# Concealed Strands of the San Andreas Fault System in the Central San Francisco Bay Region, As Inferred from Aeromagnetic Anomalies

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## Abstract

Modern high-resolution aeromagnetic surveys over the San Andreas Fault system in the San Francisco Bay region provide detailed information about the positions, shapes, and offset histories of various fault segments concealed beneath water or young alluvium. The presence of coherent, nondisrupted magnetic rock bodies within the top few kilometers of the crust beneath San Pablo Bay and spanning the right-stepover region between the Hayward and Rodgers Creek Faults precludes a simple connection between these two active faults, at least in the upper crust. The data do permit a simple midcrustal connection between the two faults, provided that discrete offset at depth is reflected in the upper crust as distributed deformation, folding, and basin subsidence. Offset pairs of distinctive geologic units and characteristic tabular magnetic rock bodies indicate that the Peninsular segment of the San Andreas Fault accommodates only 22 km of total offset, even though offsets on strands of the San Andreas Fault to the north and south are measured in the hundreds of kilometers. On the basis of interpreted aeromagnetic data, the San Andreas Fault offshore west of San Francisco exhibits an abrupt right step of 3 km about in the hypocentral zone of the great 1906 San Francisco earthquake. A local, >1-km-deep basin lying southeast of this right step is compatible with its having formed as a pullapart basin southeast of (behind) a right step in a right-lateral strike-slip-fault system. Slight local nonparallelism of the two fault segments entering the right step from the north and south can explain the puzzling fact that young sedimentary materials deposited in an extensional, pullapart basin have undergone compressional deformation and uplift within an along-strike distance of 5 km from the extensional right step. The local geometry of the fault system indicates that the original 3-km-wide depositional basin is compressed to a 2-km width over an along-strike distance of 10 km from the right step by continued relative motion across the San Andreas Fault. The Pilarcitos Fault, the presumed active strand of the San Andreas Fault before the initiation of movement on its Peninsular segment, bends into the San Gregorio Fault zone offshore, leaving open the question of whether the Pilarcitos Fault is truncated at the San Gregorio Fault or simply once coincided with what is now the northernmost segment of the San Gregorio Fault. Examination of high-resolution aeromagnetic data over the San Andreas Fault system as far north as Point Arena reveals possible offset counterparts to the pronounced magnetic anomaly that defines the Pilarcitos Fault in the San Francisco Bay region. These magnetic anomalies lie west of the San Andreas Fault and about 150 km north of the San Gregorio-Pilarcitos Fault junction. However, detailed study of the geology of this northern area is needed before a definite tie with the Pilarcitos Fault magnetic anomaly can be established. The aeromagnetic data indicate that the San Gregorio Fault zone in the Gulf of the Farallones west of San Francisco is composed of at least two long, right-stepping strands, the northernmost of which connects with a mapped strand of the San Andreas Fault at Bolinas Lagoon northwest of San Francisco. The right-stepping behavior of the San Gregorio Fault zone is consistent with the generally extensional (right step) junction between the San Gregorio-San Andreas Fault junction northwest of San Francisco.


## Introduction

The active San Andreas Fault system in the San Francisco Bay region consists of several subparallel strands, including, from east to west, the Calaveras, Rodgers Creek, Hayward, San Andreas, and Pilarcitos Faults and the San Gregorio Fault zone (fig. 1), as well as other strands farther east. Onshore, these potentially dangerous faults are reasonably well known from geologic mapping of offset geologic units, geomorphic features, and ground rupture after historical earthquakes (Bonilla, 1971; Galloway, 1977; Lienkamper, 1992; Pampeyan, 1994). However, significant reaches of many of these faults lie offshore, concealed from direct observation by water and young sedimentary deposits. Here, the positions and characteristics of the faults are known primarily from geophysical observations and the distribution of seismicity and are much less certain.

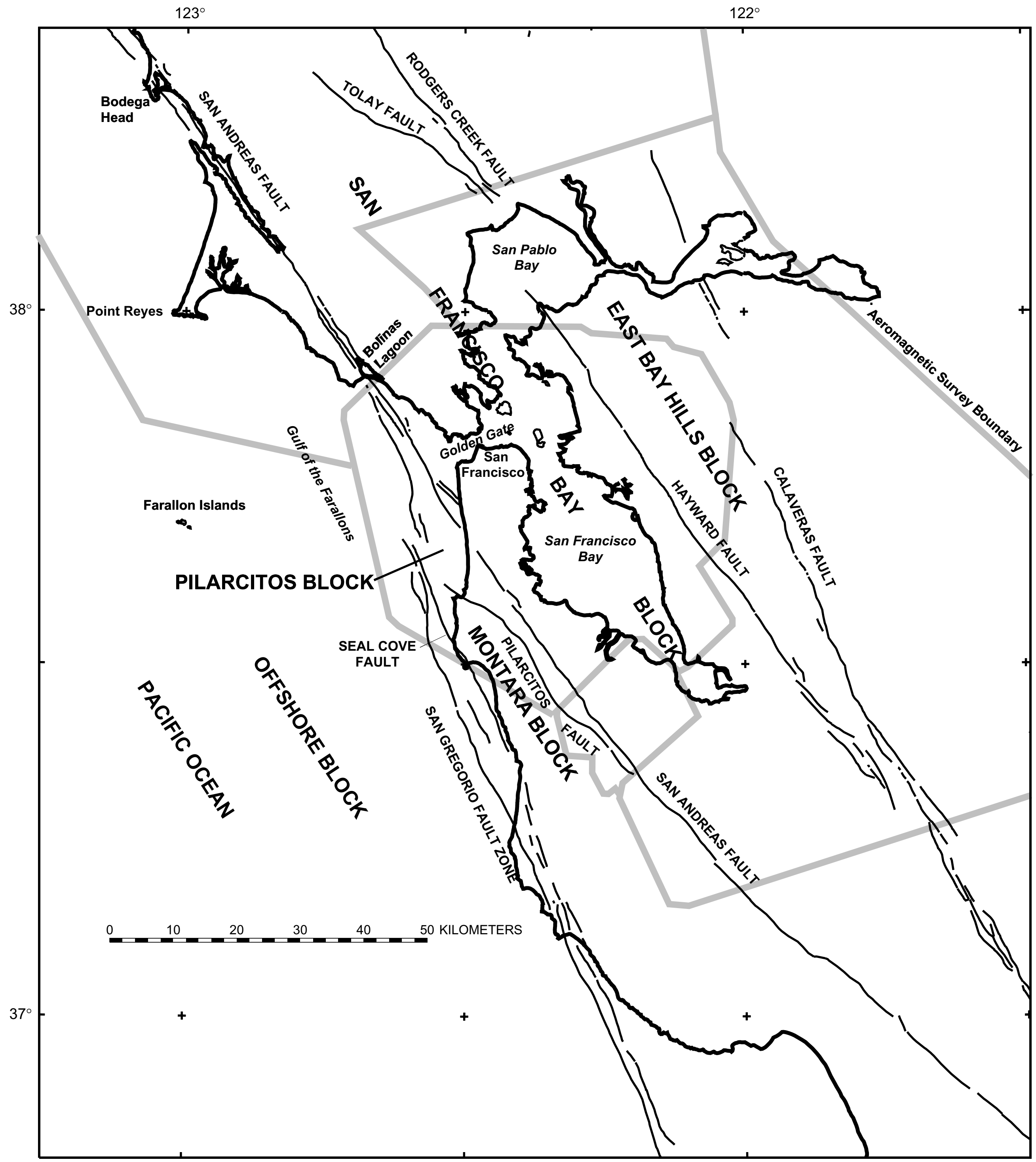


Figure 1.—San Francisco Bay region, showing locations of strands of the San Andreas Fault system, major crustal blocks discussed in this study, and boundaries of aeromagnetic surveys used to compile aeromagnetic map (see pl. 1).

It is important to understand submarine faults in order to evaluate the potential hazard they present, especially when they lie close to such heavily developed areas as the San Francisco Bay region. Precise locations of faults are needed to assess the possible distribution of damage during an earthquake, and information about the detailed structure of the faults can be useful in predicting the type of deformation likely to accompany the rupture of a specific strand. In addition, local irregularities in fault geometry, such as the concealed right step apparently required to connect the Hayward Fault with the Rodgers Creek Fault or Tolay Fault beneath San Pablo Bay (fig. 1; Smith, 1992; Wright and Smith, 1992), or a comparable right step in the San Andreas Fault offshore southwest of the Golden Gate (Cooper, 1973; Hengesh and Wakabayashi, 1995; Zoback and others, 1999; Jachens and Zoback, 1999), may be important features in understanding the initiation of earthquakes on these faults and on major strike-slip faults in general.

## Previous Work

Information about submarine strands of the San Andreas Fault system in the San Francisco Bay region has come mainly from marine geophysical surveys and aeromagnetic surveys. In his study of the structure of the Continental Shelf west of San Francisco, Cooper (1973) summarized previous investigations and compiled marine seismic-reflection data and other geophysical information. He recognized numerous faults on the basis of offset beds or disruptions in the Cenozoic sedimentary section, and he was able to correlate some of these faults across several separate profiles. Although the aeromagnetic data available for his study were sparsely distributed and of limited quality, Cooper observed that fault-bounded blocks in the area east of the Seal Cove Fault (fig. 1; now included as a strand of the San Gregorio Fault zone) produced magnetic anomalies that were related to the faults. In addition, he showed, on one profile containing both seismic-reflection and aeromagnetic data, a detailed correspondence of the faults visible in the sedimentary section with magnetic anomalies, presumably caused by basement rocks (Cooper, 1973, fig. 9, profile 5). He presented a fault map inferred from the seismic-reflection and aeromagnetic data for the area just west of San Francisco that includes several minor faults, as well as proposed locations for the Seal Cove, Pilarcitos, and San Andreas Faults, which cross the entire area from the San Francisco peninsula to the Point Reyes peninsula.

McCulloch (1987) analyzed additional marine seismic-reflection data for the shelf area west of San Francisco and recognized other faults that were traceable across multiple profiles. In the area east of the San Gregorio Fault zone, he also recognized the relation between faults and the magnetic anomalies shown on an aeromagnetic map (Brabb and Hanna, 1981), and used this information to help link faults seen on individual marine seismic profiles into long, throughgoing features.

Brabb and Hanna (1981) compiled an aeromagnetic map of the San Francisco Bay region south of lat 37°52.5′ N. that they used, in conjunction with mapped geology, locations of onshore faults, and recent seismicity, to identify concealed, potentially hazardous faults. On the basis of the known correspondence between linear magnetic anomalies produced by tabular bodies of serpentinite and such mapped faults as the Hayward Fault and the Hunters Point shear zone (compare pls. 1, 2), they identified as possible faults virtually every strong linear magnetic anomaly believed to be caused by serpentinite.

Lienkaemper and others (1991), on the basis of regional gravity data (Chapman and Bishop, 1968), projected the Hayward Fault on strike northwestward across most of San Pablo Bay. This interpretation was based on their identification of the Hayward Fault with the sharp linear southwest flank of a deep gravity low over the eastern part of San Pablo Bay, a low that extends both northwestward and southeastward from the bay. Near the north shore of the bay, Lienkaemper and others proposed a rightward (releasing) bend in the fault system over a distance of ~6 km to connect the active Hayward Fault with the active Rodgers Creek Fault.

Smith (1992) presented a more detailed gravity map of San Pablo Bay and vicinity (inset, pl. 1) that better defined the gravity anomaly associated with the Hayward Fault and its possible northwestward continuation. He also interpreted the sharp, linear southwest flank of this gravity low as the extension of the Hayward Fault beneath the bay and, on the basis of the continuity of this gravity feature, connected the Hayward Fault with the Tolay Fault, a connection that requires a more abrupt rightward bend or right step near the north shore of the bay than that shown by Lienkaemper and others (1991). This interpretation was made in the context of the continuity of structural elements (faults) that bound the west side of the Tertiary basin underlying the eastern part of San Pablo Bay. As such, Smith's (1992) interpretation was not directed toward identifying the active strand of the Hayward Fault system north of San Pablo Bay.

Wright and Smith (1992), using the same gravity data set as Smith (1992), located the Hayward Fault beneath San Pablo Bay in the same way as Smith (1992) and recognized that the Rodgers Creek Fault has no obvious gravity expression. However, they also used information from seismic-reflection surveys in San Pablo Bay and from deep wells in the surrounding area to project the Rodgers Creek Fault southeastward from its southernmost mapped position to a point near the center of the bay (see pl. 1). They argued that their data preclude any direct connection between the Hayward and Rodgers Creek Faults, and speculated about how slip is transferred from one fault to the other across a right step.

Although these studies all provide information that helps to define the positions and characteristics of concealed strands of the San Andreas Fault system in the San Francisco Bay region, important questions still remain unanswered. More detailed information is required about fault positions and local irregularities in the fault system to understand the behavior of individual faults and to properly assess the potential hazard they pose. New high-resolution aeromagnetic data provide some of this additional information.

## New Aeromagnetic Surveys

A high-resolution aeromagnetic survey of the central part of the San Francisco Bay region (fig. 1; U.S. Geological Survey, 1996) was flown on contract to the U.S. Geological Survey (USGS) during March 1995. The purpose of this survey was to provide information on concealed strands of the San Andreas Fault system as part of the USGS Earthquake Hazards Reduction Program. Total-magnetic-field data were collected with a fixed-wing aircraft along northeast-southwest-oriented flightlines spaced 500 m apart and controlled by precise Global Positioning System (GPS) navigation. The aircraft maintained a nominal height of 250 m above the surface in water-covered areas and 300 m above the land surface in developed onshore areas. Because of extreme topographic relief in some places, the aircraft was not always able to maintain a constant altitude above the land surface and typically passed closer to the ridgetops than to the bottoms of the intervening valleys. Data were collected about every 50 m along the flightlines.

The aeromagnetic data were corrected for diurnal fluctuations in the Earth's field, and the International Geomagnetic Reference Field (Langel, 1992), updated to the dates of the survey, was subtracted from the observations to yield residual-magnetic-field data (total-magnetic-field anomalies). The residual-magnetic-field values were interpolated to a square grid (grid interval, 100×100 m; projection, Universal Transverse Mercator; central meridian, 123º W.; base latitude, 0º) by a numerical technique based on the principle of minimum curvature (Briggs, 1974).

Data from three other high-resolution aeromagnetic surveys were added along the edges of the new survey area (fig. 1) to extend the map coverage northward to include the important junctions of the Hayward and Rodgers Creek Faults beneath the waters of San Pablo Bay and of the San Andreas and San Gregorio Faults northwest of San Francisco, and southward to cover important segments of the San Andreas Fault. Data from the aeromagnetic survey of Livermore, Calif., and vicinity (U.S. Geological Survey, 1992) were collected in fall 1991 along flightlines oriented N. 70º E.–S. 70º W., with the same survey specifications as the 1995 survey. Data from the aeromagnetic survey of Palo Alto, Calif., and vicinity (Abrams and others, 1991) were collected along flightlines oriented northeast-southwest, with the same specifications as for the survey of the central part of the San Francisco Bay region, but with a flightline spacing of 400 m. Data from the aeromagnetic survey of Santa Rosa, Calif., and vicinity (U.S. Geological Survey, 1997a) were collected in 1996 and 1997 along flightlines oriented east-west, with the same survey specifications as for the survey of the central part of the San Francisco Bay region. The data from all these surveys were reduced and interpolated to a square grid in the same way as for the central part of the San Francisco Bay region and were merged by smooth interpolation across a 500-m-wide buffer zone between adjacent surveys. These data are shown on the aeromagnetic map (pl. 1) as a color shaded-relief map with a color band of 25 nT.

The use of GPS navigation and high-resolution magnetic sensors in the surveys of Livermore, Santa Rosa, and the central San Francisco Bay region yielded high-quality data sets that contain coherent magnetic anomalies (local distortions of the Earth's magnetic field) spanning multiple flightlines, with some amplitudes as small as 1 nT or less. Although GPS navigation was unavailable for the aeromagnetic survey of Palo Alto, the small size of the survey area and careful reduction of the positioning data yielded reduced aeromagnetic data of a quality similar to that in the other three surveys.

In addition to the basic aeromagnetic data, inferred locations of the edges of magnetic rock bodies in the central part of the San Francisco Bay region are shown on the aeromagnetic map (lines of plus signs, pl. 1). These locations were determined automatically by means of a numerical technique applied to the aeromagnetic data which is a slight modification of that of Cordell and Grauch (1985) as implemented by Blakely and Simpson (1986). The original technique locates the edges of magnetic bodies by the use of a linear filter, the pseudogravity transform (Baranov, 1957), which converts a magnetic anomaly into an equivalent gravity anomaly. In the same way that the maximum horizontal gradients of a gravity anomaly produced by a shallowly buried body lie nearly over the edges of the body, especially if the sides dip steeply, the maximum horizontal gradients of a pseudogravity anomaly define the edges of the magnetic body that cause the magnetic anomaly. For the present study, we modified this edge-location technique slightly by applying it not to a simple pseudogravity transformation of the total-magnetic-field data for the San Francisco Bay region, but to the difference between the transformed aeromagnetic data and those same data continued upward 200 m. Upward continuation of potential-field data suppresses the shorter-wavelength components of a magnetic anomaly, such as those produced by the shallowest parts of a body, at the expense of the longer-wavelength components that reflect the deeper parts of the body (Blakely, 1995). By applying the edge-location technique to the difference, we focused on the shallowest parts of the magnetic bodies, namely, the top edges.

## Geologic Map

The accompanying geologic map (pl. 2) represents a generalized version of the map by Ellen and Wentworth (1995). For the purposes of our study, rock units that are known or suspected to be magnetic were retained as shown on the original map, but many other units were combined into single units, mostly on the basis of similarities in age and major rock type. Potentially magnetic units include serpentinite, igneous rocks of various ages, and some Tertiary sedimentary rocks. Major faults of the San Andreas Fault system are shown as on the original map and do not correspond in detail to those highlighted on the aeromagnetic map (pl. 1), on which the mapped faults of the San Andreas Fault system emphasize the most recently active strands and so do not everywhere correspond to geologic-unit boundaries.

## Geologic Setting and Magnetic Sources

The strands of the San Andreas Fault system in the San Francisco Bay region have undergone offsets measured in tens to hundreds of kilometers and, thus, typically juxtapose diverse rock types. These faults divide the region into a mosaic of crustal blocks (fig. 1) that, because of their characteristic geology and magnetic rock types, serve as a convenient framework for discussing the relations between the geology and the magnetic anomalies and the types of magnetic features that are likely to be indicators of faults in areas where the geology is not exposed. The subsequent discussion is organized according to crustal block and generally progresses from east to west. The aeromagnetic data are shown on the aeromagnetic map (pl. 1) at a scale of 1:150,000, along with a generalized geologic map (pl. 2) of the same area at the same scale. The reader also may find it helpful at times to refer to published geologic maps of the study area, for example, the Santa Rosa 1°×2° quadrangle (Wagner and Bortugno, 1982), the combined San Francisco-San Jose quadrangle (Wagner and others, 1991), and the more detailed maps referenced in these publications. In the following sections, where specific magnetic anomalies and their sources are discussed, the anomalies and their geologic sources are identified on both maps by letter designations where appropriate.

### East Bay Hills Block

The East Bay Hills block (fig. 1), immediately east of the Hayward and Rodgers Creek Faults, is made up of elements of a geologic section that, in simplest form, includes, from bottom to top, subduction-related rocks of the Franciscan Complex; the Coast Range ophiolite; forearc sedimentary rocks of the Mesozoic Great Valley sequence; and Cenozoic (mostly Miocene and younger) marine and continental sedimentary rocks and associated volcanic rocks (see pl. 2; Page, 1992). The Coast Range ophiolite, which is the depositional basement of the Great Valley sequence, structurally overlies the Franciscan Complex across the Coast Range Fault (Bailey and others, 1970) but commonly is found also as slivers and tabular bodies intimately associated with, and enclosed within, the Franciscan basement. Strong gravity lows over outcrops of the Great Valley sequence and younger sedimentary rocks of this block, relative to the gravity anomalies over exposed Franciscan basement in the surrounding area (Roberts and Jachens, 1993), indicate that the sedimentary cover of this block typically is more than 1 km thick and, in places, is many kilometers thick. This gravity interpretation is supported by limited drill-hole data (Smith, 1964; California Division of Oil and Gas, 1982; Wright and Smith, 1992) and seismic profiles (Meltzer and others, 1987; Smith, 1992), as well as cross sections based on geologic mapping (Jones and others, 1994; Crane, 1995).

Magnetic anomalies over this block are produced by mafic, ultramafic, and volcanic components of the Coast Range ophiolite (magnetic anomaly a, pl. 1); by Tertiary volcanic rocks, such as the Bald Peak basalt (magnetic anomaly b); and Late Tertiary sedimentary rocks of the San Pablo and Contra Costa Groups (magnetic anomaly c) and related rocks (Wagner and others, 1991; Wagner and Bortugno, 1982). The strongest magnetic high shown on the aeromagnetic map (a 35-km-long, 10-km-wide magnetic high near the northeast corner, pl. 1) is likely caused by a tabular body of mafic and ultramafic rocks of the Coast Range ophiolite, but most of this body is concealed, possibly cropping out only in a small window at Mount Diablo. Although sedimentary rocks seldom produce anomalies on aeromagnetic maps, the unusual magnetic rocks of the San Pablo and Contra Costa Groups are responsible for most of the linear, northwest-trending magnetic anomalies east of the Hayward Fault shown on the aeromagnetic map (pl. 1). These magnetic anomalies result from complex folding and faulting of the magnetic sedimentary rocks of these units. One exception is the strong magnetic high (magnetic anomaly b) that overlies outcrops of the Tertiary Bald Peak basalt.

### San Francisco Bay Block

The central San Francisco Bay block (fig. 1), lying between the Hayward-Rodgers Creek Fault system and the San Andreas Fault, includes Franciscan rocks as its basement, together with rocks of the Coast Range ophiolite (Wagner and others, 1991) and, possibly, ophiolitic rocks related to the oceanic plate originally at the base of the Franciscan Complex. Franciscan rocks of the San Francisco Bay block belong to several distinct tectonostratigraphic terranes, including the Alcatraz, Central, Marin Headlands, Novato Quarry, Permanente, San Bruno Mountain, and Yolla Bolly terranes (Blake and others, 1984). A major difference between the central part of the San Francisco Bay block and the East Bay Hills block is in the amount of sedimentary cover overlying the Franciscan basement. Most of the central part of the San Francisco Bay block has only a thin veneer of sedimentary cover, typically no more than a few hundred meters thick (Page, 1992; Wright and Smith, 1992; Jachens and others, 1995a). Some parts of the San Francisco Bay block north and south of the map area (pl. 1) contain substantial thicknesses of Cenozoic sedimentary deposits (California Division of Oil and Gas, 1982; Wright and Smith, 1992; Jachens and others, 1995a; Stanley and others, 1996). Within the map area, however, the sedimentary cover is as much as ~1 km thick in only a few places, for example, west of San Leandro, adjacent to the Peninsular segment of the San Andreas Fault near Lake Merced, and in a sliver north of San Pablo Bay between the Rodgers Creek and Tolay Faults (Wright and Smith, 1992; Zoback and others, 1995; Jachens and Zoback, 1999; Marlow and others, 1999).

Ultramafic ophiolitic rocks cause many of the conspicuous northwest-trending magnetic anomalies within the San Francisco Bay block shown on the aeromagnetic map (pl. 1; Brabb and Hanna, 1981). The magnetic ophiolitic bodies generally occur in tabular, sheetlike masses, commonly along the sutures between terranes or along active fault zones (Brabb and Hanna, 1981). The Tertiary Sonoma Volcanics (magnetic anomaly d, pl. 1) also is magnetic and probably causes some of the smaller magnetic anomalies within the San Francisco Bay block along the north edge of the map area.

The sources of the large magnetic anomalies just northwest of San Francisco (magnetic anomaly e, pl. 1) are mostly metabasalts of the Franciscan Marin Headlands terrane (Blake and others, 1984). These rocks are unusually magnetic relative to Franciscan metabasalts in other terranes of the San Francisco Bay region, which have a very low magnetic susceptibility and do not produce measurable aeromagnetic anomalies (Brabb and Hanna, 1981). Other metabasalts of the Marin Headlands terrane, however, also produce moderate to strong magnetic anomalies, such as those in the western hills of metropolitan San Francisco (magnetic anomaly f), in the Coyote Hills (magnetic anomaly g) on the eastern margin of southern San Francisco Bay, and, probably, along the east side of the San Andreas Fault on the central part of the San Francisco peninsula (Blake and others, 1984). Because the distribution of rocks of the Marin Headlands terrane is poorly known in the covered areas of the San Francisco Bay block, both ultramafic ophiolitic rocks and metabasalts must be considered as possible sources of the magnetic anomalies where these sources are concealed.

## Pilarcitos Block

The Pilarcitos block is triangular crustal block bounded by the Pilarcitos Fault, the San Gregorio Fault zone, and the Peninsular segment of the San Andreas Fault (fig. 1). Although the San Andreas Fault system has accommodated hundreds of kilometers of total offset north and south of the San Francisco Bay region (Irwin, 1990), Bailey and others (1964) long ago recognized that its Peninsular segment was unusual in that it did not appear to accommodate nearly as much total offset as the rest of the fault system. They noted that characteristic Calera limestone-bearing units of the Franciscan Complex (magnetic anomaly h, pl. 2) are present both east and west of the San Andreas Fault, indicating that its Peninsular segment has accommodated only 20 to 30 km of total right-lateral offset. An important implication of this limited offset is that the geology of the Pilarcitos block (see pl. 2) is similar to that of parts of the San Francisco Bay block, with crossfault Franciscan basement counterparts exposed east of the fault on the San Francisco peninsula and southward (Bailey and others, 1964; Blake and others, 1984; Page, 1990; Wagner and others, 1991).

The Franciscan basement of the Pilarcitos block includes rocks of the Permanente terrane in the southwestern part and, probably, rocks of the Marin Headlands terrane in the northeastern part of the block (Blake and others, 1984; Pampeyan, 1994; R.J. McLaughlin, oral commun., 1996), although the position of the contact between these two terranes is undefined. The dominant sources of magnetic anomalies within the Permanente terrane are ultramafic ophiolitic rocks and metabasalts, whereas over the Marin Headlands terrane they are probably metabasalts. No other sources of magnetic anomalies are known in the Pilarcitos block.

## Montara Block

The Montara block, between the San Andreas Fault and the San Gregorio Fault zone south of the Pilarcitos Fault (fig. 1), is composed of Cretaceous plutons and Sur Series metamorphic rocks of the Salinia terrane overlain by Cenozoic sedimentary and volcanic rocks (McCulloch, 1987; Wagner and others, 1991). The relative rarity of strong magnetic anomalies over this block (pl. 1; fig. 1) and over similar rocks to the south, coupled with the extremely low magnetic susceptibilities (avg <0.0001 cgs units) of samples from the Montara Mountain pluton indicates that the plutonic and metamorphic rocks of the Salinia terrane in the San Francisco Bay region are typically nonmagnetic. Isolated magnetic anomalies over outcrops of plutonic rock (for example, magnetic anomaly i, pl. 1) indicate that small magnetic zones may exist within the predominantly nonmagnetic plutons.

Two types of magnetic source rocks exist in the Cenozoic section above the Salinian basement. The Mindego basalts of Miocene age (Wagner and others, 1991) produce magnetic anomalies of both positive (magnetic anomaly j, pl. 1) and negative polarity (Brabb and Hanna, 1981), but these rocks have only limited areal extent. Sedimentary rocks of the Pliocene Purisima Formation, which are more widespread (Wagner and others, 1991), are known to be magnetic in the Santa Cruz Mountains part of the Salinia terrane 20 km to the south (Jachens and Roberts, 1993); their magnetic properties presumably are due to abundant lithic fragments of andesitic composition.

## Offshore Block West of the San Gregorio Fault Zone

The basement of the offshore block west of the San Gregorio Fault zone in the Gulf of the Farallones (fig. 1) is believed to be composed of plutonic rocks and Sur Series metamorphic rocks of the Salinia terrane (McCulloch, 1987), comparable to those found in the Montara block. Basement rocks of this offshore block crop out only on the Farallon Islands, on the Point Reyes peninsula, and at Bodega Head, 50 km west, 40 km northwest, and 90 km northwest, respectively, of San Francisco, and, as such, give only limited information on the specific rocks adjacent to the San Gregorio Fault zone in the study area (fig. 1). Restoring approximately 150 km of total right-lateral offset across the San Gregorio Fault zone, however, as proposed by Clark and others (1984) on the basis of detailed crossfault geologic correlations and by Jachens and others (1998) on the basis of magnetic anomalies, suggests that the basement rocks of this offshore block have onshore counterparts in the plutonic and metamorphic rocks of the Salinia terrane exposed near Monterey (Clark and others, 1984), about 20 km south of the south edge of the study area (fig. 1).

The absence of strong magnetic anomalies over this block (see pl. 1) indicates that its plutonic and metamorphic basement rocks are, at most, weakly magnetic, a conclusion consistent with the subdued magnetism of the comparable Montara block discussed above and with the absence of strong magnetic anomalies over the basement rocks exposed on the Point Reyes peninsula (U.S. Geological Survey, 1997a) and near Monterey (McCulloch and Chapman, 1977). By analogy with the Montara block, possible sources of other magnetic anomalies over this block include counterparts to the Mindego basalts and sedimentary rocks of the Purisima Formation. Weakly magnetic Tertiary sedimentary rocks may be responsible for the pattern of low-amplitude (10 nT), short-wavelength magnetic anomalies over this block that are evident on the detailed contour presentation of the aeromagnetic data (U.S. Geological Survey, 1996).

## Magnetic Anomalies, Magnetic Boundaries, and Faults

The numerous magnetic anomalies (see pl. 1) over the Franciscan blocks in the central part of the San Francisco Bay region (East Bay Hills block, San Francisco Bay block, and Pilarcitos block) document the pervasive distribution of magnetic source rocks throughout these blocks and provide a regional framework for identifying faults within and at the boundaries of the blocks. The wide variety of anomaly characteristics (amplitude, wavelength, trend, linearity, base level) within these blocks make it almost certain that any major fault cutting or bounding any of these blocks with more than a few kilometers of total offset will juxtapose rocks with different magnetizations, thus producing magnetic anomalies that directly define the faults. Furthermore, geologic mapping in the California Coast Ranges has demonstrated that tabular bodies of magnetic serpentinite commonly occupy both active strike-slip-fault zones and ancient suture zones within the Franciscan terranes (Brabb and Hanna, 1981) and cause linear magnetic anomalies aligned along the faults. As a result, we have sound geologic reasons to expect that the major faults of the San Andreas Fault system will be expressed in the total magnetic field of the San Francisco Bay region and that the locations of these faults will be defined by magnetic anomalies, even in areas where the faults are concealed.

Fault locations defined by magnetic anomalies should be closely related to mapped fault traces but commonly may not correspond precisely to any or all mapped strands. First, faults delineated by means of magnetic anomalies typically represent long-term positions of the faults (those defined by offset geologic units), whereas mapped fault traces commonly reflect only the most recent movement, especially in areas where the basement is covered by alluvium. Second, in areas where magnetic rocks lie in the basement buried beneath nonmagnetic cover, any dip on a fault will result in a systematic offset between the fault trace and the fault position determined from magnetic anomalies. Third, offsets of many kilometers on major faults rarely occur on single surfaces but rather are accommodated across fault zones a few hundred to a few thousand meters wide. We give examples of each of these situations for the specific faults discussed below

### Hayward Fault

The Hayward Fault in the central San Francisco Bay region is marked by a distinct, discontinuous magnetic high, varying in width and amplitude (magnetic anomalies a, k, l, pl. 1), that extends for more than 50 km. The magnetic high is caused by truncation at the fault of diverse magnetic rock units that lie northeast of the fault in the East Bay Hills block. In its central part (magnetic anomaly a), the magnetic high is caused largely by the upturned edge of a tabular body composed of serpentinite and igneous rocks of the Coast Range ophiolite (Wagner and others, 1991; Graymer and others, 1996) that has been folded and slivered up along the fault (Jones and others, 1994). Farther north, where magnetic anomaly l widens (just south of San Pablo Bay and extending northward beneath the bay). the magnetic source rocks are most likely Tertiary volcanic rocks (see Wright and Smith, 1992, profile B–B′), also folded up along the fault. In addition, magnetic sedimentary rocks of the San Pablo and Contra Costa Groups (magnetic anomaly c) that abut the Hayward Fault north of magnetic anomaly b probably contribute to the magnetic high along the fault in this area. Slabs of magnetic ophiolite probably also underlie the magnetic Tertiary rocks.

Recently active strands of the Hayward Fault (Lienkaemper, 1992) are closely correlated with the composite magnetic body and its associated magnetic anomaly (pl. 1) and generally lie within a few hundred meters of its magnetically defined southwest edge except near San Leandro (northern segment of magnetic anomaly a). Here, over a reach of about 6 km where the exposed ophiolite is more than 2 km wide, the active strand of the fault cuts across the center of the body rather than being confined along its southwest edge. The absence of apparent dissection of this body along the fault suggests that the currently active strand here accommodates a right-lateral offset of no more than 1 km, possibly much less. To the northwest along the entire 15-km-long reach of the Hayward Fault immediately southeast of San Pablo Bay, active strands of the Hayward Fault coincide with or lie within 400 m (northeast) of the sharply and continuously defined southwest edge of the composite magnetic body (pl. 1). We identify this magnetic boundary as the long-term position of the Hayward Fault trace immediately southeast of San Pablo Bay. Interpretation of the long-wavelength part of the total magnetic field over the Hayward Fault indicates that the fault dips steeply, at least to about 5-km depth (Jachens and others, 1995b)

We extend the Hayward Fault northwestward across San Pablo Bay (pl. 1) on the basis of continuity of the Hayward Fault magnetic anomaly and, primarily, the inferred southwest edge of the source of this anomaly. This offshore extension of the fault is onstrike with the onshore section to the southeast, is nearly linear, and intersects the north shore of the bay at a point about 1 km east of the mouth of the Petaluma River. Of the 16-km length of this inferred reach of the Hayward Fault, the magnetic anomaly that defines the southeast 5 km is nearly identical to its counterpart onshore immediately to the southeast. Over the next 8 km, however, the magnetic anomaly (l) widens and increases in amplitude, suggesting a change in the geometry of the magnetic source rocks. Nevertheless, the southwest edge of this magnetic body is mostly well defined and is aligned with the Hayward Fault to the southeast. A complexity occurs near the northwest end of this 8-km reach where a magnetic high (magnetic anomaly m) indicates the presence of magnetic rocks southwest of our inferred Hayward Fault. The presence of this body southwest of the fault complicates the identification of a continuous magnetic boundary that defines the Hayward Fault adjacent to this body, but the reemergence of a well-defined magnetic boundary a few kilometers to the northwest and on strike with the fault to the southeast, together with the interpretation of gravity data discussed below, leads us to locate the Hayward Fault as shown on the aeromagnetic map (pl. 1).

Detailed underwater gravity data from San Pablo Bay and from onshore surveys southeast of the bay (inset, pl. 1) indicate that the mapped Hayward Fault consistently lies near the top of a pronounced, northeast-facing gravity gradient and that this gradient continues all the way across San Pablo Bay. The Hayward Fault occupies a similar position with respect to the gravity anomaly south of this area (inset, pl. 1; Chapman and Bishop, 1968; Roberts and Jachens, 1993). Our location of the Hayward Fault beneath San Pablo Bay, as inferred from aeromagnetic data, mostly coincides with its location by Smith (1992) on the basis of gravity data, and is in the same relative position with respect to the gravity gradient (inset, pl. 1) as the mapped fault onshore to the southeast. The gravity data furthermore show that the magnetic body (magnetic anomaly m) beneath San Pablo Bay that we inferred to lie southwest of the fault is characterized by a gravity high and, thus, differs from the other magnetic sources in the immediate vicinity (inset, pl. 1). In fact, the nearest large magnetic body adjacent to and northeast of the Hayward Fault that is also characterized by a gravity high (Roberts and Jachens, 1993) is the magnetic body that causes the strong magnetic high near San Leandro (northern segment of magnetic anomaly a) about 40 km to the southeast. The dense magnetic body beneath San Pablo Bay could be a crossfault counterpart to the San Leandro body (magnetic anomaly a), suggesting a total offset on the Hayward Fault of at least 38 km.

We tentatively extend the Hayward Fault about 3 km northwestward of the north shore of San Pablo Bay, on the basis of magnetic anomalies and boundaries (pl. 1). However, the westerly divergence of this strand from the trend of the Hayward Fault to the southeast and its divergence from the strong gravity gradient that characterizes the rest of the fault (inset, pl. 1) suggest that it probably does not represent a strand which accommodates much total offset.

## Total Offset on the San Andreas Fault[1]

The Peninsular segment of the San Andreas Fault that ruptured during the 1906 San Francisco earthquake (pl. 1; location from Brabb and Olson, 1986; Pampeyan, 1994; Bonilla, 1971) is not characterized by a continuous magnetic anomaly, as is the Hayward Fault, but by truncation at the fault of several elongate magnetic anomalies (pl. 1) reflecting magnetic rock bodies that trend into the fault at low to moderate angles and are cut by the fault. Because these magnetic rock bodies are interspersed with relatively nonmagnetic rocks, the San Andreas Fault is defined by a discontinuous set of short, aligned magnetic boundaries situated where the magnetic bodies, both east and west of the fault, abut the fault plane. A fault defined by aligned, discontinuous magnetic boundaries is more difficult to recognize than one that is characterized by a continuous magnetic anomaly, such as the Hayward Fault. However, when the fault is located from geologic mapping or other information, then elongate magnetic rock bodies within the basement and truncated by the fault provide a means for estimating the total offset on the fault from the aeromagnetic map (pl. 1). Truncated magnetic rock bodies in the basement and their associated magnetic anomalies on one side of the fault should have counterparts on the opposite side of the fault separated by an along-fault distance equal to the total offset on the fault.

A strong, distinctive linear magnetic high (magnetic anomaly p, pl. 1) that lies mostly along the southwest edge of the Pilarcitos block, trending into the San Andreas Fault at an angle of 10º, reflects a magnetic body with a northeast edge that intersects the fault at point A (pl. 1). This body should have a crossfault counterpart with an associated magnetic anomaly that could be used to estimate the total offset on the Peninsular segment of the San Andreas Fault. The only magnetic anomaly east of the fault that is comparable to the anomaly at point A and is within the 20- to 30-km offset distance indicated by two displaced geologic units—a distinctive limestone-bearing unit (Bailey and others, 1964) of the Franciscan Complex (magnetic anomaly h, pl. 2) and an unusual gravel unit (Cummings, 1968) also cut by the fault—lies 22 km to the southeast and reflects a linear magnetic body whose north edge intersects the fault at point A (pl. 1). Pieces of ophiolite are found near both points A (Brabb and others, 1998) and A′ (Miller-Hoare and Liou, 1980).

[1] Much of the discussion contained in this and the following section, and in the section below entitled “Detailed Structure of the Right Step in the San Andreas Fault,” is based on the report by Jachens and Zoback (1999) and is included here for the sake of internal consistency and completeness.

If the 22-km separation along the fault between the magnetic bodies at points A and A (pl. 1) represents the total offset on the Peninsular segment of the San Andreas Fault, then other magnetic anomalies west of and truncated at the fault on the aeromagnetic map (pl. 1) should have crossfault counterparts east of the fault that are also offset by 22 km. The magnetic body that lies west of and abuts the San Andreas Fault between points B and C has a crossfault counterpart between points B′ and C′, 22 km to the southeast. Magnetic metabasalts crop out in both places, but the sources of the magnetic anomalies between points B and C and between points B′ and C′ are difficult to precisely identify because the anomaly west of the fault is mostly offshore and the anomaly east of the fault is partly caused by a sheet of serpentinite.

Restoration of 22 km of right-lateral offset places the broad, low-amplitude magnetic high that abuts the fault along the reach between 3 and 9 km southeast of point B (pl. 1) against the fault-terminated ends (along the reach between 4 and 10 km southeast of point B′) of the horseshoe-shaped magnetic high east of the fault. Although this match does not provide compelling evidence for 22 km of right-lateral offset, given the 22 km of offset clearly defined by the matches A–A′, B–B′, and C–C′, the anomalies southeast of points B and B′ are similar enough to constitute supporting evidence. Thus, the magnetic anomalies in the vicinity of the Peninsular segment of the San Andreas Fault support the geologic inference that only a few tens of kilometers of total offset are accommodated on this segment of the fault, and refine the estimate of the offset to 22±1 km.

## Offshore San Andreas Fault

For the purposes of this study, the northwesternmost reach of the San Andreas Fault on the San Francisco peninsula is well defined magnetically (near point B′, pl. 1). Here, for an onshore distance of 5 km, the long-term position of the fault coincides with the northeast boundary of a body probably composed of magnetic Franciscan metabasalt (see pl. 2). The northeast edge of this body as defined magnetically lies parallel to and 200 to 400 m northeast of the mapped trace of the San Andreas Fault (pl. 1), an apparent misalignment that we attribute to a steep northeastward dip on the upper part of the San Andreas Fault plane (U.S. Geological Survey, 1997b). The magnetic anomaly produced by this body is strongest near the coast and continues 5 km offshore as a strong, consistent magnetic feature (high values to the southwest, low values to the northeast). We interpret the offshore 5-km-long northeast boundary of the body causing this anomaly to be the continuation of the San Andreas Fault (pl. 1), on the basis of the relation of this boundary to the fault trace onshore and the fact that it is a direct onstrike projection of the onshore fault.

We end this strand of the San Andreas Fault 5 km offshore at point C (pl. 1) for the following reasons. (1) A distance of 5 km is as far as the aeromagnetic data define a boundary (separating magnetic rocks to the southwest from less magnetic rocks to the northeast) that is continuous with and consistent with the magnetically defined San Andreas Fault at the coast. (2) Northwest of this point, the projection of the fault enters a region of magnetic rocks that, though not uniform in magnetic properties, apparently belong to a single large triangular block, 6 km wide at its base, which extends 12 km northwestward from point C. The magnetic anomalies over this block suggest that the source is composed of the same types of rocks (of the Permanente and Headlands terranes) as the Pilarcitos block onshore and southwest of the fault. (3) If the San Andreas Fault were to continue on strike northwestward of point C, within 6 km it would be truncated at, but not offset, the strong north-northwest-trending magnetic lineation to the west that we identify as a strand of the San Gregorio Fault zone (see discussion below). Truncation of the Peninsular segment of the San Andreas Fault against the San Gregorio Fault zone would preclude accommodation of the 22 km of total offset on this segment documented in the previous section.

Although no continuous magnetic boundary connects the mapped trace of the Peninsular segment of the San Andreas Fault with the mapped traces at Bolinas Lagoon, a major linear offshore magnetic boundary, more than 20 km long, projects into the northeastern strand of the San Andreas Fault at Bolinas Lagoon (pl. 1). This boundary nearly parallels the Peninsular segment of the fault and occupies the same relative position with respect to magnetic rocks of the Pilarcitos block as does the Peninsular segment to the south (that is, it forms the northeast boundary of the magnetic Pilarcitos block). We identify this magnetic boundary as the location of the offshore southeastward extension of the San Andreas Fault mapped at Bolinas Lagoon. Furthermore, on the basis of the profound magnetic contrast across this segment, we interpret it to be the main strand of the San Andreas Fault that accommodates offset between the San Francisco Bay block and the Pilarcitos block across the mouth of the Golden Gate. This strand, here informally called the Golden Gate segment of the San Andreas Fault, projects southeastward to the San Francisco peninsula, intersecting the coast near Lake Merced. Although no fault is recognized in the seacliff at this place, an abrupt change in the dip of strata of the Merced Formation is visible here (Clifton and Hunter, 1987), a feature characteristic of the Golden Gate segment offshore as seen in marine seismic-reflection records (see Bruns and others, this volume). The inferred northwest end of the Peninsular segment and the inferred southeast end of the Golden Gate segment of the San Andreas Fault do not connect but are separated in a right-step sense by 3 km normal to strike. Although several workers (for example, Cooper, 1973; McCulloch, 1987; Hengesh and Wakabayashi, 1995; Zoback and others, 1999) have recognized the need for a rightward bend or right step in the San Andreas Fault offshore west of San Francisco, the interpretation presented here provides details of the position and geometry of this right step (informally called the Lake Merced right step).

## Pilarcitos Fault

The northwesternmost 14 km of the onshore Pilarcitos Fault (Pampeyan, 1994) coincides closely with a strong magnetic boundary (pl. 1) that separates magnetic Franciscan basement rocks of the Pilarcitos block from mostly nonmagnetic granitic rocks of the Montara block. This magnetic boundary, which extends northwestward an additional 8 km offshore, is inferred to mark the offshore extension of the Pilarcitos Fault. The northwest end of this extension bends slightly northward and merges with a set of north-northwest-trending magnetic boundaries that we infer to mark the San Gregorio Fault zone (see next subsection). Magnetic modeling indicates that onshore, the Pilarcitos Fault, where magnetically well defined, is nearly vertical at least to about 4-km depth, in accord with the conclusions of Parsons and Zoback (1997), who defined a vertical attitude for the Pilarcitos Fault to 7-km depth, using lateral-velocity changes inferred from seismic tomography.

### San Gregorio Fault Zone

A set of long, linear, north-northwest-trending echelon magnetic boundaries (magnetic anomaly q, pl. 1) lies in a 1- to 2-km-wide zone that marks the west offshore edge of magnetic rocks of the Pilarcitos block (pl. 1). The relative straightness of these boundaries and the profound difference in magnetism of the rocks on either side of the zone strongly suggest that these features reflect individual strands within a fault zone that has accommodated major lateral offset. Although this interpretation cannot be corroborated by correlation with aligned onshore faults to the southeast, the northernmost offshore strand projects across a 3-km gap directly into the southwesternmost mapped strand of the San Andreas Fault at Bolinas Lagoon. Recent detailed marine seismic-reflection profiling (see Bruns and others, this volume) also has shown that the magnetic boundaries within this offshore zone coincide with major faults in the sedimentary section (fig. 2).

We conclude that the north-northwest-trending set of linear magnetic boundaries identified on the aeromagnetic map (pl. 1) along the west edge of the Pilarcitos block delineates the location of the San Gregorio Fault zone between Half Moon Bay and Bolinas Lagoon, for the following reasons: (1) the zone containing the magnetic boundaries regionally lies on the northward projection of the San Gregorio Fault zone (for example, Graham and Dickinson, 1978; McCulloch, 1987); (2) the magnetic boundaries coincide with faults identified by marine seismic-reflection profiling; (3) the lengths (one is >20 km long) and straightness of the boundaries suggest major strike-slip faults; (4) the north end of the northernmost boundary projects directly into the western strand in the San Andreas Fault zone at Bolinas Lagoon, the strand that defines the east boundary of nonmagnetic Cretaceous granitic rocks and separates Franciscan basement on the east from Salinian basement on the west (Galloway, 1977; Wagner and Bortugno, 1982; Wagner and others, 1991; Clark and Brabb, 1997); and (5) the south end of the southernmost boundary coincides with a scarp on the sea floor that projects directly into the onshore Seal Cove Fault (Glen, 1959), now included as a strand of the San Gregorio Fault.

## Discussion

The newly acquired high-resolution aeromagnetic surveys constitute a rich source of structural information about strands of the San Andreas Fault system concealed beneath young sedimentary deposits and (or) water in the San Francisco Bay region. The uniform areal coverage of these aeromagnetic surveys, in combination with the clear expression of many of the faults in the aeromagnetic data, provides a coherent framework within which to integrate the exposed bedrock geology and sparsely distributed subsurface data. In addition, these data constitute a bridge between onshore geologic information and marine geophysical surveys and provide an areally uniform image of the entire fault system in the San Francisco Bay region that we have lacked in the past. Included in the data are new clues into structures at the intersections of branching major fault strands, structures within a block caught between major faults, and detailed geometries in areas of extensional stepovers within the strike-slip system.

### San Andreas-San Gregorio Fault Junction

The fault strands inferred from the aeromagnetic map (pl. 1) provide new information on the structure at the San Andreas-San Gregorio Fault junction north of San Francisco. The Golden Gate segment of the San Andreas Fault connects at Bolinas Lagoon with the northeasternmost of the three onshore strands in the San Andreas Fault zone mapped by Galloway (1977). Galloway's northeastern strand, like the Golden Gate segment offshore, has Franciscan basement on both sides, even though the basement sliver to the southwest is quite narrow and largely concealed beneath Cenozoic deposits.

We correlate the northernmost strand of the inferred offshore San Gregorio Fault zone with the westernmost onshore strand in the San Andreas Fault zone at Bolinas Lagoon because (1) the northern offshore strand of the San Gregorio Fault zone, where last clearly delineated by the aeromagnetic data, projects directly into the southwestern mapped strand in the San Andreas Fault zone at Bolinas Lagoon; and (2) the onshore and offshore strands occupy the same structural position, separating Franciscan basement rocks on the northeast from Salinian granitoids on the southwest. Thus, we argue for continuity of the westernmost strand in the San Andreas Fault zone at Bolinas Lagoon southeastward with the San Gregorio Fault zone. Cooper (1973) also connected the onshore westernmost strand in the San Andreas Fault zone at Bolinas Lagoon with a strand of the San Gregorio Fault zone (the Seal Cove Fault), but the details of his connection in the offshore differ somewhat from the path proposed here.

Within 10 to 15 km northwestward from Bolinas Lagoon, the several mapped fault strands converge smoothly

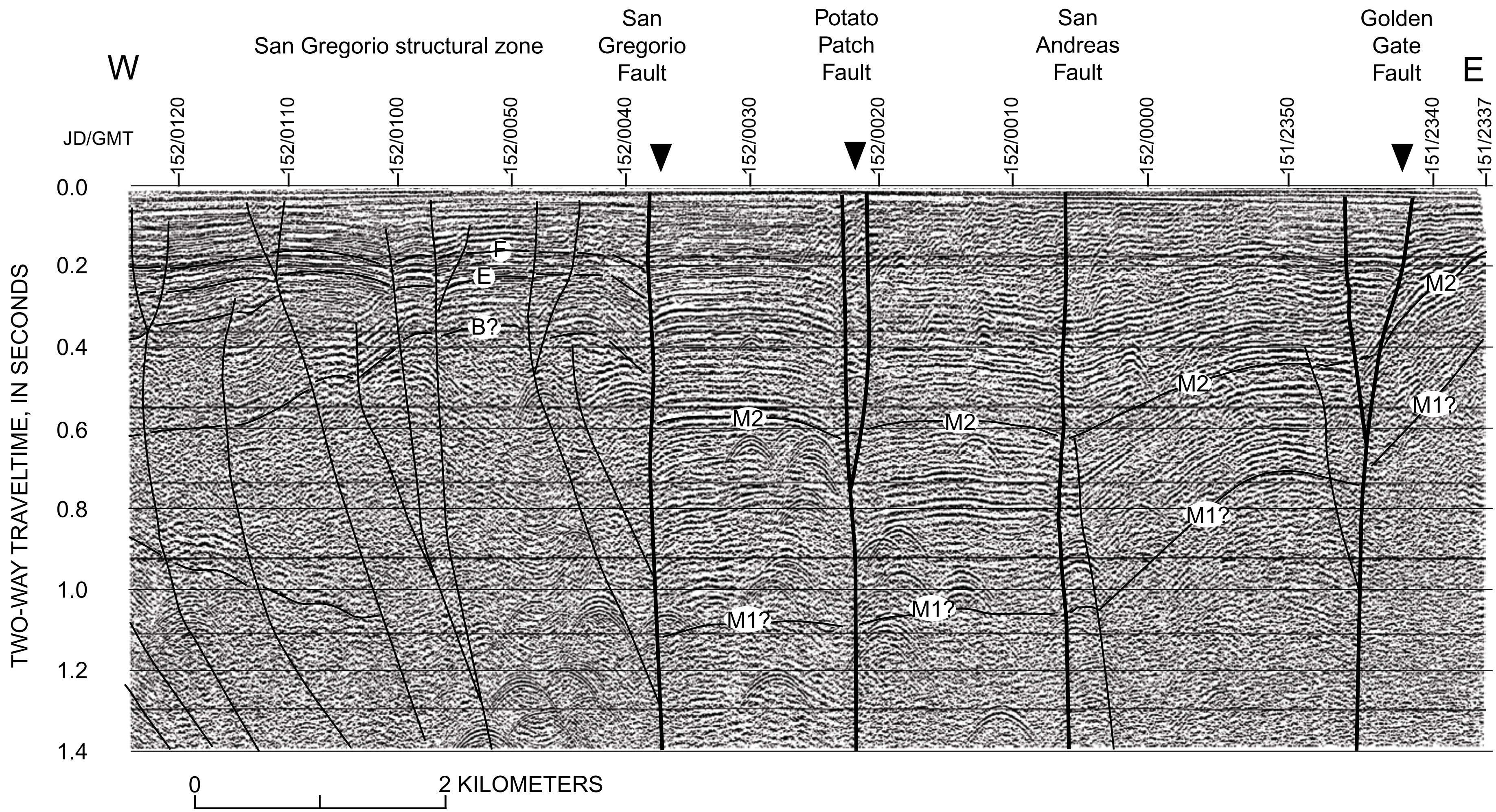


Figure 2.—Marine seismic-reflection cross section along seismic line 107 (see pl. 1 for location; from Bruns and others, this volume, fig. 17). Profile crosses two submarine strands of the San Gregorio Fault and one strand of the San Andreas Fault system in the Gulf of the Farallones west of San Francisco. Inverted triangles, locations of major fault strands interpreted from aeromagnetic data and highlighted on aeromagnetic map (pl. 1); alphanumeric symbols, interpreted seismic horizons discussed by Bruns and others (this volume).

into a zone less than about 1 km wide. Thus, on the basis of our correlation of the San Andreas and San Gregorio Fault zones at Bolinas Lagoon, the junction of these two major fault zones is characterized by the simple northwestward merging of strands into a very narrow zone. Structurally, this junction seems somewhat simpler than the junctions of other major strands of the San Andreas Fault system, such as the San Andreas-Calaveras Fault junction (Jennings and Strand, 1959), the Hayward-Calaveras Fault junction (Wagner and others, 1991; Jones and others, 1994), and the San Andreas-San Jacinto Fault junction (Morton and Matti, 1993). Those junctions are characterized by broad, complex zones where major strands of the converging fault zones remain separated by a few kilometers or more over along-strike distances of tens of kilometers. The apparent simplicity of the San Gregorio-San Andreas Fault junction may be related to the releasing-bend nature of the junction. Alternatively, the San Gregorio-San Andreas Fault junction is fundamentally an intersection of basement faults, whereas the fault junctions mentioned above are mostly expressed by faults in a young sedimentary section. These young sedimentary materials may respond to active faulting more complexly than the underlying basement rocks.

## San Gregorio-Pilarcitos Fault Junction

The San Gregorio-Pilarcitos Fault junction lies ~5 km offshore (pl. 1). Although the nominal strikes of the two faults differ by ~45º, the Pilarcitos Fault offshore bends smoothly northward, ultimately merging with the San Gregorio Fault zone or intersecting it at an angle of <15º.

Whether the Pilarcitos Fault merges smoothly with the San Gregorio Fault zone or truncates against it is important for understanding the development of total offset on, and partitioning of offset among, the various strands of the San Andreas Fault system in northern California (Jachens and others, 1998). Either the Pilarcitos Fault was cut by the San Gregorio Fault zone (Graham and Dickensen, 1978; Griscom and Jachens, 1989), or the Pilarcitos Fault always merged smoothly with the San Gregorio Fault zone. In the first case, the rightward bend at the northwest end of the Pilarcitos Fault is the result of an initial high-angle truncation of the Pilarcitos Fault at the San Gregorio Fault zone that was subsequently deformed by drag associated with continued right-lateral strike-slip movement on the San Gregorio Fault zone. In the second case, before initiation of movement on the Peninsular segment of the San Andreas Fault a few million years ago, the main plate-boundary fault separating granitic and Franciscan terranes consisted of the Pilarcitos Fault and that segment of the San Gregorio Fault zone to its north. Possible warping of this proposed Pilarcitos-northern San Gregorio Fault segment into a leftward bend (restraining bend) geometry could have ultimately resulted in abandonment of the Pilarcitos Fault when the San Andreas Fault broke through on the straighter Peninsular segment a few million years ago and movement continued on the San Gregorio Fault zone (Griscom and Jachens, 1989; Jachens and Zoback, 1999).

If the first case applies, then the offset counterpart of the strong magnetic anomaly that defines the Pilarcitos Fault on the San Francisco peninsula should exist west of, and be truncated at, the San Andreas Fault somewhere north of San Francisco (Graham and Dickensen, 1978; Griscom and Jachens, 1989). Identification of a crossfault counterpart to this anomaly would tightly constrain the total offset on a segment of the San Andreas Fault system and would document the existence of an offset strand of the fault system that would need to be taken into account in any attempt to understand the partitioning of total slip on the fault system.

If the second case applies, then no crossfault counterpart to the Pilarcitos Fault or its associated magnetic anomaly would be expected, and one potential fault element from the total San Andreas Fault system would be removed. The latest aeromagnetic survey over part of the northern section of the San Andreas Fault and adjacent Continental Shelf (U.S. Geological Survey, 1997a) shows no likely offset counterpart of the Pilarcitos Fault anomaly at least as far north as Gualala, Calif., about 150 km north of the San Gregorio-Pilarcitos Fault junction (Jachens and others, 1998). An older aeromagnetic survey of the Point Arena, Calif., area (Gulf Research and Development Co., unpub. data) reveals a possible offset counterpart of the Pilarcitos Fault magnetic anomaly west of the San Andreas Fault about 50 km farther north near Point Arena. However, more detailed study of the subsurface geology and geophysics of the Point Arena area is needed to establish whether the magnetic anomalies in this area correlate with the Pilarcitos Fault magnetic anomaly in the San Francisco Bay region.

## Structure of the Pilarcitos Block

The presence of a major right step in the San Andreas Fault strand bounding the northeast side of the Pilarcitos block, and the existence of right-stepping echelon strands of the San Gregorio Fault zone bounding the west side of the Pilarcitos block, suggest that at least the north half of this block lies in an extensional setting. This interpretation is compatible with the general releasing-bend geometry of the San Andreas-San Gregorio Fault junction and with the high level of seismicity within the block dominated by normal faulting on northerly trending fault planes (Zoback and others, 1998). A young, thick sedimentary section on the Continental Shelf between the San Andreas Fault and the San Gregorio Fault zone, as indicated by a gravity low, seismic-reflection profiling (Cooper, 1973), and wide-angle seismic-refraction profiling (Hole and others, 1993) and defined areally by new high-resolution seismic-reflection data (see Bruns and others, this volume), are also consistent with an extensional setting for the northern part of the Pilarcitos block. Bruns and others (this volume) examine the extensional regime of this block in greater detail.

## Detailed Structure of the Right Step in the San Andreas Fault

Understanding the right step in the San Andreas Fault near Lake Merced is important because it places an active segment (Golden Gate segment) of the San Andreas Fault system 3 km closer to downtown San Francisco than previously thought (previous distance, 10–15 km). The position of this segment and its proximity to the highly developed downtown area must be taken into account when estimating the local shaking from an earthquake on the San Andreas Fault here. This right step may also provide insights into conditions controlling the initiation of great strike-slip earthquakes because the epicenter of the great 1906 San Francisco earthquake is believed to lie within the right-step region (Bolt, 1968; Boore, 1977).

As several workers have pointed out, a right step in a right-lateral fault system implies, with continued movement, the formation of a pullapart basin bounded by the two fault strands composing the right step or their onstrike projections (for example, Aydin and Nur, 1982, 1985). Thus, a pullapart basin about 3 km wide might be expected to exist along the San Andreas Fault southeastward from the Lake Merced right step. Because the Peninsular segment of the San Andreas Fault has accommodated only 22 km of offset (see preceding section) and probably has been active for only a few million years (Hengesh and Wakabayashi, 1995), the pullapart basin should be filled with young, low-density sedimentary deposits and be accompanied by a gravity low.

Detailed gravity measurements on the San Francisco peninsula (Roberts, 1991) reveal such a gravity anomaly, a pronounced gravity low 2 to 3 km wide, aligned along the San Andreas Fault and bounded by the fault on the southwest. Inversion of this gravity anomaly to estimate the thickness of Cenozoic deposits above the Franciscan basement, using a slight modification of the technique of Jachens and Moring (1990), indicates a basin along the San Andreas Fault with the characteristics expected of a pullapart basin resulting from the right step in the San Andreas Fault offshore of the San Francisco peninsula (fig. 3). The basin, about 3 km wide and 1 km deep at the coast, both shallows and narrows away from the right step southeastward along the San Andreas Fault. At the coast, the northeastern margin of the basin coincides with the onshore projection of the Golden Gate segment of the San Andreas Fault (fig. 3), as expected of a pullapart caused by the inferred right step. Thus, the onshore gravity data provide strong support for the inferred 3 km right step in the San Andreas Fault system offshore from San Francisco. However, almost no gravity data are available in the critical offshore area of the right step, and so at present the gravity analysis cannot be extended into the offshore area.

Understanding the detailed structure and evolution of the Lake Merced right step may also help to explain the cause of northeastward-directed thrust faulting along the San Andreas Fault on the northern part of the San Francisco peninsula and the somewhat puzzling uplift of deposits of the Merced Formation (pl. 2) northeast of the fault, deposits that just a few million years ago or less had accumulated in a subsiding, presumably extensional environment (Hengesh and Wakabayashi, 1995). We suggest that the explanation for both of these processes lies in the detailed fault geometry within in the right-step region. The inferred Golden Gate segment of the San Andreas Fault is extremely straight and almost exactly parallels all but the northernmost section of the San Andreas Fault on the central part of the San Francisco peninsula (pl. 1). The northernmost section of this Peninsular segment (5 km offshore and 5 km onshore) strikes as much as 10º more westerly than the section to the south, leading to a decrease in fault-normal separation of the right-step strands from 3 km at point C to 2 km southeast of point C (pl. 1). The pullapart basin resulting from the right-step geometry is actively subsiding and filling immediately behind (southeast of) the right step and, on the basis of offsets mapped after the 1906 San Francisco earthquake, is progressively moving southeastward with the San Francisco Bay block. Thus, the basin is filling at a place where it is 3 km wide, but is then progressively compressed to a width of only 2 km during its subsequent 10 km of travel southeastward with the San Francisco Bay block. This progressive southeastward narrowing of the basin is evident in the flanks of the basin, as defined by the gravity inversion (fig. 3). The space problem created by the conditions described above would likely result in fault-normal compression across the basin, causing thrusting and uplift of the basin deposits. Thus, the seemingly contradictory conditions of extension and uplift within a small area may simply be the result of progressive evolution of a pullapart basin with nonparallel bounding faults.

Finally, because the Lake Merced right step lies offshore, it is concealed from direct observation. However, before the inception of movement on the Peninsular and Golden Gate segments of the San Andreas Fault, point C′ (pl. 1) would have been located at the future position of the Lake Merced right step. Therefore, today the area around point C′ might be a good place to look for evidence reflecting the initiation of major strike-slip faulting and the early evolution of a right step in a right-lateral strike-slip system.

## Right Step in the Hayward Fault-Rodgers Creek Fault

Geologic mapping (Wagner and Bortugno, 1982) and geophysical interpretations (Wright and Smith, 1992) indicates that the Hayward Fault does not continue far northward of San Pablo Bay, a conclusion consistent with the geophysical data presented above in the section entitled “Hayward Fault.” Analyses of seismicity and other evidence of active faulting (Hill and others, 1990; Budding and others, 1991) indicate that slip on the Hayward Fault south of San Pablo Bay probably is now accommodated on the Rodgers Creek Fault north of the bay. The relative positions of the northern section of the Hayward Fault and the southern section of the Rodgers Creek Fault (pl. 1; fig. 1) suggest a right step of about 6 km in the Hayward-Rodgers Creek Fault system, possibly similar to the right step in the San Andreas Fault system near Lake Merced. The details of the structure of this right step and the method of slip transfer are uncertain because the transfer region is largely concealed beneath San Pablo Bay.

The amount of right-lateral offset likely to have taken place during the lifetime of the right step is not well constrained but probably more than 10 km. Wright and Smith (1992) suggested that early slip on the Hayward Fault was taken up on the Tolay Fault to the north, but because the Tolay Fault offsets units no younger than early Pleistocene (Hart, 1982), Holocene slip must be accommodated elsewhere. If the present slip rate on the Hayward Fault (~9 mm/yr; Working Group on California Earthquake Probabilities, 1999) has persisted since the early Pleistocene, then at least 15 to 20 km of offset could have accumulated while the right step was in existence. Even more offset is predicted by the work of R.W. Graymer (unpub. data, 1999), who used offset volcanic deposits of Tertiary age to estimate the total offset on various faults east of San Francisco Bay. He estimated that the Hayward Fault accommodates 82 km of total offset, of which 39 km is partitioned onto the Tolay Fault and the remaining 43 km onto the Rodgers Creek Fault. Although these two estimates of offset differ substantially, they both suggest that a significant amount of offset has occurred across the right step from the Hayward Fault to the Rodgers Creek Fault during its lifetime.

The inferred geometry and slip history of the right step beneath San Pablo Bay (6-km-wide step, tens of kilometers of offset) are similar enough to those of the right step in the San Andreas Fault near Lake Merced to suggest that the features which characterize the Lake Merced right step might also be associated with the right step beneath San Pablo Bay. These features might include a pronounced linear gravity low extending southeastward along the Hayward Fault from

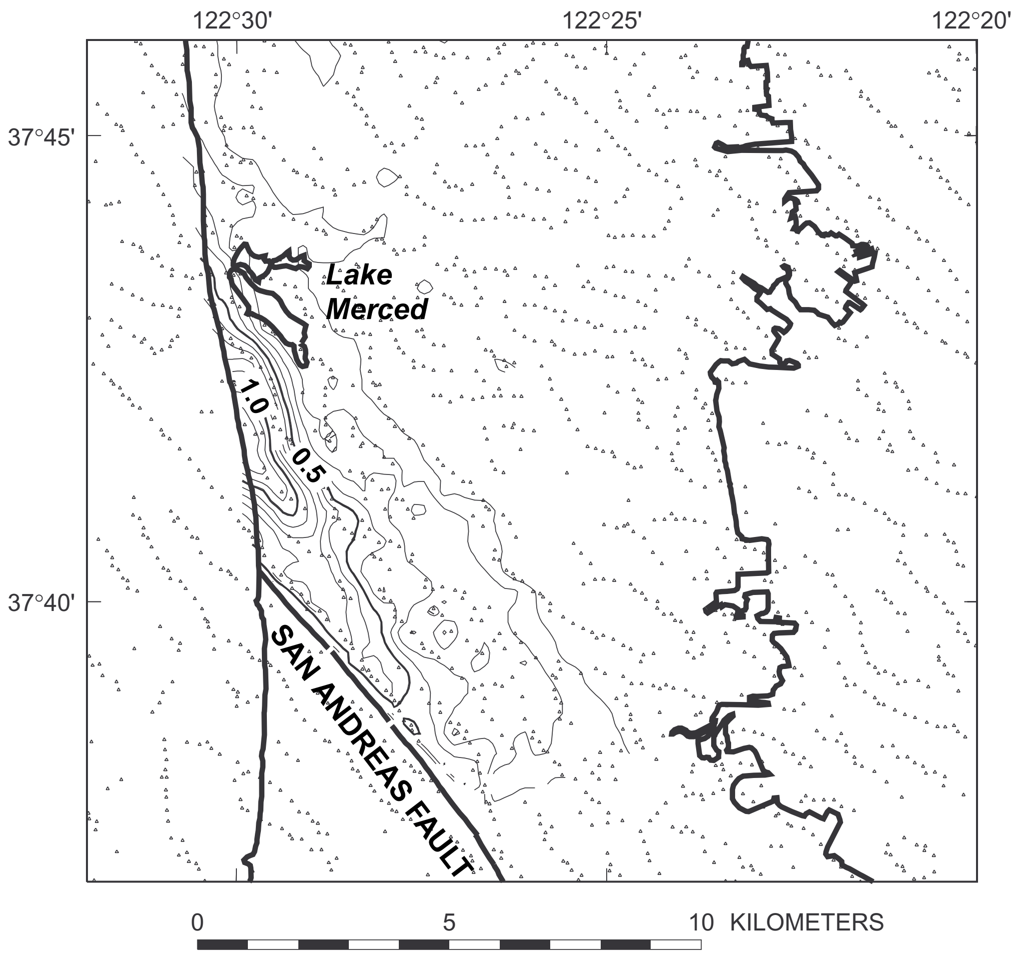


Figure 3.—Lake Merced area (see pl. 1 for location), showing thickness of Pliocene and Quaternary deposits of the Merced Formation and younger sedimentary deposits that fill inferred pullapart basin southeast of right step in the San Andreas Fault offshore. Map was produced by three-dimensional inversion of detailed gravity data (Roberts, 1991) constrained by drill-hole data and outcrop geology, using procedure of Jachens and Moring (1990) modified slightly to allow for explicit incorporation of drill-hole constraints. Contour interval, 0.1 km. Same scale as in plates 1 and 2 (1:150,000).

San Pablo Bay, a corresponding deep linear basin 6 km wide and filled with Quaternary deposits in the wake of the right step, and disrupted geologic units and structural features that predate the right step and have been dismembered by faulting associated with the recent linkage of the Hayward and Rodgers Creek Faults.

Wright and Smith (1992) presented a structural analysis of the right step beneath San Pablo Bay based on detailed onshore and bay-bottom gravity surveys, drill-hole data, and marine seismic reflection profiles. They determined that the Hayward and Tolay Faults occupy similar structural positions at the northeast edge of uplifted Franciscan rocks of the San Francisco Bay block and that the gravity data indicate that the two faults are connected by a 4-km right step beneath the north shore of San Pablo Bay. They concluded that the Tolay and Rodgers Creek Faults are separate, parallel features which bound opposite sides of a deep Late Cenozoic structural trough, a relation that precludes a direct connection between the Hayward and Rodgers Creek Faults in the upper seismogenic zone, at least north of about the center of San Pablo Bay. They projected the Rodgers Creek Fault 13 km southeastward from its outcrop area (pl. 1) on the basis of an abrupt change in the dip of Tertiary beds, as determined from drill-hole logs and seismic-reflection profiles. Finally, they identified a trough filled with sedimentary and volcanic materials beneath San Pablo Bay between the Hayward Fault and the southeastward projection of the Rodgers Creek Fault that is consistent with a pullapart basin behind a right step from the Hayward Fault to the Rodgers Creek Fault.

The gravity data of Smith (1992) reveal an enormous gravity low northeast of the Hayward Fault and over San Pablo Bay and surrounding areas (inset, pl. 1). However, the low extends more than 10 km northeastward of the projection of the Rodgers Creek Fault beneath the bay, too far northeastward to be caused by an extensional basin associated with the present right step. This low might more appropriately reflect an extensional collapse associated with an earlier right step between the Hayward-Tolay Fault system and the Franklin-Carneros Fault system. The expected local gravity low between the Hayward and Rodgers Creek Faults is not obvious on the inset on plate 1, although a low of only a few milligals might exist but would be difficult to identify because it would be superposed on the steep northeast-facing gravity gradient associated with the transition from a thick sedimentary section of the East Bay Hills block to Franciscan basement rocks of the San Francisco Bay block.

Two interpreted cross sections across San Pablo Bay approximately normal to the Hayward Fault (Wright and Smith (1992), one along the north edge of the bay and the other about 5 km to the southeast, show a unit of Tertiary and Quaternary rocks 2+ km thicker between the Hayward and Rodgers Creek Faults than in areas to the northeast and southwest. This anomalously thick section of young deposits is not easily reconciled with the absence of a pronounced corresponding gravity low. The anomalously thick part of this section may be largely Tertiary and thus denser than the Quaternary deposits, as suggested by the tentative identification of an interface (angular unconformity?) in the upper part of this section on the southernmost cross section that shows only 0.5 to 0.9 km of thickening. Finally, no narrow, linear basin filled with Quaternary deposits extends more than a few kilometers onshore southeast of San Pablo Bay, as might be expected from a right step that accommodated tens of kilometers of offset.

The magnetic anomalies over San Pablo Bay and vicinity (pl. 1) support the interpretation by Wright and Smith (1992) and may provide some additional constraints on allowable mechanisms for slip transfer between the Hayward and Rodgers Creek Faults. A southeast-trending magnetic high (magnetic anomaly n) reflects a magnetic source body, most likely composed of Tertiary volcanic rocks (Wright and Smith, 1992), deep in the structural trough between the Tolay and Rodgers Creek Faults. The continuation of this magnetic anomaly beneath San Pablo Bay indicates that the source body bends southward and ultimately truncates against the Hayward Fault from 8 to 13 km northwest of Pinole Point (pl. 1). The continuity of this magnetic source body precludes any direct connection between the upper parts of the Hayward and Rodgers Creek Faults north of the south edge of this body because any such fault that accommodated significant strike-slip offset would necessarily have offset the magnetic source body. A second magnetic high (magnetic anomaly o) parallels and lies east of both magnetic anomaly n and the Rodgers Creek Fault. Although magnetic anomaly o becomes less distinct as it continues beneath San Pablo Bay, it also suggests a source body that bends southward and continues beneath the bay in a manner conformal to the source of magnetic anomaly n, finally ending near the Hayward Fault ~3–5 km northwest of Pinole Point. The apparent continuity of the source of magnetic anomaly o appears to preclude any shallow connection between the Hayward and Rodgers Creek Faults southeast of about Pinole Point and also seems to rule out any significant strike-slip offset on an onstrike extension of the Rodgers Creek Fault southeast of its southeasternmost location on the aeromagnetic map (pl. 1). Although magnetic anomaly o is admittedly weak and difficult to trace beneath the bay, we have examined its location and continuity with several data processing and enhancement techniques and conclude that its characteristics are robust enough to support the above-stated conclusions.

In summary, the detailed structure and kinematics of slip transfer are far less clear for the right step between the Hayward and Rodgers Creek Faults than for the comparable right step in the San Andreas Fault near Lake Merced. If a direct connection exists between the Hayward and Rodgers Creek Faults in the uppermost few kilometers of crust, then it likely lies beneath San Pablo Bay somewhere between magnetic anomalies n and o (pl. 1). Alternatively, a direct connection between the two faults may exist at depth, with the uppermost few kilometers of crust decoupled in such a way as to retain continuity of older, shallow geologic units. In either case, the absence of a pronounced gravity low between the two fault strands, and the presence of possibly only a modest extensional basin filled with Quaternary deposits beneath the bay and no basin at all south of the bay, are puzzling, given the likelihood that 15 to 40 km of offset has occurred on the Rodgers Creek Fault. Complex interactions of local subsidence and uplift may have complicated the present picture, or else the Hayward and Rodgers Creek Faults may have been colinear during most of the time when slip was accumulating on the Rodgers Creek Fault, with some superposed deformational event causing the right step to form only very recently. Some combination of these possible interpretations, or others that we have not considered, may be needed to fully understand the nature of the right step beneath San Pablo Bay.

## Additional Considerations

The above discussion, though providing new insights into the structure, kinematics, and dynamics of the San Andreas Fault system in the San Francisco Bay region, has in no way exhausted the potential of the aeromagnetic data presented here for providing a new understanding of the geology and tectonics of the region. For example, we have discussed only active or recently active strands of the San Andreas Fault system. The aeromagnetic map (pl. 1), however, reveals numerous long, linear magnetic boundaries or aligned boundary segments, many of which evidently reflect faults. These features may be ancient faults left over from the initial tectonic assembly of the crust of the region many millions of years ago. Alternatively, they may be faults that are presently dormant but still represent a potential seismic hazard in the near future. As another but slightly different example, many of the magnetic anomalies shown on the map are caused by sheets of serpentinite within the basement, sheets that often are hidden beneath young sedimentary deposits. Thus, the map directly indicates in detail the distribution of serpentinite in the subsurface, information that is of possible interest because of the common association of potentially hazardous mercury and asbestos with serpentinite in the California Coast Ranges.

In more general terms, the aeromagnetic data presented here provide a type of three-dimensional “image” of the crustal geology of the San Francisco Bay region, at least insofar as this geology is reflected by the shape and distribution of magnetic rocks, even in such highly urbanized areas as those surrounding San Francisco Bay, where the deeper geology is hidden beneath alluvial deposits and where urban development has destroyed much of the geologic evidence once present at the surface. Although interpretations of magnetic anomalies are known to be ambiguous (different bodies can sometimes produce identical magnetic anomalies), nevertheless, every recognizable magnetic anomaly contains some three-dimensional information about the rock body that produces it. This three-dimensional information can be derived from the geometric characteristics of the magnetic anomalies, from their areal distribution, and from forward modeling of them with constraints imposed by geology, drill-hole data, and other geophysical information. In such areas as the San Francisco Bay region where magnetic rocks are abundant and reasonable well known, aeromagnetic data provide a powerful tool for helping to unravel the concealed geology.

Because we recognize the potential usefulness of aeromagnetic data for solving a host of other problems not discussed in this report, we have provided the aeromagnetic map (pl. 1) at a large scale and included the full suite of automatically determined magnetic boundaries (small pluses) over the entire map area, not simply those that are directly related to our interpretation. Furthermore, we have released the data for the central part of the map area in contour form at a scale of 1:100,000 (U.S. Geological Survey, 1996), along with all the digital data that went into the production of the map, through the National Geophysical Data Center (325 Broadway, Boulder, CO 80303–3328).

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