of the mountain. Whether the Montara granite has been thrust into its present position adjacent to the central basin, or has been truncated by lateral faulting at the Seal Cove fault and juxtaposed against the basin sediments, cannot be ascertained from existing information. However, vertical displacements near Pillar Point are documented onshore (Glen, 1959), and are seen in the offshore reflection profiles (Figs. 5 and 9). From the foregoing data, it is inferred that compression resulting from both strike-slip faulting and local overthrusting were important in the formation of the marginal ridge.

The inferred age for the initial deformation of the eastern marginal high is late Miocene time, which would be concurrent with the uplift of the Farallon ridge. Two lines of evidence support this age for the deformation: (1) the initial onlap sequence along the west flank of the marginal high appears to blanket the upper Miocene(?) reflector, and (2) a significant amount of subsidence within the eastern trough took place during late Miocene to early Pliocene time. The isopach map of upper Miocene(?) to lower Pliocene(?) sediments (Fig. 6) can also be used to approximate the vertical displacement of the early upper

Miocene(?) surface, from late Miocene to early Pliocene time. This line of evidence suggests that a minimum of fifty percent of the subsidence of the eastern trough occurred during this time. Part of this subsidence may have been concurrent with the initial uplift of the eastern marginal high. The compressive stage, which caused the folding of the eastern portion of the trough adjacent to the fault(?), probably occurred during late Miocene time.

CHAPTER V

GOLDEN GATE PLATFORM

I. INTRODUCTION

The Golden Gate platform is a distinct structural area within the Gulf of the Farallones between the Farallon platform and the present coastline. The western boundary of the Golden Gate platform is delineated by the Seal Cove fault. Two other major faults, the Pilarcitos and the San Andreas faults, are continuous across the platform (Fig. 11). The other subparallel faults within the platform area are probably normal faults with the landward side downthrown. A small anticline and syncline, presumed to be the continuation of onshore structures, are mapped northwest of Mussel Rock.

Smaller buried structures on the Golden Gate platform are too numerous to be shown in the structure map (Fig. 11), and thus the map only indicates major faults which are continuous between profiles. Unlike a standard geologic map, which indicates structures observed at the ground surface, the marine structural map is a composite of buried and surface features. All structures mapped in the offshore area are covered by sediments and do not show a topographic expression at the sea floor. This point should be considered when comparing the structures mapped on land with those offshore.

II. IDENTIFICATION OF ACOUSTIC UNITS

The structural complexity of the Golden Gate platform makes it

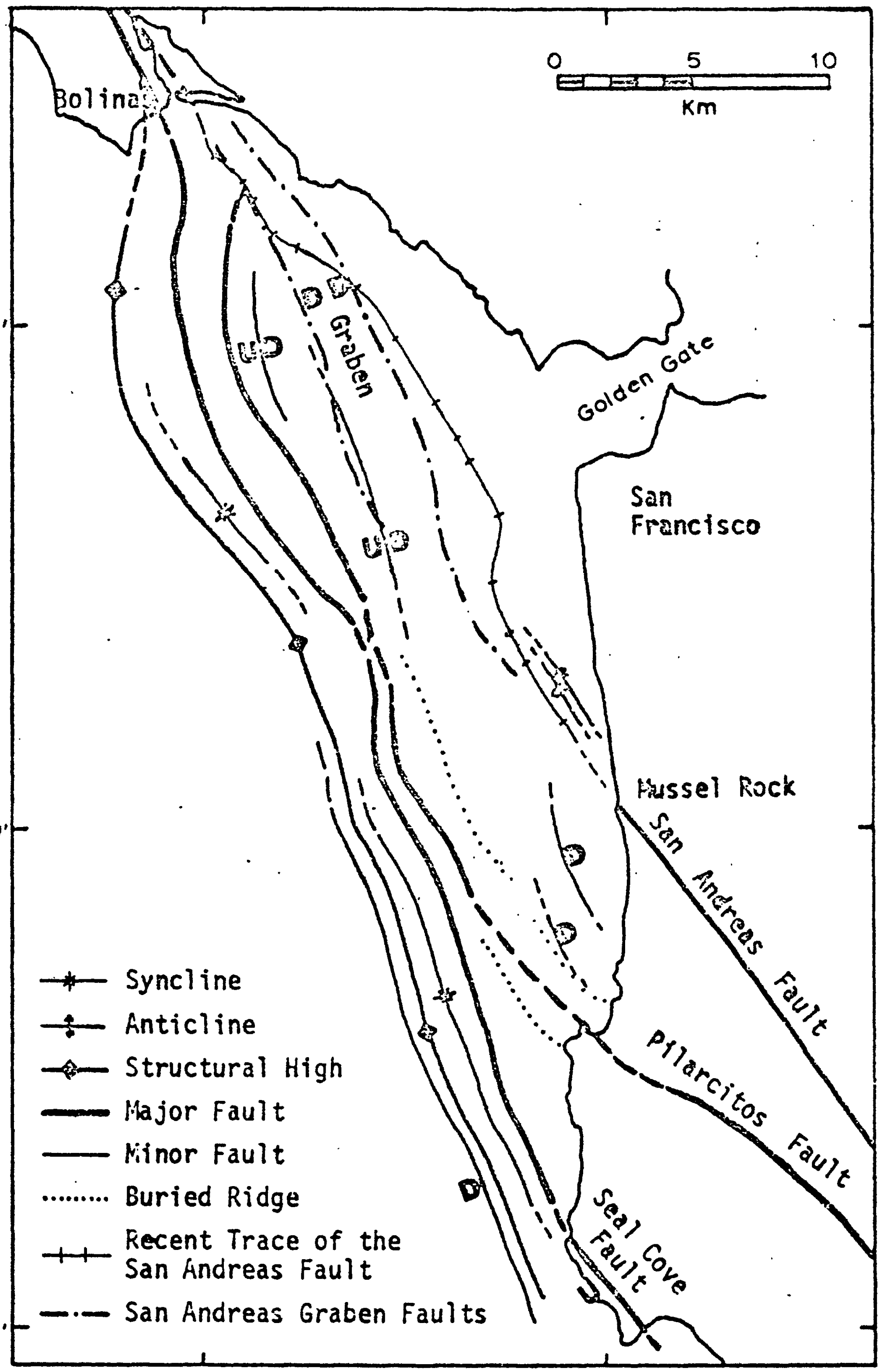

Figure 11.--Structure map of the Golden Gate platform compiled from high resolution and deep penetration seismic reflection information and magnetic data. All offshore structures are buried at varying depths and do not show scarps at the sea floor. Many smaller faults are not mapped since they are not continuous between two or more reflection profiles.

impossible to trace and correlate equivalent reflecting horizons in the seismic reflection profiles. Individual reflectors are discontinuous across faults and are often entirely missing in the highly fractured areas due to the dispersal and scattering of the seismic energy. However, the general acoustic character of the sediments appears to be consistent in some localities, indicating that the acoustic impedance probably varies with lithologic changes. Three sedimentary units are defined by their acoustic character in the seismic reflection records. The absence of bottom sample information necessitates using these acoustic units to investigate the general distribution and thickness of sediments.

Unit A (Fig. 9) is the deepest and presumably oldest of the three units and may be equivalent in age to the sedimentary rocks of the Merced Formation exposed near Bolinas. The unit is characterized by a sequence of continuous reflectors which are broken and offset across faults. It is acoustically similar to the reflectors observed near the surface within the central basin. In the southern part of the platform, unit A appears to terminate along the eastern side of the Seal Cove fault (profile 6, Fig. 9). Horizontal and/or vertical offsets which may have occured along the Seal Cove fault prevent tracing of unit A from the Farallon to the Golden Gate platform.

Unit B (Fig. 9) is an acoustically diffuse and poorly delineated sequence of reflectors without the continuity of unit A. In many areas, stratification is not apparent, and only minor internal reflections can be seen. In the high resolution profiles, the top of the sequence is characterized by an irregular surface and a lack of internal layering.

The age of unit B is possibly equivalent to the upper part of the Merced Formation or Colma Formation, which contain thick unconsolidated beach sand members (Glen, 1959 and Hall, 1966). These beach deposits would rapidly attenuate the high frequency component of the seismic energy thus causing the unit to act as an acoustic sink and not show strong internal layering (Tagg and Greene, 1970).

Unit C (Fig. 9), the uppermost unit, fills the shallow San Andreas graben (Fig. 11) and may extend as a thin covering over most of the Golden Gate platform. The material is acoustically transparent in the high resolution profiles and only shows very fine layering in areas of possible buried channels. The unit probably represents shallow water shelf deposits, which accumulated after the last rise of sea level in post-Wisconsin time. This would imply an age younger than 10,000 years because of the present water depths (Curray, 1969).

The distribution of the three acoustic units on the Golden Gate platform is shown in Figure 12; their relative position within the reflection profiles is illustrated in Figures 9 and 13. Unit A appears to be present under the entire platform (Fig. 9), with the possible exception of the area east of the San Andreas fault. Since the continuity of unit A is difficult to establish in the vicinity of the San Andreas fault, the correlation of folded sediments east of the fault (profile 6, Fig. 9) with unit A west of the fault is uncertain. However, in profiles 4 and 5 (Fig. 9), unit A may continue across the San Andreas fault. The depth to the top of unit A increases from near the surface (profile 6, Fig. 9) to a maximum of about 550 meters (profile 4, Fig. 9). The

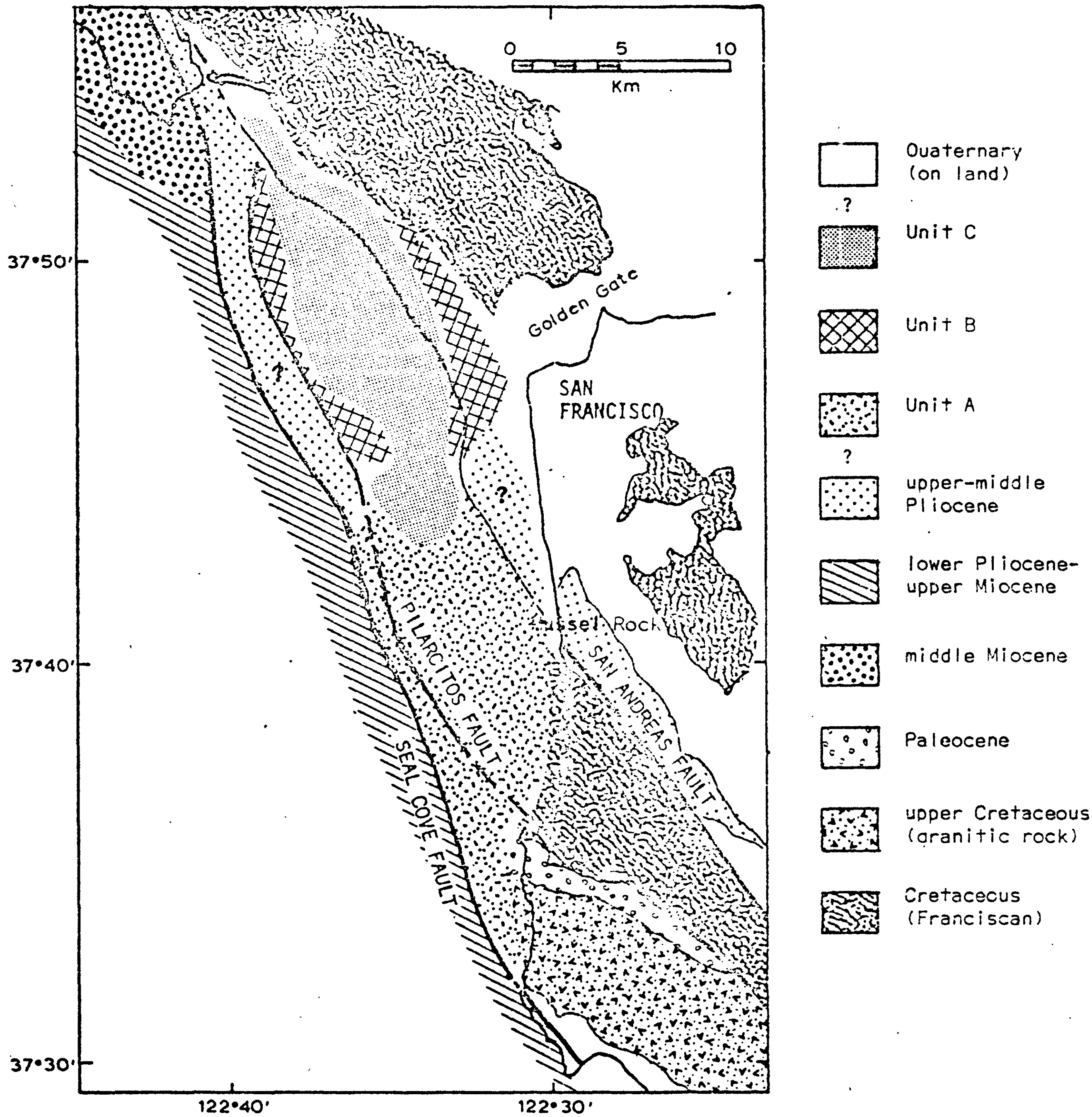

Figure 12.--Distribution of rock types on the Golden Gate platform in outcrop or shallow subcrop. Land geology is taken from Jennings and Burnett(1961). The offshore section has no bottom sample control and is based entirely upon the acoustic character of the sediments and the continuation of onshore structures and rock types.

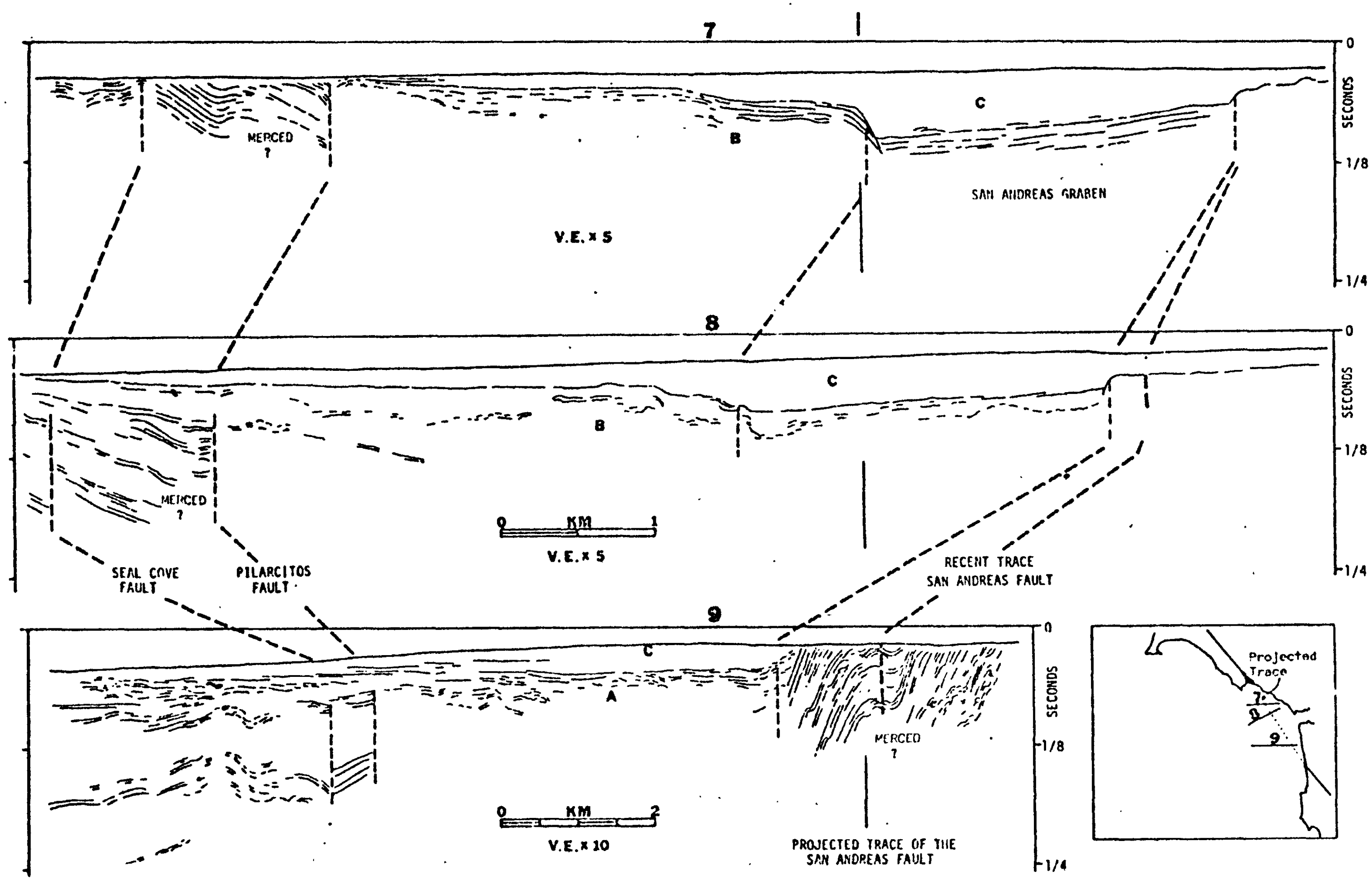

Figure 13.--Line drawings of high resolution reflection records across the Golden Gate platform. Note the absence of fault scarps at the sea floor in the vicinity of the three major faults. The projected trace of the San Andreas fault has no structural significance and is only used in the alignment of the profiles. The letters A, B, and C identify acoustic units described in the text.

thickness generally cannot be measured for unit A since the acoustic basement is buried too deeply to be observed. An increasing gravity gradient from the Golden Gate towards Montara Mountain (Fig. 10) could be explained by the southeasward thinning of unit A. South of profile 6, unit A thins rapidly and pinches out within 1/2 km of the present coastline. The contact between unit A and the acoustic basement, Franciscan Formation (?), appears to be unconformable in the near shore reflection profiles. Glen (1959) reports a similar contact at the base of the Merced Formation west of the San Andreas fault at Mussel Rock.

High resolution profiles 7 and 8 (Fig.13) show a sequence of well defined reflectors between the Seal Cove and Pilarcitos faults. This sequence can be followed northward to a point 2 km southwest of Bolinas (Figs. 11 and 12), and thus it is inferred to be an offshore continuation of the Pliocene Merced Formation. Since these reflectors are not distinctive in the deeper penetration profiles at the same location (profiles 4 and 5, Fig. 9), the Merced Formation cannot be definatively joined with the reflectors of unit A. Further south, other well defined reflectors between the Seal Cove and Pilarcitos faults (profile 6, Fig. 9) are assumed to be part of unit A.

The thickness of unit C (Fig. 14) and unit B (Fig. 15) increases northwest from the Golden Gate to a maximum thickness, 9 km south of Bolinas Lagoon. The greatest observed thickness of unit B is about 500 meters and that of unit C is 55 meters. Both units B and C seem to pinch out southeastward, so that the entire vertical section near Mussel Rock is typical of unit A.

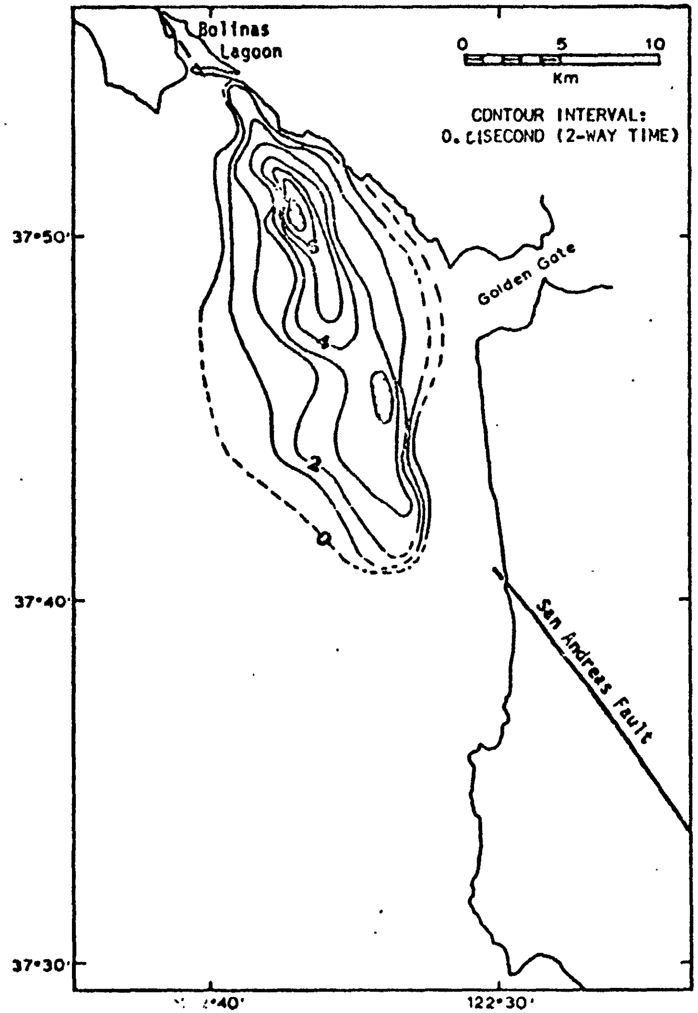

Figure 14.--Isopach map of unit C. This unit fills the San Andreas graben and may represent post-Wisconsin age shallow water shelf deposits.

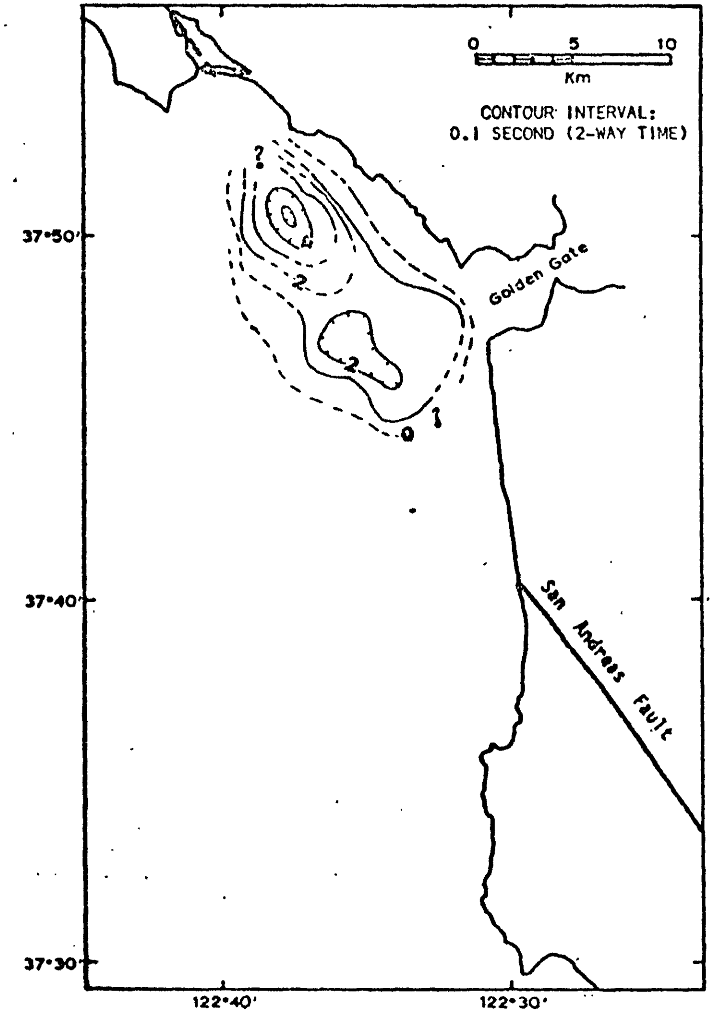

Figure 15.--Isopach map of unit B. This unit is covered by unit C and may represent older beach deposits similar to the Colma Formation.

<u>Note:</u> When comparing these figures, note the tenfold change in contour interval

III. SAN ANDREAS FAULT

The importance of the San Andreas fault as a major strike-slip feature is well documented from the field work of Gilbert(1908), Hill and Dibblee(1953), and more recently in reviews by Crowell(1962), Dickinson and Grantz(1968), Suppe(1970), and others. In the San Francisco area, the juxtaposition of Mesozoic and Cenozoic rocks near Bolinas and Mussel Rock (Fig. 12) is typical of the structural relationships seen elsewhere along the fault. The offshore portion of the San Andreas fault is characterized by: (1) vertical depression within a narrow trough paralleling the fault zone, (2) the absence of a distinct vertical boundary separating two or more different rock types, and (3) near surface structural complexity indicating a near surface graben and possible en echelon faulting.

The reflection profiles (Fig. 9) show the structural depression which delineates the San Andreas fault zone offshore. The depression is a small linear basin that narrows and deepens northwest from Mussel Rock. The axis of the basin parallels the projected trace of the San Andreas fault and is located west of the trace (Fig. 9). Near Mussel Rock (profile 6, Fig. 9), the depression is bordered on the east by folded sediments presumed to be the Pliocene Merced Formation and on the west by the Pilarcitos fault.

At the Golden Gate, the acoustic basement dips steeply to the west and becomes too deeply buried to be seen under the sediments filling the depression. The dip of the basement surface apparently increases along the eastern side of the depression, approaching Bolinas, since it is not easily identifiable in the reflection profiles and is vertical on the Point Reyes peninsula (Weaver, 1949). Flexures along the western side of the depression (profile 5, Fig. 9), appear to result from vertical displacement on low angle normal faults. This displacement affects reflectors in units A, B, and C. Magnetic signatures correspond with the two distinctive flexures in profile 5 (Fig. 9),which might indicate similar offsets of the basement surface.

The juxtaposition of different geologic formations,observed at the San Andreas fault on land, is not readily apparent within the younger sediments of the seismic reflection profiles. The acoustic character of units B and C remains unchanged in the vicinity of the fault, and both units appear to extend to the present coastline (profiles 4 and 5, Fig. 9 and profiles 7 and 8, Fig. 13). An abrupt structural change or a distinct vertical fault contact is also missing near the fault within these units. Younger sediments are confined to the northern portion of the fault zone and may cover any evidence for strike-slip faulting within the older sediments of unit A. In profile 4 (Fig. 9), unit A can be identified on the western flank of the depression as it dips eastward into the fault zone; however, the reflectors on the eastern flank are not clearly defined and may not be equivalent to unit A. Near Mussel Rock (profile 6, Fig. 9 and profile 9, Fig. 13), a distinct structural transition between folded sediments, Merced Formation (?), and flat lying reflectors, unit A, does occur. The transition, or fault, has an apparent westerly dip of 20 degrees in profile 6 and it may represent a line of breakage on the San Andreas fault. Northwest of Mussel Rock, this transition appears to migrate to the east of the projected trace and may become buried under a thick accumulation of units B and C (profile 5, Fig. 9). The approximate position of the transition is also delineated by a magnetic signature (Fig. 16).

In high resolution reflection profiles across the northern half of the San Andreas fault zone, the dominant structure is a 2 km wide graben that is covered by acoustically transparent sediments of unit C (profiles 7 and 8, Fig. 13). The sinuous structure is herein named the San Andreas graben since it extends along the San Andreas fault zone for 20 km southeast of Bolinas(Fig. 11). The boundary faults become less distinct southeast of the Golden Gate as unit C pinches out. The eastern fault may continue toward Mussel Rock and become the boundary between the folded sediments and the flat-lying sediments (profile 9, Fig. 15). Reflectors at the western fault of the San Andreas graben (profile 7, Fig. 13) appear to dip into the graben at 11 degrees and show a vertical displacement of about 20 meters.

An attempt has been made to delineate the recent line of breakage along the San Andreas fault offshore, which might correspond to the 1906 fault trace (Fig. 11). Since many possible fractures can be seen in the high resolution profiles, the exact position of the most recent trace is uncertain. The fault does not have a topographic expression at the sea floor. Consequently, it has been tentatively identified on the basis of blurred zones in the reflection profiles which do not show internal structure across the zone. These zones are generally from 30 to 200 meters in width. In attempting to trace the fault, it is

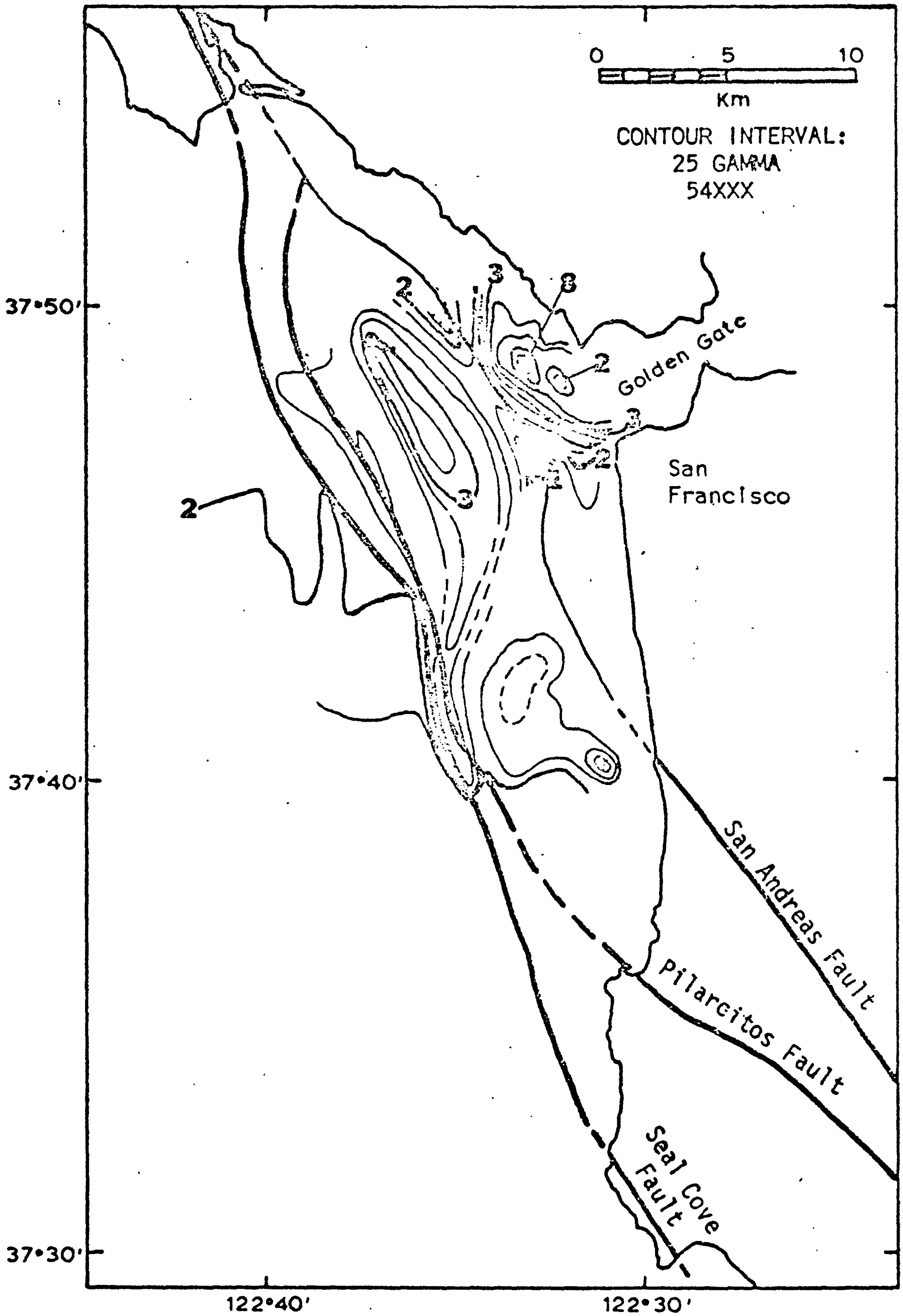

Figure 16.--Total intensity magnetic field contour map in the vicinity of San Francisco. At the Golden Gate, the contour interval is locally increased to 100 gamma. Note the magnetic lineations which presumably mark the boundary between the granitic and Franciscan rocks.

assumed that the fault is continuous. However, this may not be valid, and breakage has probably occurred to some extent along en echelon fractures.

The sharp bend in the recent trace, 10 km northwest of Mussel Rock, may represent an older northeast trending fracture which has displaced the San Andreas fault. An equivalent bend in the magnetic contours (Fig. 16) and possibly the gravity contours (Fig. 10) along a similar trend is also suggestive of this northeasterly fault. Approaching Bolinas, the recent trace crosses the San Andreas graben (Fig. 11) and thus suggests a relatively young age for the mapped recent fault trace.

IV. PILARCITOS FAULT

From the observation that the Franciscan Formation disappears on the Point Reyes peninsula west of the San Andreas fault, Oakshott (1966) has inferred that the Pilarcitos and San Andreas faults join offshore. Evidence accrued in the current marine investigation supports this observation. The exact location of the Pilarcitos fault is difficult to determine with the seismic reflection profiles since the rock types transected by the fault show a similar dispersive acoustic character. Distinctive, identifiable structures are not present across the fault, and the fault is deeply buried over most of the Golden Gate platform. Since the Pilarcitos fault separates granitic basement terrain of the Salinian block from the Franciscan Formation (Page, 1970), a magnetic signature might be expected at the boundary, due to the abundance of basalt within the Franciscan Formation onshore (Darrow, 1963). A western boundary for small magnetic anomalies is suggested in the total intensity magnetic map covering the area west of the Golden Gate (Fig. 16). Only small local magnetic variations are evident west of the Seal Cove fault. The first significant magnetic anomaly occurs 2 km east of the fault. This small anomaly probably represents the edge of the Franciscan Formation and thus may indicate the location of the Pilarcitos fault.

Two buried basement ridges, which are mapped offshore 10 km southwest of Mussel Rock (Fig. 11), give a secondary control pertaining to the nearshore location of the Pilarcitos fault. The longer ridge may represent the continuation of an onshore topographic high composed of basalt, sandstone, and shale of the Franciscan Formation (Darrow, 1963). The ridge can be followed northwest from the coastline for about 12 km until it is buried too deeply to be identified in seismic profiles. The shorter ridge, which extends offshore southwest of the Pilarcitos fault, probably represents the steeply dipping rocks which crop out at the shoreline. Since the Pilarcitos fault is located between these ridges onshore, it is presumed that it continues offshore parallel to the northwest trend of the ridges. Thus the location of the Pilarcitos fault, based on the magnetic data and the position of the buried Franciscan (?) ridges, is mapped as crossing the Golden Gate platform and joining the San Andreas fault about 6 km southeast of Bolinas Lagoon.

V. SEAL COVE FAULT

The importance of the Seal Cove fault as a major boundary between two distinctive structural areas has not been suggested previously, due to the poor exposures of the fault on land and the limited geophysical information offshore. Near Pillar Point, Glen (1959) indicates that the Seal Cove fault is a high angle, northeasterly dipping, normal fault which shows strong evidence of vertical movement. He also reports a juxtaposition of contrasting assemblages of Pliocene fauna and rock types at the fault. Jack (p. 119, 1969) has documented an offset of 13 meters in Quaternary terrace deposits along the Seal Cove fault. North and south of the Pillar Point area, reefs delineate the probable location of the fault offshore. High resolution reflection profiles north of the reefs, not illustrated, show evidence for similar vertical displacements close to the sea floor. However, the fault does not indicate a topographic expression on the sea floor.

Northwest of Pillar Point, the Seal Cove fault is mapped at the location of a shallow buried fault scarp, or where deeply buried reflectors are truncated along the landward flank of the eastern marginal high (profiles 4 and 6, Fig. 9). The fault scarp disappears west of the Golden Gate and is not observed along the northern portion of the fault. Near Bolinas, the Seal Cove fault appears to continue onshore and join with the unnamed fault that separates the middle Miocene rocks from the Merced Formation (Fig. 12).

A narrow basin adjacent to the Seal Cove fault is present in the southern part of the Golden Gate platform. The sediments within this basin appear to be truncated on the west by the Seal Cove fault and are bordered on the east by a buried ridge (profile 6, Fig. 9). These rocks also crop out in the intertidal zone near Pillar Point. Glen (1959) implies that the age of the fauna in these rocks is equivalent to the lowermost member of the Merced Formation at Mussel Rock. He further indicates that older Pliocene rocks of the Purisima Formation are present west of the Seal Cove fault. The continuity of the narrow confined basin along the Seal Cove fault and the truncation of these basin sediments,observed in profile 6 (Fig. 9), is evidence that a similar juxtaposition occurs along the offshore extension of the fault. The rocks in the narrow basin dip northwest from the Pillar Point area and join with the sediments of unit A. Thus, an offshore correlation between Pillar Point and Mussel Rock may be possible, but a correlation across the Seal Cove fault is not valid.

VI. CONTACT BETWEEN GRANITIC AND FRANCISCAN ROCKS

The presumed offshore boundary between the granitic basement and the Franciscan terrain at the Pilarcitos fault is mapped on the basis of magnetic information. This contact falls between the two large negative Bouguer gravity anomalies located west of the Golden Gate (Fig. 10). Since similar average density values are measured for the granitic rocks of Montara Mountain and the Franciscan Formation (Greve, 1962), the gravity lows are probably the result of a thick accumulation of sediments. The gravity contours north and south of the negative anomalies intersect the Pilarcitos fault at a high angle, which would suggest little or no vertical displacement of the basement surface at that contact. A steep gravity gradient parallels the San Andreas fault and reflects the steep westerly dip of the basement surface, Franciscan Formation (?). This surface can be observed in selected reflection profiles, not illustrated, and it is further suggested by the magnetic gradient observed at the Golden Gate (Fig. 16).

Large vertical offset of the granitic basement at Pillar Point is suggested by the strong gravity gradient toward the central basin (Fig. 10). Granitic rocks crop out on Montara Mountain and within a narrow belt along the present coastline (Fig. 12). In the east, they are truncated by the Pilarcitos fault; to the north, they are buried under a small basin of Pliocene (?) sediments; and on the west, they have been displaced by the Seal Cove fault. Although the offshore gravity information near Montara Mountain is incomplete, the strong gradient at Pillar Point probably continues northwest along the Seal Cove fault until it eventually crosses the Pilarcitos fault at a high angle.

CHAPTER VI

SUMMARY

For the purposes of this investigation, the Gulf of the Farallones is divided into two structural provinces at the Seal Cove fault, the Farallon platform and the Golden Gate platform. The Seal Cove fault delineates an important boundary between a slowly subsiding basin and a highly sheared region. The sediments west of this boundary are generally more continuous and are cut by fewer faults than those to the east. Middle Tertiary sediments of the central basin are in fault contact with sediments presumed to be of middle Pliocene age (or younger) at the Seal Cove fault. The juxtaposition of contrasting rocks offshore and at Pillar Point (Glen, 1959), is evidence for possible strike-slip displacement along the fault. This faulting probably began in Pliocene time and has continued into Pleistocene and possibly Holocene time. Large vertical displacements on the Seal Cove fault would explain the present distribution of rocks; however, this explanation is not supported by gravity information.

The upper Tertiary deformational history of the continental shelf west of San Francisco has been dominated by large vertical displacements along the Farallon ridge, on the Point Reyes fault, and at the eastern marginal high. Strike-slip offsets on the San Andreas, Seal Cove, and possibly Pilarcitos faults have been important in the development of the Golden Gate platform. The San Andreas fault is the only structure along which Holocene deformation is documented. The relatively young age of the other structures offshore suggests concurrent deformation.

The structural development of the Golden Gate and Farallon platforms is summarized in Table 1. Two important orogenic episodes have shown major deformation of the Farallon platform, early late Miocene time and late Pliocene to early Pleistocene time. The early late Miocene episode corresponds with the proposed termination of an offshore trench and initiation of strike-slip motion along the continental margin (Atwater, 1970). At this time, vertical displacement of the granitic basement along the Farallon ridge, and the compressive deformation of the eastern marginal high was initiated. Middle Tertiary sediments were also deformed and uplifted within the central basin, thus imprinting a different structural grain upon them. The prominant unconformity between the middle and upper Miocene sediments developed at this time.

A second episode of deformation probably corresponds to the Plio-Pleistocene orogenic period seen in the California Coast Ranges. The orogeny was characterized by strong regional compression which initiated the high angle faulting and folding in the Point Reyes area. Large vertical and possibly horizontal displacements of the granitic basement surface occurred on the Point Reyes and the central faults. Along the northern section of the eastern marginal high, compressional deformation and uplift was probably renewed at this time.

By its structural complexity, the Golden Gate platform suggests numerous episodes of horizontal and vertical faulting. Since the major faults crossing the platform transect sediments which probably are not older than middle Pliocene, only a small portion of the tectonic history can be determined. The deformation during late Tertiary time is

		PRE-MIOCENE	MIOCENE EARLY	MIOCENE MIDDLE	MIOCENE LATE	PLIOCENE EARLY	PLIOCENE MIDDLE	PLIOCENE LATE	PLEISTOCENE
FARALLON PLATFORM	FARALLON RIDGE	EMPLACEMENT OF RIDGE IN UPPER CRETACEOUS TIME	RIDGE BURIED	INITIAL UPLIFT OF RIDGE		CONTINUED UPLIFT	RIDGE PROBABLY ERODED		
FARALLON PLATFORM	CENTRAL BASIN	DEPOSITION IN A MORE EXTENSIVE BASIN		COMPRESSION AND DEFORMATION	CENTRAL RIDGE EXPOSED EASTERN TROUGH FILLED EROSION	PARTS OF POINT REYES PENINSULA EXPOSED CONTINUED SUBSIDENCE	CENTRAL RIDGE BURIED	COMPRESSION AND HIGH ANGLE FAULTING	
FARALLON PLATFORM	POINT REYES FOLDED AREA	PART OF CENTRAL BASIN		COMPRESSION AND DEFORMATION	CENTRAL RIDGE EXPOSED			VERTICAL DISPLACEMENT ON POINT REYES AND CENTRAL FAULTS	
FARALLON PLATFORM	EASTERN MARGINAL HIGH	PART OF THE CENTRAL BASIN		COMPRESSION AND INITIAL DEFORMATION		CONTINUED UPLIFT	1. INITIAL STRIKE-SLIP AND/OR VERTICAL FAULTING OF EASTERN FLANK 2. EXPOSURE OF NORTHERN HALF	RENEWED FAULTING	CONTINUED UPLIFT OF NORTHERN PORTION
GOLDEN GATE PLATFORM	SEAL COVE FAULT	? UNKNOWN ?					INITIAL STRIKE-SLIP AND/OR VERTICAL FAULTING	CONTINUED HORIZONTAL AND VERTICAL DISP.	
GOLDEN GATE PLATFORM	SAN ANDREAS FAULT	POSSIBLE HORIZONTAL DISPLACEMENTS					INITIAL DEPRESSION OF PRESENT FAULT ZONE	CONTINUED DEPRESSION	SAN ANDREAS GRABEN
GOLDEN GATE PLATFORM	PILARCITOS FAULT	? UNKNOWN ?					POSSIBLE VERTICAL FAULTING ALONG WESTERN FLANK OF SAN ANDREAS FAULT DEPRESSION		

Table 1.--Structural history of the Gulf of the Farallones

concentrated primarily on the San Andreas and Seal Cove fault zones. The narrow San Andreas rift zone widens southeast from the Point Reyes Peninsula and becomes a prominent structural depression in the offshore section. Pleistocene and younger sediments that fill the depression in the north pinch out toward Mussel Rock and allow older Pliocene sediments to crop out. This offshore fault segment is not characterized by a distinct vertical boundary that separates different acoustic rock units. In areas where the younger sediments are near the surface, the San Andreas fault is marked by a graben and possible en echelon faulting; when the older Pliocene (?) sediments are not deeply buried, a westerly dipping transition, or fault, is suggested. Strike-slip displacement on the San Andreas fault in Quaternary time is assumed from the work of other authors and it may be reflected in the orientation of presumably young extensional structures along the offshore section of the fault.

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