Structure of the Submerged San Andreas and San Gregorio Fault Zones in the Gulf of the Farallones off San Francisco, California, from High-Resolution Seismic-Reflection Data

By Terry R. Bruns, Alan K. Cooper, Paul R. Carlson, and David S. McCulloch

CONTENTS

Abstract

The San Andreas and San Gregorio Fault zones are major strike-slip-fault systems that form part of the active plate boundary between the Pacific and North American Plates. The San Gregorio Fault is offshore for most of its length, whereas the San Andreas Fault extends offshore near Daly City south of San Francisco. On the basis of magnetic and seismicity data, motion on the San Andreas Fault has been interpreted to step over to another fault, the Golden Gate Fault, that lies 3 km to the east of the San Andreas Fault and also goes offshore near San Francisco. All three faults merge and come onshore again at Bolinas Lagoon. Although the overall trend of these faults is clear, the details of what has occurred offshore on these faults is not. Therefore, we acquired about 550 km of high-resolution seismic-reflection data in the Gulf of the Farallones to image these faults between Point Montara and Bolinas Lagoon. Seismic lines were acquired on about a 2-km line spacing, and the seismic-reflection data imaged approximately the uppermost 1.5 km of the sedimentary sequence in the offshore sedimentary basins.

Our interpretation of the seismic-reflection data identifies the following major features.

1. The Golden Gate, San Andreas, and San Gregorio Faults all have recognizable continuations across the Gulf of the Farallones. The Potato Patch Fault branches eastward off the San Gregorio Fault and continues northward as another fault with significant, but unknown, offset, possibly merging with the San Andreas Fault south of Bolinas. The San Gregorio structural zone, an area of major thrust-fault deformation west of the San Gregorio Fault, also continues across the Gulf of the Farallones and widens from about 2 to more than 8 km from south to north. All of these features are undergoing modern uplift onto the Point Reyes peninsula.
2. The San Gregorio Fault separates two major offshore sedimentary basins: the San Gregorio Basin, which lies between the Golden Gate/San Andreas Faults and the San Gregorio Fault; and the Bodega Basin, which lies west of the San Gregorio Fault. Maximum sedimentary thickness in the San Gregorio Basin is poorly defined but probably approaches 2 km overlying Franciscan and Salinian basement rocks. The age of the basin fill is unknown but could be similar to that of strata in the onshore Merced Formation, which are younger than about 1.8 Ma. We cannot directly correlate strata in the San Gregorio Basin with the

Merced Formation because a structural discontinuity may separate the two sequences. In the Bodega Basin, more than 800 m of Late Miocene and younger (less than approx 6 Ma) strata overlies the Monterey Formation and older rocks.

3. Although strike-slip motion on the San Andreas Fault appears to step northeastward to the Golden Gate Fault in the area from Daly City to the Golden Gate, the offshore continuation of the San Andreas Fault has served as a locus for subsidence. The fault generally underlies the depocenter of the San Gregorio Basin. The Potato Patch Fault, which lies between the San Andreas and San Gregorio Faults, forms the edge of a structural high in the basin. Both the San Andreas and Potato Patch Faults are at least partly normal faults along which basement rocks have undergone differential subsidence during basin formation. The faults could have a strike-slip component, but we cannot determine how much from the seismic-reflection data. In the northern parts of the basin, strata appear to cross the faults with virtually no disruption.
4. The San Gregorio Fault has a long transform history. North of Pacifica, however, the fault has converted to a normal fault along which the San Gregorio Basin has subsided. The transform motion on the San Gregorio Fault appears to step over to the Golden Gate Fault through the San Gregorio Basin.
5. The underlying mechanism creating the San Gregorio Basin seems to be the combined stepover of motion on the San Andreas and San Gregorio Faults onto the Golden Gate Fault, leading to the creation of a transtensional strike-slip stepover basin—the San Gregorio Basin. A simple model with this assumption places the region of maximum subsidence of a stepover basin beneath the deepest part of the San Gregorio Basin. Although the stepover model may be adequate to explain the overall formation of the basin, the details of how motion is transferred are unclear. Deformation on the basin faults north of Lake Merced seems to be mainly normal faulting. The Potato Patch Fault, however, probably has a component of strike-slip motion and serves as a transfer fault for motion from the San Gregorio Fault to the Golden Gate Fault.
6. Finally, the San Andreas Fault broke on the Point Reyes peninsula and at Bolinas Lagoon during the great 1906 San Francisco earthquake, yet the observed offshore structure indicates that this fault was not an active transform fault during much of the formation of the San Gregorio Basin. The offshore section of the fault could now be in a transitional stage intermediate between a transtensional right stepover and a more throughgoing transform fault.

Introduction

A series of major strike-slip faults transect central California and form part of the active plate boundary between the Pacific and North American Plates (fig. 1). The best known of these faults is the San Andreas Fault, which crosses the San Francisco peninsula and extends offshore south of San Francisco. The less well known San Gregorio Fault lies west of the San Andreas Fault, mostly offshore; in the Gulf of the Farallones region, the fault zone lies onshore only on the headland north of Half Moon Bay (fig. 1). A third fault, the Pilarcitos Fault, which could have accommodated most San Andreas Fault system displacement sometime before about 3 Ma, lies between the San Andreas and San Gregorio Faults and trends offshore just north of Point San Pedro. All these faults, except the Pilarcitos Fault, cross the Gulf of the Farallones and come onshore at Bolinas Lagoon on the Point Reyes peninsula. These faults also separate the Continental Shelf into two basic structural domains—the Bodega Basin, which lies west of the fault, and the San Gregorio Basin (named herein), which lies to the east (Cooper, 1973; McCulloch, 1987, 1989).

To delineate the near-surface structure and fault history of the Gulf of the Farallones, we conducted a high-resolution seismic-reflection survey in the region in June 1995 (figs. 1–3). High-resolution aeromagnetic data (Jachens and Zoback, 1999; see Jachens and others, this volume) provide additional information on fault locations at depths greater than observable in the seismic-reflection data (fig. 4). With this data base, we use the seismic-reflection data to (1) map the offshore traces of the San Andreas and San Gregorio Fault systems and associated structures;(2) compare the mapped fault locations with other data sets, including aeromagnetic data; and (3) develop a better understanding of the fault history and kinematics of the San Andreas/San Gregorio Fault systems.

Previous Work in the Gulf of the Farallones

Previous seismic-reflection studies in the Gulf of the Farallones region were published by Cooper (1973) and McCulloch (1987, 1989). Cooper delineated the general structure of the Continental Shelf west of San Francisco. He defined the Farallon platform as lying beneath the Gulf of the Farallones west of the San Gregorio Fault (fig. 1), where as much as 3.5 km of sedimentary rocks overlies granitic basement rocks. The Golden Gate platform lies east of the fault, with more than 1 km of strata overlying basement. Cooper also outlined a structural graben between the San Gregorio Fault and the San Andreas Fault (figs. 1, 3). His seismic-reflection data penetrated to as much as 1.8-s two-way traveltime (approx 1.7–2 km deep) in areas adjacent to Point Reyes, but much less than that to the south. He traced the San Andreas, Pilarcitos, and San Gregorio Faults (his Seal Cove Fault; see Glenn, 1959) across the Gulf of the Farallones to Bolinas Lagoon.

McCulloch (1987, 1989) described the Cenozoic geologic history of the California continental margin. Using all available single-channel and multichannel seismic-reflection data, as well as gravity and aeromagnetic data, he outlined the major structural elements off central California and determined offset in basement rocks. McCulloch (1987, 1989) had more seismic-reflection data that crossed the San

Gregorio and San Andreas Fault zones than Cooper (1973) had. Thus, McCulloch's (1987, 1989) locations of the faults differ somewhat from Cooper's; whereas Cooper took the Seal Cove strand of the San Gregorio Fault as the major strand, McCulloch (1987, 1989) interpreted a wide fault zone, with the Seal Cove Fault forming the east boundary. McCulloch (1987, 1989) was able to map part of the Golden Gate Fault offshore. He also used aeromagnetic data to delineate faults, most of which show up in much more detail in recently acquired aeromagnetic data (Jachens and Zoback, 1999; Zoback and others, 1999; see Jachens and others, this volume). The details of fault interactions remained unclear,

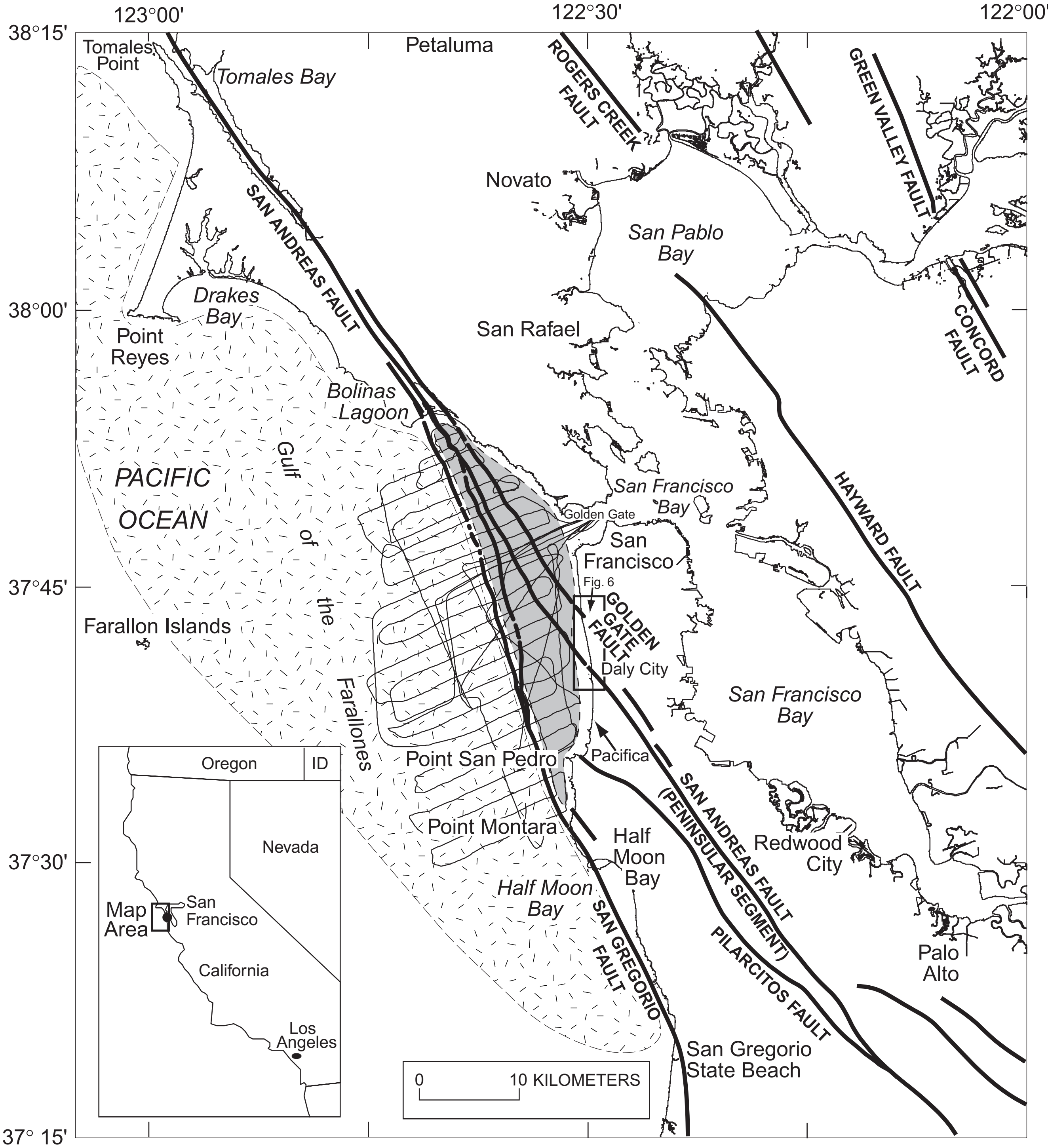


Figure 1.—Gulf of the Farallones and San Francisco Bay region, Calif., showing locations of major faults and tracklines of high-resolution multichannel seismic-reflection records acquired for this study. Shaded area, general area of the San Gregorio Basin as defined here; hachured area, the Bodega Basin of McCulloch (1987, 1989). Rectangle denotes area of figure 6.

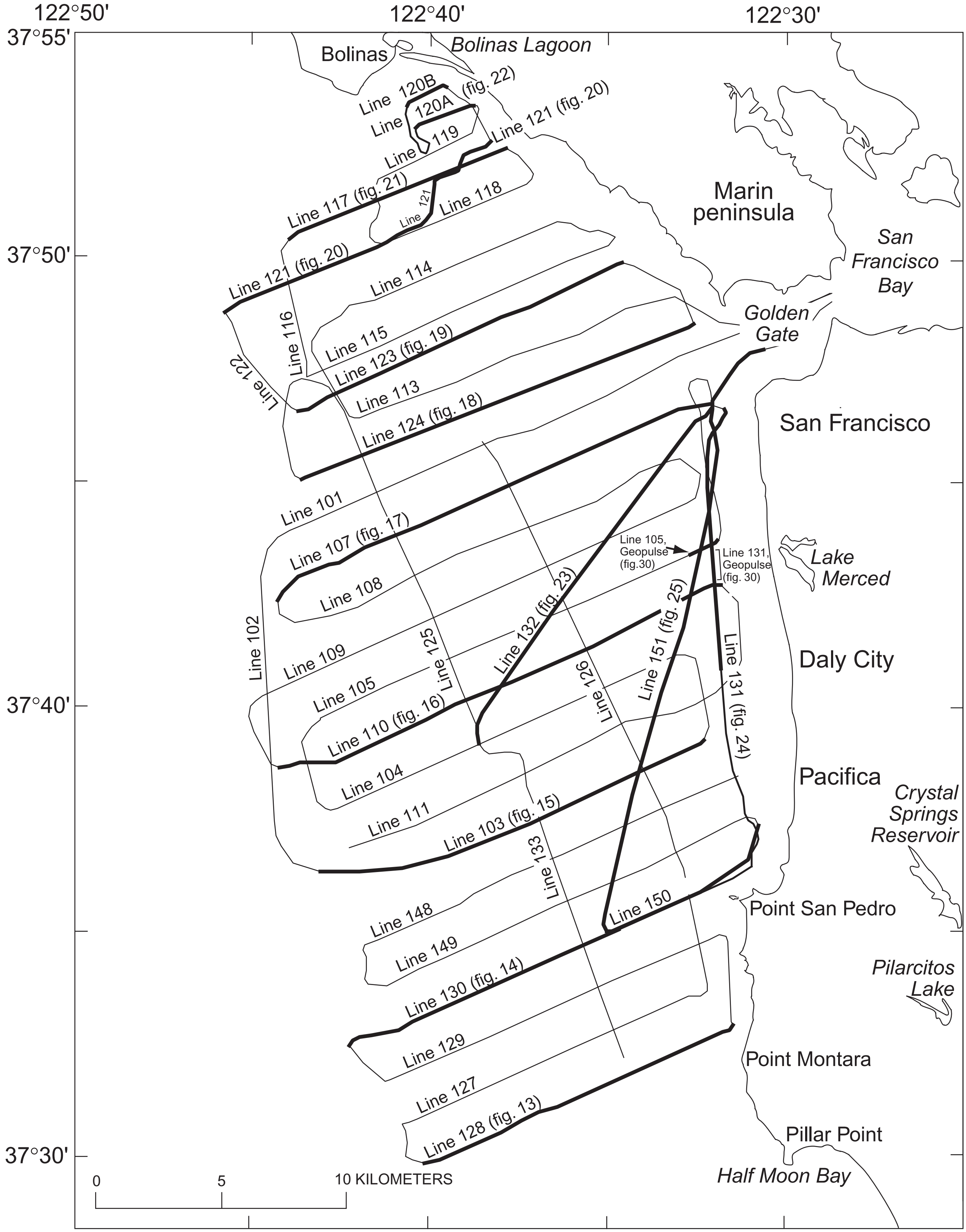


Figure 2.—Gulf of the Farallones and San Francisco Bay region, Calif., showing locations of tracklines of high-resolution multichannel seismic-reflection data; data for bold tracklines are plotted in figures 13 through 25.

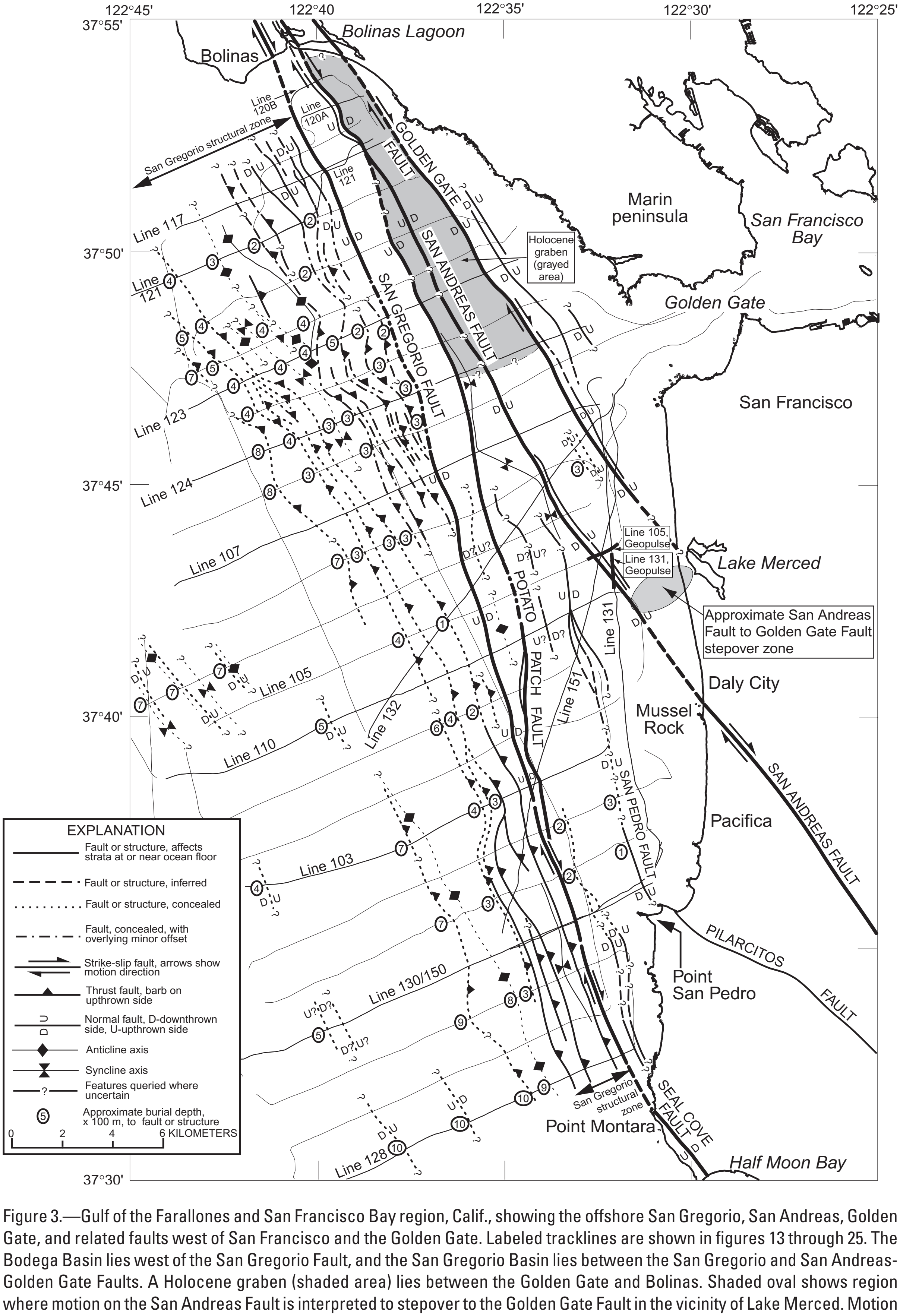


Figure 3.—Gulf of the Farallones and San Francisco Bay region, Calif., showing the offshore San Gregorio, San Andreas, Golden Gate, and related faults west of San Francisco and the Golden Gate. Labeled tracklines are shown in figures 13 through 25. The Bodega Basin lies west of the San Gregorio Fault, and the San Gregorio Basin lies between the San Gregorio and San Andreas-Golden Gate Faults. A Holocene graben (shaded area) lies between the Golden Gate and Bolinas. Shaded oval shows region where motion on the San Andreas Fault is interpreted to stepover to the Golden Gate Fault in the vicinity of Lake Merced. Motion on the San Gregorio Fault most likely steps over to the Golden Gate Fault along the Potato Patch Fault but possibly also along the San Pedro Fault, both of which would then be strike-slip transfer faults.

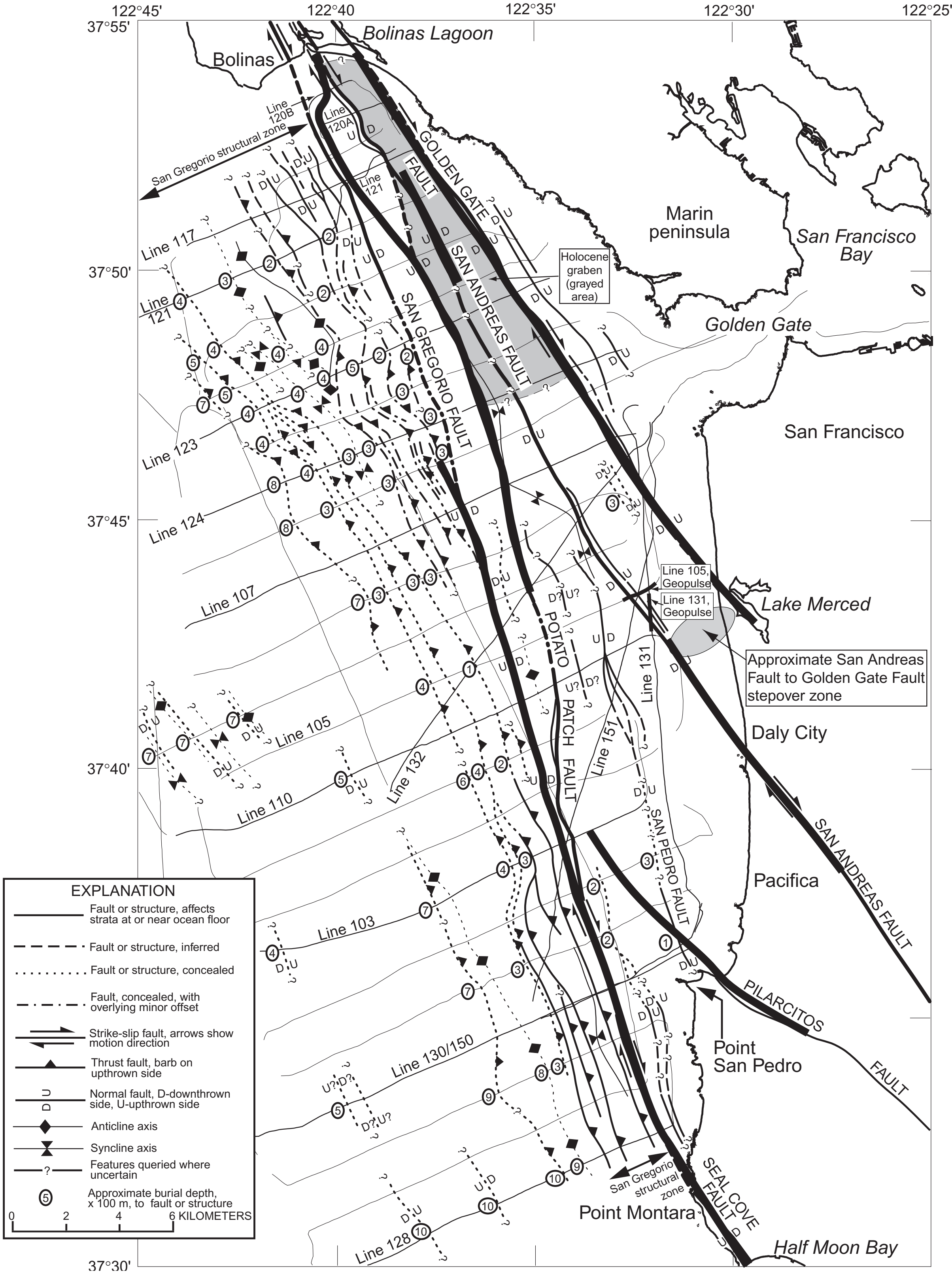


Figure 4.—Gulf of the Farallones and San Francisco Bay region, Calif., showing locations of basement faults (heavy lines) as interpreted from aeromagnetic data by Jachens and others (1999) and Jachens and others (this volume). Faults interpreted from seismic-reflection data show high correlation with magnetically located southern section of the San Gregorio Fault, northern section of the Potato Patch Fault, and the Golden Gate Fault; the Pilarcitos Fault is not evident in seismic-reflection data.

however, because of an absence of high-quality deep- to medium-penetration seismic-reflection data east of the San Gregorio Fault.

A fold-and-thrust belt lies west of the San Gregorio Fault (fig. 3). Cooper (1973) termed this belt the “Eastern Marginal High,” but McCulloch (1987, 1989) incorporated it into the San Gregorio Fault zone. We follow McCulloch’s (1987, 1989) suggestion because our interpretations indicate that the belt is tectonically linked to the San Gregorio Fault. Thus, we refer to it as the “San Gregorio structural zone” and discuss it along with the San Gregorio Fault system below.

Jachens and Zoback (1999), Zoback and others (1999), and Jachens and others (this volume) interpret high-resolution aeromagnetic data over the Gulf of the Farallones to show faulting in the magnetic basement rocks (fig. 4; see Jachens and others, this volume). They show that a long, linear magnetic anomaly associated with the Seal Cove Fault (onshore) and San Gregorio Fault (offshore) trends northwest to a position slightly southwest of the Golden Gate, where the fault is interpreted to end (fig. 4). Northward, basement fault offset is then on an east-stepping separate arcuate fault, partly corresponding to our Potato Patch Fault, that trends back onshore at Bolinas Lagoon. Aeromagnetic data indicate that the Pilarcitos Fault trends offshore for about 8 km before either merging with or being truncated by the San Gregorio Fault. The Peninsular segment of the San Andreas Fault continues offshore for about 6 km, where it is interpreted to stepover to the Golden Gate Fault, which is outlined by a conspicuous magnetic lineament that trends northwest from Lake Merced (fig. 4). These data show a continuity of the faults and fault zones present within offset magnetic basement units, but not the structure or stratigraphy in the uppermost 1 to 2 km of sedimentary strata associated with the faults.

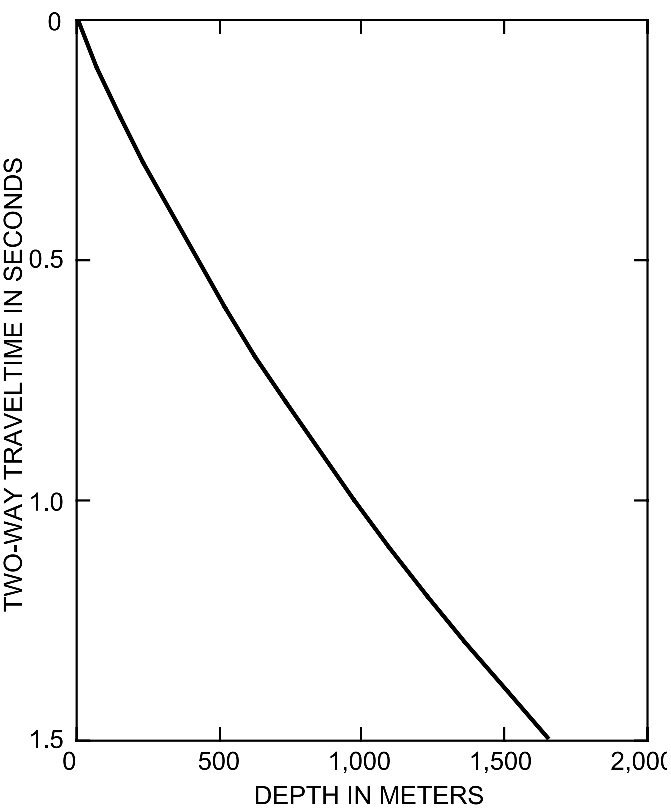


Figure 5.—Curve for converting two-way seismic-reflection time (in seconds) to approximate depth (in meters) in high-resolution seismic-reflection data presented here.

Using the earlier work by Cooper (1973) and McCulloch (1987, 1989), the aeromagnetic interpretation, and local earthquake seismicity, Zoback and others (1999) interpreted a change from compressional to extensional deformation on the Peninsular segment of the San Andreas Fault. Source studies of small seismic events beneath the Gulf of the Farallones showed normal faulting, associated with extensional deformation, instead of the compressional events that might be associated with strike-slip or thrust faults. Jachens and Zoback (1999), Zoback and others (1999), and Jachens and others (this volume) then proposed a 3-km northeastward jump of fault motion from the San Andreas Fault to the Golden Gate Fault (a right step), and Zoback and others (1999) suggested that this right stepover created the extensional tectonic regime. The stepover leads to the formation of an extensional strike-slip basin containing thick deposits of the Pliocene and Pleistocene Merced Formation, a suggestion made earlier by Hengesh and Wakabayashi (1995) on the basis of their reconstruction of offset on the San Andreas Fault system and the geologic history of the Merced Formation.

Data Acquisition and Processing

In June 1995, we collected about 550 km of high-resolution seismic-reflection data across the submerged sections of the San Gregorio and San Andreas Fault systems in the Gulf of the Farallones between Point Montara and Bolinas Lagoon (figs. 1–3; Bruns and others, 1995, 1996). The data were acquired along an approximately 2-km north-south line spacing from nearshore to about 16 km offshore and west of the San Gregorio Fault, into the Bodega Basin (figs. 1–3). Tielines between the east-west lines were acquired in the Bodega Basin, nearshore, and elsewhere as opportunity allowed during field acquisition. This seismic survey was designed to systematically examine the fault systems with adequate spatial resolution to correlate fault traces across the offshore area. The seismic-reflection data show sedimentary bedding and structure to about 1.5-km depth; the small acoustic power of the seismic source seldom penetrated farther.

We collected the data with a 24-channel recording system, a 150-m-long streamer, and two 0.65-L (40 in^3) airguns fired at 12.5-m intervals. The data were digitally recorded, and navigated with a Global Positioning System navigation program called YoNav, developed by the U.S. Geological Survey (Gann, 1992). We processed the digital airgun data through a standard set of programs on a DISCO processing system including velocity correction of common-depth-point gathers, deconvolution, stacking, muting, automatic gain control, filtering at 50 to 160 Hz, and migration.

In a few areas, single-channel high-resolution seismic-reflection profiles were acquired with a Geopulse system, a frequency range of 2,000 to 4,000 Hz, and penetration of a few tens of meters. Owing to weather conditions, we were unable to acquire these data over all the multichannel tracks. Two of these high-resolution tracklines are shown in figure 2.

Time-Depth Conversion

Seismic data are plotted in two-way traveltime, and seismic horizons must be converted to depth to interpret the geology. We do not have good velocity information for the section imaged in the high-resolution seismic-reflection data. Stacking velocities from the multichannel high-resolution data indicated that a good approximation to the velocity structure was obtained by increasing interval velocities from 1,500 to 2,400 m/s between 0.0- to 1.0-s two-way traveltime; we then assumed that interval velocities would be about 3,500 m/s by 2.0-s two-way traveltime. We used these interval velocities to construct a curve for converting time information on the seismic sections into depths (fig. 5). A substantially lower velocity model (that is, interval velocities of 2,000 m/s at 1.0-s two-way traveltime and 3,000 m/s at 2.0-s two-way traveltime) would result in an approximately 10-percent decrease in calculated depths.

About a quarter of the acquired seismic lines are shown here with interpretations. All of the lines are available in uninterpreted digital formats on a CD–ROM (Childs and others, 2000).

Regional Geologic Setting and Fault-Motion History

Terranes and Faults

The San Gregorio and San Andreas Fault systems divide the Continental Shelf into three tectonostratigraphic terranes—the Salinia terrane, the Pilarcitos block, and the Franciscan Complex, composed of several Franciscan terranes (see McCulloch, 1987, 1989).

The Salinia terrane lies west of the San Andreas and San Gregorio Faults throughout most of central California, and west of the Pilarcitos Fault on the San Francisco peninsula. Substantial separation has occurred within the terrane along the San Gregorio Fault (McCulloch, 1987, 1989). The basement of the Salinia terrane is composed of Mesozoic and older metamorphic rocks intruded by Cretaceous granitic plutons. Overlying the crystalline basement is a sequence of sedimentary rocks that range in age from Paleocene to Holocene. These sedimentary rocks underlie the Bodega Basin between the San Gregorio Fault and the Farallon Ridge structural high near the edge of the Continental Shelf (McCulloch, 1987, 1989).

The Franciscan terrane, which is composed of late Mesozoic to Tertiary rocks, underlies the onshore area immediately east of the Pilarcitos and San Andreas Faults. The Franciscan rocks in this area consist predominantly of melange that includes graywacke, serpentinite, chert, and blocks of blueschist in a penetratively sheared argillite matrix (for example, Ross, 1978; Brabb and Pampeyan, 1983; Blake, 1984; Brabb and others, 1998; Page, 1992; McCulloch, 1987, 1989). The basement units offshore are overlain by a substantial thickness of sedimentary rocks of the San Gregorio Basin, and onshore by the Merced Formation.

Throughout most of central California, the San Andreas Fault separates the Salinia terrane on the west from the Franciscan terrane. On the San Francisco peninsula, however, the Pilarcitos Fault separates these two terranes, and the San Andreas Fault lies entirely within the Franciscan terrane (Brabb and Pampeyan, 1983). Both the Pilarcitos and San Andreas Faults are steeply to vertically dipping features that extend to an upper-crustal depth of at least 10 km (Parsons and Zoback, 1997). The Pilarcitos block, which lies between the active San Andreas and San Gregorio Faults, consists of basement rocks of the Salinia and Franciscan terranes, now amalgamated together along the Pilarcitos Fault. McLaughlin and others (1996) and Parsons and Zoback (1997) concluded that the Pilarcitos Fault took up motion on the San Andreas Fault system before the Quaternary and probably before about 3 Ma.

The terms “San Andreas Fault system” and “San Gregorio Fault system” describe multiple faults on which motion has occurred. The Continental Shelf off San Francisco is cut by at least seven subsidiary faults that are segments of these fault systems (fig. 3). All of these subsidiary faults except the Pilarcitos Fault affect the basin fill in either the Bodega or San Gregorio Basin.

1. The Golden Gate strand of the San Andreas Fault trends offshore from Lake Merced in the northern part of the San Francisco peninsula (figs. 1, 3). Herein, we refer to this fault as the “Golden Gate Fault.”
2. The Peninsular segment of the San Andreas Fault extends offshore at Mussel Rock in Daly City (figs. 1, 3). Herein, this segment is routinely referred to both onshore and offshore as the “San Andreas Fault.”
3. The Pilarcitos Fault, which lies between the San Andreas and San Gregorio Faults, is a now-inactive fault that separates basement terranes with markedly different rock types (figs. 1, 3).
4. The herein-named San Pedro Fault trends north from near where the Pilarcitos Fault goes offshore, but does not follow the magnetically determined offshore trace of the Pilarcitos Fault (figs. 3, 4). Instead, the San Pedro Fault cuts across the magnetic trends and lies between the San Andreas and Potato Patch Faults. This fault’s affiliation, if any, with either the San Gregorio or San Andreas Fault system is unclear.
5. The Potato Patch Fault (after McCulloch, 1987, 1989) lies between the offshore San Andreas Fault and the San Gregorio Fault. We interpret this fault to originate at depth

from the San Gregorio Fault system at its south end; at its north end, it may merge with the San Andreas Fault south of Bolinas (figs. 1, 3).

6. The San Gregorio Fault system lies offshore as a major structural boundary between Half Moon Bay and Bolinas (figs. 1, 3), and extends onshore into the Seal Cove Fault near Half Moon Bay (R.C. Jachens, written commun., 2001).
7. The San Gregorio structural zone comprises the series of thrust faults lying west of the San Gregorio Fault (fig. 3). These faults probably merge with the San Gregorio Fault at depth.

San Andreas Fault System: The San Andreas, Golden Gate, and Pilarcitos Faults

The San Andreas Fault extends from the Gulf of California to northern California as a major strike-slip fault. About 100 km southwest of the San Francisco peninsula, the nearly linear Central California segment of the fault bifurcates, with the western strand forming the Peninsular segment of the San Andreas Fault along the San Francisco peninsula and the eastern strand forming the Hayward-Calaveras Fault system east of San Francisco Bay. Together, these two strands currently account for about 32 mm/yr of plate motion, or approximately 85 percent of the total plate motion west of the Sierra Nevada (Working Group on Northern California Earthquake Probabilities, 1999). The Peninsular segment of the San Andreas Fault trends offshore near Daly City south of San Francisco (fig. 3). The offshore trend was mapped by Cooper (1973) and McCulloch (1987, 1989), though not with certainty because of the sparse data base.

The Golden Gate Fault trends offshore from Lake Merced (figs. 3, 4). The fault, which was partly mapped by McCulloch (1987, 1989), is better shown by the aeromagnetic data of Jachens and Zoback (1999) and Jachens and others (this volume). Jachens and Zoback (1999), Zoback and others (1999), and Jachens and others (this volume) use fault geometry, seismicity patterns, aeromagnetic data, and seismic-reflection studies to infer an approximately 3-km right step from the Peninsular segment of the San Andreas Fault onto the Golden Gate Fault. Zoback and others (1999) interpreted that this right step has led to the formation of an extensional strike-slip pullapart basin which is represented onshore by the now-uplifted Merced Formation (see next section; Clifton and Hunter, 1987, 1991).

The Pilarcitos Fault lies between the San Andreas and San Gregorio Faults, is present onshore north of Half Moon Bay, and trends offshore near Point San Pedro (figs. 3, 4). Jachens and others (1999 and this volume) use aeromagnetic data to outline the fault for 7 to 8 km offshore to where the fault bends northward to lie near, merge with, or be truncated by the San Gregorio Fault (fig. 4). The onshore Pilarcitos Fault has been inactive during the Holocene (Bortugno and others, 1992) and is currently aseismic (Zoback and others, 1999). The fault has been interpreted as an abandoned strike-slip section of the Pacific-North American Plate boundary. It probably accommodated most displacement on the San Andreas Fault system before the Quaternary (McLaughlin and others, 1996; Parsons and Zoback, 1997). Parsons and Zoback (1997) argued that it became inactive by about 3 Ma. Estimates of offset along the Pilarcitos Fault based on offset rock units or geophysical anomalies range from 120 to more than 250 km before abandonment (Griscom and Jachens, 1990; Page, 1990, 1992; McLaughlin and others, 1996; Parsons and Zoback, 1997). Alternatively, Wakabayashi (1999) postulated that offset must have been less than 7 km, on the basis of local geologic interpretations. The time of cessation of motion on the fault is poorly constrained, and is tied mainly to the beginning of deposition of the Merced Formation during the Pliocene and early Pleistocene.

The current slip rate on the San Andreas Fault in the Golden Gate/San Francisco peninsula area is estimated at 17 to 24 mm/yr (Working Group on Northern California Earthquake Probabilities, 1999). The slip rate increases north of Bolinas because of added slip from the merging San Gregorio Fault system (Niemi and Hall, 1992; Noller and others, 1993). On the basis of the offset of geologic basement units and associated magnetic anomalies, Jachens and others (1999 and this volume) argue that the total offset on the Peninsular segment of the San Andreas Fault is tightly constrained to about 22 km. However, Wakabayashi (1999) believed that offset could be as much as 36 km. Thus, at present estimated slip rates of 17 to 24 mm/yr, the current trace of the fault has been active for about the past 1 to 2 m.y. This is an age similar to the initiation of deposition of the basal Merced Formation at about 1.6–1.2 Ma, although the timing is poorly constrained (Clifton and Hunter, 1987, 1991; Hengesh and Wakabayashi, 1995). The similar ages suggest a possible link between the onset of basin growth and the initiation of faulting on the Peninsular segment of the San Andreas Fault.

San Gregorio Fault System

The San Gregorio Fault zone is part of a system of strike-slip faults that includes the Hosgri and Sur Faults, which extend from Point Arguello north of Santa Barbara to Monterey Bay, and the San Gregorio Fault zone, which extends from Monterey Bay to Bolinas (McCulloch, 1987, 1989). The San Gregorio Fault system lies mostly offshore, with the easternmost faults extending onshore only between Point Año Nuevo (south of study area) and San Gregorio State Beach (fig. 1) and between Pillar Point and Point Montara, where it is also referred to as the “Seal Cove Fault” (figs. 1–3).

The San Gregorio Fault may have become active by about the middle Miocene, and has accumulated at least 150 km of offset since then (Clark and others, 1984; Simpson and others, 1997; Jachens and others, 1999). Onshore trenching studies have shown a slip rate of about 6 to 8 mm/yr on the Seal Cove Fault (Simpson and others, 1997; Lettis, 1999), and regional geologic correlations give a similar slip rate of about 6 mm/yr (Clark, 1999; Sedlock, 1999; Weber and others, 1999). Hengesh and Wakabayashi (1995) and Wakabayashi and Hengesh (1995) estimated slip rates of 5 mm/yr averaged over the past 2 m.y. Clark (1998, 1999) discussed geologic correlations indicating that about 50 to 60 km of the total displacement occurred from 10 to 8 Ma, 81 km from 8 to 3 Ma, and 19 km from 3 to 0 Ma. This last offset gives an average slip rate of 6 mm/yr for the past 3 m.y.

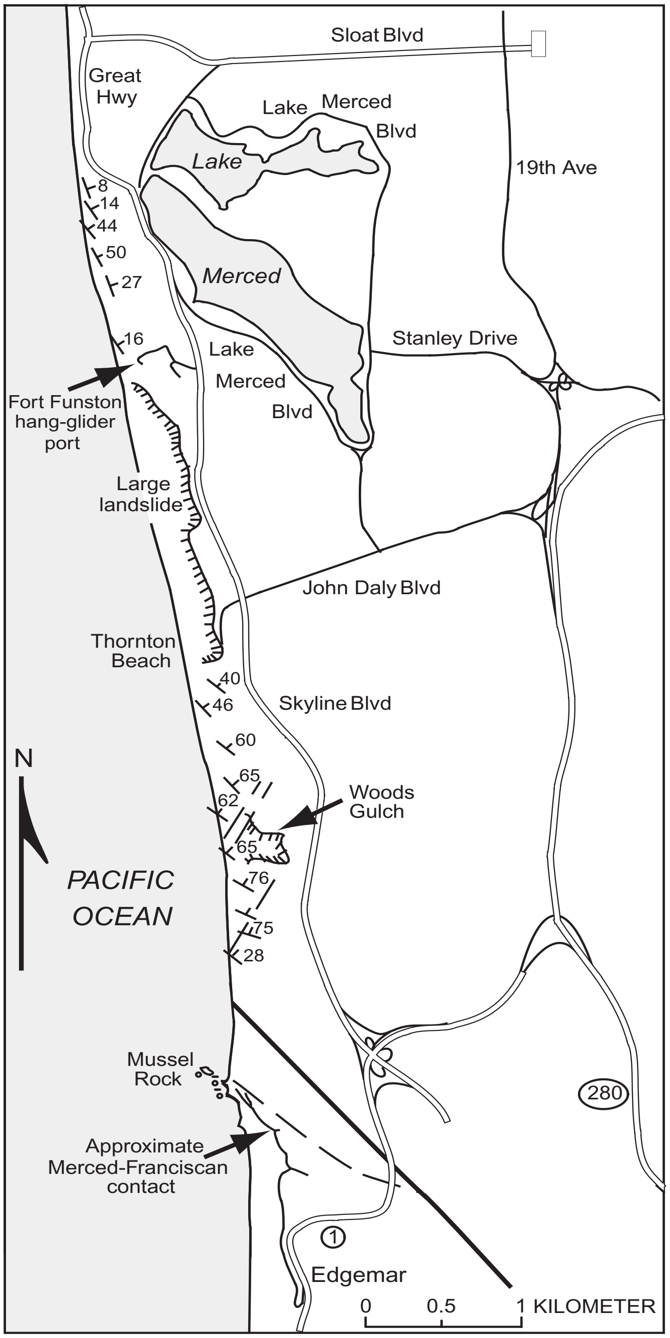


Figure 6.—Coastal area south of San Francisco (fig. 1), showing geologic features of the Merced Formation in seacliff exposures. From Clifton and Hunter (1987, 1991).

Stratigraphy

West of the San Gregorio Fault: The Monterey Formation and Other Units (Late Miocene and Older)

Basement rocks west of the San Gregorio Fault in the study area (fig. 1) are composed of granitic rocks of the Salinia terrane (McCulloch, 1987). Overlying basement is a transgressive succession of sedimentary rocks composed of conglomerate and sandstone of the Paleocene Point Reyes Conglomerate, overlain by the Miocene Laird Sandstone and the deep-water siliceous Miocene Monterey Formation (McCulloch, 1987; Clark and others, 1991; Clark and Brabb, 1997). The rocks were uplifted, deformed, and erosionally truncated early in the Late Miocene. The resulting erosional unconformity, which truncated folded strata of the Monterey Formation on the Point Reyes peninsula (Clark and others, 1991; Clark and Brabb, 1997), is identified in the offshore as a gently eastward sloping erosional surface in the Bodega Basin that is truncated at the San Gregorio Fault (see next section).

West of the San Gregorio Fault: The Santa Margarita Sandstone, Santa Cruz Mudstone, and Purisima Formation (Late Miocene and Pliocene)

The Miocene Santa Margarita Sandstone and Santa Cruz Mudstone and the Miocene and Pliocene Purisima Formation are extensively exposed in the Santa Cruz Mountains, and these formation names have been applied to correlative units on the Point Reyes peninsula (Clark and others, 1984; Clark and Brabb, 1997). The units lie entirely east of the San Gregorio Fault in the Santa Cruz Mountains, and west of the fault at Point Reyes. Offshore units in the Bodega Basin west of the San Gregorio Fault, which have been sampled in boreholes (Hoskins and Griffiths, 1971; McCulloch, 1987), are correlated with the strata on the Point Reyes peninsula and into the offshore area surveyed by seismic-reflection data.

Development of the Late Miocene unconformity at the top of the Monterey Formation was followed by subsidence and deposition of as much as 3 km of Late Miocene and Pliocene marine claystone and siltstone. The strata thin westward across the basin and, locally, adjacent to the San Gregorio Fault, where thinning and onlap in the San Gregorio structural zone reveal a deformation history along the fault. The late Miocene Santa Margarita Sandstone on the Point Reyes peninsula is a thin (max 50 m thick) glauconitic sandstone overlying the Monterey Formation with angular unconformity. The thick overlying Santa Cruz Mudstone is sandy and glauconitic where it conformably overlies the Santa Margarita Sandstone, and grades upward into mudstone. The Santa Cruz Mudstone is as much as 2,000 m thick in the Bolinas area and thins northward to pinch out north

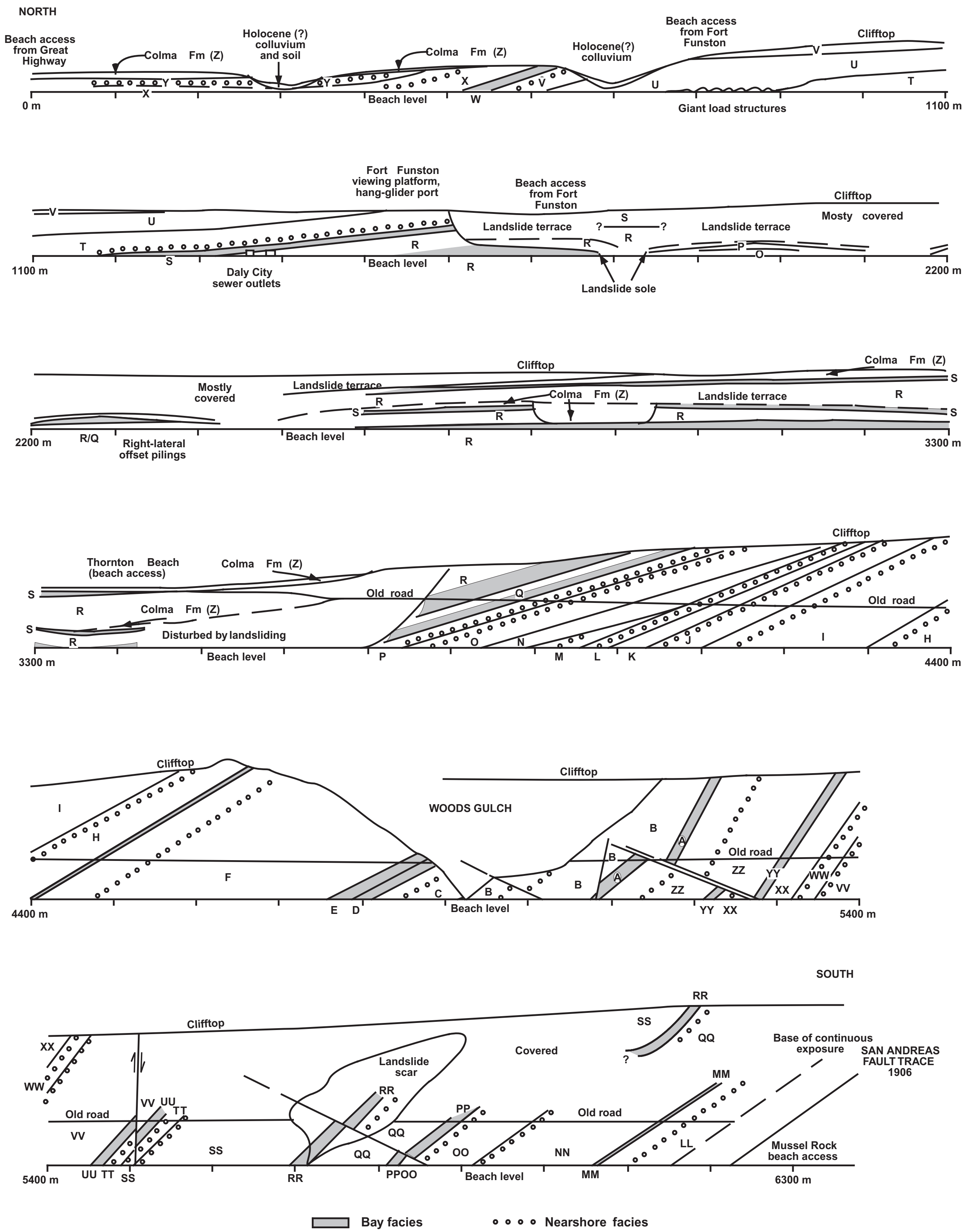


Figure 7.—Generalized cross sections of exposures of the Merced and Colma Formations in seacliffs between Lake Merced and Mussel Rock on the San Francisco peninsula. South end of section is approximately 500 m north of Mussel Rock (fig. 6). Letters denote sequences and lithologic units of Clifton and Hunter (1987, 1991). Sections tie together end to end from northernmost (top) to southernmost (bottom). Scale in meters; no vertical exaggeration.

of Drakes Bay. The Purisima Formation, which is the uppermost shallow-marine phase of basin filling, is as much as 490 m thick onshore (Clark and others, 1991; Clark and Brabb, 1997). Offshore, McCulloch (1987, 1989) interpreted the local upper Miocene and younger section to be more than 2 km thick near the Point Reyes peninsula. The upper Miocene and younger section ranges from 800 to 1,100 m in thickness (north-to-south maximum thickness) on McCulloch's (1987) interpreted seismic lines in the Golden Gate area.

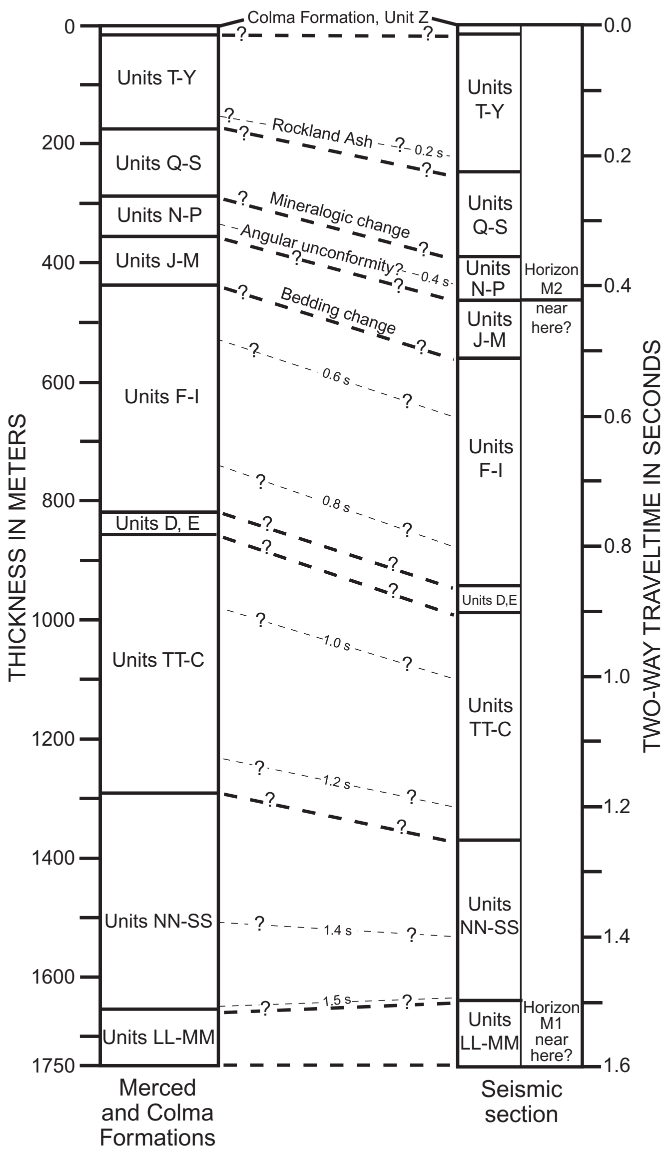


Figure 8.—Unit designations for the Merced and Colma Formations, and comments on significant features within formations (from Clifton and Hunter, 1987, 1991). A possible correlation to seismic-reflection records in the San Gregorio Basin is also shown but is uncertain. Conversion of seismic-reflection time to depth is from figure 5.

East of the San Gregorio Fault: The Merced and Colma Formations (Pliocene and Pleistocene)

The Merced Formation is a poorly dated Pliocene(?) and Pleistocene sequence of marine to eolian gravel, sandstone, and siltstone. The Merced Formation is overlain by a thin (less than 10 m thick), sandy nonmarine unit, the Pleistocene Colma Formation, which is probably about 75 to 135 ka old (fig. 6; Hall, 1966; Clifton and Hunter, 1987, 1991). The Merced Formation crops out in two localities. The type section on the northern San Francisco peninsula lies east of the San Andreas Fault and is exposed in seacliffs extending from Mussel Rock 6 km northward to near Lake Merced (figs. 6, 7; Hall, 1966; Clifton and Hunter, 1987, 1991). The section is as much as 1,750 m thick and less than 2.5 km wide. These strata extend southward along the San Andreas Fault for about 19 km. A thinner, narrower section is exposed west of the San Andreas Fault at Bolinas, where it is as much as 100 to 150 m thick and 2 km wide, lies at elevations of as much as 130 m, and extends northward from the lagoon for about 15 km (Galloway, 1977; Clark and Brabb, 1997). The type section was described in considerable detail by Clifton and Hunter (1987, 1991), whose description forms the basis for the following discussion. The stratigraphic section at Bolinas has not been studied in similar detail.

On the San Francisco peninsula, the Merced Formation consists of sedimentary sequences that require a shallowing open-ocean, wave-dominated depositional environment. Complete sequences begin with a marine-shelf siltstone and progress upward from shelf sand through nearshore, foreshore, shore, and backshore units and, in some sequences, through eolian, fluvial, and marsh units. Shelf facies predominate in the lower 1,300 m of the sequence, and nonmarine facies in the upper 300 m. The change corresponds to a conspicuous mineralogic change (see below) that occurs at 290 m below the top of the section. These sequences indicate alternating transgressions and regressions of the sea, reflecting a combination of eustatic changes in sea level, fluctuations in sediment supply, and continuing tectonic subsidence. The cycles appear generally similar in scale and duration to known Pleistocene glacioeustatic sea-level fluctuations (Clifton and others, 1988).

Merced strata lie in a homoclinal succession with a northeasterly strike (figs. 6, 7). Dips commonly exceed 50º in the lower third of the unit. In the upper two-thirds of the unit, dips are less than 20º except near Lake Merced, where the range is 40º–50º across a short stratigraphic interval. The stratigraphic succession is broken only by small faults across which strata can be readily correlated. The great thickness of very shallow marine deposits indicates rapid subsidence during deposition. These strata have been subsequently uplifted, tilted, and truncated into their present outcrop position at elevations of as much as 200 m. The most recent deformation occurred after deposition of the Colma Formation, which rests with angular unconformity on deformed strata of the Merced Formation and is, in turn, gently tilted northward in seacliff exposures.

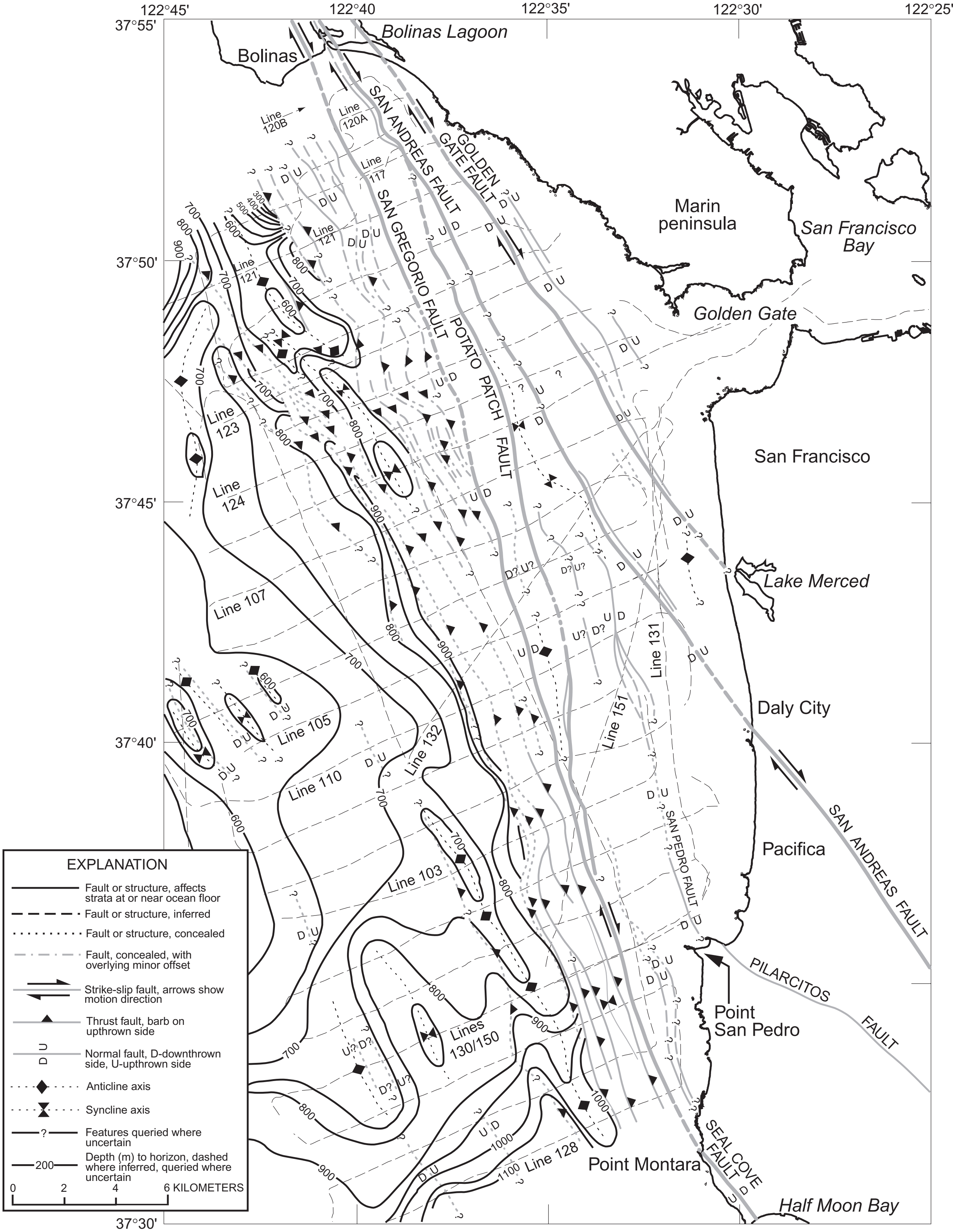


Figure 9.—Gulf of the Farallones and San Francisco Bay region, Calif., showing contours of depth to seismic horizon A (approximate top of the Monterey Formation) in the Bodega Basin west of the San Gregorio Fault. Contours in meters; contour interval, 50 m. Contoured horizon is shown on interpreted seismic sections in figures 13 through 25.

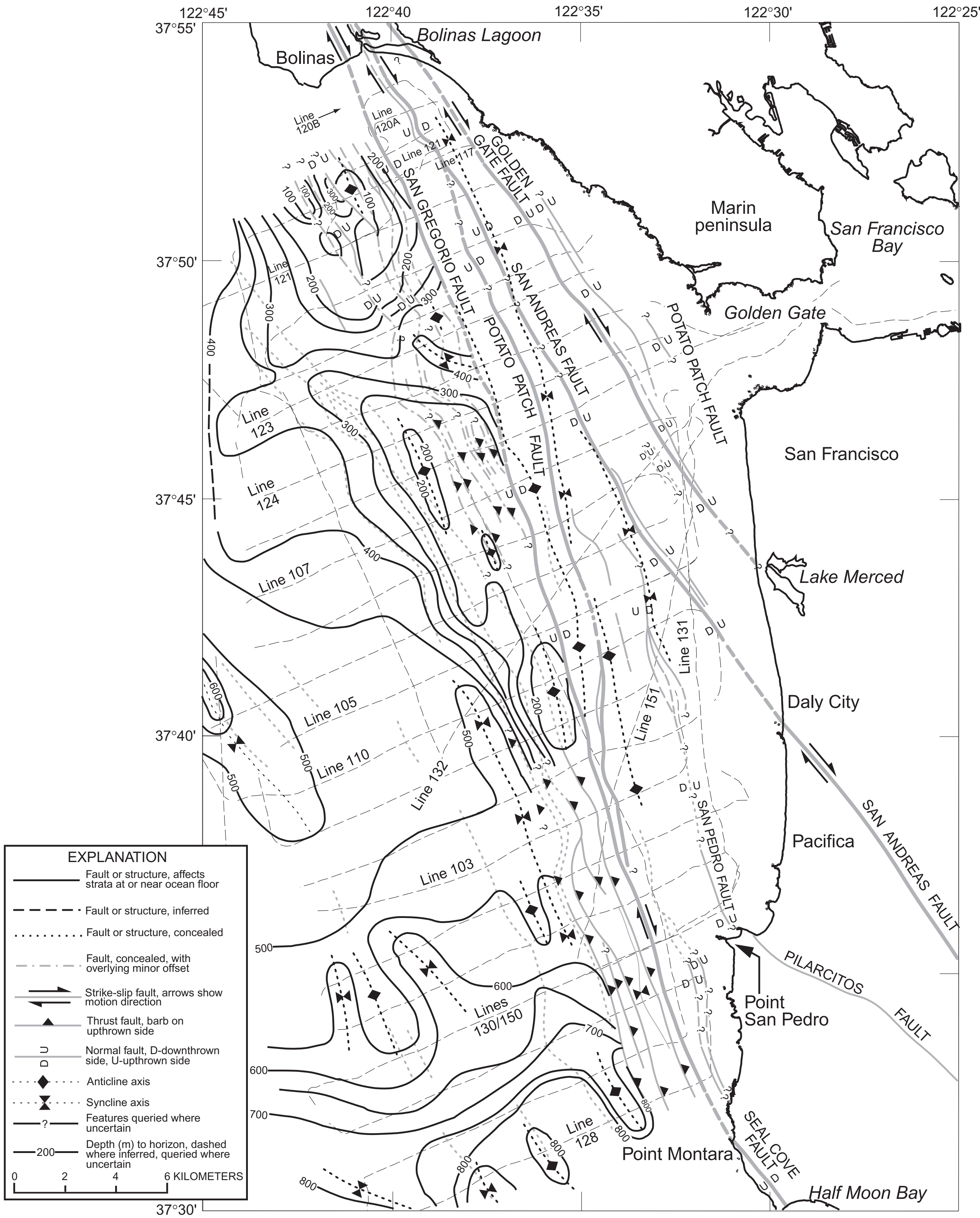


Figure 10.—Gulf of the Farallones and San Francisco Bay region, Calif., showing contours of depth to seismic horizon C in the Bodega Basin west of the San Gregorio Fault. Contours in meters; contour interval, 50 m. Contoured horizon is shown on interpreted seismic sections in figures 13 through 25.

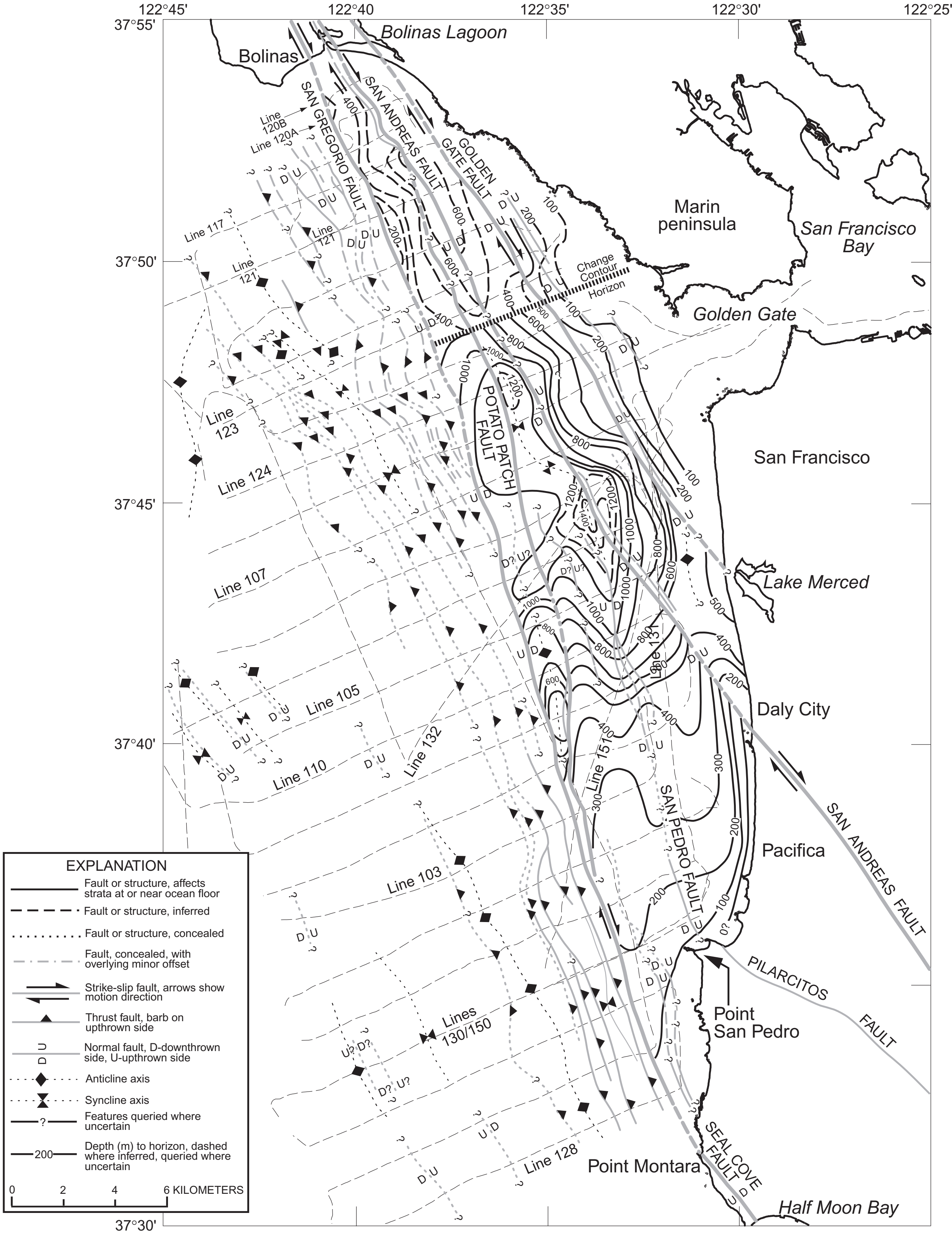


Figure 11.—Gulf of the Farallones and San Francisco Bay region, Calif., showing contours of depth to seismic horizon M1 in the San Gregorio Basin east of the San Gregorio Fault. Horizon is at approximate base of strata in shallowest parts of the San Gregorio Basin but is in lower part of strata in deepest parts of basin, where acoustic energy was insufficient to penetrate to base of sedimentary section. Horizon thus gives a minimum thickness of strata in the San Gregorio Basin. Contours in meters; contour interval, 100 m. Contoured horizon is shown on interpreted seismic sections in figures 13 through 25.

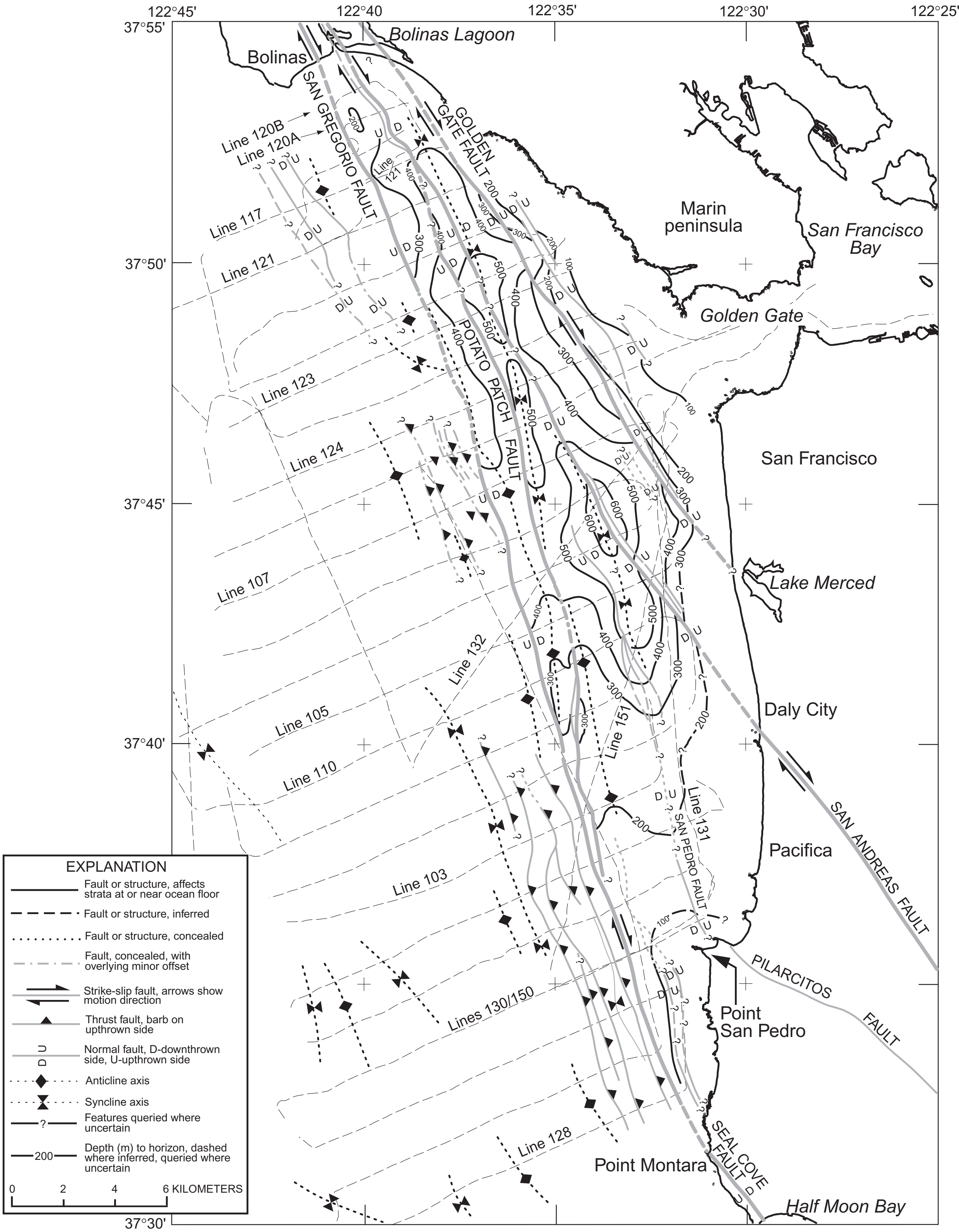


Figure 12.—Gulf of the Farallones and San Francisco Bay region, Calif., showing contours of depth to seismic horizon M2 in the San Gregorio Basin, east of the San Gregorio Fault. Seismic horizon is within strata of the San Gregorio Basin, possibly at approximate level of a bedding change or angular unconformity in the onshore Merced Formation identified by Clifton and Hunter (1987, 1991). In offshore basin, this horizon marks time when significant folding of strata in the San Gregorio Basin began over the Potato Patch Fault. Contours in meters; contour interval, 100 m. Contoured horizon is shown on interpreted seismic sections in figures 13 through 25.

The Merced Formation has been assigned a late Pliocene and Pleistocene age (Clifton and Hunter, 1987, 1991; Lajoie, 1996; Clark and Brabb, 1997), but age data for the units are meager. A mineralogic change 290 m below the top of the section reflects a change in provenance at about 0.62 Ma from local sources dominated by the Franciscan Complex to sources dominated by rocks of the Sacramento-San Joaquin River drainage basin (Hall, 1966; Clifton and Hunter, 1991). The Rockland ash bed at 175 m from the top of the section (fig. 7) has been dated at 400 ka (Sarna-Wojcicki and others,

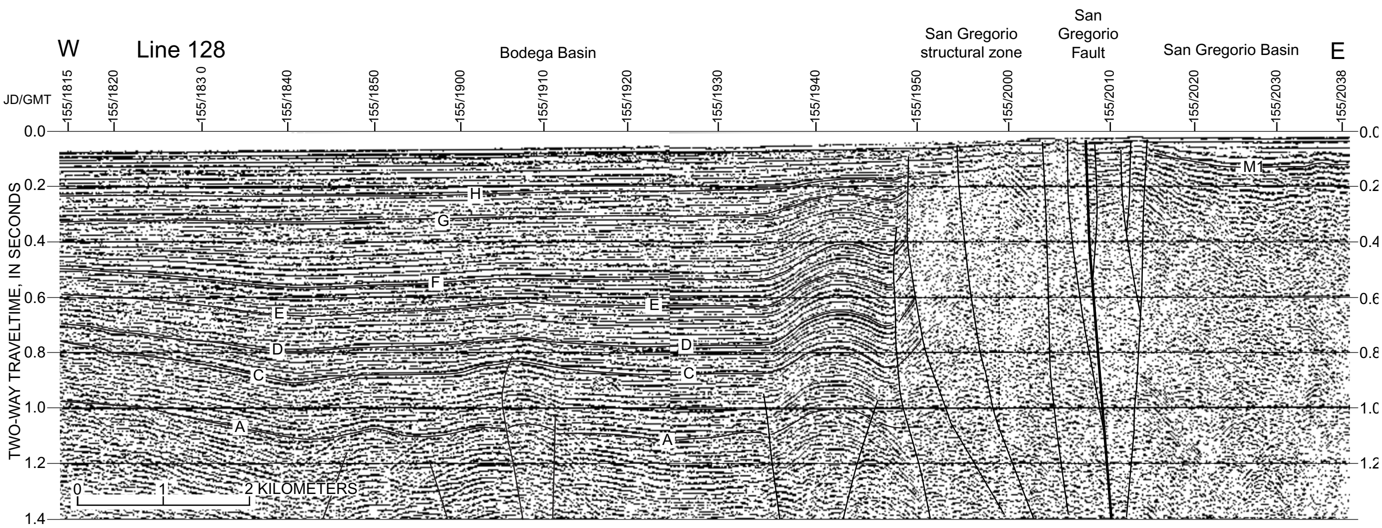


Figure 13.—Seismic line 128 off Point Montara at south end of study area (figs. 2, 3, 9–12). Seismic horizon A in the Bodega Basin is approximately at top of the Monterey Formation; rocks above unconformity correspond to the Late Miocene and younger onshore Santa Margarita Sandstone, Santa Cruz Mudstone, and Purisima Formation (Cooper, 1973; McCulloch, 1987, 1989). Horizons B through G are local to regional unconformities but cannot be directly tied to onshore sequences. Line shows truncation of units below horizon A at unconformity that characterizes horizon A, and narrow (less than 2 km wide) deformational region associated with the San Gregorio structural zone.

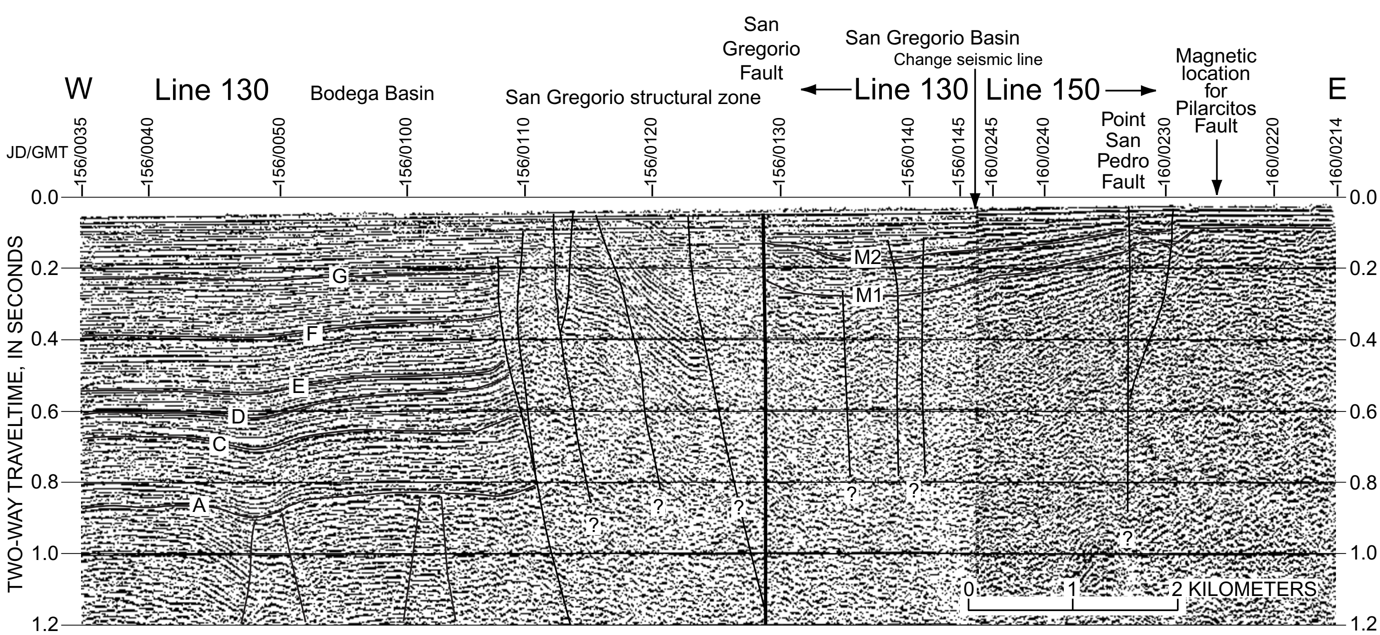


Figure 14.—Seismic line 130/150 off Point San Pedro (figs. 2, 3, 9–12). Same horizons in the Bodega Basin as in figure 13. In the San Gregorio Basin, between the San Andreas and San Gregorio Faults, horizon M1 is acoustic basement on flanks of basin, but acoustic basement cannot be seen in deepest parts of basin, and horizon M1 indicates a minimum mapped sediment thickness. Horizon M2 is an unconformity within basin. Age of strata in the San Gregorio Basin is unknown but is inferred to be younger than about 3 Ma. The San Gregorio structural zone is still narrow. Location of offshore extension of the Pilarcitos Fault is based on aeromagnetic data; seismic-reflection records do not show a fault. A nearby fault, the Point San Pedro Fault, seems to be independent of the Pilarcitos Fault.

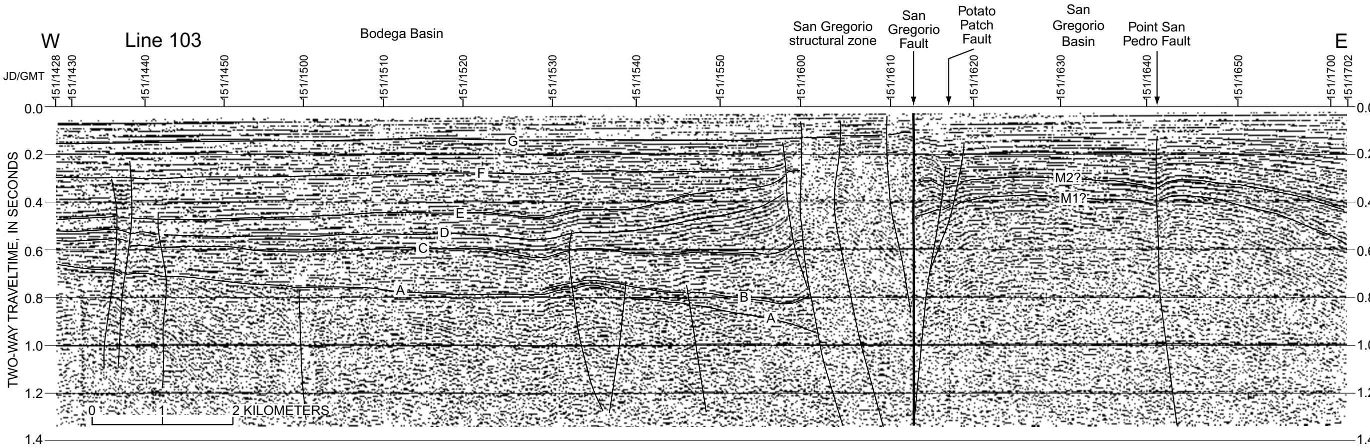


Figure 15.—Seismic line 103 west of Pacifica/Daly City, Calif. (figs. 2, 3, 9–12). Fault just east of the San Gregorio Fault is mapped here as beginning of the Potato Patch Fault. Small offset associated with the Point San Pedro Fault is also visible at east end of line. Strata overlying basement in the San Gregorio Basin here are about 400 to 500 m thick (approx 0.4–0.5-s two-way traveltime; see fig. 5). West of the San Gregorio Fault, horizon B appears for first time, and unit between horizons A and B thickens northward. Thickening of strata into the San Gregorio structural zone to horizon D is apparent; above that horizon, units thin into structural zone, indicating that uplift in structural zone started after horizon D time. Same seismic-horizon annotations as in figures 13 and 14.

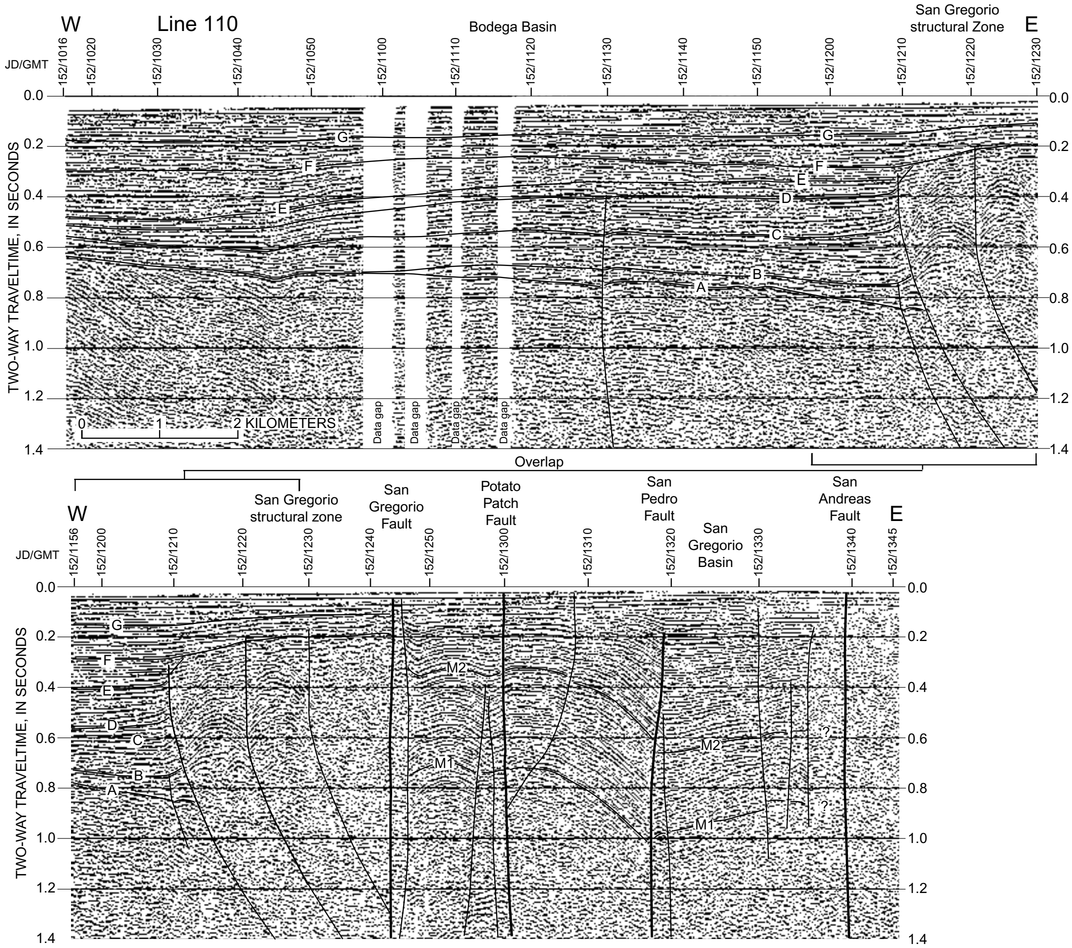


Figure 16.—Seismic line 110 (figs. 2, 3, 9–12), off Lake Merced. The San Gregorio structural zone has widened to 3 km and is covered by about 200 m of relatively flat lying sediment. Strata in the San Gregorio Basin have thickened significantly relative to strata on seismic line 103 to south. Anticline has developed west of the San Pedro Fault. Horizon M2 here marks initiation of growth on anticline; strata below horizon M2 thicken seaward, whereas strata above horizon thin onto growing structure.

1985), although more recent dating suggests an earlier age of 600 to 610 ka (Lanphere and others, 1999), indicating that further study is needed.

We assume that the Merced and Colma Formations are at least partly correlative with sedimentary strata in the offshore San Gregorio Basin. However, we lack seismic-reflection data that directly tie the Merced Formation to the offshore strata, and the age and timing of deposition could differ substantially, as discussed below.

Seismic Stratigraphy

We divide the offshore seismic stratigraphy into two fundamentally different sequences at the San Gregorio Fault, on the basis of our interpreted correlations with onshore strata. West of the San Gregorio Fault (figs. 1, 3), we correlate the offshore sedimentary section with units that crop out on the Point Reyes peninsula. Between the San Gregorio Fault and the San Andreas/Golden Gate Faults (figs. 1, 3), the seismic

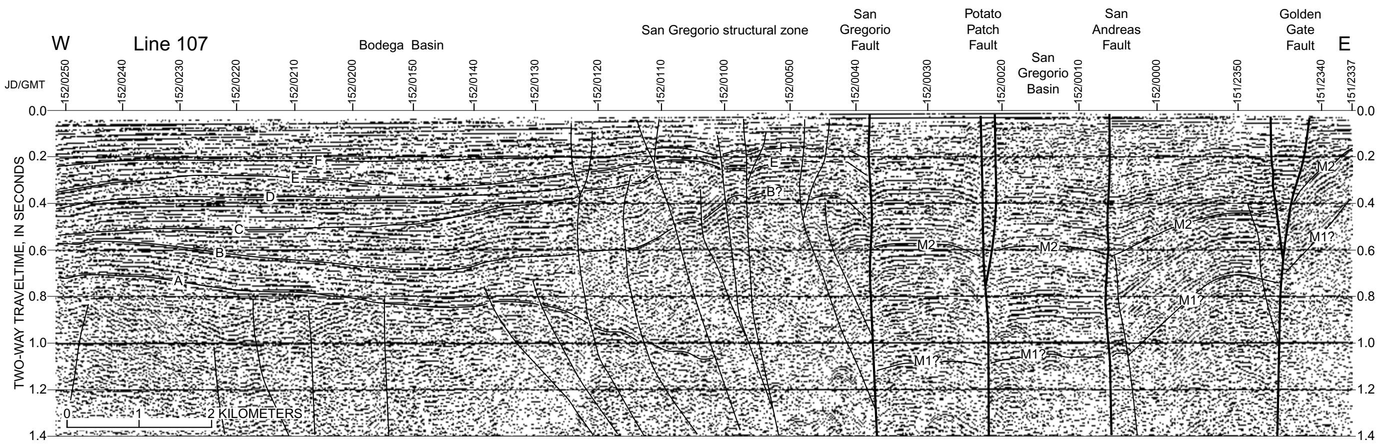


Figure 17.—Seismic line 107 just southwest of the Golden Gate (figs. 2, 3, 9–12). The San Gregorio structural zone has widened to more than 4 km, and strata between horizons A and B in the Bodega Basin have thickened substantially relative to same features on lines to south. Similarly, strata in the San Gregorio Basin have significantly thickened relative to strata visible on seismic line 103. Horizon M1 is almost certainly not at base of sedimentary section in the San Gregorio Basin; section probably approaches 2 km thickness for basin fill estimated from seismic-refraction data (or greater than 1.5-s two-way traveltime on a seismic line; see fig. 5). Same seismic-horizon annotations as in figures 13 and 14.

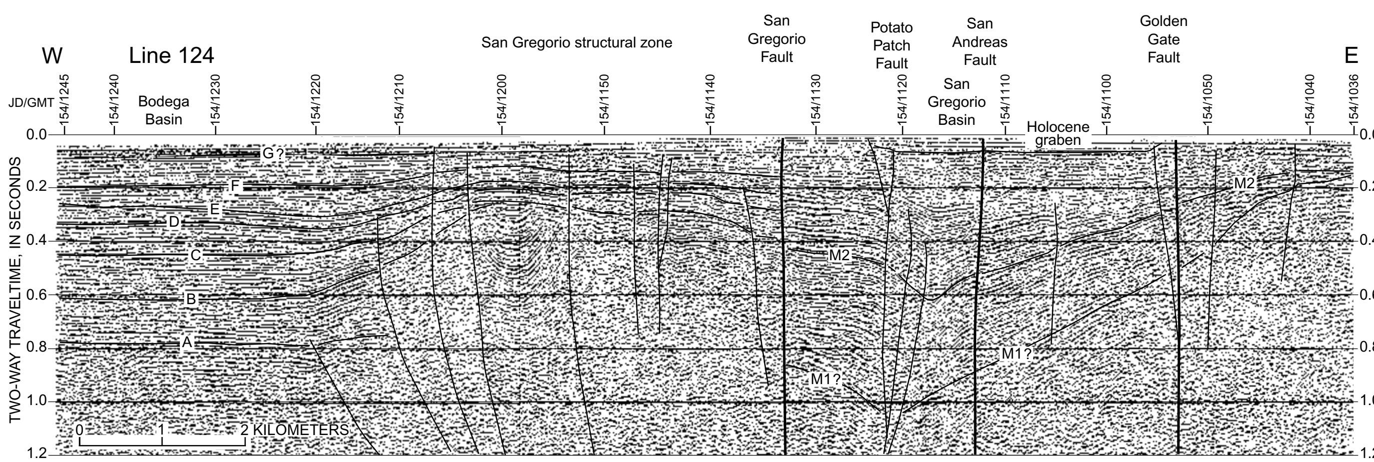


Figure 18.—Seismic line 124 west of the Golden Gate (figs. 2, 3, 9–12). The San Gregorio structural zone has widened to more than 6 km, and a marked unconformity is apparent over top of structures at about 0.2- to 0.3-s two-way traveltime. Especially obvious is truncated syncline below JD/GMT 154/1200. The San Gregorio, Potato Patch, and San Andreas Faults are not characterized by clearly broken, discontinuous, or terminating seismic reflectors and so are poorly defined. Faults are herein considered to be mainly active as normal faults in this part of basin, with subsidence creating the San Gregorio Basin. Faults would thus not be throughgoing major transform faults. Instead, most or all transform motion has probably transferred over to the Golden Gate Fault. Same seismic-horizon annotations as in figures 13 and 14.

sequence is probably composed of units that are at least partly, if not entirely, equivalent to the onshore Merced and Colma Formations (fig. 8). We have mapped horizons in the seismic-reflection data to show the stratigraphy and structure of the basins (figs. 9–12), and we show these horizons on the interpreted seismic data (figs. 13–25).

Seismic Stratigraphy West of the San Gregorio Fault—the Bodega Basin

In the seismic-reflection data west of the San Gregorio Fault, we map an unconformity, here designated horizon A (figs. 13–25). Rocks below horizon A have been at least

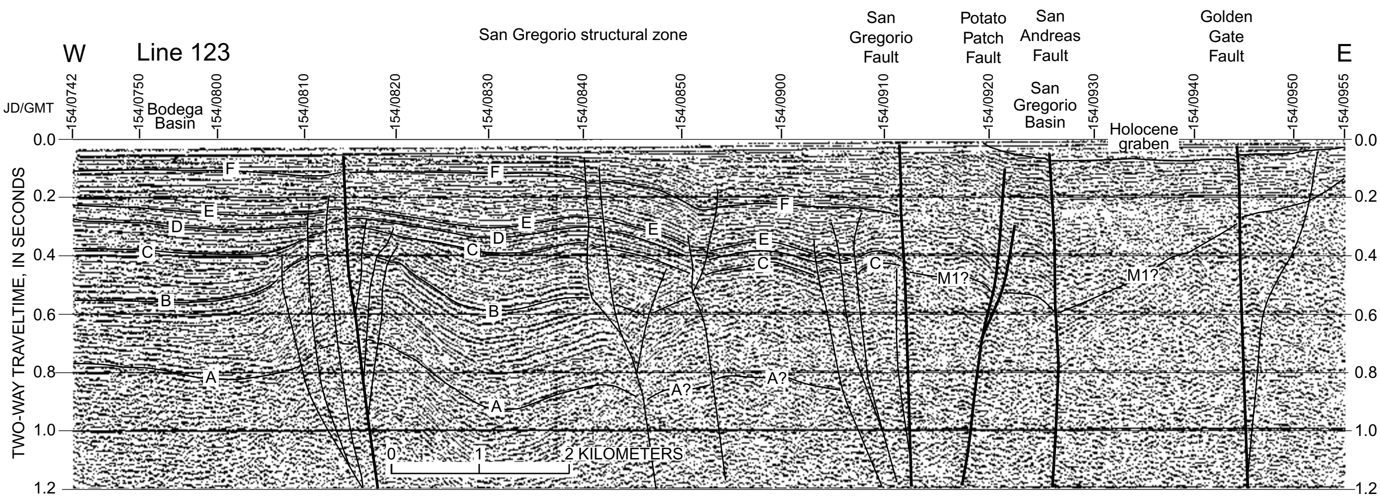


Figure 19.—Seismic line 123 northwest of the Golden Gate (figs. 2, 3, 9–12). The San Gregorio structural zone is now almost 8 km wide and is buried beneath from 0.3- to 0.4-s two-way traveltime of relatively undeformed strata. A Holocene graben is apparent at east end of line between the Potato Patch/San Andreas Faults and the Golden Gate Fault. The San Gregorio, Potato Patch, and San Andreas Faults are not characterized by clearly broken, discontinuous, or terminating seismic reflectors and so are poorly defined. Faults are herein considered to be mainly active as normal faults in this part of basin, with subsidence creating the San Gregorio Basin. Faults would thus not be throughgoing major transform faults. Instead, most or all transform motion has probably transferred over to the Golden Gate Fault. Same seismic-horizon annotations as in figures 13 and 14.

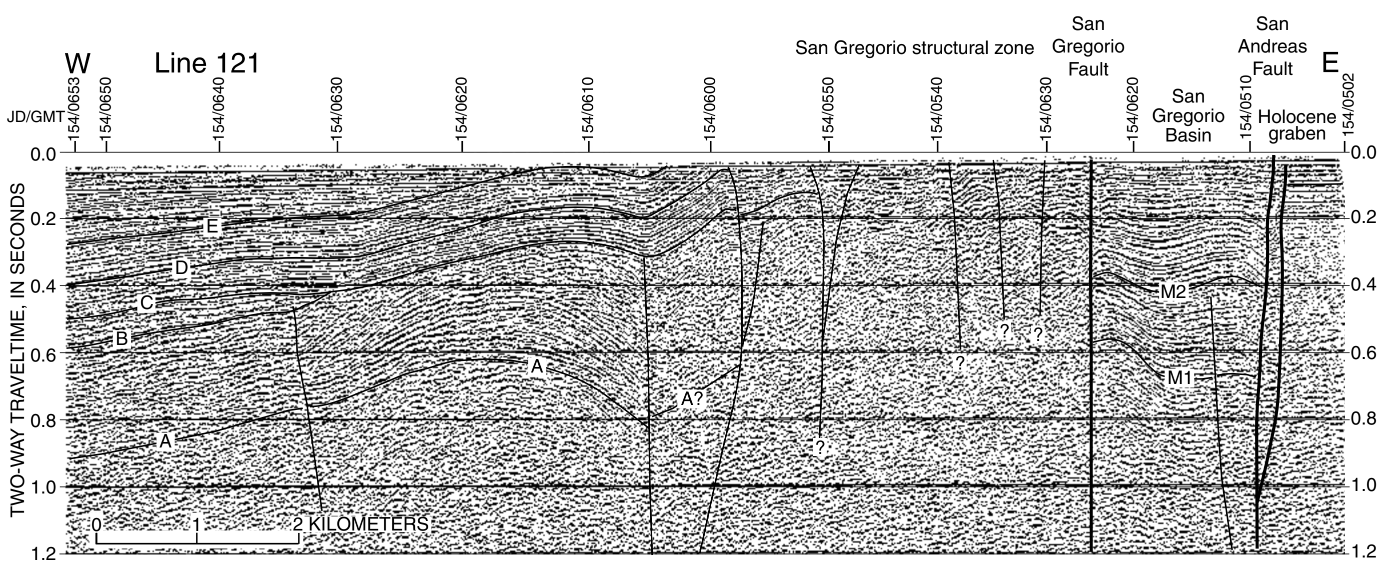


Figure 20.—Seismic line 121 about 5 km south of Bolinas Lagoon (figs. 2, 3, 9–12). Uplift begins to affect northern part of study area (fig. 1) as offshore section is uplifted onto the onshore Point Reyes peninsula. The San Gregorio and San Andreas Faults are much more distinctive than on lines farther to south (figs. 18, 19); fault traces are well defined by discontinuous or terminating seismic reflectors. Seismic horizons M1 and M2 are not definitively tied to lines farther to south and are projected on the basis of seismic reflections. Same seismic-horizon annotations as in figures 13 and 14.

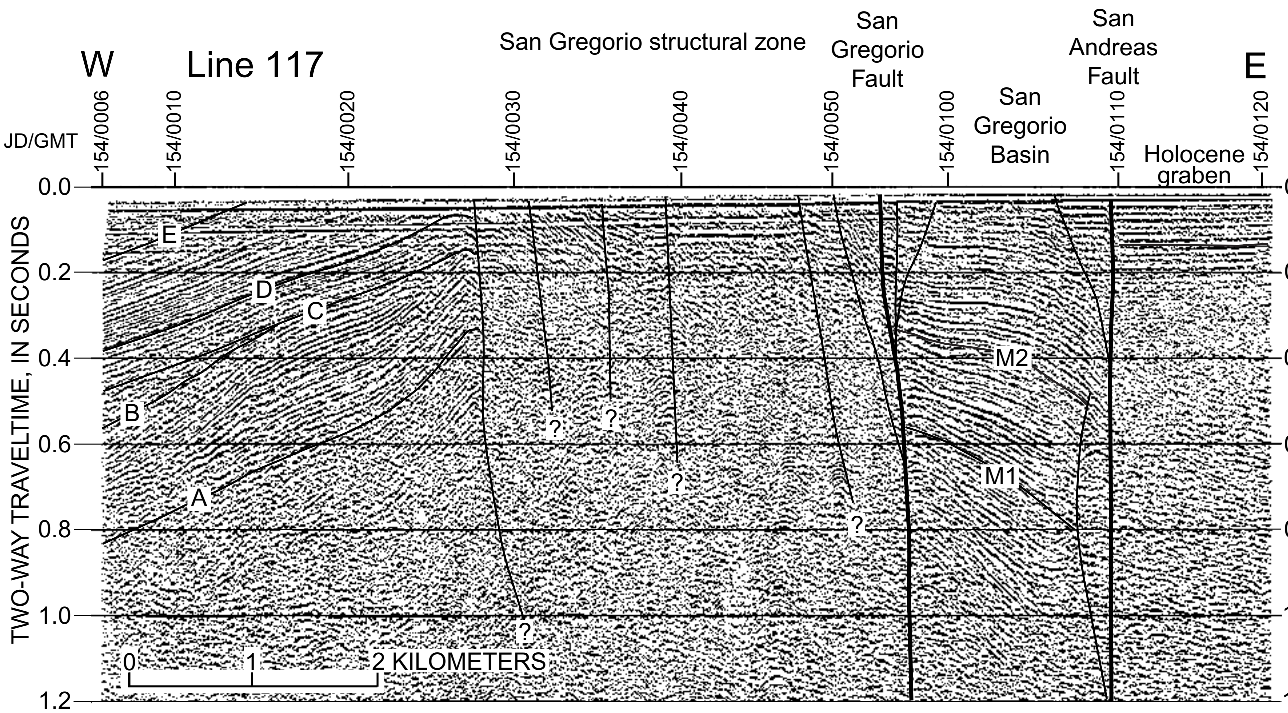


Figure 21.—Seismic line 117 about 5 km south of Bolinas Lagoon (figs. 2, 3, 9–12). Section of line east of the San Gregorio Fault partly overlaps seismic line 121 (see fig. 20). Line shows continuing uplift of section onto the Point Reyes peninsula, as well as well-defined San Gregorio and San Andreas Faults. Seismic horizons M1 and M2 are not tied to lines farther to south, and are projected on the basis of seismic reflections. Same seismic-horizon annotations as in figures 13 and 14.

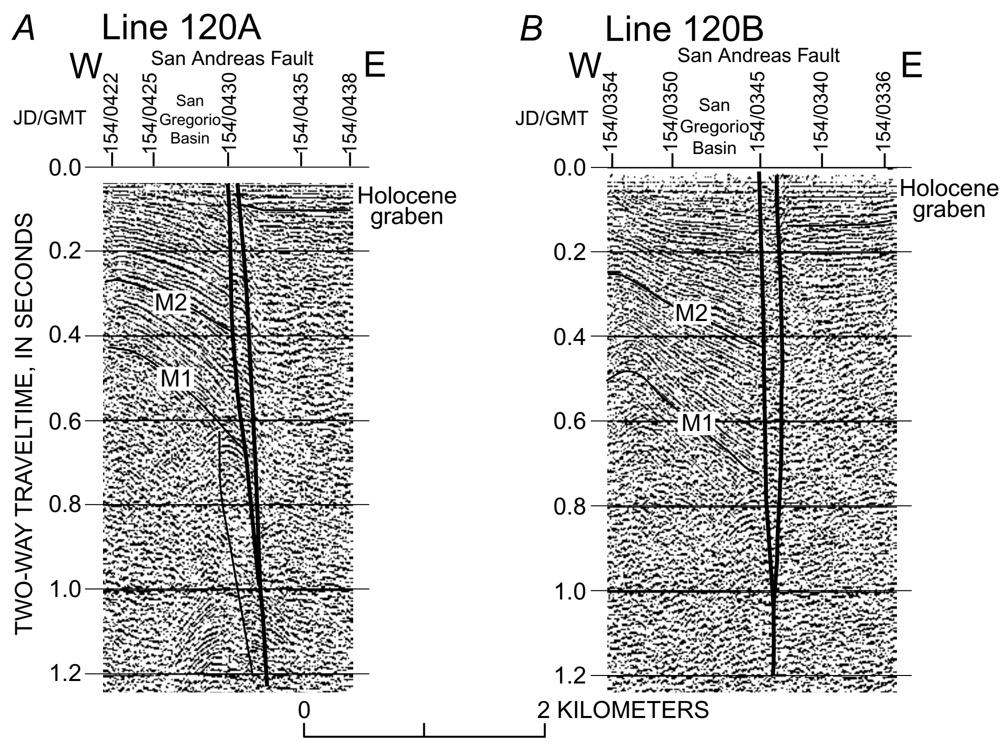


Figure 22.—Seismic lines 120A (*A*) and 120B (*B*), 2 and 3 km, respectively, south of Bolinas Lagoon (figs. 2, 3, 9–12), which are closest lines we were able to acquire near lagoon. The San Andreas Fault is well defined as a dual strand on both lines, yet horizons could be easily carried across fault—for example, note seismic reflection associated with horizon M2, suggesting only a small offset on fault. As on seismic lines 121 (fig. 20) and 117 (fig. 21), seismic horizons M1 and M2 are not tied to lines farther to south and are projected on the basis of seismic reflections. Same seismic-horizon annotations as in figures 13 and 14.

locally deformed and are eroded and truncated at horizon A. Deformation is most apparent at the west end of the seismic lines (for example, seismic line 110, figs. 16; seismic line 107, fig. 17), where dipping beds are clearly truncated at about 0.65- to 0.70-s two-way traveltime. Near the San Gregorio structural zone, units are largely conformable across horizon A. The onshore Monterey Formation is similarly separated from overlying Late Miocene and younger formations by an unconformity. Following Cooper (1973) and McCulloch (1987, 1989), we correlate horizon A with the top of the Monterey Formation. Units above the unconformity, then, are age equivalent to the onshore Santa Margarita Sandstone, the Santa Cruz Mudstone, the Purisima Formation, and the Merced Formation.

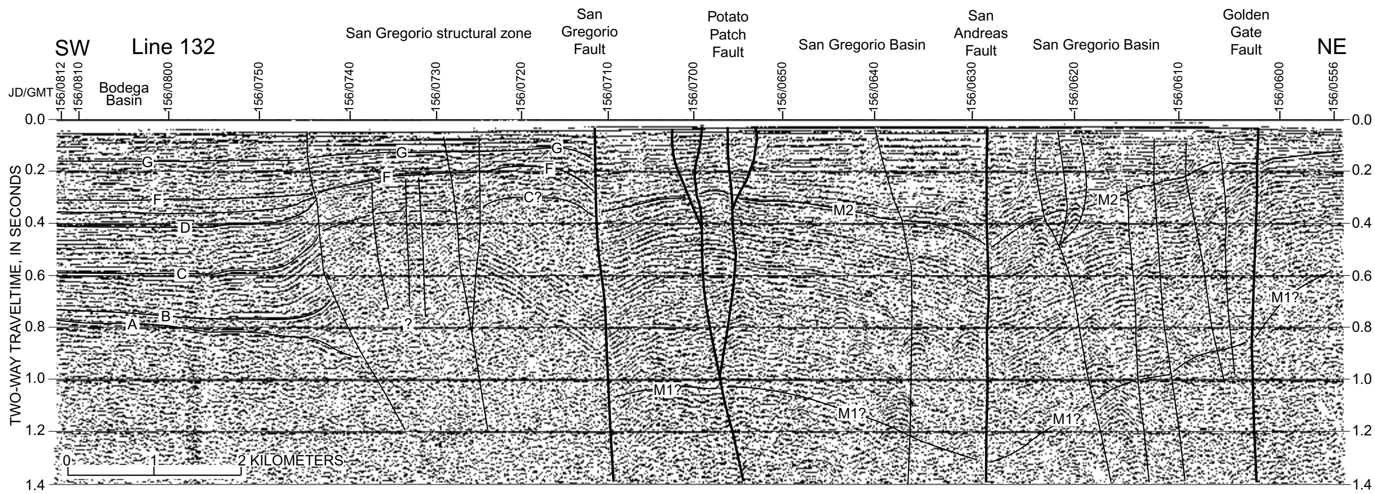


Figure 23.—Seismic line 132 southwest of the Golden Gate (figs. 2, 3, 9–12). Line shows maximum thickness of the San Gregorio Basin that is visible on seismic-reflection records, and serves as a partial tieline to several other lines that allow mapping of seismic horizons M1 and M2 in central part of the San Gregorio Basin. Line is plotted from southwest (on left) to northeast (on right) so that tectonic features can be easily compared to features on west-trending seismic lines. Same seismic-horizon annotations as in figures 13 and 14.

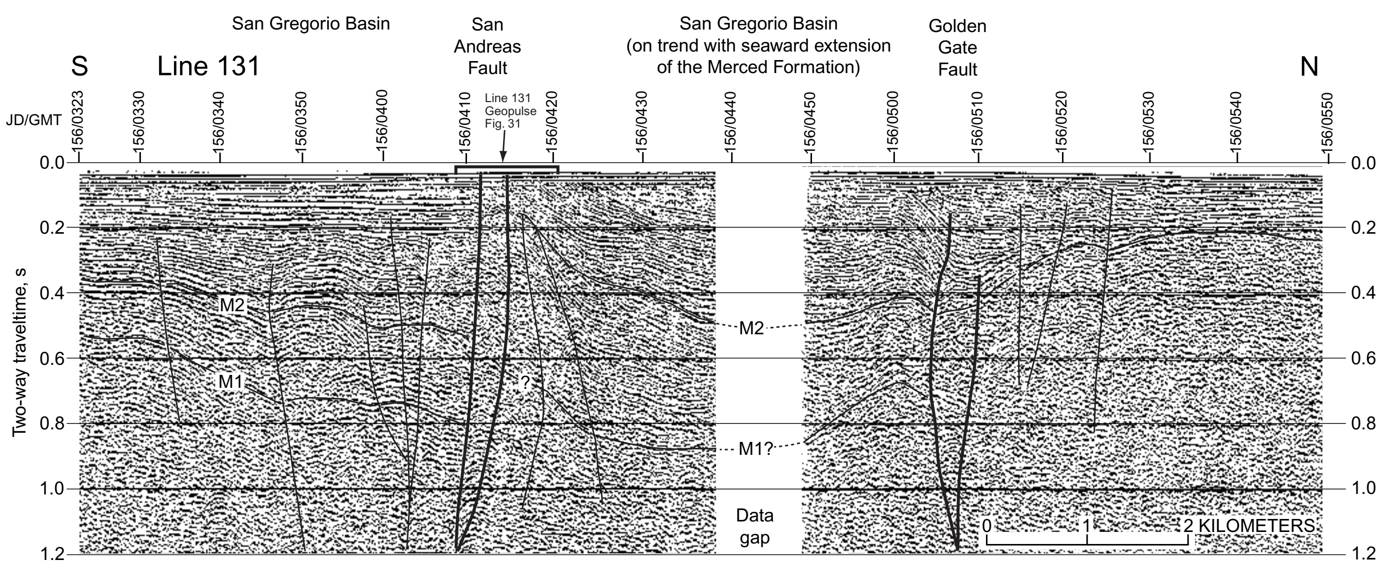


Figure 24.—Seismic line 131 across the Golden Gate and San Andreas Faults (figs. 2, 3, 9–12), at closest approach to land on this cruise. Section visible on seismic-reflection record is nearly identical to that visible onshore in seacliffs, with north-dipping beds near the San Andreas Fault, relatively flat lying beds between the two faults, and a monocline over the Golden Gate Fault. Major difference is that onshore dips are at least 30º steeper than those on this nearby offshore line (3 km away). We believe that this substantial uplift within a very short distance is caused by rotation and uplift of section between the San Andreas and Golden Gate Faults (see figs. 27, 28). Line is plotted from south (on left) to north (on right) so that tectonic features can be easily compared to features on west-trending seismic lines. Direction of line is reversed in figure 28 for comparison with onshore stratigraphic section of Clifton and Hunter (1987, 1991). Same seismic-horizon annotations as in figures 13 and 14.

Numerous local and regional unconformities, shown here as horizons B through G (figs. 15, 16, 18, 23), are present within the offshore section. We cannot correlate these unconformities to unconformities within onshore sections. On the basis of correlations with McCulloch's (1987, 1989) interpretations, the strata above horizon C are approximately Late Pliocene and younger and probably correspond to the upper part of the Purisima Formation and, at least in age, partly to the Merced Formation. We also cannot correlate any of these seismic horizons with those in the San Gregorio Basin because we are unable to unequivocally trace seismic reflectors across the San Gregorio Fault. Independent stratigraphic or age control is needed to make such a correlation.

Structure-contour maps constructed on horizons A and C show the configuration of strata in the Bodega Basin (figs. 9, 10). Both horizons can be mapped with a high degree of confidence throughout the basin because seismic reflectors are continuous and good tielines exist.

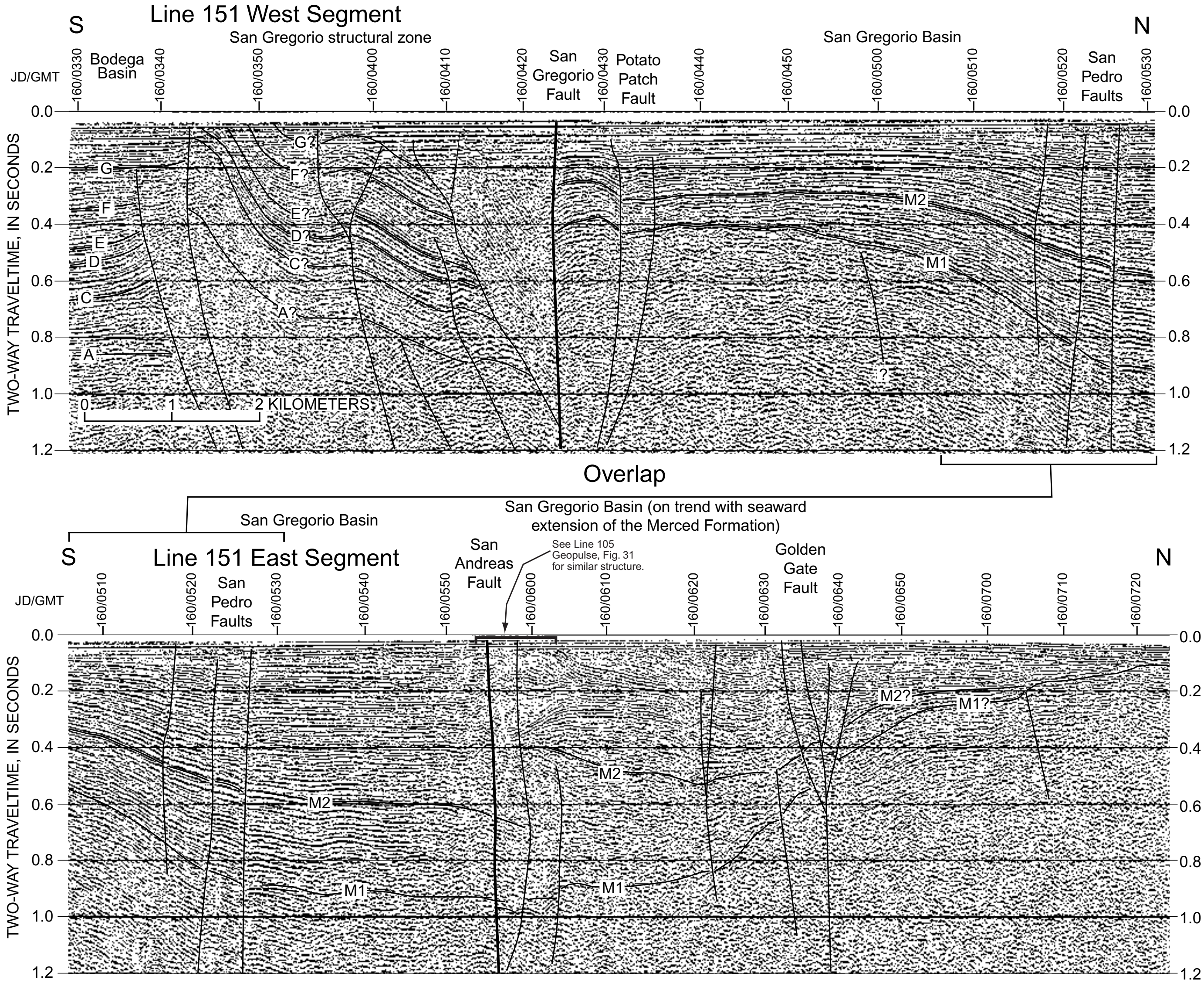


Figure 25.—Seismic line 151 south of the Golden Gate (figs. 2, 3, 9–12). Line is a tieline that allows mapping of seismic horizons through south end of seismic grid. Seismic section spreads out appearance of structures in the San Gregorio structural zone because it crosses structural zone at an angle of about 45º. Faults in structural zone are clearly thrust faults, probably rooted in the San Gregorio Fault. Structure between the Golden Gate and San Andreas Faults is similar to that visible on seismic line 131 (see figs. 24, 27). Line is plotted from south (on left) to north (on right) so that tectonic features can be easily compared to features on west-trending seismic lines. Same seismic-horizon annotations as in figures 13 and 14.

Seismic Stratigraphy Between the San Gregorio and Golden Gate Faults—the San Gregorio Basin

In the seismic-reflection data east of the San Gregorio Fault, a sedimentary section at least 1,300 to 1,500 m thick (figs. 13–25; approx 1.3–1.4-s two-way traveltime in the seismic-reflection data) is imaged in the fault-controlled San Gregorio Basin. The seismic-reflection data show relatively continuous seismic reflections south of seismic line 107 (fig. 2), and tielines between the east-west seismic lines allow a high degree of confidence in correlations from line to line. North of seismic line 107 (fig. 2), however, no tielines are available, and our interpreted correlations are based on matching the acoustic characteristics of the seismic reflections from line to line—an inexact process. Thus, our confidence in the position of the mapped horizon is low. From seismic line 114 northward (fig. 2), seismic reflectors become less continuous to discontinuous and chaotic, no tielines exist, individual horizons are uncorrelatable between lines, and structure contours are based solely on the general form of the basin (formline contours). We changed contour horizons here because no continuous reflections are present below about 0.5-s two-way traveltime. Thus, the structure contours north of seismic line 114 serve only as a guide to basin form.

We mapped a seismic horizon, M1, at or near the base of strata in the San Gregorio Basin; the resulting structure contours (fig. 11) show the depth to that horizon below sea level. In the contoured area, water depths range from less than 10 m to about 30 m; the contoured horizon depth is therefore close to being an isopach map of strata in the San Gregorio Basin. In the shallow parts of the basin, the acoustic basement is a strong reflector. In the deep parts of the basin, below about 1,000- to 1,200-m depth, horizon M1 is not well defined, the contoured depth to the base of the strata is a minimum thickness, and basin strata could be substantially thicker.

We also mapped a second seismic horizon, M2, throughout the basin (fig. 12). This horizon, which is an unconformity throughout at least the central part of the basin (see seismic line 110, fig. 16), divides strata that thicken seaward into the San Gregorio Fault from strata that thin onto growing folds over the Potato Patch Fault and across the San Andreas Fault extension. The horizon thus dates the beginning of vertical deformation on both of these fault strands.

We do not know the age of strata in the San Gregorio Basin. We cannot directly tie the onshore outcrops of the Merced Formation to the offshore strata shown in the seismic-reflection data, because the offshore strata have not been sampled or dated, and we have no seismic tieline between onshore and offshore. If the Merced Formation was deposited in a stepover basin that formed between the San Andreas and Golden Gate Faults, as suggested by Hengish and Wakabayashi (1995), Zoback and others (1999), Jachens and Zoback (1999), and Jachens and others (this volume), then a fundamental tectonic discontinuity could be present between the onshore and offshore sections, possibly causing markedly different subsidence rates on either side of the discontinuity or leading to markedly different depositional settings. Therefore, we cannot straightforwardly assume that the strata of the Merced Formation and the San Gregorio Basin are equivalent.

We can, however, consider two possible end-member correlations. First, the slip rate on the San Gregorio Fault is about a third of the slip rate on the San Andreas Fault. If the Merced Formation and San Gregorio Basin strata were both deposited in transtensional strike-slip stepover basins (Jachens and Zoback, 1999; Zoback and others, 1999; Jachens and others, this volume), then presumably deposition would be about 3 times as rapid in the Merced Basin (opening at the San Andreas Fault slip rate) as in the San Gregorio Basin (opening at the San Gregorio fault rate). Thicknesses onshore would be about 3 times greater than coeval thicknesses offshore. Thus, the approximately 2 km of sediment in the San Gregorio Basin could have taken much longer to accumulate than the sediment in the Merced Basin, and could be substantially older.

For the second end member, our favored interpretation, we make a straightforward correlation of San Gregorio Basin strata with the Merced Formation, assuming that basin formation for both sets of strata started when motion on the Pilarcitos Fault stopped, and that onshore and offshore strata are equivalent. In figure 8, we show the simplified onshore section on the left (from Clifton and Hunter, 1987, 1991) and its conversion to two-way traveltime on the right. Then, in the thickest parts of the San Gregorio Basin, we assume that the onshore section provides an approximate correlation with the offshore section. The potentially useful part of this correlation is that horizon M2 in the seismic lines nearest shore (seismic line 131, fig. 24; seismic line 151, fig. 25) lies at a depth of about 0.4- to 0.5-s two-way traveltime and approximately corresponds to the angular unconformity and nearby bedding change (change from thick regressive-bedded sequences to thin sequences) observed in the onshore section. Thus, the unconformity visible in the basin could correspond to a time of changing depositional style recorded in the onshore section as well.

Structure and Offshore Faults

On the basis of previous work (Cooper, 1973; McCulloch, 1987, 1989) and new seismic-reflection data, the San Gregorio Fault separates the Bodega Basin to the west from the San Gregorio Basin to the east (figs. 1, 3). The two basins are affected by six active structural elements: the San Gregorio structural zone, the San Gregorio Fault, the Potato Patch Fault, the San Pedro Fault, the San Andreas Fault, and the Golden Gate Fault (fig. 3). The Pilarcitos Fault does not deform strata in the San Gregorio Basin above acoustic-basement horizon M1 and has not been an active tectonic feature during the formation of the San Gregorio Basin.

Bodega Basin

The Bodega Basin lies between the edge of the Continental Shelf and the San Gregorio Fault (figs. 1, 3, 9, 10; McCulloch, 1987, 1989). Rocks below horizon A have been deformed and truncated at the horizon (see figs. 13–17); structures in the pre-early Miocene rocks were mapped by McCulloch (1987, 1989).

Rocks above horizon A are little deformed west of the San Gregorio structural zone. Some doming occurs in these rocks over structural highs in the older rocks (figs. 13–15). Some relatively young deformation occurs off Point Montara and Point San Pedro just seaward of the San Gregorio Fault (figs. 13, 14), and minor faulting extends upward from older, buried structures, particularly in strata that overlie the most deeply buried parts of the San Gregorio structural zone (figs. 14–19).

Strata in the Bodega Basin above horizon A range in thickness from about 900 m near Bolinas to about 1,100 m at the south end of the study area (fig. 9). The strata thin to less than 600 m westward in the seismic-reflection data and continue to thin westward of our data set until they truncate against the Farallon Ridge at the edge of the Continental Shelf (see McCulloch, 1987, 1989). Within the post-horizon A sequence, strata between horizons A and B thicken northward from 200 to 250 m on the south to 400 to 450 m on the north. In contrast, strata between horizon B and the sea floor thin northward from more than 800 m on the south to 350 m on the north (figs. 13–25). Clearly, the depocenter for the basin shifted southward beginning at about horizon B time.

Onshore, on the Point Reyes peninsula, the total thickness of units above the Monterey Formation is estimated at as much as 2,500 m (Galloway, 1977; Clark and others, 1984, 1991), with about 2,000 m of Santa Cruz Mudstone and 500 m of Purisima Formation. Nowhere offshore south of Bolinas do we see so great a thickness of units above horizon A. Adjacent to and north of Point Reyes, Cooper (1973) and McCulloch (1987, 1989) showed offshore sedimentary deposits more than 2 km thick above the Monterey Formation, in general agreement with what is observed on the Point Reyes peninsula. They also showed sediment thicknesses in the Golden Gate area similar to what we see. Thus, units above horizon A thicken substantially northward and westward towards Point Reyes. Much of this thickening could occur between horizons A and B, as a continuation of the northward-increasing thickness observed in the seismic-reflection data near Bolinas.

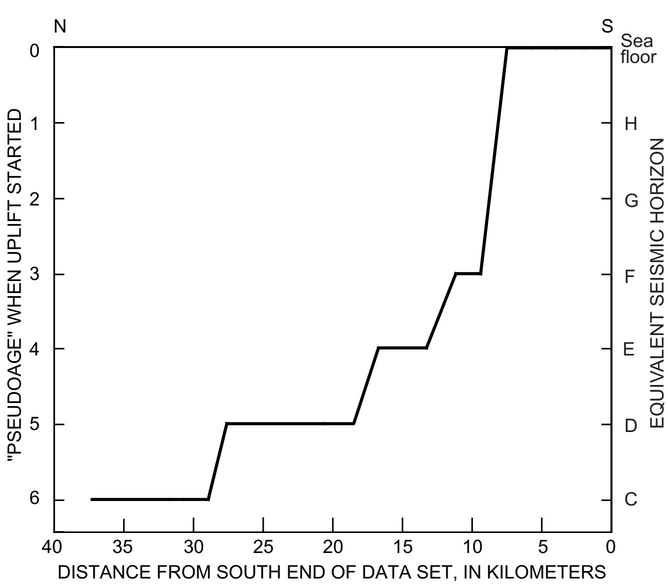


Figure 26.—Relative age of deformation of strata above horizon A in the San Gregorio structural zone versus distance from south end of study area near Point Montara (fig. 1), showing increasing age of deformation with offset. True age of strata above horizon A is unknown, but mapped seismic horizons can be used to give a “pseudoage” based on relative age of horizon. In this case, each horizon is assigned a number 0 (sea floor) to 8 (horizon A) from youngest to oldest, and that number is plotted against distance along the San Gregorio Fault from south end of study area (figs. 2, 3). Uplift at a horizon starts when thinning begins between that horizon and overlying horizon. Plot simply shows increasing age of deformation with offset.

San Gregorio Fault and San Gregorio Structural Zone

The San Gregorio Fault (fig. 3) is clearly a major tectonic boundary across the Gulf of the Farallones, as indicated by major differences across the fault in inferred basement-rock types, based on seismic-reflection and aeromagnetic data. Throughout its length across the Gulf of the Farallones, the San Gregorio Fault separates Early Eocene and younger strata in the Bodega Basin on the west from mildly deformed Late Pliocene(?) and Pleistocene rocks in the San Gregorio Basin on the east. The San Gregorio structural zone, which consists of the thrust-faulted strata on the west side of the San Gregorio Fault, is about 2 km wide near Point Montara and widens northward to at least 8 km near Bolinas.

In the Gulf of the Farallones region, the San Gregorio Fault can be divided into three segments with slightly different characteristics and direction. The first segment, from Point Montara to just south of the Golden Gate, from lat 37º33′ to about 37º46′ N. (figs. 1, 3; from seismic line 128 northward to seismic line 107, figs. 2, 13–17), trends about N. 17º W. and is a clearly defined, major break in the seismic-reflection data throughout the sedimentary section. At the south end of this first segment, the fault and associated structural zone crop out at the sea floor. To the north, a cover of flat-lying to gently dipping strata, as much as 300 m thick, overlaps the structural zone and appears to continue across the San Gregorio Fault with only minor vertical offset. Strike-slip offset, if any, cannot be determined from the available data. Throughout this segment of the fault, aeromagnetic data (fig. 4) also show a sharply defined fault (Jachens and Zoback, 1999; see Jachens and others, this volume), and the locations of the fault based on seismic-reflection and aeromagnetic data virtually coincide. In the seismic-reflection data, the fault is vertical in the uppermost 1.5 km of crust, and the aeromagnetic data indicate that it continues to be near-vertical down to magnetic basement.

The second segment, the next 6 km, of the San Gregorio Fault, from about lat 37º45′ to 37º48′ N. (figs. 1, 3; from seismic line 101 northward to seismic line 123, figs. 2, 18, 19), also trends N. 17º W., but displacement across the fault in shallow parts of the seismic-reflection data is less distinct than to the south, and here from 300 to 500 m of strata overlap the San Gregorio structural zone with only minor faulting. Along this second segment, the aeromagnetic data (fig. 4) do not show a basement break corresponding to the mapped trace in the seismic-reflection data but, instead, show a basement fault that is stepped eastward about 2 km, beneath the mapped position of the Potato Patch Fault. The aeromagnetic data also track the Potato Patch Fault for about 3 to 4 km both northward and southward of this segment of the San Gregorio Fault. Within this area, the adjacent San Gregorio structural zone begins to markedly widen, from 3 to more than 5 km.

The third segment of the San Gregorio Fault, from about lat 37º48′ N. to Bolinas (fig. 1), trends about N. 22º W. (fig. 3; from seismic line 123 northward to seismic line 119, figs. 2, 19–21), slightly more westerly than the segment to the south. The fault is well defined by seismic reflections that are truncated at the fault at all levels. The aeromagnetic data, again, do not track a basement fault lying vertically below this third segment of the San Gregorio Fault but, instead, partly track the Potato Patch Fault and partly lie between the mapped traces of the two faults. The main fault trace as mapped in the seismic-reflection data could dip east to join the magnetically mapped basement fault or the Potato Patch Fault; alternatively, the fault at depth could extend westward into nonmagnetic rocks below the San Gregorio structural zone. The structural zone continues to widen, to more than 8 km, and becomes more deeply buried, to more than 500 m.

Numerous thrust faults are present along each of the seismic lines crossing the San Gregorio structural zone. We have attempted to correlate these faults from line to line, but the structure changes rapidly in short intervals within the structural zone, and even with a 2-km line spacing, we are not confident that faults are correctly correlated between seismic lines. In figure 3, the faults are interpreted as long strands that trend subparallel to the San Gregorio Fault.

Within the San Gregorio structural zone, structures are tightly folded in the southern, narrow part of the zone but become much broader and less tightly folded northward. The thrust faults and amount of offset on these faults are well illustrated on seismic line 151 (fig. 25), which crosses the structural zone at an oblique angle at the south end of the study area (fig. 3), where the structural zone is about 2 km wide. On this line, seismic reflectors are correlated across the fault on the basis of acoustic characteristics. If the correlations are correct, we estimate that almost 700 m of uplift has occurred at the initial thrust fault (at JD/GMT 160/0340, fig. 25). Seismic lines 130/150 (fig. 14) and 103 (fig. 15) are near seismic line 151 and cross perpendicular to the structural zone, showing the tight folding that characterizes the south end of the structural zone.

The broadened San Gregorio structural zone to the north is illustrated on seismic lines 124 (fig. 18) and 123 (fig. 19), where a syncline is bracketed by thrust faults. On these lines, the deformation zone is almost 7 km wide. We cannot determine the amount of uplift across the faults because we cannot correlate seismic reflectors across the faults with any assurance, but the deformed section has clearly been uplifted and eroded, and subsequently has subsided and been covered by largely undeformed strata during its post-Miocene geologic history.

Near Bolinas, the entire sedimentary section in the Bodega Basin has been uplifted onto the Point Reyes peninsula, and this uplift is superposed on the buried structural zone, which now gets exhumed. In the seismic-reflection data, this uplift is first visible north of seismic line 123 (figs. 3, 19) as a doming west of the San Gregorio Fault over the San Gregorio structure zone. By seismic line 121 (figs. 3, 20), substantial uplift has occurred, forming a broad anticline. The intensity of folding increases northward on seismic lines 117 (fig. 21) and 120A and 120B (fig. 22). Mapped seismic horizons indicate that this uplift begins at least after horizon E time and, possibly, after horizon F time, as shown by the absence of thinning between horizons C, E, and F on seismic line 121 (fig. 20). Thus, the uplift is very young and is an active, ongoing process.

The structures in the San Gregorio structural zone show a northward progression in both age and depth of burial; the northern structures are significantly older than those at the south end of the structural zone, and are gradually buried beneath thicker strata than those to the south. This progression is shown by numerous unconformities within the structural zone where seismic reflections show pronounced thickening and thinning between unconformities. In the lower part of the section above horizon A, strata thicken into the fault zone. Thinning onto the structures indicates when structural growth began, and deposition of relatively undeformed strata over the structures indicates when uplift ceased. At the south end of the data set, structures deform strata at the sea floor (for example, seismic lines 128, 130/150, and 151; figs. 13, 14, 25). Northward, however, structures are buried under increasingly thick undeformed strata (see seismic lines 103, 110, 132, 107, 124, 123, from south to north, figs. 2, 3, 15–19, 23). In any one locality, however, initial basin subsidence and deposition are followed by thrust-fault uplift, and these uplifted strata, in turn, begin to subside once again.

The sequential formation of structures, from young on the south to old and deeply buried on the north, can be partly quantified by plotting a pseudoage of the time when uplift began versus distance northward along the San Gregorio Fault zone (fig. 26). Horizons A through H and the sea floor are numbered from 8 to 0 to serve as a proxy for age (thus, pseudoage), with “8” assigned to horizon A and “0” assigned to the sea floor. Initiation of uplift is then assigned the pseudoage when the seismic horizons switch from thickening into the fault zone to thinning over the growing structures. The plot of this pseudoage against distance northward along the fault (fig. 26; distance 0 km is on the San Gregorio Fault on seismic line 128 at the south end of the data set) shows a clear trend of earliest structural growth to the north (strata thin between horizons C and D, indicating that structural growth began after horizon C time) and latest structural growth at the south (structures still actively deforming the sea floor).

The structural zone appears to be an inherited feature that developed south of Half Moon Bay, and subsequently rides passively northward. We believe that these structures

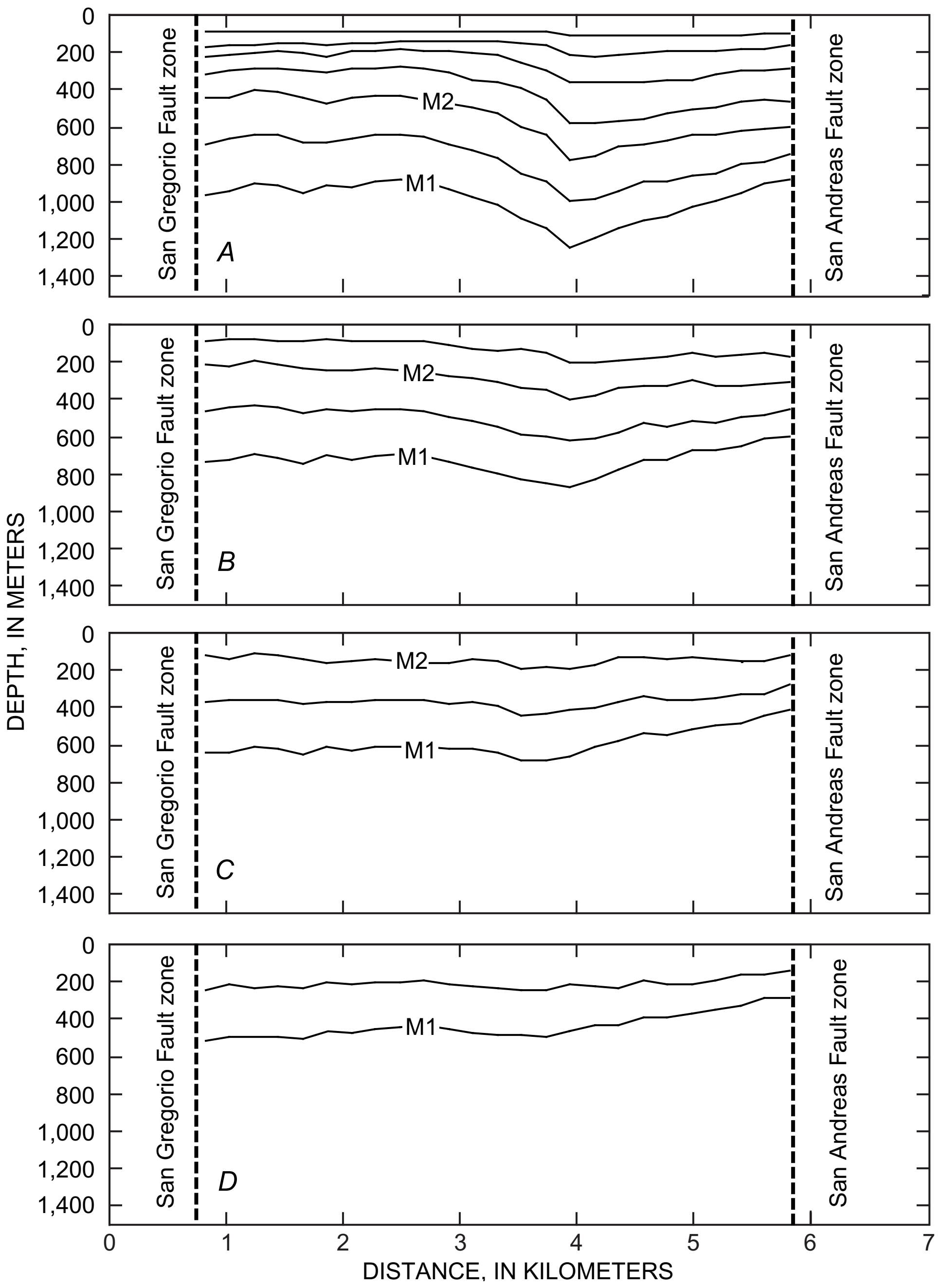


Figure 27.—Seismic horizons from seismic line 110 (fig. 16) between the San Gregorio and San Andreas Faults. *A*, Depth to seismic horizons, based on time-depth-conversion curve in figure 5. Vertical exaggeration, about 1.6 to 1. *B*, Reconstructed horizons after flattening on second layer. *C*, Reconstructed horizons after flattening on fourth layer. *D*, Reconstruction after flattening on horizon M2. Reconstructed horizons show that structural growth visible on seismic-reflection record did not begin until after horizon M2 time.

have formed in a transpressional strike-slip setting on the San Gregorio Fault south of Half Moon Bay. North of Half Moon Bay, the structures enter a transtensional tectonic environment and begin to subside.

Continuation of the San Gregorio Fault Onshore as the Seal Cove Fault

The relation of the San Gregorio Fault at the south end of the study area to the onshore Seal Cove Fault (figs. 1, 3, 4) is not defined by the seismic-reflection data. The offshore fault closely approaches the trace of the Seal Cove Fault but could either attach to the Seal Cove Fault or continue as a separate fault just offshore. A pronounced magnetic anomaly, however, continues from the mapped trace of the offshore San Gregorio Fault through the Seal Cove Fault (R.C. Jachens, written commun., 2001). Thus, almost certainly, the main trace of the San Gregorio Fault as mapped here also continues to join the onshore Seal Cove Fault, and faults of the San Gregorio structural zone cut offshore rocks west of the Seal Cove Fault.

Other unnamed minor faults lie just east of the main trace of the San Gregorio Fault (fig. 3). These faults have multiple strands (at least two mapped) just offshore but merge into a single strand northward. The fault mainly affects basement units but also causes small offsets and minor structures within overlying strata in the San Gregorio Basin (for example, seismic line 128, fig. 13; seismic lines 130/150, fig. 14). We interpret that this fault continues about 10 km to the north of Seal Cove, mainly as a concealed fault. This offshore fault trends onshore to either join or lie just east of the Seal Cove Fault. In the seismic-reflection data, we interpret the fault to be a small eastward splay off the San Gregorio Fault.

San Gregorio Basin

The boundaries of the San Gregorio Basin are controlled by the San Gregorio Fault on the west and by the San Andreas and Golden Gate Faults on the east (figs 3, 11, 12). Between these two faults, a triangular basin contains strata more than 1.5 km thick. The basin begins near Point San Pedro, widens to about 8 km near where the Golden Gate Fault trends onshore west of Lake Merced, narrows northward to about 6 km throughout much of the central part of the basin off the Golden Gate, and further narrows to about 3 km near Bolinas (figs. 3, 11, 12).

Strata in the San Gregorio Basin are cut or folded by four major faults, including, from west to east, the Potato Patch Fault (after McCulloch, 1987, 1989), the here informally named San Pedro Fault, the offshore San Andreas Fault (which is the offshore extension of the onshore Peninsular segment of the San Andreas Fault), and the Golden Gate Fault (fig. 3). The Pilarcitos Fault, a major onshore tectonic boundary, does not significantly disrupt sedimentary rocks above the seismic acoustic basement offshore.

The form of the San Gregorio Basin is shown by structure contours on horizons M1 and M2 (figs. 11, 12). From south to north, the depositional axis of the San Gregorio Basin lies along the San Pedro Fault, then shifts to the San Andreas Fault off the Golden Gate and continues mostly along the San Andreas Fault to Bolinas Lagoon. The thickest part of the San Gregorio Basin, between the San Andreas and Golden Gate Faults, trends onshore into the Merced Formation. Unlike onshore, however, where little or no Merced Formation is present west of the San Andreas Fault, strata in the San Gregorio Basin maintain a more or less constant thickness across the San Andreas Fault and extend to the San Gregorio Fault. Offshore, basin strata dip west; in contrast, onshore strata dip northeast, indicating that the onshore Merced Formation must lie on the east limb of an anticline which lies beneath or immediately offshore from the present shoreline.

At the south end of the basin, a shallow basement horizon extends northward from Point San Pedro (fig. 11). In this shallow basement region, little or no deformation is observed in basin strata above horizon M1 over the magnetically located Pilarcitos Fault. Minor deformation, however, is present over the San Pedro Fault over this shallow basement region (figs. 14, 15).

For about 10 km northward of Point San Pedro, the sedimentary section gradually thickens from less than 100 to about 500 m (dip, approx 2º–3º). Then, the dip of the basement surface steepens northward, and basin sediment thicknesses increase rapidly to more than 1,400 m over a northward distance of about 5 km (average dip, approx 10º). This thick section continues in the basin axis northward for at least another 15, possibly 20, km to near Bolinas (fig. 11). The maximum offshore sediment thickness could approach 2,000 m, as suggested by interpretations of seismic-refraction data (Hole and others, 1993; Holbrook and others, 1996; Tom Parsons, oral commun., 2001); we have insufficient acoustic-energy penetration to see this thickness on the seismic-reflection data. On east-west seismic-line crossings, strata in the San Gregorio Basin extend at least 2 km eastward of the Golden Gate Fault, where they range from 0 to 300 m in thickness in the Golden Gate area. To the north, basin rocks are uplifted onto the Point Reyes peninsula and may correlate with the 150-m-thick Merced Formation mapped onshore.

Structural relief in the San Gregorio Basin has resulted from differential subsidence of basement rocks. A major structural high underlies the central part of the basin west of Lake Merced between the San Gregorio and Potato Patch Faults (seismic line 110, fig. 16) and between the San Gregorio and San Andreas Faults (seismic line 132, fig. 23). The structure bends steeply upward from the San Pedro Fault west of Lake Merced (fig. 11). This structure could have resulted from compressional deformation, an interpretation that seems unlikely in a basin where the general tectonic regime is one of rapid subsidence. The structural high corresponds to a negative magnetic anomaly associated with basement rocks of the Salinia terrane, and the adjacent structural low correlates with a high, positive magnetic anomaly, characteristic of basement rocks of the Franciscan terrane. The deformation history of basin strata (as discussed below) indicates that the structural high resulted from differential subsidence within the developing basin—that is, the Salinia block beneath the high has stayed relatively high, and the adjacent Franciscan block has subsided.

The structural high dies out northward, and west and north of the Golden Gate, a somewhat simpler basin architecture prevails (figs. 11, 12), as strata dip into the basin and truncate against the San Gregorio Fault (seismic line 107, fig. 17). Farther north, strata rise slightly from a basin axis just east of the Potato Patch Fault into the San Gregorio Fault (seismic lines 123, 124, figs. 18, 19). In the 10-km stretch south of Bolinas, dips between the San Gregorio and San Andreas Faults steepen northward, reaching a maximum dip of about 12º–14º E. on seismic lines nearest Bolinas.

The seismic stratigraphy indicates that the San Gregorio Basin initially formed as a half-graben, with subsidence occurring along the San Gregorio Fault during deposition of the lower two-thirds of the basin fill. Formation of the faults and the structural high within the basin was relatively late in the basin history. Horizon M2 divides strata that thicken westward into the basin from strata that thin westward over a developing structure, a relation best seen on seismic line 110 (fig. 16). In figure 27, we converted seismic horizons on seismic line 110 to depth, then sequentially flattened each depth-converted horizon. The reconstructed section before horizon M2 time (fig. 27*D*) shows that the strata below horizon M2 are relatively flat lying and thicken from east to west into the San Gregorio Basin. Only after horizon M2 time does significant vertical deformation begin along any of the major basin-cutting faults—the Potato Patch, San Pedro, or San Andreas Fault. During deposition of about the upper third of the strata in the San Gregorio Basin, part of the basin basement continued to subside, while another part of the basement stayed high, producing the structural high at the south end of the basin (seismic line 110, fig. 16). Thus, horizon M2 marks the time of initiation of basin deformation. Only during deposition of the upper third of the basin strata did the faults become a significant factor in basin development. The surprising conclusion is that about two-thirds of the sedimentary section in the San Gregorio Basin was deposited before the Potato Patch, San Pedro, or San Andreas Fault actively began to deform the strata.

Holocene Graben

A small active graben is present in the north third of the San Gregorio Basin, beginning at about seismic line 124 and continuing to Bolinas Lagoon (fig. 3). The maximum sediment thickness in the graben is about 100 m on seismic line 123 (fig. 19). On seismic line 124 (fig. 18), the graben is a broad low, without well-defined east or west boundaries; but on seismic lines 123 and 121 (figs. 19, 20), the faults forming the west boundary are well defined. On seismic lines 124 through 115 (fig. 3), the bounding fault on the west is the Potato Patch Fault. From there northward to Bolinas Lagoon on seismic lines 114 through 121 (fig. 3), the Potato Patch merges with the San Andreas Fault, which is the bounding fault. The Golden Gate Fault forms the east boundary.

Cooper (1973) and McCulloch (1987, 1989) assumed that this graben formed during the Holocene, because sea-level rise would presumably have eroded an older feature. Cooper also noted, and we concur, that the material filling the graben is acoustically transparent and probably consists of fine sand or mud. The unit probably represents shallow-water Holocene shelf deposits.

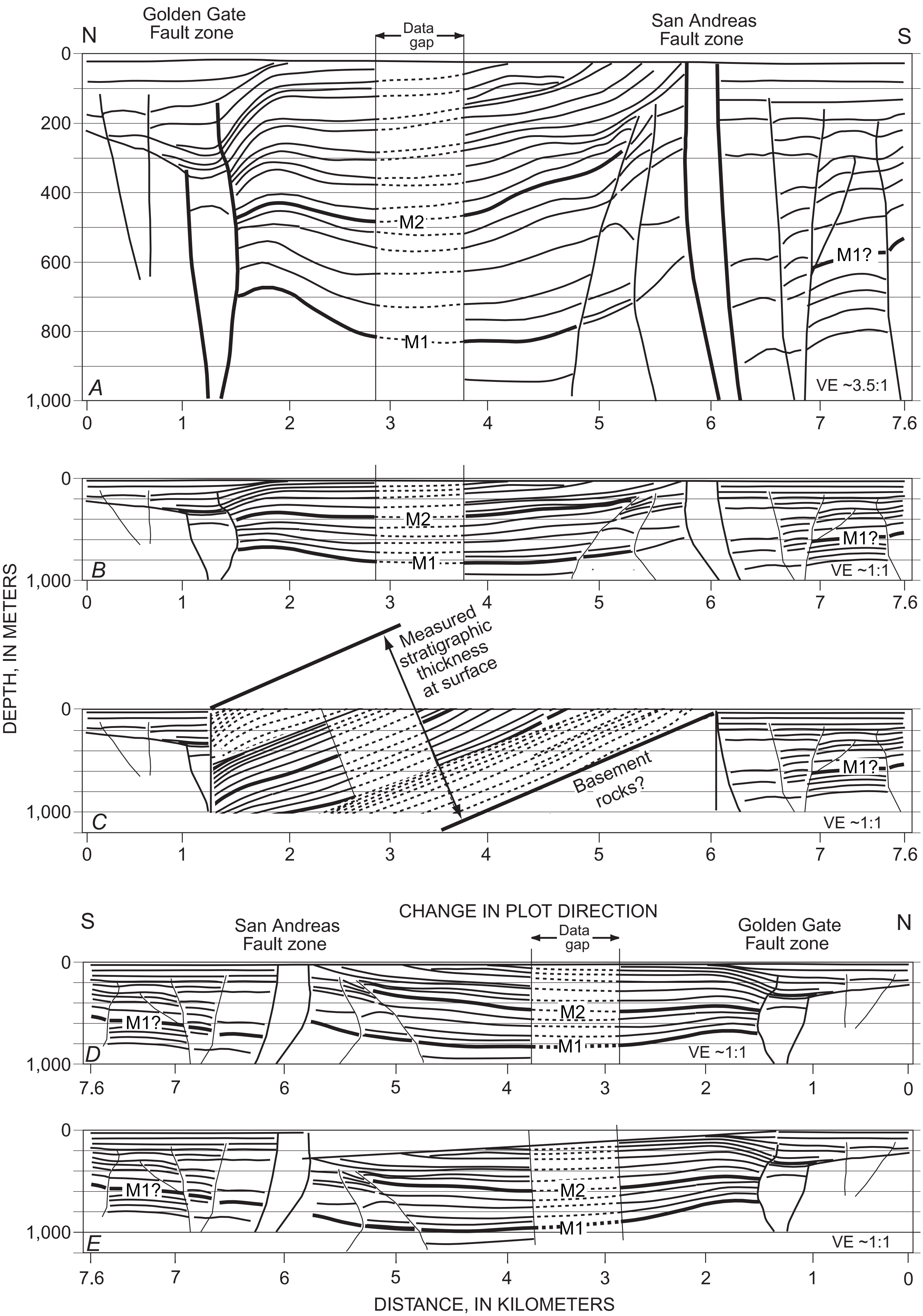
The presence of the graben indicates that the faults cutting the San Gregorio basin are still active—although the graben only shows vertical motion and does not give information on possible horizontal offset. Although the Holocene graben shows unequivocal ongoing subsidence between the San Gregorio-Potato Patch-San Andreas-Golden Gate Faults, uplift of young strata is occurring onto Point Reyes immediately to the west across the San Gregorio Fault and adjacent to the subsiding graben (for example, seismic line 121, fig. 20; seismic line 117, fig. 21). Thus, similar to the area near Daly City, both uplift and subsidence are occurring within a very short distance.

Potato Patch Fault

The Potato Patch Fault is a curvilinear fault that runs diagonally between the San Gregorio and San Andreas Faults (fig. 3), branching off the San Gregorio Fault on the south and joining the San Andreas Fault on the north. The Potato Patch Fault starts just south of the seismic-line 103/151 intersection (fig. 3, approximately at lat 37º37′ N., long 122º35′ W.), then trends north (figs. 15–17, 25). The fault lies along the east side of the magnetic high associated with the San Gregorio Fault on the south end (fig. 4) and trends along a separate conspicuous magnetic-anomaly boundary for the rest of its length. On the basis of the aeromagnetic data (fig. 4), Jachens and Zoback (1999) and Jachens and others (this volume) interpret the fault as continuing almost to Bolinas (fig. 2). On the seismic-reflection records, the shallow fault either dies out near lat 37º50′ N., south of seismic lines 121 (fig. 20) and 117 (fig. 21), or merges with the San Andreas Fault.

The southern segment of the Potato Patch Fault deforms strata in the San Gregorio Basin adjacent to a structural high, where the anticlinal high lies west of the fault, and double fault strands form a small graben along and east of the fault (seismic line 110, fig. 16). The amount of deformation decreases northward to only minor apparent offset by seismic line 107 (fig. 17). The north end of the Potato Patch Fault forms the west boundary of the Holocene graben on seismic lines from 124 northward to 114 (figs. 3, 18, 19); from seismic line 114 northward, the Potato Patch fault has died out or merged with the San Andreas Fault.

The Potato Patch Fault is currently active, as shown by deformation of the shallowest strata on the southern reaches of the fault and by the active graben margin formed by the fault in the northern reaches. As shown earlier, however, the fault was active in only a minor way during deposition of the



Golden Gate
Fault zone
N
Data
gap
San Andreas
Fault zone
S
M2
M1
M1?
A
VE ~3.5:1
B
VE ~1:1
C
Measured
stratigraphic
thickness
at surface
Basement
rocks?
VE ~1:1
CHANGE IN PLOT DIRECTION
S
San Andreas
Fault zone
Data
gap
Golden Gate
Fault zone
N
D
VE ~1:1
E
VE ~1:1
DEPTH, IN METERS
DISTANCE, IN KILOMETERS

lower two-thirds of the basin strata (fig. 27). In the seismic-reflection data, defined motion is dip slip, with the east side dropping down relative to the west side. Along the southern seismic lines crossing the fault, the Potato Patch Fault can be interpreted as a normal fault arising from the San Gregorio Fault. The data are not definitive, however, because the fault is mostly imaged as vertical in the upper 1- to 1.5-s two-way traveltime of data, and so alternative interpretations include that the fault could arise as a normal fault splay of the San Andreas Fault, or as a vertical fault caused by differential settling of basement blocks within the San Gregorio Basin. In any of these cases, the fault markedly affects the basement rocks. Seismic-reflection data with deeper penetration are needed to fully resolve the roots of the fault.

We cannot unequivocally determine whether a component of strike-slip motion exists on the Potato Patch Fault, although we would strongly expect such motion on a fault that ties two major strike-slip faults. We observe two possible indications of transfer motion along the Potato Patch Fault. First the south end of the Potato Patch Fault is located adjacent to the area where undeformed or mildly deformed sediment begins to cover the San Gregorio Fault, possibly because transform motion moves from the San Gregorio Fault to the Potato Patch Fault. Second, the structural low west of the Potato Patch Fault could be offset about 4 km north from the deepest part of the San Gregorio basin. We suggest, but cannot prove, that motion on the San Gregorio Fault transfers to the Potato Patch Fault, which then transfers the motion to the San Andreas Fault in the vicinity of Bolinas.

San Andreas Fault

The offshore extension of the San Andreas Fault begins where its Peninsular segment trends offshore at Mussel Rock (fig. 3). For about 12 km, from lat 37º40′ to 37º45′ N. off San Francisco, the fault trends about N. 34º W., then changes trend slightly to N. 30º W. for the 20-km stretch from lat 37º45′ to 37º55′ N. at Bolinas (fig. 2). Overall, it trends about N. 32º W., slightly more northerly than the average trend of N. 36º W. along the onshore Peninsular segment. For 5 km offshore of Mussel Rock, the fault trends along the northeast edge of a magnetic high (fig. 4). Jachens and Zoback (1999) and Jachens and others (this volume) interpret that the fault is active only in this first 5-km offshore stretch. From there northward, the aeromagnetic data do not require faulting of basement rocks anywhere along the San Andreas Fault except along a short (approx 4 km long) segment near seismic line 121 (fig. 4), but, instead, show block-bounding basement faulting along the Golden Gate Fault (fig. 4). Jachens and Zoback (1999) and Jachens and others (this volume) use these data, along with earthquake-epicenter information, to interpret a 3-km stepover in transform motion from the San Andreas to the Golden Gate Fault.

Seismic-reflection data across the San Andreas Fault off Lake Merced show a complex fault system. Nearshore, the fault has multiple splays (at least three; see figs. 11, 12; seismic line 151, fig. 25), and strata between the splays appear to dip steeply and be highly contorted. Strata east of the fault dip about 14º N. in the shallow section (see seismic lines 131, 151, figs. 24, 25, 28, 29), but on seismic line 151 (fig. 25), strata slightly deeper in the section dip south, forming a triangular bedding configuration (at GMT 160/0400, figs. 25, 29). This configuration could have resulted from a combination of early deposition and infilling into a narrow depositional low (channel or fault valley?), followed by uplift and tilting of the section between the Golden Gate and San Andreas Faults (as discussed below). Immediately west of the San Andreas Fault, strata are relatively undeformed.

The San Andreas Fault continues northward as a significant fault that deforms strata in the San Gregorio Basin. Basement subsidence along the fault is indicated by the coincident basin depocenter (fig 11), and near Bolinas, the San Andreas Fault is, with the Potato Patch Fault, a significant element in the formation of the Holocene graben. As with the Potato Patch Fault, however, the San Andreas Fault has disrupted beds crossing the fault only during or after deposition of the upper third of strata in the San Gregorio Basin (fig. 27). Structure contours and seismic reflectors can be carried across the fault with little or no displacement. On the basis of structural contours, the basin axis is little affected by the fault, although the deepest part of the basin may be slightly offset northward. Thus, only minor horizontal offset appears to have occurred within the San Gregorio basin along the presumed

Figure 28.—Cross sections across the Golden Gate and San Andreas Fault zones. *A*, Cross section along part of seismic line 131 (figs. 2, 3, 24), plotted north to south, in opposite direction from seismic line in figure 24, to better correlate with onshore stratigraphic section. Seismic-reflections are converted to approximate depth based in time-depth-conversion curve in figure 5. Vertical exaggeration, about 3.5 to 1. This line, which is closest to the Merced Formation exposed in seacliff, shows same structural features seen onshore, including monocline over the Golden Gate Fault and steepening dips near the San Andreas Fault. Major difference is that onshore dips of 25° to greater than 50° are significantly steeper than offshore dips, which are a maximum of about 10°–20°. *B*, Same cross section as in figure 28*A*, reduced to true scale and simplified (some horizons removed). *C*, Cross section between the Golden Gate and San Andreas Faults, tilted up 20° along a hingeline at the Golden Gate Fault. Dips in resulting cross section range from 40° near the Golden Gate Fault to 25°–30° near the San Andreas Fault. This section more closely matches dips in the onshore Merced Formation, although onshore dips are still steeper (see fig. 6). *D*, Same cross section as in figure 28*B*, plotted south to north to match seismic line shown in figure 24, and to match direction of seismic line 151 in figures 25 and 29. *E*, Segment in figure 28*D* between the Golden Gate and San Andreas Faults flattened by rotating about 3° downward along the San Andreas Fault, with a hingeline at the Golden Gate Fault. Reconstruction shows that about 250 m of uplift has occurred along the San Andreas Fault since deposition of horizon M1.

San Andreas strike-slip fault. We interpret this observation to mean that, in the basin, the San Andreas Fault may have been active as a strike-slip fault for only a short time. Any significant strike-slip motion along the onshore Peninsular segment of the San Andreas Fault appears to have been transferred elsewhere, presumably onto the Golden Gate Fault, during early San Gregorio Basin deposition.

Golden Gate Fault

The Golden Gate Fault extends offshore from Lake Merced and trends about N. 33º W. to Bolinas Lagoon (fig. 3). On the seismic lines that cross the fault just south of the Golden Gate (see seismic line 107, fig. 17), shallow basement rocks on the east are downdropped into the basin on the west, and overlying sedimentary rocks are deformed into a faulted monocline, similar to that seen onshore across the extension of the fault toward Lake Merced (fig. 7; Clifton and Hunter, 1987, 1991). North of seismic line 124, off the Marin Headlands, the fault is less clearly defined, relatively flat lying strata in the San Gregorio Basin are slightly offset by the fault, and the basement dips seaward (seismic lines 124, 123, figs. 18, 19). In these areas, little evidence exists for dip-slip motion, and so we infer that motion is mainly strike slip. The fault is characterized throughout its length by a coincident linear magnetic anomaly arising from the basement rocks (fig. 4; Jachens and Zoback, 1999; see Jachens and others, this volume).

Onshore to Offshore Transition—the Golden Gate and San Andreas Faults

The dominant tectonic mechanism forming the San Gregorio Basin is subsidence. Yet, within a very small distance

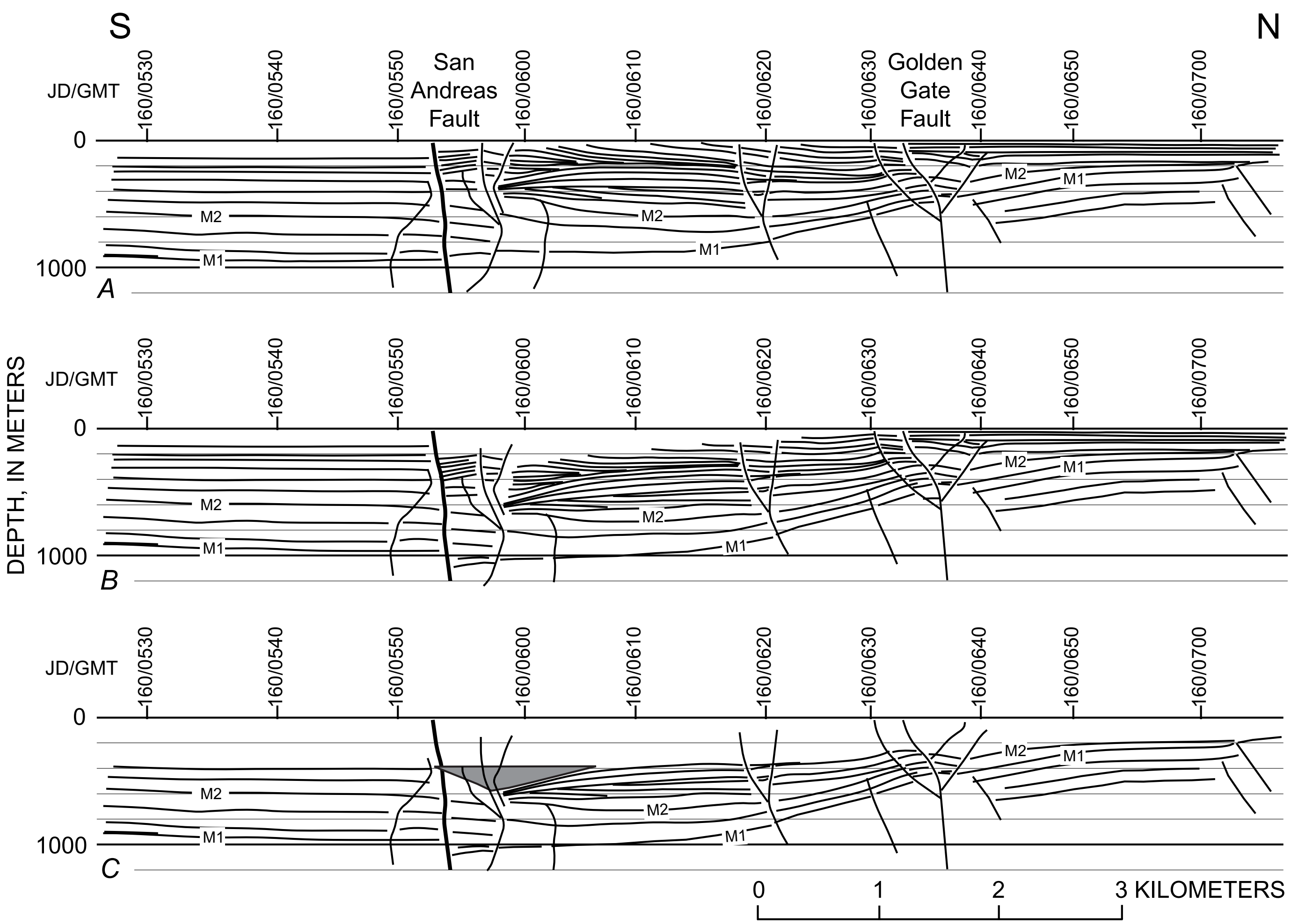


Figure 29.—Cross section along part of seismic line 151 across the Golden Gate and San Andreas Fault zones (see figs. 2, 3, 25). *A*, Cross section with two-way traveltime converted to depth by time-depth-conversion curve in figure 5. Approximately true scale. *B*, Same cross section with upper-sequence beds flattened by rotating with a hingeline at the Golden Gate Fault and rotating downward about 200 m along the San Andreas Fault. *C*, Same cross section with flattened upper beds removed. Dipping beds at the San Andreas Fault have appearance of a channel or valley with about 200 m of relief (shaded triangular area) that was subsequently filled in and covered by about 400 m of flat-lying strata. Resulting cross section is now being uplifted along the San Andreas Fault as a popup structure.

along the San Andreas and Golden Gate Faults, marked compressional deformation occurs locally. The Merced and Colma Formations have undergone recent extensive uplift, but within 3 to 4 km offshore, strata in the adjacent San Gregorio Basin are relatively undeformed and subsiding.

The seismic lines nearest shore show part of how this rapid change occurs. Three seismic lines approach within about 3 km of the onshore section (seismic lines 105/106 through a 90º bend, seismic line 131, and seismic line 151, figs. 2, 3, 24, 25). These lines cross the faults offshore about 4 km north along the Golden Gate Fault and about 6 km north along the San Andreas Fault (figs. 2, 3). Two of these seismic lines (131, 151) are shown as depth sections at 1:1 scale in figures 28 and 29.

Onshore, as mapped in the coastal cliffs, the Merced Formation is deformed into a gentle monocline just south of the Golden Gate Fault (figs. 6, 7; Clifton and Hunter, 1987, 1991). All dips are northeastward, in contrast to westward dips offshore. Strata in the Merced Formation dip 8º–14º east of the Golden Gate Fault (north end of exposed section). Dips steepen to more than 50º in the monocline off Lake Merced, and then the section flattens to relatively gentle dips on the west side of the Golden Gate Fault (south of the fault in the coastal cliffs), finally steepening to 40º–70º on the east side of the San Andreas Fault (north of the fault in the coastal cliffs). No unequivocal Merced Formation rocks are exposed onshore south of the San Andreas Fault (that is, on the west side of the fault), according to Clifton and Hunter (1987, 1991). All dips are northeastward, and the monocline indicates relative east-side-down deformation across the Golden Gate Fault.

Offshore, the observed structure in the three closest seismic lines (figs. 2, 3, 28, 29) is similar to that in the onshore section. As onshore, a monocline is present just south of the Golden Gate Fault, indicating relative east-side-down deformation. Strata adjacent to the San Andreas Fault are tilted upward. Along each of these lines, a small anticlinal structure is present below a depth of about 0.2- to 0.3-s two-way traveltime on the west side of and adjacent to the Golden Gate Fault. Along seismic line 151 (fig. 25), gentle doming is present in the youngest section adjacent to the San Andreas Fault. In contrast to onshore, however, the

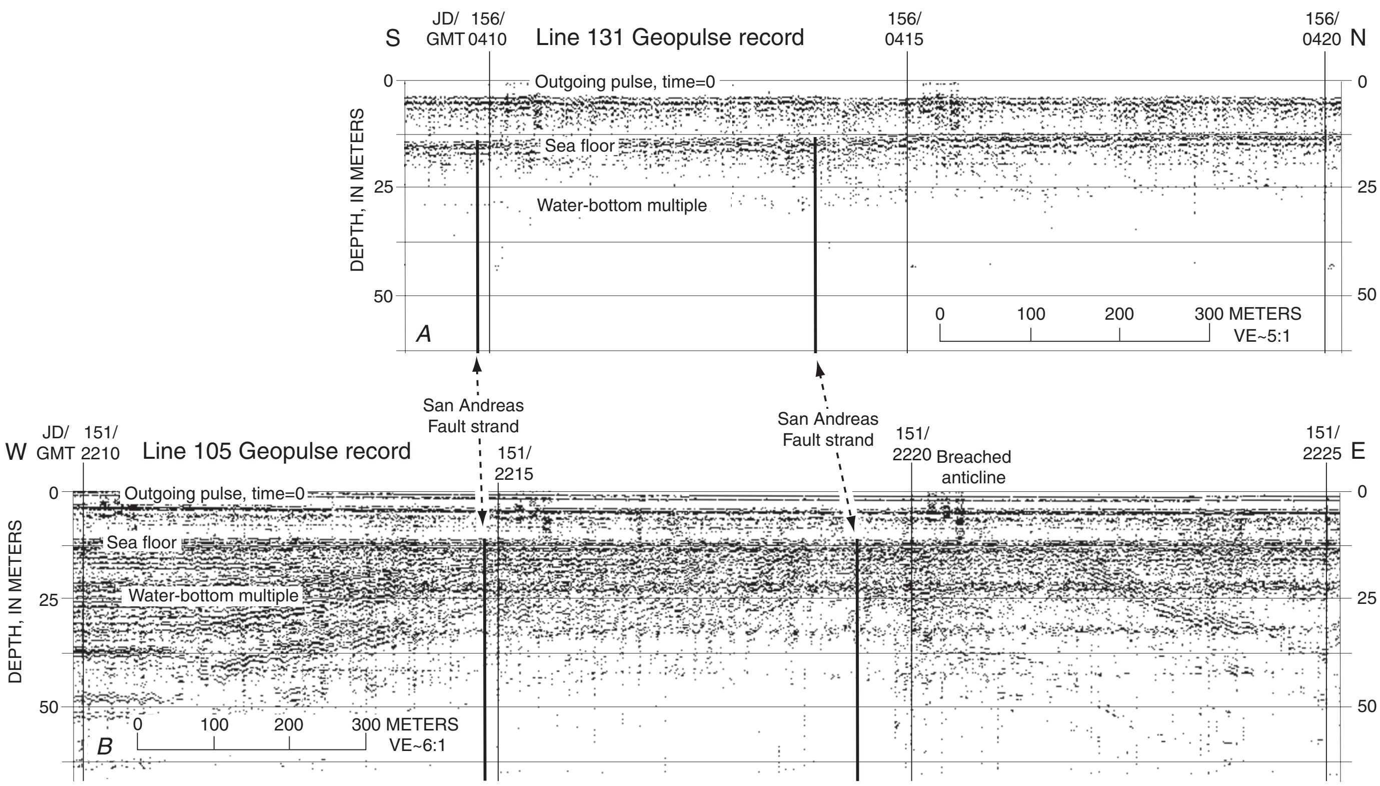


Figure 30.—Single-channel Geopulse profiles across nearshore part of the San Andreas Fault (see figs. 2, 3 for location). *A*, Part of Geopulse profile 131 (location shown on seismic line 131, fig. 24), showing strata dipping about 7º N. just north of the San Andreas Fault. These dipping beds outcrop at sea floor, but neither faulting nor outcropping beds have an offset at sea floor. *B*, Part of profile 105, showing a young anticline just north of the San Andreas Fault, breached at sea floor. Again, neither faulting nor deformed beds disrupt sea floor. Profile crosses the San Andreas Fault in same place as seismic line 151 (fig. 25). On both profiles 131 and 105, even youngest beds are somewhat deformed, indicating ongoing compressional deformation. Absence of offset at sea floor is probably due to erosion of friable beds by intense current and wave action.

steepest dips are all less than about 15º, as opposed to dips of 50º–75º onshore. Also, the dips are westward rather than eastward, indicating that an anticline is present between the shoreline and the seismic lines (fig. 11). The configuration of strata along the San Andreas Fault also is decidedly unusual, especially on seismic line 151 (figs. 25, 29), where downdipping, flat, and updipping reflectors overlie each other near the fault.

On Geopulse high-resolution seismic-reflection profiles through this area (fig. 30), faulting and compressional deformation extend to but do not disrupt the sea floor. On a single-channel Geopulse high-resolution profile along part of seismic line 131 (fig. 30*A*), strata dip north away from the eastern strand of the San Andreas Fault. Geopulse data along part of seismic line 105 (fig. 30*B*) show at least two fault strands, with an anticline present below the sea floor east of the fault. Deformation is clearly young and ongoing because even the youngest beds are tilted into the fault (for example, between JD/GMT 151/2215 and 151/2220). The absence of sea-floor offset is probably due to rapid erosion by currents and waves of unconsolidated to highly friable strata, similar to the strata immediately onshore in the Merced Formation.

By about 6 km north from shore along both the San Andreas and Golden Gate Fault strands, the structure changes markedly. Along seismic line 132 (fig. 23), dips are uniformly westward into the San Gregorio Basin, and the convoluted bedding observed on seismic line 151 (figs. 25, 29) along the San Andreas Fault has given way to strata that dip into the fault at a relatively gentle angle. Clearly, the tectonic regime is also now one of subsidence, rather than the uplift that characterizes the onshore Merced Formation and the strata shown on the nearshore lines.

A detailed look at the nearshore lines shows that the most likely cause of the observed deformation is rapid onshore and nearshore uplift along the San Andreas Fault, with a hingeline at the Golden Gate Fault. This uplift is most visible along seismic line 131 (figs. 24, 28). The San Andreas Fault cuts strata of the San Gregorio Basin, which are uplifted and truncated at the sea floor just north of the San Andreas Fault and then dip about 7º N. for 2 km. The strata flatten through the next 2 km, then dip 14º into the monocline over the next 500 to 1,000 m. In figure 28, the seismic-reflection data along seismic line 131 (fig. 28*A*) are converted to depth, with no vertical exaggeration (fig. 28*B*), so that a simple rotation can then give dips similar to those measured onshore in the Merced Formation (fig. 28*C*). If the section is rotated with a hingeline at the Golden Gate Fault and with upward motion on the San Andreas Fault, then dips can approach those seen onshore. For example, in figure 28*C*, rotation by 20º leads to dips of about 35º in the tilted section. This uplift is recent, because virtually all units below 0.1-s two-way traveltime (less than 75-m depth) in the seismic-reflection data thicken into the fault zones, rather than thin, as would happen once uplift started.

The dipping beds near the San Andreas Fault can be restored to a generally horizontal position by simply rotating the uppermost section downward along the San Andreas Fault, again with a hingeline on the Golden Gate Fault (figs. 28*D*, 28*E*). The amount of rotation needed is then a measure of uplift along the fault. On this seismic line, the total amount of uplift along the San Andreas Fault is about 250 m, and is clearly more for the deeper beds.

The geometry of the strata along seismic line 151 leads to the same conclusion of rotation and may explain the triangular configuration of strata on the north side of the fault (fig. 29). Here, the upper 300 m of strata (0.4 s) shows the deepest beds dipping about 7º–10º down, then merging upward with a generally flat lying reflector, overlain in turn by reflectors dipping about 7º–10º up. On this line, subsidence or depositional fill of a channel can explain the downdipping seismic reflectors. Downward rotation of the section along the San Andreas Fault by about 200 m flattens the uppermost reflectors (fig. 29*B*). If we then strip away the upper reflectors, we find that the downdipping reflectors form a channel or topographic low with about 200 m of relief (fig. 29*C*). If this topographic low is filled, followed by deposition and uplift, we obtain the reflection geometry of the strata observed in the seismic-reflection data. Thus, our interpretation is that along seismic line 151 (and seismic lines 105/106, which have a similar configuration), a topographic low was filled and then covered by about 400 m of strata, and the resulting package was uplifted and everted by rotation along the San Andreas Fault.

Another difference in the structure between onshore and offshore is that an anticline must be present nearshore. Rotation of the sedimentary section between the San Andreas and Golden Gate Faults can create the onshore structure seen in the cliff face, but both the cliff face and the seismic lines are close to being plungelines along an antiform that must be present nearshore. We were unable to acquire seismic lines near enough to shore to cross the axis of the presumed structure, and northward along the faults, the anticline may be absent because the deformation dies out.

Tilting and uplift may explain the onshore structure, but do not explain how the dominant subsidence of the San Gregorio basin observed elsewhere can convert to uplift in such a local domain. However, in the same area where motion along the San Andreas Fault steps over to the Golden Gate Fault, the tectonic pattern changes from subsidence to uplift and tilting. The section between the two faults is being squeezed upward by convergence between the two faults caused by different trends in the faults or by differing strengths of basement rocks on either side of the faults, as discussed below.

Pilarcitos Fault

Jachens and Zoback (1999) interpreted aeromagnetic data to indicate that the onshore Pilarcitos Fault continues on a trend of about N. 50º W. into the offshore basement and may merge with the San Gregorio Fault (fig. 4). No deformation is observed in 300- to 400-m-thick strata in the San Gregorio Basin that overlie the magnetically determined trace of the

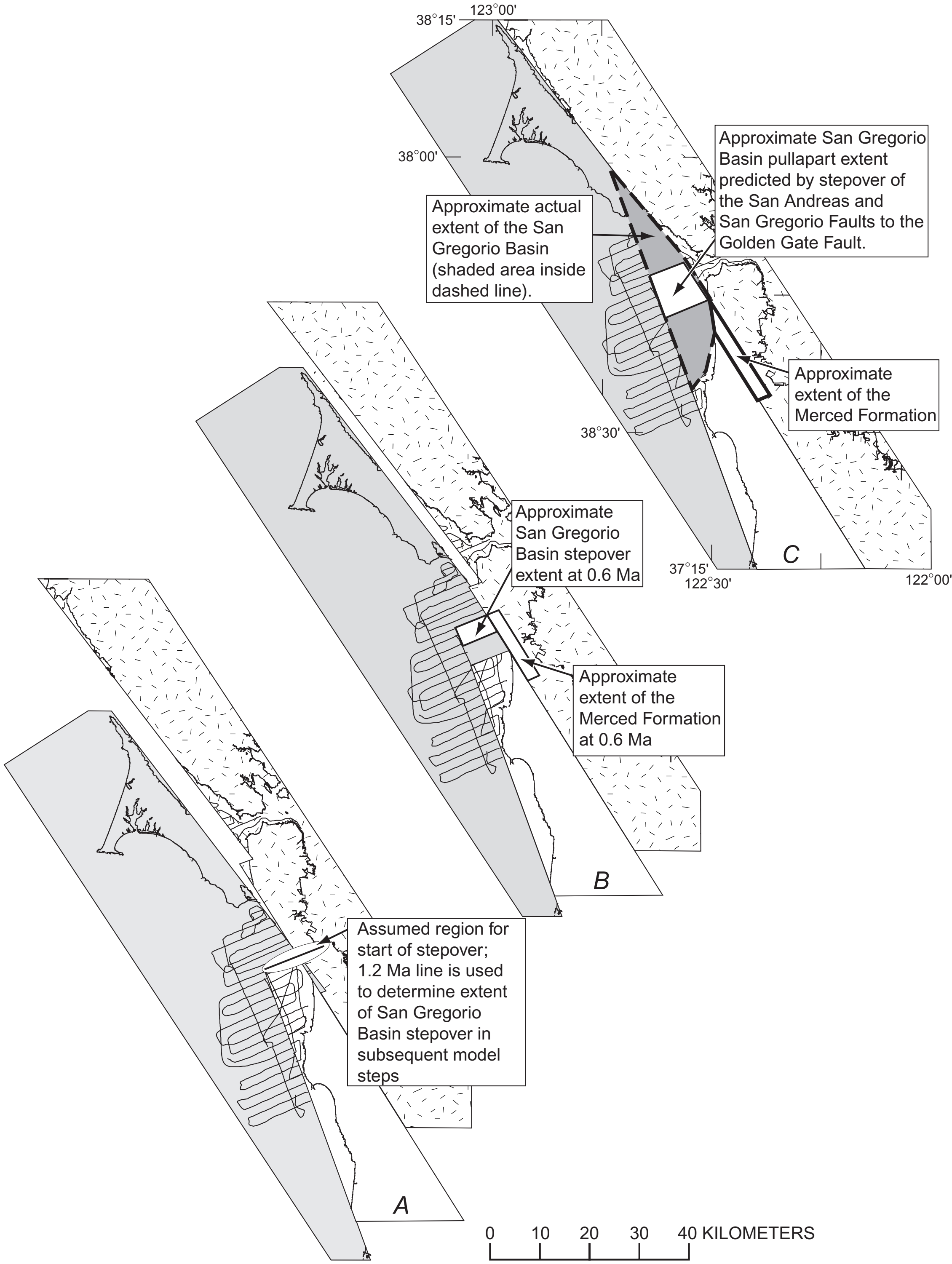


Figure 31.—Model for formation of the San Gregorio Basin as a transtensional strike-slip stepover basin, with all offset on the San Gregorio and San Andreas Faults transferring to the Golden Gate Fault. *A*, Initial position of the Pacific Plate, Pilarcitos block, and North American Plate at 1.2 Ma. Positions shown assume maximum offset of 22 km on the San Andreas Fault and an average slip rate of 18 mm/yr, giving an age of 1.2 Ma when this offset started, and assume an average slip rate of about 6 mm/yr on the San Gregorio Fault, giving about 8 km of offset over 1.2 Ma. *B*, Approximate position of blocks at 0.6 Ma. By that time, an 11-km-long, narrow pullapart basin has formed because of offset along the San Andreas Fault, and a 4-km-wide basin has formed as a result of motion along the San Gregorio Fault. *C*, Present, with a 22-km-long basin developed as a result of motion on the San Andreas Fault, and an 8-km-long basin as a result of San Gregorio motion. Area with maximum pullapart is in central part of the actual San Gregorio Basin; rest of basin's extent could be due to subsidence along north and south ends of pullapart basin.

Pilarcitos Fault. These strata are in the upper part of the basin, indicating no substantial deformation along the Pilarcitos Fault trend during at least the late stage of basin deposition. We cannot prove that the fault has been inactive throughout the entire time the San Gregorio basin has formed, although we believe that this interpretation is likely on the basis of the absence of deformation anywhere along the magnetically defined offshore extension of the fault.

San Pedro Fault

A minor fault that cuts strata in the San Gregorio Basin begins near Point San Pedro and trends N. 15º W. (fig. 3). In the seismic-reflection data, the fault has caused a slight vertical offset in strata just north of Point San Pedro (seismic lines 130/150, fig. 14), and deformation over the fault has created a small anticlinal structure a little farther north (seismic line 103, fig. 15). The fault extends into a major fold and fault at the base of the structural high in the western part of the San Gregorio Basin off Lake Merced (seismic line 110, fig. 16). Thus, at least locally, the fault controls basement-rock deformation, uplifting the horst-block anticline on the west and downdropping basement on the east beneath the basin depocenter. We herein informally name this fault the "San Pedro Fault." We cannot uniquely correlate this fault with an onshore fault. The San Pedro Fault cuts across the magnetically defined basement trends and is far from the magnetically mapped or inferred trace of the offshore Pilarcitos Fault (Jachens and Zoback, 1999; see Jachens and others, this volume), and so we do not believe that the San Pedro Fault is the offshore continuation of the Pilarcitos Fault.

Discussion

Previous studies (Hengesh and Wakabayashi, 1995; Wakabayashi and Hengesh, 1995, Jachens and Zoback, 1999; Zoback and others, 1999; see Jachens and others, this volume) concluded that strike-slip motion transfers from the San Andreas Fault to the Golden Gate Fault just offshore of Lake Merced and that this stepover led to the deposition of the Merced Formation along the San Francisco peninsula. These studies relied heavily on the observed eastward step of the San Andreas Fault rupture in the 1906 San Francisco earthquake from the Peninsular segment of the fault to the trace at Bolinas Lagoon, on magnetic anomalies that outline faults in basement units, and on the distribution of the onshore Merced Formation. So far, the stepover has been defined as occurring between the Peninsular segment of the San Andreas Fault and the Golden Gate Fault. With the additional details shown here in the structure of the San Gregorio Basin, we believe that a stepover also occurs as a result of the rapid transfer of motion from the San Gregorio Fault to the Golden Gate Fault.

The San Gregorio Basin formed by subsidence of basement rocks in an area bounded by the Golden Gate and San Gregorio Faults. Major basin subsidence began southwest of Lake Merced, starting where the basement of the San Gregorio Basin dips steeply north. South of this area, a gently undulating basement subsides from sea level to about 500-m depth. North of this line, the basement drops into the 1,400-m-deep basin depocenter. The ending point of the basin is approximately defined by an east-west line about 10 km south of Bolinas Lagoon, where the basin depocenter ends and basin strata rapidly begin to rise toward Bolinas (figs. 1, 2). This north boundary is significantly less well known, because the quality of the seismic information is not as good in this part of the San Gregorio Basin as it is to the south. Between these two boundaries, the deepest part of the subsiding basin is about 15 to 18 km long and narrows northward from about 7.5 to about 5 km wide.

This part of the San Gregorio Basin began to develop as a half-graben hinged at the Golden Gate Fault, with maximum subsidence along the San Gregorio Fault. During deposition of the lower two-thirds of the section (pre-horizon M2), the basin maintained this half-graben architecture. Only minor vertical deformation is observed in the strata deposited during this initial depositional period, on the basis of depth reconstructions of the seismic-reflection data. Significant horizontal offset, particularly on the San Andreas Fault, does not seem likely but is not completely precluded, on the basis of the general continuity of seismic reflections across the fault in most of the San Gregorio Basin and on the absence of offset of basin contours along the fault. During deposition of the upper third of the section (post-horizon M2), differential subsidence of basement rocks began along the Potato Patch and offshore San Andreas Faults, which led to the formation of horst-and-graben structure within the basin. These faults may have initiated as strike-slip transfer faults that also began to step motion from the San Gregorio Fault over to the Golden Gate Fault.

The subsidence history of the San Gregorio Basin includes subsidence along and over all the major faults that bound or cut the basin. North of the area where the basin basement begins to dip steeply north, the San Gregorio structural zone begins to get buried. Even the San Gregorio Fault is covered by sediment that seems continuous across the fault. Presumably, if the San Gregorio Fault were still an active transform fault with from 4 to 10 mm/yr of slip, it would remain a fundamental tectonic boundary with significant offset extending to the sea floor, as is visible on the southernmost seismic lines. Instead, the entire northern reach of the fault seems to be covered by only moderately disrupted sediment, and is mainly affected by subsidence.

Our interpretation is that the San Gregorio Basin formed as a result of a transtensional right stepover of motion from the San Gregorio Fault onto the Golden Gate Fault. The stepover may be accommodated by motion on the Potato Patch, San Andreas, and San Pedro Faults acting as strike-slip transfer faults. Motion on the San Gregorio Fault is rather slow; if this motion were partitioned onto the other faults, we might be unable to detect strike-slip motion from the basin structure but would see them as major areas of vertical deformation and subsidence. Other studies have concluded that a stepover occurs near Lake Merced (fig. 2), with motion transferring from the San Andreas to the Golden Gate Fault (Hengesh and Wakabayashi, 1995; Wakabayashi and Hengesh, 1995, Jachens and Zoback, 1999; Zoback and others, 1999; see Jachens and others, this volume), and so the concept is not original here; we extend this concept only to include motion on the San Gregorio Fault.

We can consider a relatively simple model (fig. 31) to gain insight into how the San Gregorio Basin and Merced Formation might have developed as a result of motions on both the San Andreas and San Gregorio Faults. Although the model does not explain the details of basin structure, it does show how movement of terranes along the fault has created the space needed for basin formation as pullapart basins. Variables for this model include fault-motion rates, the onshore extent of the San Gregorio Basin, and offset on the San Andreas Fault.

Initial deposition of the Merced Formation, opening of the San Gregorio Basin, initiation of motion on the Peninsular segment of the San Andreas Fault, and cessation of motion on the Pilarcitos Fault all began since about 3 Ma and could have begun approximately contemporaneously. The timing of all these events is poorly constrained. Offset on the Peninsular segment is about 22 km, based on correlating magnetic anomalies and source bodies across the fault (Jachens and Zoback, 1999; see Jachens and others, this volume). Suggested present-day offset rates range from 16 to 24 mm/yr (Hall and others, 1999; Jachens and Zoback, 1999; Zoback and others, 1999; see Jachens and others, this volume), giving a date of from 2 Ma to about 1 Ma for offset along the Peninsular segment. Long-term slip rates of about 7 to 12 mm/yr have been suggested by geologic studies (for example, Taylor and others, 1980) and could make offset as old as about 3 Ma. The age of the Merced Formation is poorly constrained from fossil dating but is most likely not much older than late Pliocene(?), about 1.8 m.y., and possibly younger (Clifton and Hunter, 1987, 1991). Subsidence of the San Gregorio Basin and motion on the Peninsular segment of the San Andreas Fault probably started no earlier than after the abandonment of the Pilarcitos Fault, inferred to be about 3 Ma by Parsons and Zoback (1997). Basin formation is presumably post-Pilarcitos motion and so is not affected by the Pilarcitos Fault.

For our model, we make the following assumptions.

1. Total offset on the Peninsular segment of the San Andreas Fault is 22 km (Jachens and Zoback, 1999; see Jachens and others, this volume). We arbitrarily chose a slip rate of 18 mm/yr for the San Andreas Fault, within the range 16–24 mm/yr discussed above, giving a period of 1.2 m.y. for the simple model with 22 km of total offset. A lower rate—that is, something close to the long-term slip rates of 7 to 12 mm/yr—would give a period of from 1.8 to 3 m.y., possibly in better agreement with the abandonment of the Pilarcitos Fault and the oldest ages for the Merced Formation. Alternatively, we could use the 22-km offset and the estimated age of 1.8 m.y. for the Merced Formation to give a slip rate of about 12 mm/yr, similar to the long-term slip rate of 7 to 12 mm/yr. In any case, the main result of using different slip rates is to change the length of the stepover basin of the Merced Formation that formed between the Golden Gate and San Andreas Faults.
2. A reasonable slip rate for the San Gregorio Fault is 6 mm/yr (Clark, 1998, 1999), which determines the along-strike length of the modeled San Gregorio Basin caused by motion on the San Gregorio Fault. Again, as mentioned above, changes in slip rate and duration can lead to a longer or shorter basin. Slip rates could have been much higher when the Pilarcitos Fault was active and joined with the San Gregorio Basin, but here we are looking only at post-Pilarcitos motion.
3. The starting point for the stepover basin is at the south end of onshore outcrops of the Merced Formation. Variation in this starting position affects the final position of the modeled offshore depocenter of the San Gregorio Basin.
4. All motion on both the San Gregorio Fault and the Peninsular segment of the San Andreas Fault steps over to the Golden Gate Fault. This stepover occurs at the south end of the San Gregorio Basin, where the basement drops rapidly off into the basin depocenter (approximately corresponding to the area between the 400- and 1,000-m contour lines, fig. 11).
5. The San Gregorio Basin then forms as a transtensional right-stepping strike-slip basin as the margin segment north of the stepover is pulled northward with the Pacific Plate. Basin opening is at San Andreas Fault slip rates between the Golden Gate and San Andreas Faults, and at combined San Andreas and San Gregorio Fault slip rates west of the San Andreas Fault.

The model (fig. 31) shows two resulting basin segments defined by the faults. The first basin segment is a long, narrow basin of Merced Formation that forms between the San Andreas and Golden Gate Faults; the width of this basin is determined by the distance between the two faults, and its length is simply the total offset along the fault. The size and length of this narrow basin are nearly identical to what is actually observed onshore in the Merced Formation. The second basin segment is the San Gregorio Basin that forms between the San Gregorio and Golden Gate Faults; again, the width of this basin is determined by the distance between the faults, and its length, 8 km, is determined by the total assumed offset along the San Gregorio Fault during the model period. This second basin segment closely matches the deepest part of the San Gregorio Basin. The shallow parts of the basin north and south of the modeled segment could be the subsiding basin margins. This simple model shows that motion on both the San Gregorio and San Andreas Faults is essential to correctly explain the actual extent of the San Gregorio and Merced Formations. The two basin segments result from motion on the San Gregorio Fault and the Peninsular segment of the San Andreas Faults stepping over to the Golden Gate Fault.

The simple model matches conditions necessary for deposition of the Merced Formation. The Merced Formation was adjacent to an open ocean during its deposition (Clifton and Hunter, 1987, 1991). In the model, the basin would always be open to the sea, because the uplifted (or uplifting) Point Reyes peninsula would always lie to the north of the developing basin. Also, the long, narrow finger of onshore Merced Formation would always be open to the ocean at its north end, as the basin grew northward with continuing motion along the San Andreas Fault. The Merced Formation could be deposited in a shingled basin (Sylvester, 1988), formed as the depositional area migrated northward with the pullapart line and left behind north-dipping strata. The Merced Formation can be used to test the pullapart model if sufficiently detailed age controls are obtainable, because the rocks at the south end of the basin should be older than those to the north. This relation is true where the stratigraphic sequence is observable in the sea cliffs, but should continue to be true at the south end of the Merced Formation.

Formation of the San Gregorio Basin has been accompanied by subsidence of the basement blocks beneath the basin and along the bounding faults, particularly the San Gregorio Fault. Earthquake seismicity (Zoback and others, 1999) and the structure of the San Gregorio Basin shown here clearly indicate that subsidence has been the dominant structural regime during basin formation. Motion on the San Gregorio Fault before the emergence of the stepover led to formation of the San Gregorio structural zone along the San Gregorio Fault; this structural zone is an inherited feature. The stepover onto the Golden Gate Fault would have isolated the block of material between the San Gregorio and Golden Gate Faults from transform motion on the faults to the south. This isolated block would be coupled to the Pacific Plate along the San Gregorio Fault and would move with the Pacific Plate with an eastern margin on the Golden Gate Fault (fig. 31). Decoupling of the block from transform motion would allow subsidence to occur both within this block and along and over the San Gregorio Fault and associated structural zone, thus leading to burial of the San Gregorio structural zone. Basically, everything north of the stepover line and west of the Golden Gate Fault lies in a subsiding tectonic environment.

Maximum subsidence in the center of the San Gregorio Basin is associated with the 8-km pullapart necessary to accommodate the shift of motion from the San Gregorio Fault to the Golden Gate Fault. The basin itself, however, extends well beyond the central area—offshore contours show significant thicknesses of sediment extending about 15 km both northward and southward of the main basin depocenter (figs. 11, 12). The total extension along the pullapart zone could be more than the 8 km shown in the simple model because slip rates were faster, because more time was available for motion to occur on the San Gregorio Fault, or because the basin began to form while the Pilarcitos Fault was still active. Alternatively, gentle subsidence of basement rocks occurred both north and south of the area of maximum subsidence in the stepover basin. In the San Gregorio Basin, at least, formation of the pullapart basin was accompanied by subsidence along the basin trend for distances both north and south of the pullapart zone of about twice the pullapart distance.

How is motion transferred to the Golden Gate Fault, and how does the pullapart basin begin and end? Obviously, the motion involved in stretching of the Earth's crust in a pullapart basin must be accommodated along active faults. Motion could be accommodated on a series of east-west normal faults that drop into the basin—but the few lines trending north-south, though not particularly well located for seeing north-south faults, do not show a series of such downdropping normal faults. More likely, fault motion was and is currently being taken up on the subsidiary faults that cross the basin and that may be acting as strike-slip transfer faults. We need more information on the age and offset on these faults to see the details of how motion is transferred from one side of the basin to the other.

A puzzle is the cause of the substantial uplift that has elevated rocks of the Merced Formation to more than 200 m above sea level onshore, with uplift occurring since deposition of the overlying Colma Formation. Offshore seismic data, in combination with the onshore structure of the Merced Formation in the seacliffs, indicate that the section between the Golden Gate and San Andreas Faults is being both uplifted and rotated upward on a hingeline on the Golden Gate Fault. Jachens and others (this volume) suggest that this uplift results from slight compression of the section between the converging San Andreas and Golden Gate Faults. Fault separation in the offshore area is about 3 km, whereas onshore it decreases to 2 km. Thus, material deposited between the faults is being sequentially squeezed from 3 to 2 km as the stepover between the San Andreas and Golden Gate Faults rolls northward.

This compression may also be due to the basement structure west of the San Andreas Fault. The uplift and compression are occurring in exactly the area occupied by the structurally high, coherent basement terrane that underlies the shallow basement rocks at the south end of the San Gregorio Basin. These coherent basement rocks are riding northward with the Pilarcitos block, possibly squeezing the Merced Formation to the east. Also, the San Andreas Fault dips about 70º E. in this same area (see Jachens and others, this volume), and so the basement rocks would be slightly underthrusting the Merced Formation east of the San Andreas Fault. The combination of converging fault traces (as described by Jachens and others, this volume) and converging and underthrusting coherent basement terrane could lead to the observed uplift and tilting of the Merced Formation.

Conclusions

The San Andreas and San Gregorio Fault systems, far apart near Half Moon Bay, converge by Bolinas Lagoon. Within this zone lies the 2-km-deep San Gregorio Basin. The tectonic regime responsible for basin formation is a transtensional strike-slip stepover, in which motion from both the San Gregorio and San Andreas Faults steps eastward onto the Golden Gate Fault in the vicinity of Lake Merced. North of this stepover and west of the Golden Gate Fault, subsidence occurs in a pullapart basin, as the stepover zone moves passively northward with the Pacific Plate. Even as far north as

Bolinas Lagoon, subsidence occurs between the major faults, creating a surface and near-surface graben from the Golden Gate to Bolinas Lagoon. Southward, however, between the San Andreas and Golden Gate Faults, local compressional deformation is squeezing up the onshore Merced Formation between the two faults, with maximum uplift along the San Andreas Fault and a hingeline on the Golden Gate Fault. At the north end of the fault system, adjacent to the active graben on the San Gregorio Basin block, rocks west of the San Gregorio Fault are being uplifted onto the Point Reyes peninsula, leading to significant compressional deformation.

Within this tectonic regime, the Golden Gate, San Andreas, and San Gregorio Faults all have recognizable fault continuations across the Gulf of the Farallones; but north of the stepover zone, both the San Andreas and San Gregorio Faults are characterized by normal faulting as basin blocks subside in the pullapart basin. The Potato Patch Fault branches eastward off the San Gregorio Fault and continues northward with significant, but unknown, offset. The San Gregorio structural zone, a zone of major thrust-fault deformation west of the San Gregorio Fault, also continues across the Gulf of the Farallones and widens from about 2 to more than 8 km from south to north; but this deformation is an inherited feature, originating to the south and now moving and subsiding with the Pacific Plate.

These active faults separate two major sedimentary basins: the San Gregorio Basin, which lies between the Golden Gate/San Andreas Faults and the San Gregorio Fault; and the Bodega Basin, which lies west of the San Gregorio Fault. Maximum sediment thickness in the San Gregorio Basin is poorly defined but probably approaches 2 km overlying basement rocks of the Franciscan and Salinia terranes. The basin most likely formed after motion on the Pilarcitos Fault ceased, or later than 3 Ma. The age of these strata could be similar to that of the onshore Merced Formation, also poorly dated but probably younger than about 1.8 m.y. In the Bodega Basin, more than 800 m of Late Miocene and younger (less than about 6 Ma) strata overlies older sedimentary rocks (the Monterey Formation and older rocks).

North of about Pacifica (fig. 1), subsidence on the east side of the San Gregorio Fault is creating the San Gregorio Basin. The San Andreas Fault generally underlies the basin depocenter. The Potato Patch Fault, lying between the San Andreas and San Gregorio Faults, in part forms the edge of a structural high in the basin. These three faults are all at least partly normal faults along which basement rocks beneath the faults have undergone differential subsidence during basin formation. In the northern parts of the basin, strata appear to cross the fault virtually undisrupted. The Potato Patch, San Pedro, and San Andreas Faults could also be transfer faults, as strike-slip motion steps over from the San Gregorio to the Golden Gate Fault. Strike-slip motion could be small enough that we cannot interpret it in the available seismic-reflection data.

The stepover of motion on the San Gregorio Fault onto the Golden Gate Fault leads to the creation of a pullapart basin—the San Gregorio Basin. A simple model with this assumption places the maximum area of subsidence of the pullapart basin beneath the deepest part of the San Gregorio Basin.

Acknowledgments

This report greatly benefited from discussions, comments, and reviews by Michael Marlow, Robert Jachens, Ed Clifton, Robert McLaughlin, Joe Clark, and John Wakabayashi. We thank Larry Kooker, Pat Hart, Ray Sliter, Dennis Mann, Fred Payne, Hal Williams, and Stephen Bruns for their help in acquiring the data, and Dave Hogg, Mike Boyle, Kevin O'Toole, Walt Olson, Susan Hunt, John Gann, Jon Childs, and Stephen Wallace for the logistical support needed to run the cruise.

References Cited

Blake, M.C., Jr., 1984, Franciscan geology of northern California: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section Field Trip Guidebook, v. 43, 254 p.

Bortugno, E.J., McJunkin, R.D., and Wagner, D.L., 1992, Map showing recency of faulting, San Francisco-San Jose quadrangle, California: California Division of Mines and Geology Regional Geologic Map Series Map 51, sheet 5, scale 1:250,000.

Brabb, E.E., Graymer, R.W., and Jones, D.L., 1998, Geology of the onshore part of San Mateo County, California; a digital database: U.S. Geological Survey Open-File Report 98–137, 9 p.

Brabb, E.E., and Pampeyan, E.H., compilers, 1983, Geologic map of San Mateo County, California: U.S. Geological Survey Miscellaneous Investigations Series Map I–1257–A, scale 1:62,500.

Bruns, T.R., Carlson, P.R., and Cooper, A.K., 1996, Structure of the submerged San Andreas and San Gregorio fault zones off San Francisco, CA, from high resolution seismic reflection data [abs.]: Eos (American Geophysical Union Transactions), v. 77, no. 46, supp., p. F742.

Bruns, T.R., Carlson, P.R., Mann, D.M., and Cooper, A.K., 1995, High resolution seismic reflection survey of the San Andreas Fault zone in the Gulf of the Farallones, offshore San Francisco, CA [abs.]: Eos (American Geophysical Union Transactions), v. 76, no. 46, supp., p. F397–F398.

Childs, J.R., Hart, P.E., Bruns, T.R., Marlow, M.S., and Sliter, Ray, 2000, High resolution marine seismic-reflection data from the San Francisco Bay area: U.S. Geological Survey Open-File Report 00–494 [URL: http://geopubs.wr.usgs.gov/open-file/of00-494/].

Clark, J.C., 1998, Neotectonics of the San Gregorio Fault zone; age dating controls on offset history and slip rates [abs.]: American Association of Petroleum Geologists Bulletin, v. 82, no. 5A, p. 844–845.

———1999, San Gregorio Fault zone; progress and problems [abs.]: American Association of Petroleum Geologists Bulletin, v. 83, no. 4, p. 684.

Clark, J.C., and Brabb, E.E., 1997, Geology of the Point Reyes National Seashore and vicinity, Marin County, California; a digital database: U.S. Geological Survey Open-File Report 97–456, 8 p.

Clark, J.C., Brabb, E.E., Greene, H.G., and Ross, D.C., 1984, Geology of Point Reyes peninsula and implications for San Gregorio Fault history, *in* Crouch, J.K., and Bachman, S.B., eds., Tectonics and sedimentation along the California margin: Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section Field Trip Guidebook, v. 38, p. 67–86.

Clark, J.C., Wahrhaftig, Clyde, and Brabb, E.E., 1991, San Francisco to Point Reyes; both sides of the San Andreas Fault, *in* Sloan, Doris, and Wagner, D.L., eds., 1991, Geologic excursions in northern California; San Francisco to the Sierra Nevada: California Division of Mines and Geology Special Publication 109, p. 11–24.

Clifton, H.E., and Hunter, R.E., 1987, The Merced Formation and related beds; a mile-thick succession of late Cenozoic coastal and shelf deposits in the seacliffs of San Francisco, CA, *in* Hill, M.L., ed., Centennial field guide: Boulder, Colo., Geological Society of America, Cordilleran Section, v. 1, p. 257–262.

———1991, Depositional and other features of the Merced Formation in sea cliff exposures south of San Francisco, CA, *in* Sloan, Doris, and Wagner, D.L., eds., 1991, Geologic excursions in northern California; San Francisco to the Sierra Nevada: California Division of Mines and Geology Special Publication 109, p. 35–44.

Clifton, H.E., Hunter, R.E., and Gardner, J.V., 1988, Analysis of eustatic, tectonic and sedimentologic influences on transgressive and regressive cycles in the late Cenozoic Merced Formation, San Francisco, California, *in* Paola, Chris, and Kleinspehn, K.L., eds., New Perspectives in Basin Analysis: New York, Springer-Verlag, p. 109–128.

Cooper, A.K., 1973, Structure of the continental shelf west of San Francisco, California: U.S. Geological Survey Open-File Report 1907, 65 p.

Galloway, A.J., 1977, Geology of the Point Reyes peninsula, Marin County, California: California Division of Mines and Geology Bulletin 202, 72 p.

Gann, J.T., 1992, YoNav; your own integrated navigation system for DOS platforms: U.S. Geological Survey Open-File Report 92–565, 62 p.

Glen, William, 1959, Pliocene and lower Pleistocene of the western part of the San Francisco Peninsula: University of California Publications in Geological Science, v. 36, no. 2, p. 147–197.

Griscom, Andrew, and Jachens, R.C., 1990, Crustal and lithospheric structure from gravity and magnetic studies, chap. 9 *of* Wallace, R.E., ed., The San Andreas fault system, California: U.S. Geological Survey Professional Paper 1515, p. 239–259.

Hall, N.T., 1966, Late Cenozoic stratigraphy between Mussel Rock and Fleishhacker Zoo, San Francisco peninsula: California Division of Mines and Geology, Mineral Information Service, v. 19, no. 11, p. S22–S25.

Hall, N.T., Wright, R.H., and Clahan, K.B., 1999, Paleoseismic studies of the San Francisco Peninsula segment of the San Andreas fault zone near Woodside, California: Journal of Geophysical Research, v. 104, no. B10, p. 23215–23236.

Hengesh, J.V., and Wakabayashi, John, 1995, Dextral translation and progressive emergence of the Pleistocene Merced basin and implications for timing of initiation of the San Francisco peninsula segment of the San Andreas Fault, in Sangines, E.M., Andersen, D.W., and Buising, A.B., eds., Recent geologic studies in the San Francisco Bay Area: Society of Economic Paleontologists and Mineralogists, Pacific Section Field Trip Guidebook, v. 76, p. 47–53.

Holbrook, W.S., Brocher, T.M., ten Brink, U.S., and Hole, J.A., 1996, Crustal structure of a transform plate boundary; San Francisco Bay and the Central California continental margin: Journal of Geophysical Research, v. 101, no. B10, p. 22311–22334.

Hole, J.A., Holbrook, W.S., Klemperer, S.L., Ten Brink, U.S., and Brocher, T.M., 1993, Crustal structure in the San Francisco Bay area from wide-angle seismic refraction data [abs.]: Eos (American Geophysical Union Transactions), v. 74, no. 43, supp., p. 445.

Hoskins, E.G., and Griffiths, J.R., 1971, Hydrocarbon potential of northern and central California offshore, *in* Future petroleum provinces of the United States; their geology and potential: American Association of Petroleum Geologists Memoir 15, v. 1, p. 212–228.

Jachens, R.C., Wentworth, C.M., and McLaughlin, R.J., 1999, Pre-San Andreas location of the Gualala block inferred from magnetic and gravity anomalies, *in* Elder, W.P., ed., 1998, Geology and tectonics of the Gualala Block, northern California: Society of Economic Paleontologists and Mineralogists, Pacific Section Field Trip Guidebook, v. 84, p. 27–64.

Jachens, R.C., and Zoback, M.L., 1999, The San Andreas Fault in the San Francisco Bay region, California; structure and kinematics of a young plate boundary: International Geology Review, v. 41, no. 3, p. 191–205.

Lanphere, M.A., Champion, D.E., Clynne, M.A., and Muffler, L.J.P., 1999, Revised age of the Rockland Tephra, Northern California; implications for climate and stratigraphic reconstructions in the western United States: Geology, v. 27, no. 2, p. 135–138.

Lettis, W.R., 1999, The San Gregorio/Hosgri fault system, California—an evaluation of the style and range of Quaternary deformation [abs.]: American Association of Petroleum Geologists Bulletin, v. 83, no. 4, p. 693–694.

McCulloch, D.S., 1987, Regional geology and hydrocarbon potential of offshore central California, *in* Scholl, D.W., Grantz, Arthur, and Vedder, J.G., Geology and resource potential of the continental margin of western North America and adjacent ocean basins—Beaufort Sea to Baja California (Earth Science Series, v. 6): Houston, Tex., Circum-Pacific Council for Energy and Mineral Resources, p. 353–401.

———1989, Evolution of the offshore central California margin, *in* Winterer, E.L., Hussong, D.M., and Decker, R.W., eds., The eastern Pacific Ocean and Hawaii, v. 5 *of* The geology of North America: Boulder, Colo., Geological Society of America, p. 439–447.

McLaughlin, R.J., Sliter, W.V., Sorg, D.H., Russell, P.C., and Sarna-Wojcicki, A.M., 1996, Large-scale right-slip displacement on the East San Francisco Bay Region fault system, California; implications for location of late Miocene to Pliocene Pacific plate boundary: Tectonics, v. 15, no. 1, p. 1–18.

Niemi, T.M., and Hall, H.T., 1992, Late Holocene slip rate and recurrence of great earthquakes on the San Andreas Fault in northern California: Geology, v. 20, no. 3, p. 195–198.

Noller, J.S., Kelson, K.I., Lettis, W.R., Wickens, K.A., Simpson, G.D., Lightfoot, Kent, and Wake, T., 1993, Preliminary characterization of Holocene activity on the San Andreas Fault based on offset archaeologic sites, Ft. Ross State Historic Park, California: final technical report for U.S. Geological Survey, National Earthquake Hazard Reduction Program, 16 p.

Page, B.M., 1990, Evolution and complexities of the transform system in California, U.S.A.: Annales Tectonicae, v. 4, no. 2, p. 53–69.

———1992, Tectonic setting of the San Francisco Bay Region [abs.], *in* Galehouse, J.S., ed., Conference on Earthquake Hazards in the Eastern San Francisco Bay Area, 2d, Hayward, Calif., 1992, Programs and Abstracts: California Division of Mines and Geology Special Publication 113, p. 53.

Parsons, T.E., and Zoback, M.L., 1997, Three-dimensional upper crustal velocity structure beneath San Francisco Peninsula, California: Journal of Geophysical Research, v. 102, no. B3, p. 5473–5490.

Ross, D.C., 1978, The Salinian Block; a Mesozoic granite orphan in the California Coast Range, in Howell, D.G., and McDougall, K.A., eds., Mesozoic paleogeography of the United States (Pacific Coast Paleogeographic Symposium 2): Los Angeles, Society of Economic Paleontologists and Mineralogists, Pacific Section, p. 509–522.

Sarna-Wojcicki, A.M., Meyer, C.E., Bowman, H.R., Hall, N.T., Russell, P.C., Woodward, J.J., and Slate, J.L., 1985, Correlation of the Rockland ash bed, a 400,000-year old stratigraphic marker in northern California and western Nevada, and implications for middle Pleistocene paleogeography of central California: Quaternary Research, v. 23, no. 2, p. 236–257.

Sedlock, R.L., 1999, The San Gregorio Fault zone; late Cenozoic dextral slip and slip rate, and southward linkage with the Sur, San Simeon, and Hosgri Faults [abs.]: American Association of Petroleum Geologists Bulletin, v. 83, no. 4, p. 701.

Simpson, G.D., Thompson, S.C., Noller, J.S., and Lettis, W.R., 1997, The northern San Gregorio Fault zone; evidence for the timing of late Holocene earthquakes near Seal Cove, California: Seismological Society of America Bulletin, v. 87, no. 5, p. 1158–1170.

Sylvester, A.G., 1988, Strike-slip faults: Geological Society of America Bulletin, v. 100, no. 11, p. 1666–1703.

Taylor, C.L., Cummings, J.C., and Ridley, A.P., 1980, Discontinuous en echelon faulting and ground warping, Portola Valley, California, in Streitz, Robert, and Sherburne, R.W., eds., Studies of the San Andreas fault zone in northern California: California Division of Mines and Geology Special Report 140, p. 59–70.

Wakabayashi, John, 1999, Distribution of displacement on and evolution of a young transform fault system; the northern San Andreas Fault system, California: Tectonics, v. 18, no. 6, p. 1245–1274.

Wakabayashi, John, and Hengesh, J.V., 1995, Distribution of late Cenozoic displacement on the San Andreas fault system, northern California, in Sangines, E.M., Andersen, D.W., and Buising, A.B., eds., Recent geologic studies in the San Francisco Bay Area: Society of Economic Paleontologists and Mineralogists, Pacific Section Field Trip Guidebook, v. 76, p. 19–29.

Weber, G.E., Nolan, J.M., and Zinn, E.N., 1999, Late Quaternary slip across the San Gregorio Fault zone, San Mateo County, California; estimates from marine terrace offsets [abs.]: American Association of Petroleum Geologists Bulletin, v. 83, no. 4, p. 705.

Working Group on California Earthquake Probabilities, 1999, Earthquake probabilities in the San Francisco Bay region: 2000 to 2030—a summary of findings: U.S. Geological Survey Open-File Report 99–517, 60 p.

Zoback, M.L., Jachens, R.C., and Olson, J.A., 1999, Abrupt along-strike change in tectonic style; San Andreas Fault zone, San Francisco Peninsula: Journal of Geophysical Research, v. 104, no. B5, p. 10719–10742.