MAGNETIC DATA AND REGIONAL STRUCTURE IN NORTHERN CALIFORNIA[1]

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In the 20 years that have passed since the advent of the airborne magnetometer, much aeromagnetic data have been collected in California. Measurements have been made both by Federal agencies, including the U.S. Geological Survey, the U.S. Coast and Geodetic Survey, and the U.S. Naval Oceanographic Office, and by private companies, primarily for the use of State agencies and the petroleum and mining industries. Most of the company data, which covers virtually all potentially petroliferous areas in the State, is not available to the public and will not be further discussed here. Measurements made for State agencies generally were related to specific problems, such as planning for dams and other structures, and have not generally been published. The published or released aeromagnetic data, however, contain a wealth of information concerning details of California geology, and in addition indicate several broad regional magnetic features associated with the major tectonic or crustal units of the State. It is these major features which are the prime concern of this paper, and for convenience, the discussion will treat the State from west to east. However, because the aeromagnetic coverage of northern California is so extremely incomplete, especially north of lat 40°N., this paper can only be a preliminary report.

COAST RANGES AND CONTINENTAL MARGIN

Pacific Ocean

A north-south trending pattern of linear magnetic anomalies in the deep ocean area west of the continental slope has been described by Mason and Raff (1961) and by Raff and Mason (1961). Near the continental margin the north-south grain swings to a trend of N. 30° E—particularly in the region southwest of San Francisco—and continues to where it intersects the continental margin. In addition, near the continental margin the anomaly amplitudes diminish and the lengths of the horizontal projections of the marginal gradients increase, strongly suggesting that the magnetic material causing the anomalies becomes much more deeply buried as the continent is approached. These facts bear on the space problem caused by the left-lateral displacement of 735 miles along the Mendocino fault as deduced from the magnetic pattern offset by Vacquier, Raff, and Warren (1961). This east-west fault intersects the California coast at Cape Mendocino, and Vacquier and colleagues have suggested as one possibility that the oceanic crust may be sliding smoothly under the continent without disrupting the magnetic pattern. According to Affleck (1962), near-surface magnetic anomaly trends over the postulated eastward extension of the fault into California support the hypothesis that the fault is also present in the continental crust. Using a crustal thickness of 12 miles at San Francisco (Eaton, 1963) and an average geothermal gradient, the Curie point isotherm is likely to be near the base of the crust so that no magnetic anomalies can be expected from greater depths even though former oceanic crust material may now be present there. Moderately high heat flow has been measured from the continental slope off San Francisco (Von Herzen, 1964). Thus the Curie point isotherm under the continental shelf in this area may be located a substantial distance above the base of the crust.

A contoured transcontinental strip of aeromagnetic data 100 miles wide flown by the U.S. Naval Oceanographic Office (Zietz and others, 1965) extends west through San Francisco, a distance of 120 miles into the deep ocean. The magnetic pattern over the oceanic crust is well displayed and clearly terminates at the foot of the continental slope near the 1,500-fathom contour. A portion of a profile from this aeromagnetic survey is illustrated in figure 1.

Continental Shelf

The continental shelf from Santa Cruz to Point Arena is a block of crystalline basement rocks overlain by Cretaceous and younger sedimentary rocks. This block is bounded on the east by the San Andreas fault and on the west probably by an extension of the Nacimiento fault (Bailey, Irwin, and Jones, 1964), which here may define the western limit of continental crystalline basement rocks. Gravity minima and seismic data offshore from San Francisco suggest the presence of large basins of low-density Tertiary sedimentary deposits both west of the Farallon Islands on the continental slope (Thompson and Talwani, 1964, p. 4829; Curray, 1965) and also east of the granitic Farallon Islands, where Jones (1963) inferred a graben of sedimentary rocks with border faults parallel to the San Andreas fault. The Bouguer gravity low associated with the graben has an amplitude of about 50 mgal,[2]

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[1] Publication authorized by the Director, U.S. Geological Survey.

[2] Orlin, Hyman, Fanning, K. F., Jones, R. B., and Garoutte, S. K., 1962, Sea gravity phase, oceanographic equipment evaluation range, San Francisco, California: U.S. Coast and Geod. Survey and U. S. Naval Oceanographic Office, July 1962, 24 p.

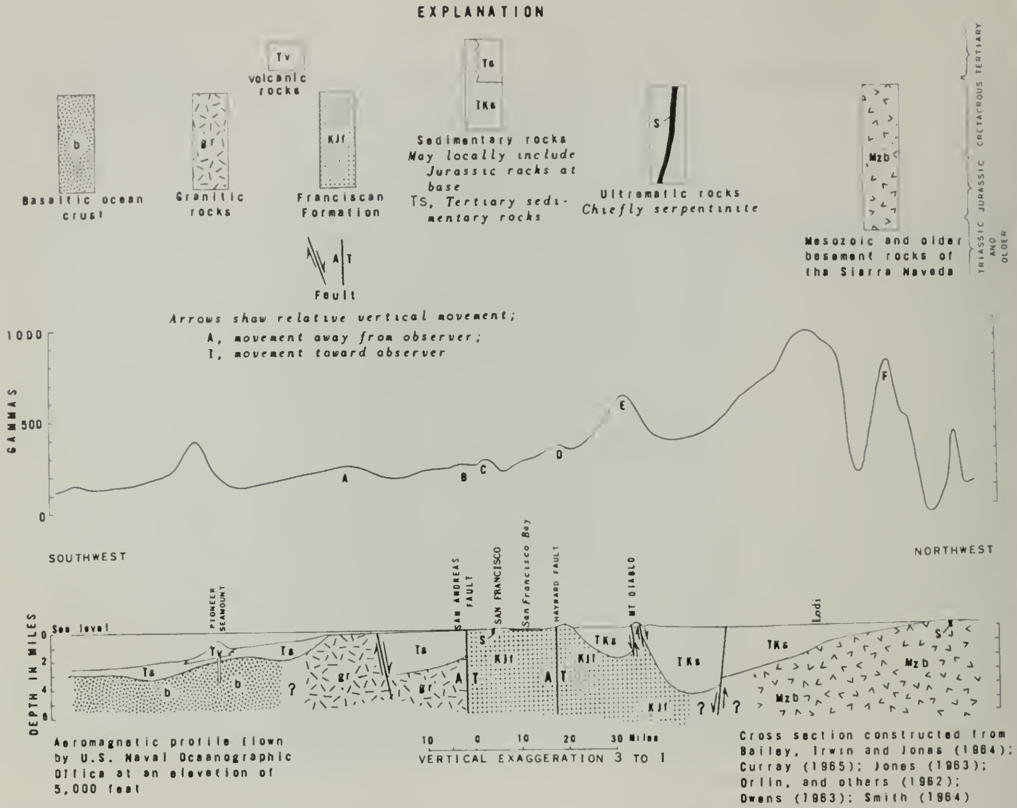

Figure 1. Total intensity aeromagnetic profile and generalized geologic cross-section from the Pacific Ocean through San Francisco to the Sierra Nevada.

indicating a rock thickness of about 2.5 miles, assuming a density contrast of 0.3 g/cm^3. Because this contrast is probably a maximum, the calculated thickness is a minimum. The granitic ridge (quartz diorite) associated with the Farallon Islands produces a broad magnetic high, shown as Point A on figure 1, and the inflection point on the east side of the magnetic anomaly corresponds in position with the fault inferred from the gravity data.

San Andreas Fault

Affleck (1962) traced the San Andreas fault northwest into the Pacific from Point Arena (39°N. lat) for a distance of 40 miles by means of aeromagnetic data, and his aeromagnetic map is reproduced here (fig. 2). An elongate magnetic high with an amplitude of about 200 gammas is clearly cut off on its northeast side by the fault. The anomaly is at least 10 miles wide and 40 miles long, and because of its distinctive character, suggests the possibility of searching on the opposite side of the fault for the missing portion of the magnetic mass in order to measure the displacement along the San Andreas. Available aeromagnetic data indicate that the missing magnetic mass is probably not north of Hollister, and in 1966 the U.S. Geological Survey will make reconnaissance aeromagnetic measurements over the more southerly extension of the fault zone. Assuming possible strike-slip movement of 350 miles since Jurassic time (Hill and Dibblee, 1953) and magnetic source rocks of nearly similar age, one might expect the missing portion of the magnetic anomaly to be located near the south end of the San Joaquin Valley. Another possibility is considered in a later section discussing the magnetic anomaly on the east side of the Great Valley.

At the projected intersection of the San Andreas fault with the Mendocino fault, Menard (1960) has pointed out that the Mendocino fault offsets the con-

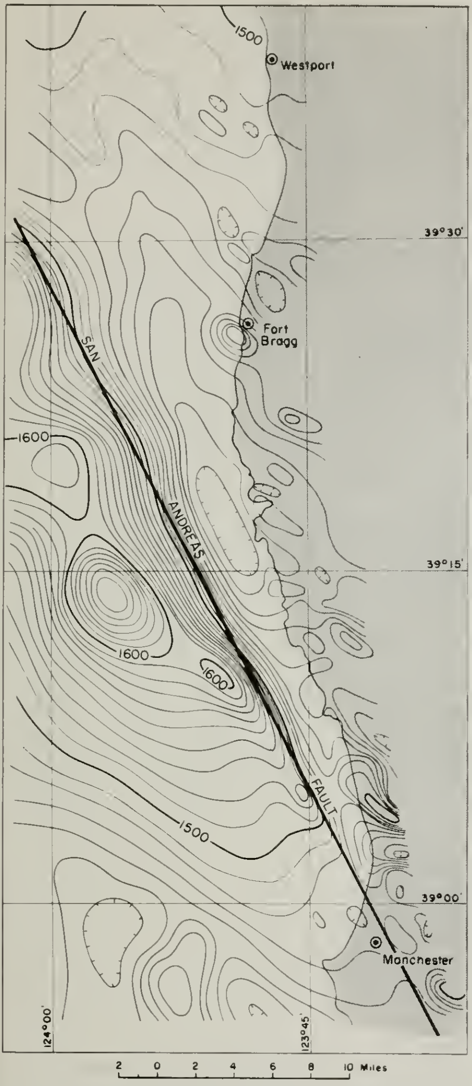

Figure 2. Total intensity aeromagnetic map showing the extension of the San Andreas fault on the continental shelf north of 39° N latitude (after Affleck, 1962). Contour interval 10 gammas.

tinental slope in northern California, a distance of about 65 miles in a right-lateral sense, the reverse of the sense of movement determined from magnetic data. The San Andreas fault, being also right lateral, may curve to the west at its north end and merge with the Mendocino fracture zone. The north-south linear magnetic grain north of the Mendocino fracture zone (Raff and Mason, 1961) shows no sign of offset in the area on strike with the San Andreas fault, so that if the fault continues north beyond the Mendocino fault, it cannot extend on strike toward the deep ocean but must bend northward at Cape Mendocino, following the continental slope. At lat 42°N. the magnetic data suggest that the fault, if present, must still be at the top of the continental slope, but a northwest-trending discontinuity in the magnetic pattern permits the speculation that the fault may extend into the Pacific Ocean north of this latitude (Wilson, 1965).

Aeromagnetic profiles across the San Andreas fault (fig. 1) indicate that in general the rocks on both sides of the fault are relatively nonmagnetic and that there are no regional magnetic anomalies which might indicate significant crustal differences on the two sides. Thompson and Talwani (1964a, p. 4823) make a similar statement about gravity data which indicates "no systematic density difference in crustal rocks on the two sides." In contrast with the above is the seismic refraction data of Eaton (1963), which show that the crustal velocity of P is 6.0 km/sec west of the San Andreas fault but only 5.6 km/sec east of the fault. Local magnetic highs over the fault, such as B on figure 1, are known from magnetic data elsewhere to be caused by serpentinite masses within the fault, and this explanation is adopted for anomaly B. The frequent occurrence of magnetic highs over the San Andreas fault suggests that serpentinite may be more common in the fault at shallow depth than is indicated by geologic mapping.

Franciscan Formation

The belt of Franciscan rocks lying between the San Andreas fault and the Great Valley sequence of sedimentary rocks (Bailey and others, 1964) is characterized by abundant serpentinite masses which account for most of the small magnetic anomalies associated with this unit on figure 1. In general, the Tertiary volcanic rocks are not sufficiently thick to generate magnetic anomalies at a flight elevation of 5,000 feet. The serpentinites of San Francisco form a 50-gamma magnetic high (C on fig. 1) and the serpentinite belt along the Hayward fault also generates a magnetic anomaly (D on fig. 1).

The large magnetic high over Mount Diablo (E on fig. 1) is a unique feature deserving separate comment. The northern half of the Mount Diablo piercement structure is shown as Franciscan rocks by Bailey, Irwin, and Jones (1964) and is mapped as intrusive diabase by Pampeyan (1963), who states that although it seems very similar to Franciscan greenstones in the southern half of the structure, it is younger than the Franciscan Formation. No other area of Franciscan greenstone is known to generate such a large magnetic anomaly. The great width of magnetic anomaly E indicates a magnetic mass approximately 7 miles wide along the profile, whereas the exposed diabase has a maximum mapped width of only about 3 miles in this same direction. A large positive gravity anomaly associated with this diabase mass has an amplitude of about 50 mgal and has been studied in detail by Wood (1964). He calculates a laccolithic or mushroom-shaped mass of diabase about 1.5 miles thick and 8 miles in diameter, having a stem about 2 miles wide and extending downward about 8 miles. The association of the two geophysical anomalies and the similar anomalous mass widths determined from the data indicate that both anomalies are caused by the same mass, that is, the diabase. In addition, the unique magnetic and gravity expression of this mass indicates that it should not be regarded as a part of the Franciscan Formation.

The eastern contact of the Franciscan Formation with the sedimentary rocks of the Great Valley sequence is generally a zone of faulting, and a sheet of serpentinite or other ultramafic rock commonly intervenes beneath the Great Valley sequence but above the Franciscan Formation. Irwin (1964) and Bailey, Irwin, and Jones (1964) hypothesize that the Great Valley sequence may have been thrust toward the west over the Franciscan rocks and that a sheet of ultramafic rocks, including serpentinite, simultaneously has been emplaced along the thrust plane. Ultramafic rocks such as pyroxenite and peridotite are usually not very magnetic but their altered equivalent, serpentinite, is highly magnetic because of the magnetite formed during the alteration of the anhydrous silicates to serpentine minerals. Aeromagnetic data of the U.S. Naval Oceanographic Office indicate a continuous magnetic high which can be traced along the eastern border of the Franciscan Formation at least as far south as Pacheco Pass (lat 37°N.). The magnetic data support the concept of a nearly continuous belt of ultramafic rock, predominantly serpentinite, along the eastern margin of the area of the Franciscan, and thus support the hypothesis of Irwin (1964). At Pacheco Pass, ground magnetic and gravity data (Woollard, 1943; Schroll, 1963) show that at the exposed east contact of the Franciscan a small gravity high may be associated with the magnetic high. Here, in addition to serpentinite, relatively unaltered ultramafic rock may be present to account for the gravity anomaly.

An important magnetic feature is found associated with this same serpentinite belt farther north, between lat 39°15'N. and 30°45'N. Here, aeromagnetic data released by the California Department of Water Resources (unpublished data, July 1966) and also aeromagnetic data collected by the U.S. Geological Survey (Irwin and Bath, 1962) show a broad regional magnetic anomaly associated with a sharp, local magnetic anomaly generated by the exposed ultramafic rock. The regional anomaly is apparently caused by a buried magnetic mass lying 1 to 2 miles below the surface along the belt of ultramafic rocks. The upper surface of the mass dips both east and west from its highest point at average angles of less than 15°, and its total width must exceed 12 miles. The association of this regional magnetic anomaly with exposed serpentinite suggests that it is caused by a large concealed mass of serpentinite, possibly a gently folded thick sheet. The western half of the sheet would underlie Franciscan rocks, and from its crest a zone of serpentine-filled, eastward-dipping thrust faults would extend up to the earth's surface.

GREAT VALLEY

Great Valley Magnetic Anomaly

A large broad magnetic high extends the entire length of the Great Valley of California from Red Bluff to Bakersfield. This feature has been known at least since 1932 (Jenny, 1932), and a contoured aeromagnetic map with flight intervals of 3 to 12 miles has been published by Grantz and Zietz (1960) for the interval between lat 37°30'N. and 40°N. The close association of the magnetic high with a corresponding gravity high was noted by Woollard (1943), and subsequent publications (Bayoumi, 1961; Oliver and Mabey, 1963; Thompson and Talwani, 1964a) have emphasized the good correlation of the two highs along the entire valley, although contoured magnetic data are not generally available between approximately lat 35°40'N. and 36°40'N.

The explanations for this major geophysical feature fall into two general categories. Some writers have suggested a large mass of mafic intrusive igneous rock; such writers include: Woollard (1943), who interpreted the anomaly as caused by a mass of gabbro with its top 3.6 miles below the surface; Grantz and Zietz (1960); Irwin and Bath (1962), who believe the anomaly may be caused primarily by ultramafic rock; and Oliver and Mabey (1963). The second proposed explanation (Thompson and Talwani, 1959; Bayoumi, 1961; Thompson and Talwani, 1964a) is that the Great Valley anomaly is caused by old deformed extrusive mafic volcanic rocks like those exposed in the western Sierra Nevada foothills. The evidence upon which these dissimilar conclusions are based includes: basement rock samples from drill holes in the Great Valley, a supposed continuation of the anomaly north of the Great Valley, and analogies with the geophysical expression of rock units of the western Sierra Nevada foothills.

Available data from drill holes over the anomaly north of lat 37°30'N. are scanty and have been discussed by Irwin and Bath (1962, p. B67). They mention 10 holes which penetrate "chiefly intrusive rocks of intermediate composition," and they note one core of gabbro and one of ultramafic rock. Basement lithology in the Fresno-Madera area near lat 37°N. is illustrated by Thompson and Talwani (1964a, fig. 5) with data modified from Bayoumi (1961). Here, along the higher portion of the gravity anomaly are shown 7 mafic metaigneous cores, 1 serpentine core, and 14 granitic cores. The gravity high in this area is broad and relatively low in amplitude, but depth calculations by Bayoumi (1961) based on contoured ground magnetic data suggest that the anomaly-producing rocks crop out at the basement surface. Abundant basement core data are available for the Bakersfield area (May and Hewitt, 1948; Thompson and Talwani, 1964a, fig. 6) where gravity and magnetic highs are associated with 4 gabbro cores, 2 diabase cores, 2 serpentine cores, and at least 13 mafic metaigneous cores in addition to other cores of granitic and metasedimentary rocks. It should be noted that the abundant quartz diorite samples recorded from the Great Valley basement are classified as granitic rocks because of their low density and generally low magnetization.

Evidence for continuation of the gravity and magnetic anomalies north of the valley is uncertain. The gravity high between lat 40°15′N. and 40°45′N. near Redding shown in figure 1 of Chapman (this bulletin, page 396) is probably only a relative high caused by the large flanking gravity lows to the east and west. The northern extension of the Great Valley magnetic anomaly to the magnetic gabbroic and ultramafic rocks of the Klamath Mountains is suggested by Irwin and Bath (1962) on the basis of a few widely spaced aeromagnetic profiles and the fact that the major magnetic anomalies, where definitely explained, are caused by ultramafic rocks, chiefly serpentinite. A small map published by Affleck (1962, p. 170) shows in the area north and northwest of Red Bluff magnetic anomaly axes trending east-west directly across the projected trend of the Great Valley anomaly; farther north, however, a return to the Great Valley trend is suggested. The magnetic data of Affleck (1962), and the probable absence of an associated gravity high at the north end of the Great Valley, raise considerable doubt as to the validity of this postulated northern extension of the anomaly.

The explanation that the Great Valley magnetic and gravity feature is caused primarily by mafic volcanic rocks is based largely on the presumption that the greenstone belt of the Sierra Nevada foothills is both magnetic and of relatively high density (Thompson and Talwani, 1964a). The abundant gravity and magnetic data now available from the foothills indicate that the volcanic rocks probably do not cause substantial magnetic or gravity highs. Most of the major gravity and magnetic highs known in the western Sierra Nevada foothills (see, for example, fig. 1; Balsley, 1953; Henderson, 1953) are caused by belts of serpentinite and mafic intrusions associated with the serpentinites. One gravity high of uncertain origin is crossed by the gravity profile of Thompson and Talwani (1964a) about 30 miles northwest of Sacramento, but it is precisely at this location that a belt of serpentinite and associated small mafic intrusions intersects the gravity profile. Furthermore, a large mafic pluton about 10 miles long and 5 miles wide is located less than 10 miles south of, and on strike with, the gravity anomaly. Gravity measurements over this pluton by the U.S. Geological Survey indicate a local Bouguer gravity high of about 25-mgal amplitude. Thompson and Talwani (1964b) believe that the gravity anomalies of this area merge to the southwest with the Great Valley anomaly, thus proving the greenstone association. However, more recent gravity data suggest that the two gravity features may not be connected (H. W. Oliver, oral communication, 1965). Even if they should prove to be connected, the indicated lithologic association is mafic intrusive rocks rather than extrusive greenstone. It appears that geophysical evidence from the rock units of the Sierra Nevada foothills does not favor the interpretation that mafic volcanic rocks similar to those of the greenstone belt cause the Great Valley feature.

A detailed aeromagnetic map of the Great Valley in the area between lat 37°15′N. and 39°10′N. is illustrated in figure 3. Small isolated local anomalies on individual flight lines are caused by well casings or industrial areas. The broad regional anomaly is well shown, as also are the smaller, sharper anomalies which are probably caused by magnetic rock masses extending up to the basement surface. A few anomalies, such as those along the northwest border of the map near Colusa, are caused by igneous rocks, presumably volcanic rocks, located relatively high in the sedimentary section above the basement. The Great Valley magnetic anomaly is situated approximately in the center of figure 3, trending parallel to the long direction of the map. The northeastern limit of the high is a relatively steep magnetic gradient extending downward into a rather linear associated magnetic low. The low is commonly below the regional magnetic level and is probably in part a polarization low associated with a relatively steep northeast-dipping contact on the northeast side of a magnetic mass of rock, the declination being N.17°E. and the inclination of the earth's field being 63°. A belt of relatively nonmagnetic basement rocks is presumably associated with the magnetic low, and it is not necessary to invoke reverse remanent magnetization to explain this low. The southwestern side of the Great Valley magnetic anomaly has a relatively even slope of great width which suggests that the west contact of the magnetic rock mass dips to the southwest but is below the basement surface.

As far south as Stockton, well-defined inflection points are observed on each transverse profile high on the southwest side of the magnetic anomaly. This line of inflection points probably defines the approximate location of the southwest contact of the magnetic rock mass where exposed at the basement surface. A width of 6 to 10 miles at the basement surface is indicated for this basement unit north of Stockton and the unit must become much wider at depth. The excellent correlation of this feature with the gravity high can be noted by comparing figure 3 with the gravity map (fig. 1 of Chapman, 1966, this bulletin).

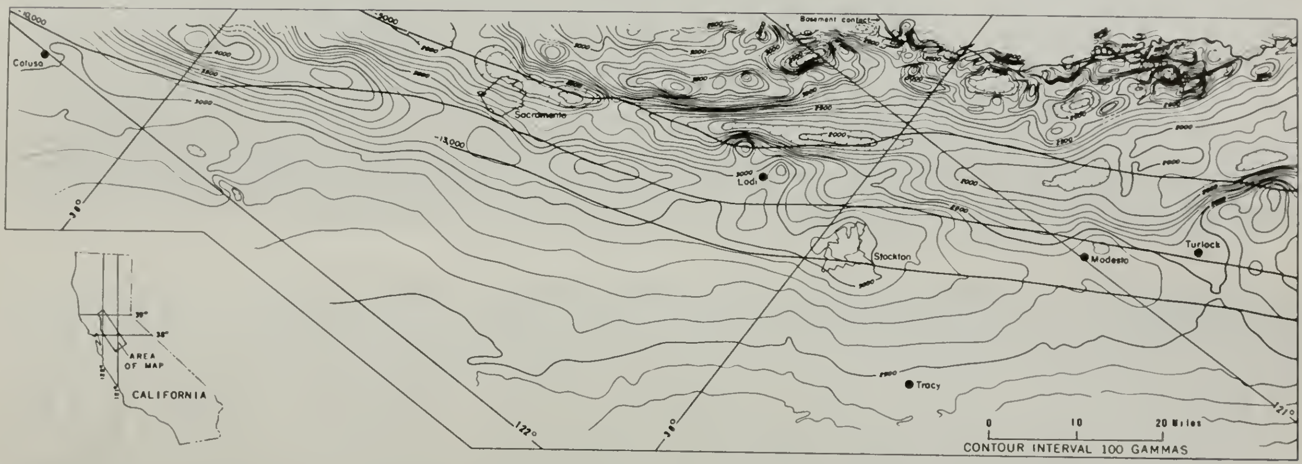

Figure 3. Total intensity aeromagnetic map of portions of the Sacramento and San Joaquin River valleys, California, after Meuschke and others, 1966. Flown 500 feet above ground at a traverse spacing of 1 mile. Basement depth contours in feet below sea level from Smith (1964).

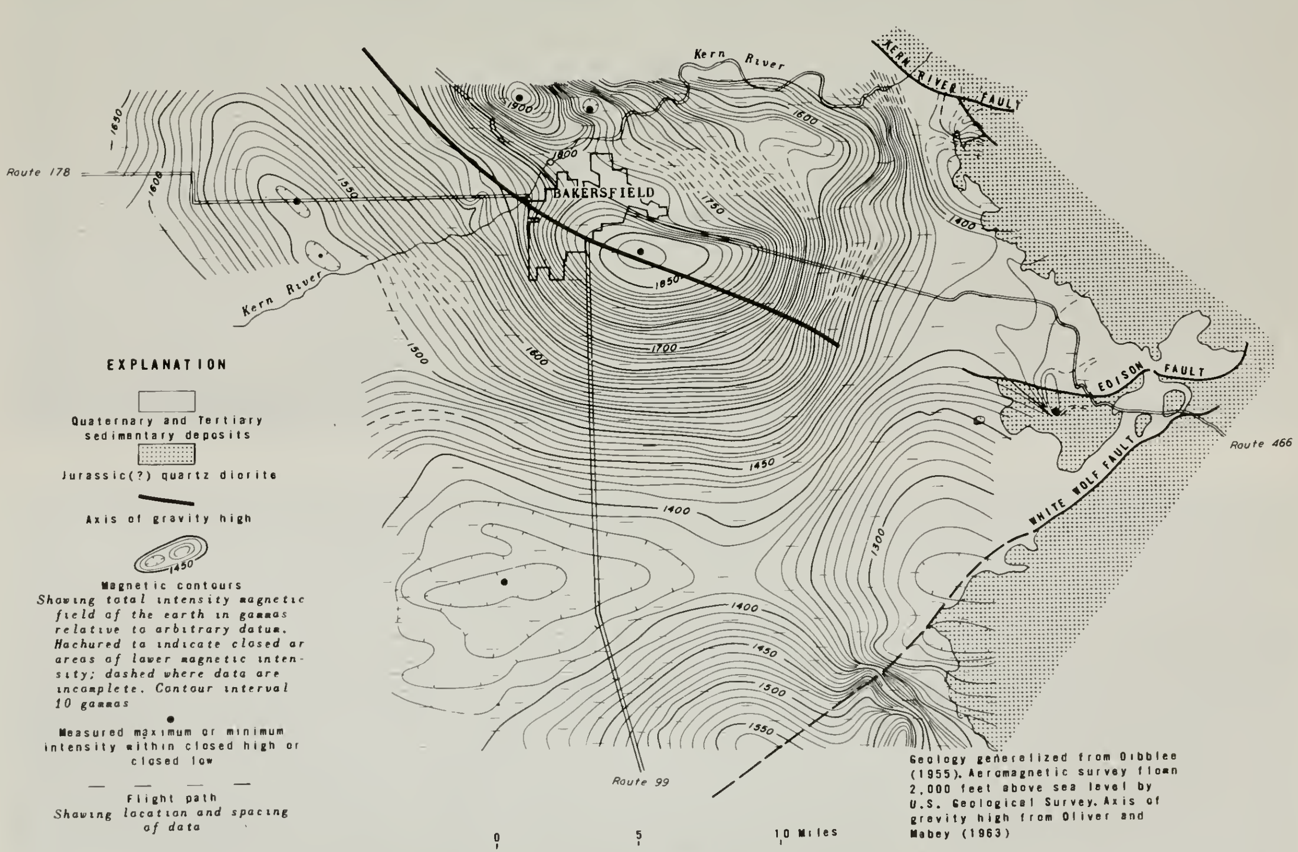

Figure 4. Total intensity aeromagnetic and generalized geologic map of the Bakersfield area, California, showing correlation of magnetic high with axis of the Great Valley gravity high.

The gravity data cannot be used to provide much information about the southwest contact of this magnetic, high-density rock responsible for the anomaly because of the large but poorly known thickness of low-density sediments on the west side of the Great Valley (Repenning, 1960). Southeast of Stockton as far as Turlock, the southwest contact of the magnetic rock mass is poorly defined and there are no inflection points high on the southwest side of the feature. Throughout this distance the gravity map indicates a low saddle on the associated Great Valley gravity ridge, so it is possible that the magnetic rock unit here may not be exposed at the basement surface, except perhaps locally at the magnetic high 2 miles east of Modesto. Southwest of Turlock the magnetic anomaly resumes an appearance more similar to the portion northwest of Stockton, and at the same location the associated gravity anomaly resumes its former amplitude.

At the extreme southern end of the Great Valley, in the Bakersfield area, both the magnetic high and the gravity high (fig. 4) do not extend to the place where the basement rocks crop out on the southeast side of the White Wolf fault. In the area of figure 4, the exposed basement rocks are predominantly quartz diorite which appears to be relatively nonmagnetic. The association of the positive gravity anomaly with mafic basement rocks in this area has been well documented by Thompson and Talwani (1964a), and by using their figure 6, it is possible to draw a geologic contact about 10 miles long between mafic and granitic rocks. This line approximates the position of the 1,450-gamma contour line southeast of Bakersfield on figure 4, the mafic rocks being northwest of the contact and associated with the magnetic high. It is difficult to decide from the drill-hole samples whether mafic plutonic or volcanic rocks (or both) are the main source of the magnetic and gravity anomalies. The northern magnetic high clearly is not associated with the gravity high.

The magnetic contours southeast of the White Wolf fault indicate by steep, narrow gradients the shallow depth to basement relative to the northwest side of the fault. In addition the magnetic contours suggest that left-lateral movement of the fault must be less than a mile. The 1.5-mile-downward displacement of the northwest side shown by Smith (1964) at the location where the 1,450-gamma contour crosses the fault is probably sufficient to cause the left-lateral offset in the magnetic contour line, owing to increase in distance of the magnetic rocks from the aircraft. This conclusion contradicts various writers who consider the fault movement to be predominantly strike slip and confirms the statement of Dibblee (1955, p. 23) that the "White Wolf fault is essentially a reverse fault, locally a thrust, elevated in the southeast block, with a small left-lateral component of movement."

In summary, the close association of the magnetic and gravity highs trending the length of the Great Valley demonstrates that the gravity anomaly is at least in part caused by a mass of high-density magnetic rock, and that it is not merely a relative maximum between the gravity lows caused by the valley sediments to the west and the Sierra Nevada to the east, as suggested by Ivanhoe (1957). The Great Valley magnetic anomaly can be considered the expression of one of the principal structural features in California (Bailey and others, 1964, p. 150), and an explanation of its origin should take into consideration the regional structural setting. The anomaly is located in the central portion of the Great Valley, an asymmetrical elongate synclinal sedimentary basin which is parallel to the uplifted Sierra Nevada to the east and of about the same length. The anomaly appears to be situated at the contact between two very different geologic and tectonic terranes, the Franciscan rocks to the west and the Sierra Nevada basement rocks to the east. Two major east-west oceanic fault zones, the Mendocino fault to the north and the Murray fault to the south, intersect the continental margin at the approximate latitude of the north and south ends of both the anomaly and the Sierra Nevada. The sense of movement of continental strike-slip faults on strike with these oceanic faults suggests that the continental block west of the magnetic anomaly and between the faults may be moving west relative to the adjacent portions of the continent. Yet the sense of movement on the oceanic faults as determined from magnetic data (Vacquier and others, 1961) is the reverse.

The oblique-rifting hypothesis of Bailey (1964) and Bailey, Irwin, and Jones (1964, p. 160) offers a possible way to synthesize the regional structural setting with the geologic and geophysical information concerning the Great Valley feature. This hypothesis proposes that beginning in Late Jurassic time the block of granitic rocks "between the San Andreas and Nacimiento faults has drifted laterally from a position adjacent to the present central part of the Great Valley" (Bailey, Irwin, and Jones, 1964, p. 162), the north end of the block moving along the Mendocino fault. It seems logical that the Late Jurassic zone of tension and fracture along the present location of the Great Valley might have been intruded at that time by substantial masses of mafic and ultramafic rocks, coming possibly from the upper mantle (Oliver and Mabey, 1963). This large elongate mass of magnetic high-density rocks would be the source of the Great Valley anomaly and could possibly contain associated volcanic rocks, and locally, some serpentinite. The association of the structural depression of the Great Valley with this high-density mass implies that the valley may in part be caused by the subsidence of this block of mafic rock, perhaps in order to regain isostatic equilibrium after it was intruded; however, other factors must also have been operating because isostatic equilibrium can be regained relatively rapidly and the Great Valley has been subsiding at least since Cretaceous time. The parallel association of the high-density descending mass of valley basement with the complementary low-density rising mass of the Sierra Nevada suggests that these two areas behaved in the main as a single crustal block rotating in response to isostatic forces about a horizontal axis trending slightly west of north. This idea has been advanced by Kane (*in* Kane and Carlson, 1961) for ranges in Nevada. Presumably the Sierran root has been growing during the uplift, and perhaps the crust under the Great Valley has thinned during its descent.

Magnetic Anomoly on the East Side of the Great Valley

Another major regional belt of magnetic highs follows along the northeast border of figure 3 to the latitude of Sacramento, where it appears to terminate against the circular, mostly covered mass of granite that causes the large gravity low northeast of Sacramento (Thompson and Talwani, 1964a). This magnetic high does not seem to be present north of Sacramento, according to the limited data that was available to Irwin and Bath (1962). Along the very linear high-amplitude portion of this magnetic anomaly between a point 8 miles east of Sacramento and another point 10 miles northeast of Lodi, there is a large associated gravity high, interpreted as caused by a mafic intrusion, but farther to the southeast the amplitude of the magnetic anomaly is lower and the gravity expression is subdued. The more complex pattern of local magnetic highs and lows along this regional magnetic high can be attributed for the most part to the relatively shallow depth of the magnetic rocks below the aircraft (about 1,500 feet), and the profile of figure 1 gives an indication of the appearance of this anomaly northeast of Lodi at F under circumstances where the magnetic rocks are approximately 6,000 feet below the aircraft. The shape of this magnetic anomaly, its generally lower amplitude than that of the Great Valley magnetic anomaly, and the absence of a major associated gravity high except for the local linear feature a few miles southeast of Sacramento, suggest that this anomaly is not caused by rocks similar to those causing the Great Valley anomaly. The irregular pattern of smaller magnetic highs and lows is similar to magnetic patterns observed over volcanic rocks in many areas of the United States, but the volcanic rocks of this belt would have to contrast sharply in their magnetic properties with the volcanic rocks of the Sierra foothills. Another possible explanation (Henderson, Stromquist, and Jespersen, in press) is a second major belt of ultramafic rocks, similar to, and parallel with, the belt of associated ultramafic and gabbroic rocks in the Sierra foothills. This hypothesis is not confirmed by any geologic mapping or drill-hole data.

South of 38°15′N. the northeast border of the magnetic map (fig. 3) locally overlaps exposed basement rocks for distances of up to 3 miles, and the source of the magnetic anomalies must crop out. In this area a detailed aeromagnetic map that extends from long 120°W. to 121°W. (Henderson and Bass, 1953; Henderson, Stromquist, and Jespersen, in press) indicates that although the volcanic rocks of the foothills give rise to a few low-amplitude magnetic anomalies, these rocks are at best weakly magnetic and major magnetic anomalies are caused by serpentinite masses in fault zones. At the western border of this detailed aeromagnetic map, the belt of magnetic rocks associated with the northeast side of the Great Valley is mostly covered by younger sediments, but H. W. Oliver (written communication, 1964) has noted that one magnetic anomaly of this belt correlates well with volcanic rocks of the Logtown Ridge Formation of Taliaferro and Solari (1948). No serpentinite has been mapped along this edge of the Great Valley, so the best evidence points to a volcanic rock source for this belt of magnetic anomalies.

The apparent termination of this anomaly belt in the vicinity of Sacramento gives rise to a speculation based on the oblique-rifting hypothesis of Bailey (1964). If, as previously mentioned, the granitic block between the San Andreas and Nacimiento faults achieved its present position by drifting westward from a former location in the Great Valley, it might be possible to locate the northwest extension of this seemingly terminated magnetic anomaly belt by examining magnetic patterns on the west side of the San Andreas fault. Bailey, Irwin, and Jones (1964, fig. 33, p. 161) indicate that the original location and subsequent direction of oblique rifting may have been in such a manner that basement rocks once in the Sacramento area would now lie a few miles northwest of Manchester (fig. 2). Perhaps by coincidence, this is the precise location of the unusual linear magnetic high shown on figure 2, and it would thus be of considerable interest to compare the rocks causing this anomaly west of the San Andreas fault with those rocks causing the magnetic anomaly belt on the east side of the Great Valley southeast of Sacramento.

SIERRA NEVADA

Aeromagnetic profiles flown across the Sierra Nevada by the U.S. Geological Survey and the U.S. Naval Oceanographic Office (Zietz and others, 1965) indicate a regional magnetic high with a peak amplitude at the crest of the range of about 400 gammas. This regional magnetic high trends parallel with the mountain range, and its margins extend from the edge of the Great Valley on the west to the Owens River Valley on the east. North of 38°N. (the latitude of Mono Lake) the anomaly becomes less distinct, and it is not visible on two profiles crossing the Sierra Nevada between lat 39°15′N. and 39°30′N. (Balsley, 1953; Agocs, Rollins, and Bangs, 1954). The anomaly may be present on the ground magnetic profile of Woollard (1943), which crosses the southern end of the Sierra Nevada at 35°40′N., but his data can also be interpreted as indicating two separate local highs superimposed on a broad regional high of only 150 gammas. The amplitude of the Sierra Nevada magnetic anomaly is such that the topography, assuming a reasonable susceptibility, cannot cause the feature (H. W. Oliver, oral communication, 1965). Correlation of the magnetic anomaly with the regional topography of the Sierra Nevada south of Mono Lake is good, but the geologic correlation is uncertain. There may be a correlation with the southern portion of the Sierra Nevada batholith, but it is then unclear why the magnetic anomaly does not persist over the northern portion of the batholith. The anomaly may be related in some way to the deeper root under the central and southern portions of the Sierra Nevada. Seismic evidence for this deeper root is discussed by Romney (1957) and by Eaton (this bulletin). A regional depression of the Curie point isotherm could account for the anomaly and might be related to the deeper root, but data on heat flow and on the thickness of the more radioactive granitic rocks of the batholith are still needed in order to evaluate this hypothesis.

An unexplained feature on the two northerly profiles across the Sierra (Balsley, 1953; Agocs, Rollins, and Bangs, 1954) is the large abrupt eastward increase (800–1,300 gammas) in the magnetic field encountered while crossing the crest of the range. Agocs, Rollins, and Bangs (1954) explain this increase as probably caused by surficial volcanic rocks, but it seems unlikely that this is a sufficient explanation because the increase shown on the profile of Balsley (1953) occurs shortly after crossing into the Sierra Nevada batholith and before reaching any substantial or continuous outcrops of volcanic rocks. It is possible that the sudden increase is caused by exposed or shallow-depth rocks of the Sierra Nevada batholith, but data on the magnetic properties of these rocks are not available.

GREAT BASIN

East of the Sierra Nevada, the Mono Lake volcano-tectonic depression has been studied by combined geophysical techniques, including aeromagnetic profiles (Pakiser, Press, and Kane, 1960). A magnetic high over the center of Mono Lake coincides with a small, poorly defined gravity high and "may be caused by a pile of intrusive and flow rocks that were emplaced during the deposition of the basin fill" (Pakiser, Press, and Kane, 1960, p. 435). A larger and wider magnetic high is also associated with the center of Long Valley, a calderalike volcano-tectonic depression located about 20 miles south of Mono Lake (Pakiser, 1961; Henderson, White, and others, 1963; Pakiser, Kane, and Jackson, 1964). The depth to this magnetic anomaly has been determined by Isidore Zietz (Pakiser, Kane, and Jackson, 1964, p. 41) to be about 3,000 feet below the ground surface. The preferred interpretation (in Pakiser, Kane, and Jackson, 1964) of this central magnetic feature is that it is caused by volcanic necks surrounded by a sequence of associated flows located high up in the valley fill of Cenozoic clastic deposits. It is also possible that the anomaly may represent a relatively shallow intrusion within the caldera.

Farther south, at lat 35°45′N., an aeromagnetic survey by the U.S. Geological Survey has been described by Zbur (1963). His magnetic map covers Indian Wells Valley on the east side of the Sierra Nevada fault at China Lake. Two magnetic highs are attributed to basaltic volcanic rocks interbedded in the Cenozoic sedimentary rocks, while two other magnetic highs are thought to be caused by mafic plutonic rocks within the basement because they are associated with gravity highs.

In the Darwin area, at lat 36°20′N. between Owens Lake and Panamint Valley (pl. 1), an aeromagnetic survey located a large magnetic high about 5 miles in diameter, interpreted by Mabey (1961) as being caused by a large intrusive body. On the east side of Death Valley, aeromagnetic data over the Black Mountains (Andreasen and Petrafeso, 1963) show a series of broad aeromagnetic highs which appear to be caused for the most part by the Mesozoic grantic plutons along the crest of the range. Aeromagnetic surveys in the Great Basin have proved extremely useful in the delineation of concealed stocks and other plutons, and they thus provide a valuable method for locating areas of potential economic interest.

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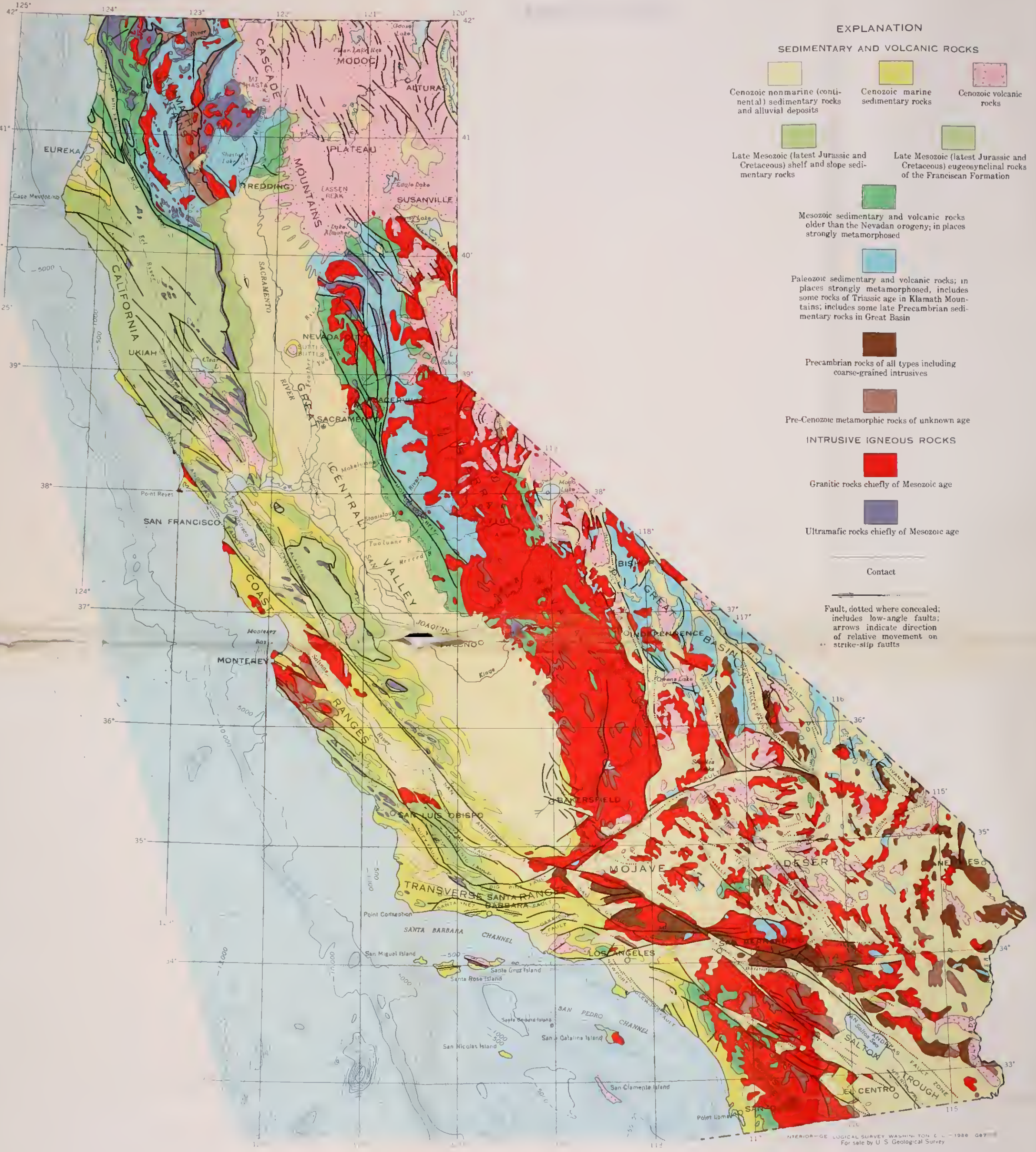
DEPARTMENT OF INTERIOR
UNITED STATES GEOLOGICAL SURVEY

MISCELLANEOUS GEOLOGICAL INVESTIGATIONS
MAP I-512



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For sale by U S Geological Survey

EXPLANATION

SEDIMENTARY AND VOLCANIC ROCKS

- 🟨 Cenozoic nonmarine (continental) sedimentary rocks and alluvial deposits
- 🟨 Cenozoic marine sedimentary rocks
- 🟪 Cenozoic volcanic rocks
- 🟩 Late Mesozoic (latest Jurassic and Cretaceous) shelf and slope sedimentary rocks
- 🟩 Late Mesozoic (latest Jurassic and Cretaceous) eugeosynclinal rocks of the Franciscan Formation
- 🟩 Mesozoic sedimentary and volcanic rocks older than the Nevadan orogeny; in places strongly metamorphosed
- 🟦 Paleozoic sedimentary and volcanic rocks; in places strongly metamorphosed, includes some rocks of Triassic age in Klamath Mountains; includes some late Precambrian sedimentary rocks in Great Basin
- 🟫 Precambrian rocks of all types including coarse-grained intrusives
- 🟫 Pre-Cenozoic metamorphic rocks of unknown age

INTRUSIVE IGNEOUS ROCKS

- 🟥 Granitic rocks chiefly of Mesozoic age
- 🟪 Ultramafic rocks chiefly of Mesozoic age

Contact

Fault, dotted where concealed; includes low-angle faults; arrows indicate direction of relative movement on strike-slip faults

GEOLOGIC MAP OF CALIFORNIA

COMPILED BY U.S. GEOLOGICAL SURVEY
AND CALIFORNIA DIVISION OF MINES AND GEOLOGY

SCALE 1:2 500 000
0 50 100 MILES

SUBMARINE CONTOUR INTERVALS 500 AND 1000 FEET DATUM IS SEA LEVEL

1966