DEPARTMENT OF THE INTERIOR
UNITED STATES GEOLOGICAL SURVEY

GEOPHYSICAL INVESTIGATIONS MAP
GP-918

INTRODUCTION

Ophiolite consisting typically of serpentinized peridotite overlain by gabbro, diabase, and basalt is now widely accepted as having formed at an accreting plate boundary, such as a mid-ocean ridge, and subsequently emplaced on land along consuming plate boundaries including subduction and obduction zones (Moores, 1970; Dewey and Bird, 1971; Colman, 1971).

In California, alpine-type ultramafic rocks have long been known to be associated with major thrust faults (Irwin, 1964, 1966). Recently many of these ultramafic bodies have been recognized as parts of typical ophiolite sequences (Bailey and others, 1970; Page, 1972) lying along megathrusts and marking former consuming plate boundaries (Hamilton, 1969; Moores, 1970; Colemen, 1971).

Because of its great magnetic susceptibility, serpentinized ultramafic rock, which makes up a large part of the California ophiolites, can be recognized on aeromagnetic maps, even where it is covered by younger rocks (Irwin and Bath, 1962). By examination of available aeromagnetic data we correlate a number of ophiolite belts in California and relate these belts to former plate boundaries.

First we present a resume of the regional geology. Then we describe major aeromagnetic anomalies and, finally, interpret the tectonic history on the basis of the plate tectonics model.

The aeromagnetic data shown on the map were compiled from published and unpublished maps that were based on different kinds of data. In some areas the survey was made by a low-flying aircraft in which the flight lines were closely spaced (½ or 1 mile), but in other areas the flight altitude was high and the lines spaced as much as 5 miles apart. The aeromagnetic data were prepared by removing the earth's field (IGRF) from the original data, using Fabiano and Peddle's (1969) method, and contouring at 100-gamma intervals. Because of differences in flight altitude it is not possible to establish continuity at some survey boundaries.

The geology shown on the map is a modification of a 1:1,000,000-scale compilation by Bailey and Blake, U.S. Geological Survey, prepared as a preliminary to the Geologic Map of the United States (King and Beikman, 1974).

GEOLOGIC RESUME

The area shown on the map includes parts of several major physiographic units: the Franciscan rocks were deposited in the Great Valley, the Sierra Nevada, the Great Basin, the Mojave Desert, and the Transverse Ranges; however, this report deals chiefly with the first three.

The Coast Ranges are largely underlain by rocks of the Franciscan assemblage. These are chiefly graywacke-type sandstone and minor amounts of limestone and rare conglomerate, but also include serpentinized ultramafic rock, altered mafic volcanic rock (greenstone), radiolarian chert, and coarse-grained glaucophane schist and eclogite. The stratigraphy and structure are poorly understood; however, recent mapping indicates that the Coast Ranges include a number of fault-bounded, northwest-trending belts containing four lithologic assemblages: (1) relatively well-bedded graywacke and mudstone with interbedded chert and greenstone; (2) metagraywacke plus metachert and metagreenstone—these differ from the preceding rocks in having a faint to pronounce metamorphic fabric and by containing metamorphic minerals such as lawsonite, jadeite, and glaucophane; (3) tectonic melange made up largely of blocks and slabs of greenstone, chert, serpentinite, and high-grade glaucophane schist, amphibolite, and eclogite in a highly sheared mudstone matrix; and (4) massive arkosic sandstone and mudstone alternating with thin-bedded fysch-like sandstone and mudstone. Fossils are rare; those found thus far are largely confined to the tectonic melange and are of latest Jurassic (Tithonian) to Early Cretaceous (Valanginian) age. Some of the graywacke-schist assemblage are terminated by the Elder Creek fault (Jones and others, 1969; Jones and Irwin, 1971) one of three northwest-trending faults along which there has been postulated nearly 100 kilometers of left-lateral displacement. South of the latitude of Sacramento (38°30' N.), the ophiolite is largely covered by younger sedimentary rocks but the serpentinite data suggest that it continues south to latitude 37° N. (Griscom, 1966) near where there is a known outcrop of ophiolite (locality 1a = locality 6 of Bailey and others, 1970, p. C7s).

To the west, within the Coast Ranges, are several other small linear magnetic anomalies which in many cases are associated with ophiolite at the base of the Great Valley sequence (for example see anomaly 1b). These have been considered as klippen of an originally continuous thrust sheet (Irwin, 1964; see also figs. 34 and 35, Bailey and others, 1964). However, many of the small magnetic highs seen on the map, between the main ophiolite sequence and the San Andreas fault such as the one found at San Francisco, are caused by serpentinite bodies along imbricate thrusts within the Franciscan assemblage (Blake and others, 1971; 1972).

west side of the valley, the Great Valley sequence has been thrust over the rocks of the Franciscan Formation. The thrust, known as the Coast Range thrust, in most places lies below serpentinite at the base of the ophiolite sequence but locally it is higher, and Knoxville strata are thrust over Franciscan rocks and the ophiolite is presumably cut out by the thrusting. Klippen of the Great Valley sequence found on deformed Franciscan terrane as much as 80 km west of the main trace of the thrust attest to the magnitude of the thrusting (Bailey and others, 1970).

The Sierra Nevada province is largely underlain by Paleozoic to late Mesozoic (but pre-Tithonian) sedimentary and volcanic rocks. These are extensively intruded by Mesozoic granitic plutons, many of which are equivalent in age to the sediments of the Franciscan Formation and Great Valley sequence. Clark (1960, 1964) studied the stratigraphy and structure of the western part of the province, generally referred to as the Sierra Foothills. He subdivided the rocks into three major lithologic belts that are separated by two serpentinite-marked fault zones. The western belt, which is overlapped by Tertiary and Quaternary sediments of the Great Valley, is made up chiefly of steeply dipping strata and andesitic to rhyolitic volcanic rocks representing a Middle and Late Jurassic volcanic arc. To the east, separated from the previous unit by the Bear Mountains fault zone, is a similar lithologic unit made up chiefly of volcanogenic sedimentary rocks but containing peridotite-gabbro masses and tectonic breccia (melange) similar to parts of the Franciscan assemblage (Moores, 1972; Duffield and Sharp, 1975). The Melones fault zone marks the eastern boundary of this belt with late Palezoaic sedimentary and volcanic deposits of the Calaveras Formation.

Older metamorphic rocks intruded by Cretaceous granitic plutons are also found west of the San Andreas fault in the Salinian block. Originally part of the southern Sierra Nevada terrane (according to some geologists), these older metamorphic rocks have been carried as much as 4 kilometers northwestward by right-lateral movement along the San Andreas fault (Hill and Dibblee, 1953; Page, 1972) and are now part of the Coast Ranges.

By analogy with present-day island arcs and active continental margins, the Franciscan rocks have been proposed to represent material deposited on the Asian and North Pacific sequence an arc-trench gap accumulation: and the Sierra Nevada batholithic terrane, the roots of the eroded arc (Dickinson, 1971b). The Coast Range thrust is thought to be a fossil subduction zone beneath which the Franciscan rocks were metamorphosed and deformed. At the same time, to the east, the granitic rocks of the Sierra Nevada batholith were generated above this same zone (Dickinson, 1971a). These relationships are shown (highly generalized) in figure 2. While this model fits many of the geologic data, other evidence, including the age and distribution of granitic rocks in the Sierra Nevada, the presence of ophiolite (oceanic crust?) between the former continental plate and the presumed oceanic plate, and the age and distribution of Franciscan rocks in the Coast Ranges, suggests a much more complicated tectonic history. Some of these problems and some possible modifications of the model will be discussed in the final section, which summarizes the aeromagnetic and geologic data.

AEROMAGNETIC DATA

COAST RANGE ANOMALY

The high-amplitude anomaly along the western boundary of the Great Valley (anomaly 1) marks the ultramafic and mafic rocks which separate the highly deformed Franciscan rocks on the west from the Great Valley sequence. This ultramafic-mafic igneous sequence (ophiolite) is considered to be late Mesozoic oceanic crust upon which the sedimentary rocks of the Great Valley sequence were deposited. Some of the ophiolite and the Franciscan rocks in the Coast Ranges, suggests a much more complicated tectonic history. Some of these problems and some possible modifications of the model will be discussed in the final section, which summarizes the aeromagnetic and geologic data.

It has been suggested (Griscom, 1966, p. 414) that the inferred ultramafic-mafic mass that underlies the Great Valley of California may have been emplaced during a period of Late Jurassic sphenochasmic rifting. This hypothesis was first proposed by Bailey and others (1964) to account for many of the perplexing geologic relationships recognized in the Coast Ranges. A similar mechanism was proposed for the much younger Gulf of California (Hamilton, 1961; Ruanak and Fisher, 1964). In terms of present-day plate tectonics, the inferred Late Jurassic sphenochasm might be more analogous to the marginal (interarc) basins recently described from the western Pacific (Karig, 1971) than the combined spreading center and transform fault system that formed the Gulf of California.

FOOTHILLS FAULT SYSTEM

Within the Sierran Foothills, two subparallel linear anomalies (anomalies 4 and 5) coincide with the Bear Mountain fault zone on the west and the Melones fault zone on the east. Comparison of the geologic and aeromagnetic data indicates that these fault zones are better defined by the latter because the serpentinized ultramafic rock, which is found along both fault zones, is apparently more extensive at depth. Although these fault zones have been considered to be transcurrent in nature (Clark, 1960, 1964), they have also been interpreted as steeply dipping thrusts by Davis (1969) who correlated them with well-documented low-angle thrust faults in the Klamath Mountains (Irwin, 1964, 1966; Davis, 1966, 1969). Furthermore, detailed analysis of the magnetic anomalies over the Melones fault zone (Oliver and Hanna, 1970, p. 127) suggest that the serpentinite (and the fault) dips to the east. In both of these areas then, the presence of ultramafic rock within the fault zones, the mélange structure style (Duffield and Sharp, 1975), and the geometry of progressively younger rocks from east to west even though the rocks dip steeply to the east, all argue for a structural history similar to that proposed for the Coast Ranges. The Melones fault zone cuts granitic rocks which according to radiometric dating (Evernden and Kistler, 1970, pl. 2) are assigned to the Inyo Mountains intrusive epoch of Early and Middle Jurassic age (180 to 160 m.y. B.P.). On the other hand, both the Melones and Bear Mountains fault zones and associated sheared and serpentinized ultramafic rock are intruded by the intrusive rocks of the Yosemite intrusive epoch of Late Jurassic age (148 to 132 m.y. B.P.). The termination of the linear magnetic anomalies associated with these fault zones can be clearly seen at the southern end of the Foothills belt (locality 5a) where the magnetic pattern becomes one of scattered, rather equidimensional, moderate highs and associated lows which typifies the entire batholithic terrane.

A third major magnetic anomaly, herein referred to as the East Side anomaly (anomaly 6), is seen along the extreme western margin of the Sierra Foothills between 38°30' N. and 37°30' N. Most of this area is covered by younger sedimentary and volcanic rock but just north of latitude 38° N. (locality 6a), two basement wells are reported to have bottomed in basalt (Henderson and others, 1966). Near the south end of this anomaly, mafic volcanic rocks of the Sierran Foothills belt are exposed and Griscom (1966, p. 415) concluded that the anomaly was probably related to these volcanic rocks. However, he now feels that the local gravity high over the northern, highly magnetic, portion of this magnetic anomaly suggests mafic and(or) ultramafic rocks possibly representing ophiolite (written commun., 1972). A similar conclusion was reached by Cady (1972), who referred to it as the East Valley anomaly. Cady considered this anomaly to be largely caused by gabbro and that marks a former east-dipping subduction zone which later migrated westward to the position of the Coast Range thrust. We agree that this anomaly is very similar to that seen along the Coast Range thrust even though it is not continuous south of about 37°30' N. Possibly the large anomaly to the south (anomaly 3) is a segment of this same ophiolite belt related to the East Side anomaly which has been locally intruded by granitic rocks or tectonically disrupted such that it is no longer continuous. In any case, the East Side anomaly appears to be another ophiolite belt related to a predated Jurassic zone.

SAN ANDREAS FAULT

North of San Francisco the San Andreas fault zone is marked by a discontinuity between broad, low-amplitude magnetic anomalies to the west and smaller higher amplitude anomalies to the east. The basement rocks to the west are part of the Salinian block and consist of Cretaceous granitic rocks that include metamorphic rocks of pre-Cretaceous age. They are largely covered by Upper Cretaceous and Tertiary sedimentary rocks about 10,000 meters thick in the Gualala area (Wentworth, 1968). The Franciscan basement to the east of the fault is made up chiefly of sheared graywacke-type sandstone and siltstone but includes minor lenticular bodies of altered volcanic rocks, chert, and serpentinite, most of which do not appear on the geologic map. The latter rock is probably responsible for most of the small, lenticular, positive magnetic anomalies seen to the east of the San Andreas fault.

The alignment of the San Andreas fault, north of latitude 39° N., can be inferred from the magnetic data to lie east of the large, positive magnetic anomaly (anomaly 7a), eventually curving westward to intersect the Mendocino fracture zone (Affleck, 1962; also see Griscom, 1966, fig. 2, p. 409). In recent years other workers (Nason, 1968) have drawn the fault on the basis of sparker profiles to intersect the coast line near Shelter Cove.

Aeromagnetic data along the San Andreas fault south of San Francisco to San Bernardino, have recently been analyzed by Hanna and others (1971, 1972), some of whose data are included on the map. The northern part of this segment is similar to that described above, but between 36°30' N. and 34°45' N., where the fault bends to the east, there are a number of large, positive anomalies along the fault. According to the map, these anomalies are in areas underlain by Franciscan basement. The two northern anomalies (anomalies 7b and 7c) have been attributed on the basis of both magnetic and gravity data to steeply dipping serpentinite bodies immediately northeast of the San Andreas fault (Hanna and others, 1971). The southern anomaly (anomaly 7d), which lies northeast of the San Andreas and north of the Garlock fault, is associated with a gravity high and is believed to be caused by mafic igneous rocks possibly representing oceanic basement (ophiolite) upon which the Franciscan was deposited (Hanna and others, 1972, Ross, 1970). A number of similar occurrences of mafic gabbro along the San Andreas fault have recently been attributed to displacement of an originally more continuous body of oceanic crust (Ross 1970, and Ross and others, 1973). The radiometric data presented in the latter paper indicate that the oceanic crust was formed over a considerable period of time, with hornblende K-Ar ages on gabbro ranging from 134±4 to as old as 207±10 m.y.

OTHER FAULTS OF THE SAN ANDREAS SYSTEM

Within the San Francisco Bay Region, there are a number of faults including the Hayward and Calaveras (see map) which are subparallel to the San Andreas fault. Large-scale offsets along these faults have not been documented even though historical activity has been noted (Borchardt, 1975). On the map, anomalies 8a and 8b are caused by fragments of the Coast Range ophiolite which appear to have been offset in a right-lateral sense by several unnamed faults north of San Francisco.

NACIMIENTO FAULT ZONE

Another belt of Franciscan basement lies west of the Salinian block. The contact between the two basement terranes is generally referred to as the Nacimiento fault or Sur-Nacimiento fault zone (Page, 1970a, b; Vedder and Brown, 1968). However, except for the northern segment along the Sur fault, the contact is concealed by younger sedimentary rocks, and the fault or faults referred to as the Nacimiento separate rocks as young as Eocene. The aeromagnetic data reveal an prenaly pattern composed of isolated highs and low similar to that over the Sierra Nevada batholith. Both the aeromagnetic and gravity data in this area have recently been analyzed by Hanna (1970). The supposed fault contact is along the axis of line of a pronounced northwest-trending linear low, presumably related to nonmagnetic sediments (anomaly 9). This low is in turn flanked to the west by a fairly continuous narrow, linear, magnetic high (anomaly 10). Comparison of the magnetic data with the geologic data indicates that the linear magnetic anomaly is caused by serpentinized ultramafic rocks, localized near the contact between the Great Valley sequence and the Franciscan assemblage. According to Bailey and others (1970), this area is similar to that along the west side of the Great Valley in that the serpentinized ultramafic rocks (and associated mafic rocks) are at the base of the Great Valley sequence above the Coast Range thrust. These ultramafic and mafic rocks (ophiolite) and their structural relation to the Franciscan and Great Valley sequence have been described in more detail by Page (1972) and Hopson and others (1973).

GARLOCK FAULT

Another pronounced contrast in magnetic properties can be seen north and south of the Garlock fault near the southeast corner of the mapped area. According to Smith (1962), the rocks north of the fault are mainly schists and gneisses of Precambrian age, whereas the rocks to the south are chiefly Mesozoic granitic rocks and partly metamorphosed Paleozoic sedimentary rocks. An offset dike swarm suggests about 64 km (40 miles) of left-lateral displacement. Atwater (1972) has suggested that this relatively minor left-lateral movement on the Garlock is a secondary adjustment that occurred when the purely transcurrent motion of the San Andreas fault acquired a component of compression on entering the homogeneous basement of the Transverse Ranges. More recently, Burchfiel and Davis (1972b) have proposed that the Garlock fault represents an intracontinental transform fault that separates a northern crustal plate distended by late Cenozoic basin-and-range faulting from a southern Mojave plate much less affected by dilatational tectonics.

SUMMARY AND INFERRED GEOLOGIC HISTORY

Available aeromagnetic data for a large part of central California define a number of subparallel, northwest-trending anomalies. These anomalies are believed to be largely caused by serpentinized ultramafic rock and associated mafic intrusive and extrusive rock (ophiolite) marking former subduction or obduction zones. In contrast, areas underlain by granitic rocks, such as parts of the Sierra Nevada and the Salinian block, are characterized by nonlinear, isolated aeromagnetic highs and lows.

The location of the major aeromagnetic anomalies are discussed in the text. The inferred geologic structures giving rise to them, are shown in figure 3, a generalized structure section across western California at about the latitude of Sacramento. The Coast Range thrust is shown as a deformed low-angle fault that overlies the Franciscan assemblage and underlies the Great Valley sequence, including basal ophiolite. The magnetic data indicate (as pointed out by Griscom, 1966, p. 410) that the Coast Range thrust is underlain by a buried magnetic mass that dips both east and west at angles of less than 15°. We interpret the western half of this mass to be the mafic-ultramafic magnetic basement beneath the Franciscan assemblage, which has been overridden by the Great Valley sequence and similar magnetic basement.

To the east, beneath the Great Valley, the mafic-ultramafic basement was doubled up by subduction of the Knoxville strata and underlying oceanic crust.

Farther east, the mafic layer is shown as overriding itself in a structure similar to the Coast Range thrust. This we believe is a reasonable explanation for the East Side anomaly, although the data are far less convincing than for the younger structure to the west.

Two other highly sheared ophiolite belts are shown in the Sierran Foothills; both belts are locally engulfed by Late Jurassic granitic plutons.

The San Andreas fault marks the last major tectonic event, the destruction of the consuming plate margin and the beginning of transform faulting that continues to the present day.

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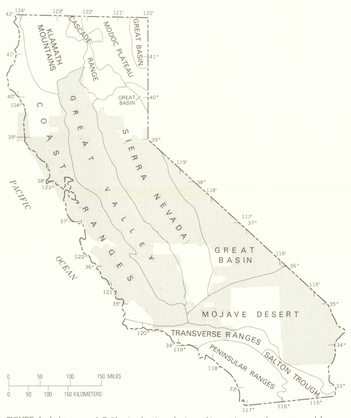

FIGURE 1.—*Index map of California showing physiographic provinces and area covered by aeromagnetic and geologic data in this report.*

FIGURE 2.—*Generalized hypothetical cross section of northern California during the late Mesozoic and early Tertiary showing the relationship of geologic units to plate-tectonic elements seen in present-day island arcs and active continental margins. (Modified from Dickinson, 1971b).*

FIGURE 3.—*Generalized structure section across western California at about the latitude of Sacramento. (Modified from Bailey, Irwin, and Jones, 1964).*

INDEX MAP SHOWING SOURCES OF DATA

SOURCES OF DATA

(From U.S. Geological Survey)

1 Aeromagnetic map of the southern part of the San Francisco Bay region, California, Open-file report 71–294, scale 1:125,000
2 Aeromagnetic map of the Clear Lake area, Lake, Sonoma, Napa, and Mendocino Counties, California, Open-file report 73–299, scale 1:62,500
3 Aeromagnetic map of parts of the Walker Lake and Mariposa 1° by 2° quadrangles, eastern California, Open-file report 74–109, scale 1:250,000
4 Aeromagnetic map of the Cholame-Taft area, southwestern California, Open-file report 74–8, scale 1:125,000
5 Aeromagnetic map of parts of the San Jose, Santa Cruz, and San Francisco 1° by 2° quadrangles, California, Open-file report 74–79, scale 1:125,000
6 Aeromagnetic map of parts of the San Jose, Santa Rosa, and Sacramento 1° by 2° quadrangles, California, Open-file report 74–80, scale 1:125,000
7 Aeromagnetic map of parts of the Santa Rosa and San Francisco 1° by 2° quadrangles, California, Open-file report 74–81, scale 1:125,000
8 Aeromagnetic map of Santa Barbara and vicinity, California, Open-file report 75–132, scale 1:125,000
9 Aeromagnetic map of southeastern California and part of southern Nevada, Open-file report 75–52, scale 1:250,000
10 Preliminary aeromagnetic maps of Nevada City and Allegheny 15-minute quadrangles, California, Open-file report 76–274, scale 1:62,500
11 Aeromagnetic map of Long Valley and northern Owens Valley, California, GP–329, scale 1:62,500
12 Aeromagnetic map of parts of the Mother Lode gold and Sierra Foothills copper mining districts, California and its geologic interpretation, GP–561, scale 1:62,500
13 Aeromagnetic map of Sacramento and vicinity, California, GP–574, scale 1:250,000
14 Aeromagnetic strip map across the central Sierra Nevada, California, GP–657, scale 1:125,000
15 Aeromagnetic map of the northern Mother Lode area, California, GP–671, scale 1:62,500
16 Aeromagnetic map of Antelope Valley and part of the Garlock fault zone, south-central California, GP–695, scale 1:250,000
17 Aeromagnetic map of parts of the Walker Lake, Reno, Chico, and Sacramento 1° by 2° quadrangles, Nevada-California, GP–751, scale 1:250,000
18 Aeromagnetic map of parts of the Goldfield, Mariposa, and Death Valley 1° by 2° quadrangles, Nevada-California, GP–753, scale 1:250,000
19 Aeromagnetic reconnaissance and generalized geologic map of the San Andreas fault between San Francisco and San Bernardino, California, GP–815, scale 1:250,000
20 Aeromagnetic and gravity features of the western Franciscan and Salinian basement terranes between Capa San Martin and San Luis Obispo, California, PF 700–B, p. 66–77
21 Mineral resources of the Emigrant Basin primitive area, California, B 1261–G, scale 1:62,500

(From other sources)

22 Aeromagnetic investigation of crustal structure for a strip across the westerrr United States: Geol. Soc. America Bull., v. 80, no. 9, p. 1703–1714 (Zietz and others,