DEPARTMENT OF THE INTERIOR

UNITED STATES GEOLOGICAL SURVEY

Maps showing aeromagnetic anomalies, faults, earthquake epicenters and igneous and volcanic rocks in the southern San Francisco Bay Region, California

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Open-file report
79-827

Introduction

The identification of active faults is crucial to developing means for reducing earthquake hazards (see, for example, Wallace, 1975). Some active faults are discernible by traditional methods based on observations of the ground surface; others escape detection because they are covered by overburden or are exposed only in highly inaccessible areas. Traditional methods for identifying active faults include studies of geomorphic forms, such as offset streams, shutter ridges, sag ponds, and linear valleys; field mapping to find places where lithologic or structural units are truncated or displaced; geodetic observations to determine differential movement of large areas of land; measurement of strain; monitoring of small earthquakes; and direct observation of features displaced during major earthquakes. Methods needed to detect faults not identifiable by traditional means are based largely on geophysical and geochemical approaches.

Of special interest in the present study is the use of aeromagnetic anomalies to identify fault systems, notably those systems which contain anomalously magnetic material within the fault zone or those which displace highly magnetic rock terranes in the earth's upper crust. This study was prompted by the observation that the Hayward fault--one of the major earthquake generating faults in the San Francisco Bay region (Wesson and others, 1975, Table 1)--is associated with a prominent magnetic anomaly. The fault also coincides with a line of earthquake epicenters, shown on the map of Brown and Lee (1971). We decided to investigate these correlations in a larger area in order to evaluate the usefulness of magnetic anomaly and earthquake epicenter maps in looking for active faults.

Acknowledgments

We wish to express our appreciation to J. R. LeCompte, who assisted in the compilation and drafting of the maps of faults and igneous and volcanic rocks; W. H. K. Lee, who facilitated the preparation of the map of earthquake epicenters; and D. G. Herd, who provided data for the fault map.

General Methodology

An aeromagnetic survey (index map, area 1, sheet 1) was planned by the authors in 1972 to include all of the known or suspected active faults in the San Francisco Bay region over which data had not previously been obtained. The aeromagnetic survey was conducted in 1973 and was released to the public the following year (U.S. Geol. Survey, 1974). The anomaly map was combined with three older maps (index map, areas 2, 3, and 4, sheet 1), and with one recent map (index map, area 5, sheet 1) in an attempt to complete, as economically as possible, coverage of Sheet 3 of the U.S. Geological Survey's 1:125,000 topographic map of the San Francisco Bay region.

As an aid in interpreting the sources of the magnetic anomalies, a special geologic map (sheet 2) was compiled showing all known and suspected exposures of magnetic rocks. Next, the trends of elongate magnetic anomalies were plotted through the areas of greatest magnetic intensity, in much the same way that axes of anticlines are shown on a geologic map. Areas with distinctively different magnetic character were differentiated (sheet 3). After the trend lines were plotted, information on mapped faults (sheet 4) and earthquake epicenters (sheet 5) was superimposed. Upon inspection of the overlapping magnetic anomaly, fault, and epicenter data, one change was made

in the anomaly trend map, (sheet 3). Trend lines corresponding to the Doolan-Tesla anomalies, which originally extended across the Grenville fault, is now interrupted at this fault. Closer inspection of these anomalies showed subtle differences in character on opposite side of the fault, suggesting that two completely different bodies of magnetic rocks have been fortuitously brought into juxtaposition. The final compilation of inferred faults was based on a combination of geologic, magnetic, fault, and epicenter data.

Magnetic Anomaly Interpretation

Type of analysis. Interpretation of magnetic anomaly data was restricted to a qualitative analysis because of the objectives of the study and the nature of the data set. The composite anomaly map (sheet 1) consists of five data sets, each having distinctive flight specifications and data reduction histories. Despite the contrasting characteristics of adjoining surveys, it was possible to define a number of coherent magnetic anomalies which extend throughout parts of the study area. Those anomalies which appear to be of greatest use in defining fault systems are linear or elongate features which reflect magnetic material narrowly confined to the zones rather than gradient features which reflect the truncation of terranes of magnetic rock.

Assumptions. In the present study faults inferred from magnetic anomaly data are defined in a broad sense to mean zones of crustal weakness. Sources of elongate anomalies are inferred to be steeply dipping tabular bodies generally in the form of pliable ribbons which in places are confined to vertical strike-slip fault zones and in other places form steeply dipping segments of folded sheets. Most of the tabular sources are inferred to consist of serpentinite because this magnetic material is commonly exposed beneath parts of anomalies in the study area and because serpentinite bodies characteristically generate linear anomalies in neighboring areas of the California Coast Ranges (Griscom, 1966; Hanna and others, 1972). The occurrence of serpentinite, whether lodged within a fault zone or forming part of a folded sheet, generally signals a zone of crystal weakness, both on the basis of the stressed environment permitting its emplacement and on the basis that the serpentinite itself is relatively incompetent mechanically.

Blake, Zietz and Daniels (1977), on the other hand, believe that the serpentinite and associated ultramafic rocks were a subhorizontal unit of mid-Mesozoic age that has subsequently been folded and faulted during several periods of younger deformation. They would interpret the linear magnetic anomalies not as serpentinite intruded into a fault zone, but as ophiolite fortuitously located near or offset by such young fault systems.

The term, magnetization, as used in this report refers to total magnetization, the combined remanent and induced components. With regard to inferred sources of serpentinite, we assume that the magnetization is parallel to the ambient magnetic field of the earth and, therefore, that either the remanent magnetization is aligned with the field or that it is sufficiently random within the material to produce no appreciable external field. This assumption is based in part on reports by Saad (1969a, b), who studied the magnetism of serpentinite and other rocks in the east-central part of the map area (sheet 2). It may be noted that in those regions where magnetic anomalies are not associated with rocks believed to be magnetic on the basis of field mapping, either the rocks are (1) unexpectedly nonmagnetic, (2) small in volume, such as very thin sheets, compared to the distance between magnetic rocks and the magnetometer, (3) oriented in such a way, such as horizontally,

so that the demagnetizing field of the body causes the anomalous external field in the vicinity of the magnetometer to be small, or (4) a combination of these parameters.

Magnetic Anomalies

Distinctive patterns. Although it will not be possible to make specific inferences about the overall distribution of linear anomalies throughout the study area until an internally consistent data set can be obtained in a future low-level survey, the current composite map shows that many such elongate features occur in the region northeast of the San Andreas fault. Southwest of the fault and in an area east of Hollister northeast of the fault, anomalies appear to be less highly linear, that is, either more equidimensional or irregular. Sources of the linear anomalies are inferred to be serpentinite; sources of the other anomalies are inferred to be various volcanic and plutonic rocks. In the following discussion, it is convenient to consider in sequence (1) anomalies southwest of the San Andreas fault, (2) nonlinear anomalies northeast of the San Andreas fault, and (3) linear anomalies northeast of the San Andreas fault.

Anomalies southwest of the San Andreas fault: Seven anomalies southwest of the fault are considered sufficiently important for special mention. Of these, the Montara, Half Moon Bay, Mindego Hill, and Logan anomalies have sources which are at least partly exposed. The Año Nuevo, Boulder Creek, and Corralitos anomalies have unknown source rocks buried beneath sedimentary cover.

The negative Montara anomaly is largely associated with quartz diorite of the Montara Mountain area, rocks inferred to possess reversed magnetization. The circular negative anomaly in offshore data southwest of Montara Mountain may mark an offshore continuation of this plutonic rock massif, but the anomaly is on the opposite side of the San Gregorio fault and may not be related. The local northeast-trending Half Moon Bay anomaly is associated with isolated outcrops of Mindego basalt which is inferred to be normally polarized. The Mindego Hill anomalies to the southeast, which are mainly negative in polarity, are associated with piles of Mindego basalt inferred to possess predominantly reversed magnetization. There is no strong evidence on the basis of the magnetic data that this basalt extends continuously in the subsurface between the magnetic anomalies.

The Año Nuevo anomaly, a high-amplitude, broad wavelength, positive feature, has a buried source possessing high-intensity normal magnetization. The source rock of this anomaly is separated from that of the Boulder Creek anomaly by the San Gregorio fault, but it has generally similar magnetic character.

The Boulder Creek anomaly is one of the largest magnetic features known in the vicinity of the San Andreas fault system (Hanna and others, 1972). Its source is largely confined in the subsurface between vertical projections of the Zayante and Butano faults traces and it is terminated in small part by the San Andreas fault. The southeast margin of this anomaly is not precisely defined, although reconnaissance data suggest that its source rock may extend to the region of the Corralitos anomalies. The Corralitos anomalies, like the Boulder Creek feature, have buried source rocks that are normally polarized.

A clue to the nature of source rocks of the Corralitos, Boulder Creek and Año Nuevo anomalies may be provided by the local high-amplitude Logan anomaly, also at the southwest margin of the San Andreas fault. The Logan anomaly is

associated with quartz gabbro and anorthosite gabbro (Ross, 1970) having relative high density (Clark and Rietman, 1973) and strong normal magnetization. Source of the Boulder Creek and Corralitos anomalies, at least, seem to require magnetizations similar to those of gabbros at the Logan anomaly site. Further, sources of all of these anomalies appear to be confined between the Zayante or Vergeles faults on the southwest and the Butano or San Andreas faults on the northeast. Confirmation of identical sources on the basis of gravity data cannot be established because of occurrences of large accumulations of low-density sedimentary cover.

Nonlinear anomalies northeast of the San Andreas fault: A group of local positive anomalies, confined to the southeast corner of the map area, are related mainly to andesite, basalt, and associated igneous intrusive rocks. Maximum values of these anomalies correspond closely to peaks and ridges of ground terrain above 760 m (2,500 ft). The magnetic data suggest that these rocks have normal magnetization in contrast to the reversed magnetization inferred to reside in most of the Mindego basalt on the opposite side of the San Andreas fault.

Other nonlinear anomalies northeast of the San Andreas fault include six oval or equidimensional features in the terrane of serpentinite generally characterized by linear anomalies. Each of these anomalies has a characteristic which suggests that its source is either a folded or faulted serpentinite sheet, an accumulation of serpentinite at the intersection of two fault zones, or a diapiric intrusion of serpentinite which emerges at the surface through three or more radiating cracks. Three of the nonlinear features, the Point Bonita, San Francisco, and Searsville anomalies are relatively small (less than 8 km in diameter) and are within 10 km of the San Andreas fault. The Calaveras Reservoir, Red Mountain, and Orestimba Creek anomalies are significantly larger and are east of the Hayward or Calaveras faults. Because none of the six anomalies is strongly related to topography, their high amplitudes must be attributable to distinctive shapes of sources rather than to fortuitous proximity of the magnetometer to highly elevated magnetic rocks.

The Point Bonita anomaly, defined by three sets of anomaly data, is characterized by a horseshoe-shaped trend with shallow internal gradients and steep external gradients. This feature is interpreted to be caused by a serpentinite sheet fragment in the form of a syncline which plunges southeast. The nearby San Francisco anomaly, marked by four radiating ridgelike trends, may be caused by a complexly folded sheet or by serpentinite injected into intersecting zones of weakness. Some of the complexity could also be due to superimposed cultural effects. The Searsville lake anomaly appears to be caused by either a northwest-plunging synclinal sheet of serpentinite or by an accumulation of serpentinite at two intersecting segments.

The larger Calaveras Reservoir anomaly is partly associated with serpentinite which has been mapped as a northwest-plunging anticline. Steep gradients on the northeast side of this part of the anomaly indicate that the northeast dip of the serpentinite is steep, within about 15° of vertical. Farther southeast, the Red Mountain and Orestimba Creek anomalies are broader in wavelength and higher in amplitude than all others shown on the map. Each has a distinctive multiple bifurcation of magnetic trends near their anomaly crests, and each has a serpentinite source of massive proportions. These sources may be fragments of a tabular serpentinite body known to separate the northeast-sloping contact between Franciscan rocks and Jurasic and Cretaceous

marine sedimentary rocks of the Great Valley sequence in many places of the Coast Ranges of northern California and Oregon. Whether the serpentinite source forms part of a fossil subduction zone or represents material emplaced near the contact of these rock sequences, its restricted extent in appreciable quantities along the strike of the contact remains to be explained. The association of part of the group of Red Hill anomalies with Franciscan volcanic rocks may be accidental. A likely source of this part of the anomaly cluster is serpentinite which may be emplaced beneath these volcanic rocks.

Linear anomalies northeast of the San Andreas fault: Numerous narrow, elongate positive anomalies occur in most of the map area northeast of the San Andreas fault. Most of these features are somewhat isolated and have a strike length of less than 20 km. A few of the features, all having northwest strike directions, extend for as much as 100 km in well-defined zones. Over half of all of the linear anomalies are associated with mapped serpentinite and few are associated with other rock types believed to be magnetic source rocks. One exception is the Mount Diablo anomaly which is a narrow southeast extension of a major positive anomaly north of the map area, associated with gabbroic and serpentinite source rocks. Among the various linear anomalies, bifurcating trends occur within the Redwood City, San Jose, Mount Madonna, Gavilan College, Del Valle, and Doolan features. These trends are inferred to be caused by faulting of serpentinite sheets, perhaps accompanied by folding. The group of linear anomalies, as previously noted, is of greatest interest for establishing relationships with faulting and seismic activity.

Relationship of Linear Anomalies to Faults

Apart from the established correlation of linear anomalies with occurrences of mapped serpentinite, most of these anomalies are also coincident to some extent with mapped bedrock faults. Although uncertainty still exists as to whether the sources of some linear anomalies should be regarded as fragments of folded sheets or as material squeezed into fault segments, the direct association of some linear anomalies with mapped faults is evident. Examples of such correlations with recently active faults include the Hayward anomaly and Hayward fault, the Pulgas Ridge anomaly and Pilarcitos fault, the Mount Madonna anomaly and Sargent fault, and the Gilroy Springs anomaly and the Calaveras fault.

Anomalies within the map area which appear to indicate extensions or connections of fault trace segments which have been previously mapped include the Hunters Point (correlation with thrust fault), Doolan, San Jose, Chesboro, and Gavilan College features. Other linear anomalies may be generally suspected of indicating serpentinite-filled fault zones, with the most probable location of the axis of serpentinite emplacement just northeast of (say, 0.25 cm at scale 1:125,000) and parallel to the magnetic anomaly trend lines. It may be emphasized that only those faults containing serpentinite in sufficient quantities for aeromagnetic survey detection will be discovered using this technique. A future low-level aeromagnetic survey of the study area would very likely uncover additional unrecognized faults which contain quantities of serpentinite too small for detection on the current composite anomaly map.

The alternative magnetic anomaly method of identifying faults by truncation of magnetic signatures is of some interest in that a number of linear anomalies in the study area appear to be truncated or separated from nonlinear anomalies by faults. In the heavily serpentinized terrane northeast

of the San Andreas fault, two examples of such fault truncation are evident. It appears likely that the Calaveras fault truncates the Chesboro, San Jose, and Alum Rock anomaly sources and possibly the Las Trampas and Danville anomaly sources. The Grenville fault appears to truncate the Red Mountain, Del Valle, and Mount Wallace anomaly sources and possibly the Tesla and Doolan anomaly sources. Inspection of the anomaly map has not revealed any previously unsuspected faults truncating groups of anomalies.

Relationship of Linear Anomalies to Seismicity

Because the magnetic anomaly map provides new information about possible locations of faults, it is of interest for purposes of hazards studies to consider the relationship of these suspected faults to earthquake activity. A plot of epicenters (sheet 5) for events having a Richter magnitude of over 0.5 covering the period 1969 through 1974 serves as a basis for this comparison. The epicenter plot indicates that a strong positive correlation between linear anomalies and linear distributions of epicenters occurs at the Hayward and Mount Madonna anomaly sites and over the northwest-trending part of the Calaveras Reservoir anomalies; the epicenters and anomalies are along the Hayward, Sargent and Calaveras faults, respectively. Much weaker positive correlations occur over parts of the San Jose, Los Trancos, San Pedro, Pacifica, Tassajara, San Felipe, and Mount Diablo (presumably having a gabbroic source) anomalies.

If the magnetic and seismic data are compared with locations of mapped faults, other relationships become apparent. For example, strong correlation between epicenters and mapped faults occurs at the Calaveras fault and southern part of the San Andreas fault within the map area although magnetic anomalies are absent in these places. Alignments of epicenters between the Hayward and Calaveras faults and between the Del Valle and Tesla anomalies are associated with neither magnetic anomalies nor mapped faults.

Apart from linear distributions of epicenters, the seismic data indicate that tightly grouped clusters of epicenters corresponding to earthquake swarms occur in a few regions of the map area. The most conspicuous of these is the Danville cluster (Lee and others, 1971) which has an approximately circular distribution at the northwest extremity of the Doolan anomaly. Although several other epicenter clusters may be identified in various parts of the map area, clusters at the northwest extremity of the Santa Teresa anomaly, northwest extremities of the Calaveras Reservoir anomalies, and southeast break in the Mount Madonna anomaly trend bear approximately the same relationship to linear anomalies as the Danville cluster does to the Doolan anomaly. A postulated diapiric intrusive mechanism suggested by Lee and others (1971), for the Danville epicenter distribution may be operative in the other cluster areas. If so, it is possible that the cluster distribution results from sporadic emplacement of serpentinite progressively along a fault zone which is partially filled with serpentinite.

Conclusions

Of special importance to considerations of geologic hazards, the magnetic, geologic, and seismic data indicate that (1) several elongate magnetic anomalies northeast of the San Andreas fault define steeply dipping ribbons of serpentinite within previously unsuspected fault zones. These fault zones should be studied further to determine whether they are hazardous; (2) none of the previously unsuspected faults are associated with linear