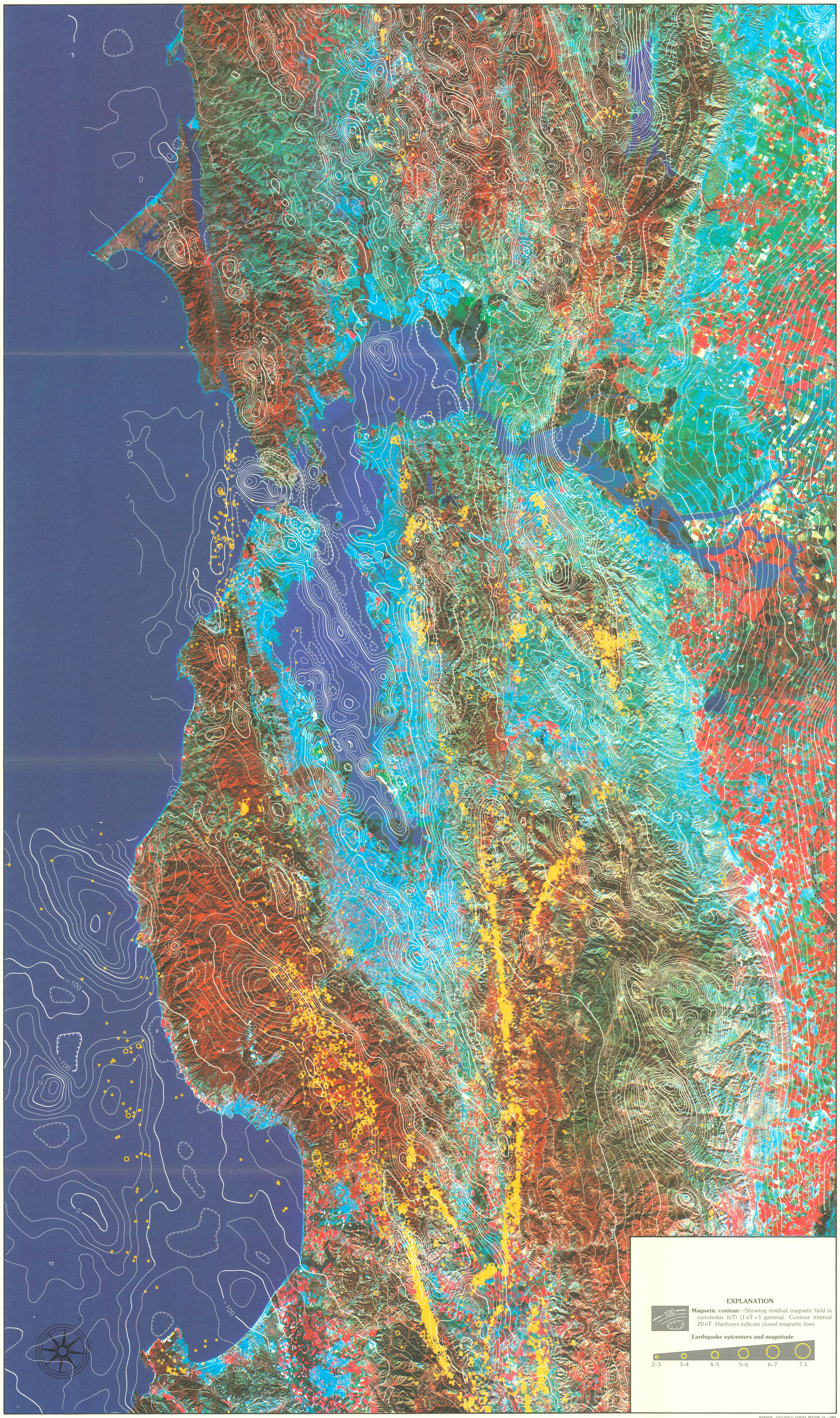

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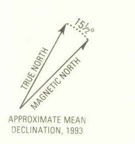

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AEROMAGNETIC MAP OF THE SAN FRANCISCO BAY AREA, CALIFORNIA

By
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INTRODUCTION

This map of the magnetic field of the San Francisco Bay area and vicinity and the companion gravity map are part of a series of regional geologic and geophysical maps designed to provide the basic data necessary for establishing a geologic and tectonic framework for the region. The magnetic-field data base and resultant contour map were produced under the joint auspices of the U.S. Geological Survey's Earthquake Hazards Reduction Program and National Geologic Mapping Program. To emphasize the relations between the magnetic field and active faults, contours of equal magnetic field intensity are shown on a false-color satellite image with earthquake epicenters highlighted for the period 1972-89 (U.S. Geological Survey, 1990).

Detailed knowledge of the Earth's local magnetic field provides a means for visualizing and remotely mapping subsurface geology in three dimensions. Rock bodies that contain magnetic minerals generate their own magnetic fields that locally distort the Earth's main field. The shapes and amplitudes of the local magnetic field distortions (magnetic anomalies) contain information about the locations, shapes, and magnetizations of the causative bodies. Quantitative values for a source body's location, shape, and magnetization can be obtained by calculating the magnetic anomaly of a model body having an assumed shape and magnetization, comparing this anomaly with the magnetic anomaly actually observed, and then modifying the model body until the observed and calculated anomalies agree. The modeling results, in turn, place constraints on the types of rock and geologic structures that could be concealed beneath the surface. Although unambiguous determination of a source body's shape and magnetization is not possible on the basis of its magnetic anomaly alone (bodies with different shapes and magnetizations can sometimes generate identical magnetic anomalies), interpreting magnetic anomalies in conjunction with a knowledge of the local geology and with other geophysical information effectively reduces or eliminates interpretive ambiguity as a practical problem in most cases.

Application of the magnetic method to regional framework investigations is particularly useful in the San Francisco Bay area because many of the important rock units that make up the crust of the region contain magnetic minerals. Extensive areas are underlain by pieces of former oceanic crust and upper mantle that subsequently have been partially altered to highly magnetic serpentinite. Mafic plutonic rocks and Cenozoic volcanic rocks in the mountains surrounding the bay also give rise to magnetic anomalies. Rare sedimentary units containing unusual concentrations of magnetic minerals constitute a minor but potentially important source of low-amplitude magnetic anomalies. Many of the magnetic anomalies in the San Francisco Bay area are discussed by Brabb and Hanna (1981), Robbins (1971, 1982), and Griscom and Jachens (1990a).

DATA SOURCES AND REDUCTIONS

The magnetic map of the San Francisco Bay area and vicinity was compiled from eight separate aeromagnetic surveys (fig. 1) that do not have uniform specifications of flight-height, flight-line spacing, and flight-line direction (table 1).

Table 1. *Aeromagnetic surveys used to compile aeromagnetic map*

Survey area (reference)	Year flown	Flight height[1] (in meters)	Flight-line spacing	Flight-line direction
San Francisco (U.S. Geological Survey, 1971)	1950-51	305 m/agl	1.6 km	E-W
Coastal California (Brabb and Hanna, 1981)	1954	914 m/cbe	1.6 km	NE-SW
Sacramento Valley (Meuschke and others, 1966)	1954	152 m/agl	1.6 km	NE-SW
San Francisco Bay area (U.S. Geological Survey, 1974a,b,c)	1973	914 m/cbe	1.6 km	NE-SW
Offshore central California (McCulloch and Chapman, 1977)	1976	610 m/cbe	1.6 km	NE-SW
Northern Great Valley (California Division of Mines and Geology, 1979)	Not available	1067 m/cbe	1.6 km	NE-SW
Palo Alto, California (Abrams and others, 1991b)	1989	244 m/agl	0.4 km	NE-SW
San Jose, California (Abrams and others, 1991a)	1989	305 m/agl	0.4 km	NE-WSW

[1] agl, height above ground level. cbe, constant barometric elevation.

Because aeromagnetic maps based on surveys flown at different elevations above a magnetic source tend to portray the source's magnetic anomaly differently, an aeromagnetic map constructed by simply compositing the individual maps from surveys with different flight specifications is difficult to analyze and of limited use in solving regional problems. Therefore, to enhance the usefulness of the magnetic data, the following procedures were used to construct the map. First, the International Geomagnetic Reference Field (IGRF), updated to the date that the survey was flown, was removed from each survey to generate a temporally consistent set of residual magnetic data. Next, all surveys were placed on a common geographic datum located 305 m above the ground surface. The San Francisco and San Jose surveys (table 1) originally were collected at a nominal height of 305 m above the surface and the Palo Alto survey was collected at a height just slightly lower, therefore none of these surveys was modified at this stage. The other surveys were mathematically modified in such a way that the resulting maps approximated the magnetic field that would have been measured if the various surveys had been collected at a height of 305 m above the ground surface (Cordell 1985). Finally, the individual surveys were interpolated to a 1-km grid following a procedure based on a minimum curvature criterion (Briggs, 1974) and merged by superposition where surveys overlapped. The hierarchy of superposition, based on our evaluation of each survey's quality and specifications, was as follows:

Coastal California+Northern Great Valley<Sacramento Valley<San Francisco Bay area<San Francisco+Offshore central California<San Jose+Palo Alto

Surveys to the left of the "<" were superceded by surveys to the right wherever data overlap occurred.

DISCUSSION

The magnetic anomalies shown on the map mark subsurface boundaries across which rock magnetic properties change and may directly or indirectly indicate faults. Tabular bodies of serpentinite commonly occupy fault zones of major strike-slip faults of the San Andreas system and generate narrow linear anomalies along the faults. Numerous basement blocks are fault bounded and prominent anomalies are present where these faults have juxtaposed basement rocks with different magnetizations. Finally, any fault that truncates structures, which themselves are expressed in the magnetic field (for example, faults or folded sheets of serpentinite), should manifest itself as an alignment of truncated linear magnetic anomalies. Examples of each of these cases can be seen on the map by comparing the magnetic anomalies with the distribution of earthquake epicenters.

Precisely locating magnetic property boundaries directly from this map is not a straightforward process because of complications introduced by the local orientation of the Earth's main field and by the geometry of the source rocks. Because the Earth's main field is not vertical in the San Francisco Bay area, magnetic anomalies will not in general be located directly above their sources. Instead, the anomaly high will be shifted toward the south edge of the source body and a magnetic low caused by the source body will exist over the north edge and to the north of the body. Precise locations of the boundaries of the source bodies generally will require modeling the anomalies (Saltus and Blakely, 1983; Webring, 1985), perhaps aided by automated boundary locators that operate on gridded data (Blakely and Simpson, 1986). However, at the scale of the present map, potentially useful approximations of boundary locations can, in some cases, be made directly from the map by applying some "rules of thumb" (fig. 2). For a steep-sided (dips >45°), tabular body located at the magnetic latitude of the San Francisco Bay area, the north (magnetic) edge of the body will lie near the bottom or just south of the bottom of the northside low, whereas the south edge will lie near the top or just south of the top of the magnetic anomaly high. The east and west edges will lie along the east and west magnetic gradients that bound the anomaly and close to the mid-level contour for vertical sides. Anomalies over boundaries that are not oriented parallel to magnetic north-south or east-west will display characteristics intermediate to those over boundaries oriented along the cardinal directions. Many other examples (similar to those shown in fig. 2) can be found in Vacquier and others (1951) and Andreason and Zietz (1969). Vacquier and others (1951) also present a graphical method for estimating the depth to the top of a magnetic source on the basis of its magnetic anomaly shape.

RELATIONS BETWEEN MAGNETIC ANOMALIES AND EARTHQUAKE EPICENTERS

Most of the strong alignments of earthquake epicenters in the San Francisco Bay area bear one of three possible consistent relations to the magnetic anomalies: (1) alignments that cross linear magnetic anomalies without offsetting them; (2) alignments that truncate linear magnetic anomalies; and (3) alignments that parallel linear magnetic anomalies. The only clear alignment of epicenters that crosses a linear magnetic anomaly lies east of the southern tip of San Francisco Bay (1 on fig. 3). Although there is a reduction in amplitude of the magnetic anomaly at about the place where the epicenters cross it, the continuity of the anomaly suggests that only minor strike-slip movement has occurred along this zone. In contrast, the epicenters aligned along the southern Calaveras Fault (2 on fig. 3) closely coincide with the truncation of at least two major linear magnetic anomalies (probably caused by fault-bounded pieces of ophiolite) that extend to the northwest (Brabb and Hanna, 1981). The lack of counterpart anomalies northeast of the Calaveras Fault suggests major lateral offset across this fault. Interestingly, the epicenters along the Calaveras fault appear to step eastward 1 to 2 km over the stretch between the ends of the two truncated anomalies, perhaps as a result of offset across bounding faults that were recently active but not during the 1972-89 period.

Alignments of earthquake epicenters parallel to magnetic anomalies are common in the San Francisco Bay area. Along the Hayward Fault (3 on fig. 3), the epicenters are aligned beneath a linear magnetic anomaly for a distance of more than 40 km. Although the spatial correlation between the magnetic anomaly and the epicenters is unmistakable, understanding the precise relation between the source body and the distribution of earthquake hypocenters will require detailed modeling. Epicenters along the San Andreas Fault near the south edge of the map (4 on fig. 3) parallel a magnetic anomaly (peak amplitude 200 nT) whose source body lies southwest of the fault. The hypocenters do not lie directly beneath the inferred northeast edge of the body (see example in fig. 2), especially toward its southeast end. This apparent discrepancy could be explained by a dipping fault plane (steeply to the southwest) as has been proposed for the San Andreas Fault near here by Pavoni (1973) and Spieth (1981). Farther north along the San Andreas Fault offshore from San Francisco (5 on fig. 3), the hypocenters appear to be scattered throughout a thin sliver of magnetic crust caught between the San Gregorio Fault on the southwest and the San Andreas Fault on the northeast. Perhaps the diffuse nature of the hypocenter distribution indicates that the earthquakes are not confined to the major faults, but rather that the thin sliver caught between them is being shattered. Finally, in the southern part of the map near the junction of the San Andreas and Calaveras Faults (6 on fig. 3) a number of unusual epicenter alignments occur that are not easily explained by known faults. However, these alignments are parallel to the local magnetic anomalies, suggesting that there are linear subsurface structures associated with the earthquakes.

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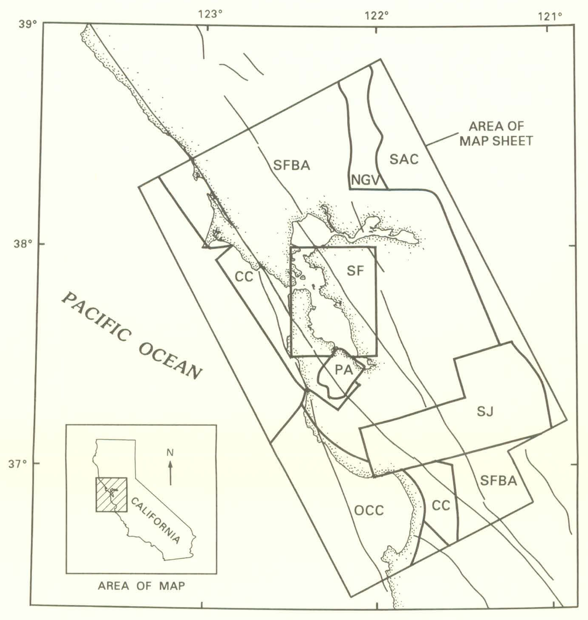

Figure 1. Boundaries of aeromagnetic surveys used to compile aeromagnetic map of San Francisco Bay area, California. Symbols: CC, Coastal California; NGV, Northern Great Valley; OCC, Offshore central California; PA, Palo Alto; SAC, Sacramento Valley; SF, San Francisco; SFBA, San Francisco Bay area; SJ, San Jose. Thin lines, major faults.

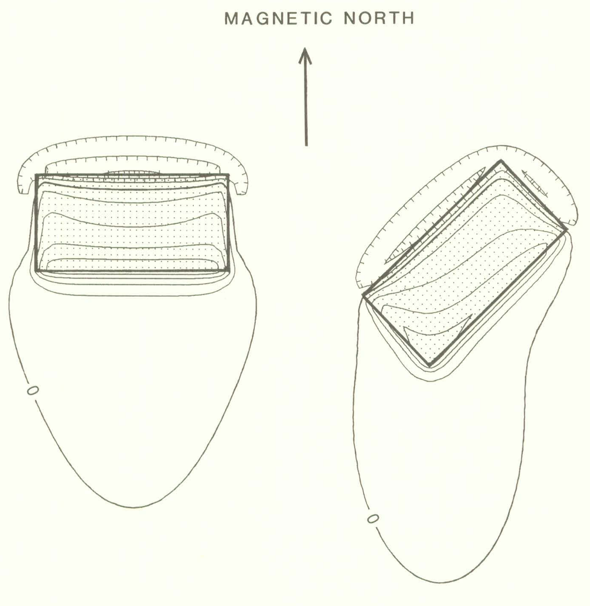

Figure 2. Theoretical magnetic fields over ideal rectangular source bodies. Model parameters: Main field inclination, 60°; Magnetic susceptibility, 0.001 cgs; Body (shaded), 12 km long, 6 km wide, 3 km thick; "Survey" height, 305 m above top of body. Plot is at scale of map. Contour interval 100 nT. Hachures indicate closed lows.

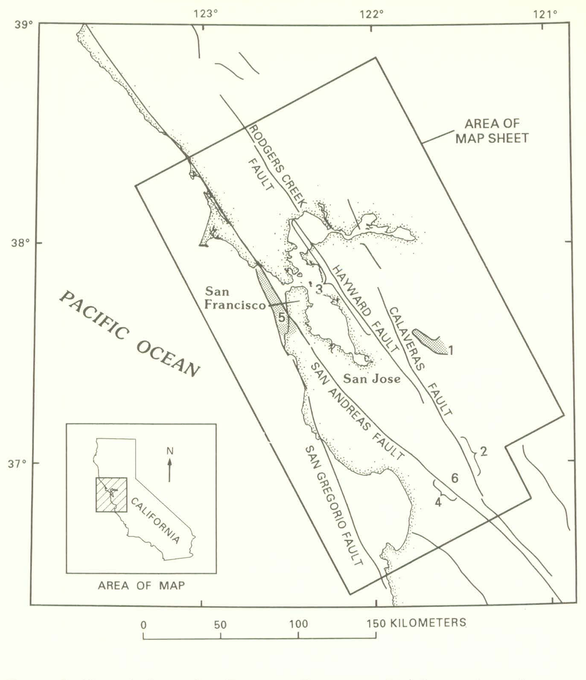

Figure 3. Major faults in San Francisco Bay area. Numbers indicate locations of anomalies discussed in the text. Shaded areas represent magnetic highs.

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