THE GRAVITY FIELD IN NORTHERN CALIFORNIA

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Gravity surveys have proved useful in the study of the geology of northern California, particularly in interpreting some of the varied and complex structures found in this part of the State. Such surveys have been conducted by Federal and State government agencies, universities, and private industry. The U.S. Geological Survey is responsible for most of the published gravity data in the State, as a result of both Survey projects and student theses supported by the Survey. Oil companies have conducted extensive gravity surveys in the northern part of California, largely in potential gas or petroleum producing areas. Some local surveys and regional data have been released by the companies but most of this kind of data has remained confidential. A large number of projects are currently underway in California, including work by the U.S. Geological Survey and the California Division of Mines and Geology (Oliver, 1965; Chapman, 1965).

The present gravity coverage in northern California is far from uniform: good regional coverage is now available in parts of the Great Valley, the Sierra Nevada, some central parts of the Coast Ranges, and the southern Cascade Mountains, for example, but little has been done in many other areas in the State, such as the northern Coast Ranges.

A gravity measurement is the summation of many mass effects. Ideally, if we can assume that the effects of elevation, topography, latitude, and tides have been correctly removed, the anomalies in a map of the gravity field are caused by lateral density changes in the materials composing the earth. Geologic structures often bring into contact rocks of different densities, hence, gravity surveys may help locate these structures where they are hidden or buried. Local gravity surveys are frequently used directly in the search for mineral deposits, oil and gas, and in solving geologic problems. Regional surveys yield data on larger geologic features, such as the thickness and density of the earth's crust and the nature of isostatic compensation.

GENERAL FEATURES OF THE GRAVITY FIELD

Figure 1, a generalized Bouguer gravity map of the northern part of California with a contour interval of 20 mgal, has been adapted from a recently published 10 mgal map of the United States (Woollard and Joesting, 1964). This map was compiled from many sources and includes airport gravity base stations (Woollard, 1958) and regional traverses by the University of Wisconsin, as well as data from oil companies, universities, the U.S. Geological Survey, and the U.S. Coast and Geodetic Survey. The data were reduced using a density of 2.67 g/cm^3, yielding Bouguer gravity values, but terrain corrections are included only for the Sierra Nevada region between latitudes of 35°45′ and 37°00′.

The Bouguer gravity values along the coastal areas usually are positive or slightly negative, being often about 0 mgal. These decrease eastward to strongly negative values, −200 mgal or less, in the vicinity of the Sierra Nevada and Great Basin provinces. Superimposed on this general trend are numerous smaller anomalies ranging in size from some that are as large as a geologic province to others too small to be shown at the contour interval and scale of figure 1.

Thompson and Talwani (1964, p. 4820) have analyzed in detail a gravity profile that extends from the Pacific Basin in a northeasterly direction, approximately normal to the regional geologic structure, through the Coast Ranges near San Francisco, the Great Valley, the Sierra Nevada, and the western Great Basin provinces to a point near Fallon, Nevada (profile A-A′, figs. 1 and 2). The starting point for their crustal section, which is derived from the gravity anomaly profile, is based on seismic evidence that the depth to the base of the crust in the San Francisco Bay area is 21 km (Thompson and Talwani, 1964, p. 4823, who cite Healy, 1963, and Eaton, 1963). According to this interpretation, the regional anomaly from the Pacific Basin to the Great Basin, as shown on figure 2, is caused primarily by the effect of the crust, which thickens eastward from the margin of the continent, and secondarily by a decrease in the density of both the crust and upper mantle in the same direction. A gradation in the density of the crust from 2.9 g/cm^3 in the oceanic area to 2.8 g/cm^3 in the continental area was assumed to take place under the continental slope. Also assumed is an anomalous upper mantle with a density of 3.3 g/cm^3 under the continental area separated from the normal mantle with a density of 3.4 g/cm^3 at a depth of about 50 km (Thompson and Talwani, 1964, p. 4822).

The local anomalies, shown on both the contour map (fig. 1) and profile (fig. 2) are caused principally by density differences in the rocks of the upper crust, although in some cases deeper effects, including isostatic compensation, are also believed to be present. The locations of some of these anomalies are identified

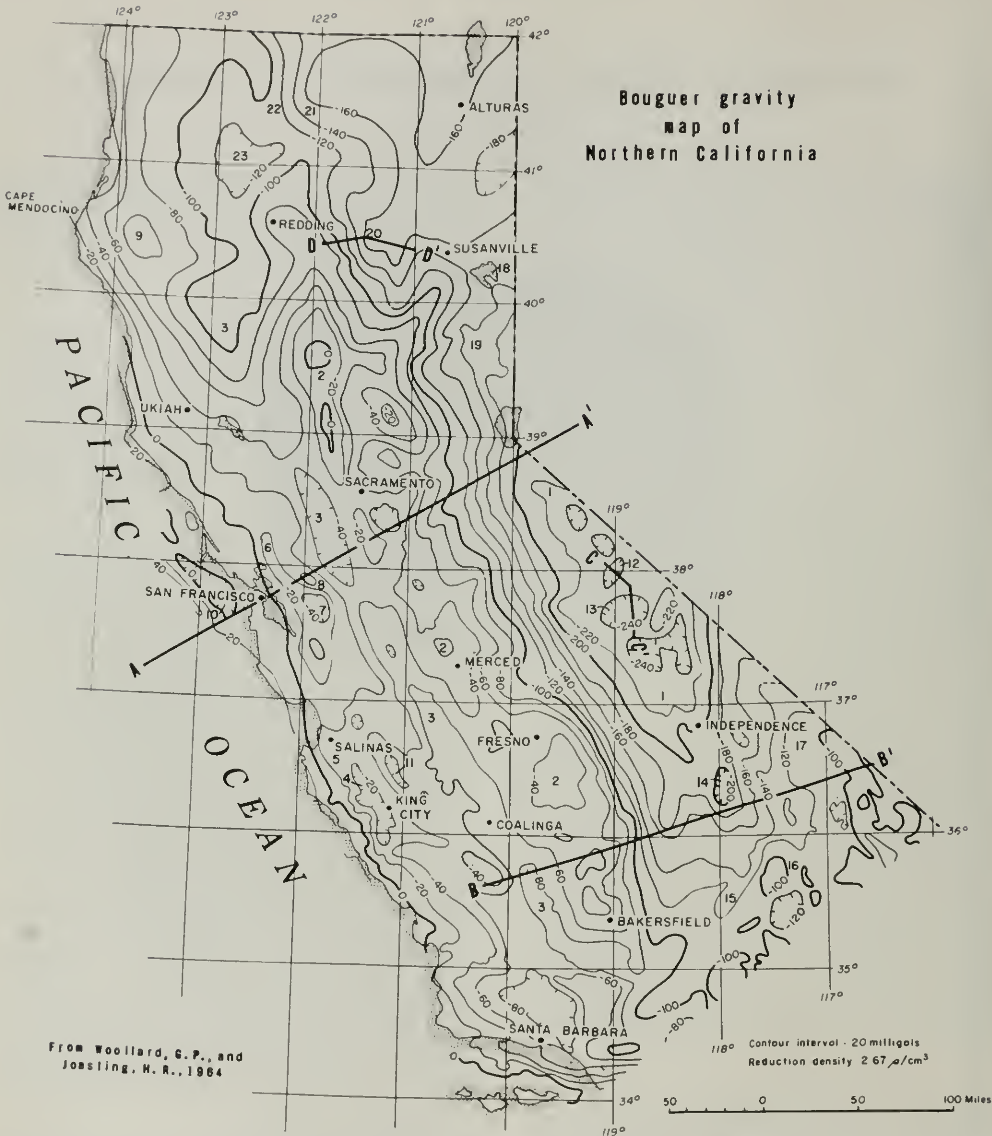

Figure 1. Bouguer gravity map of northern California (after Woollard and Joesting, 1964).

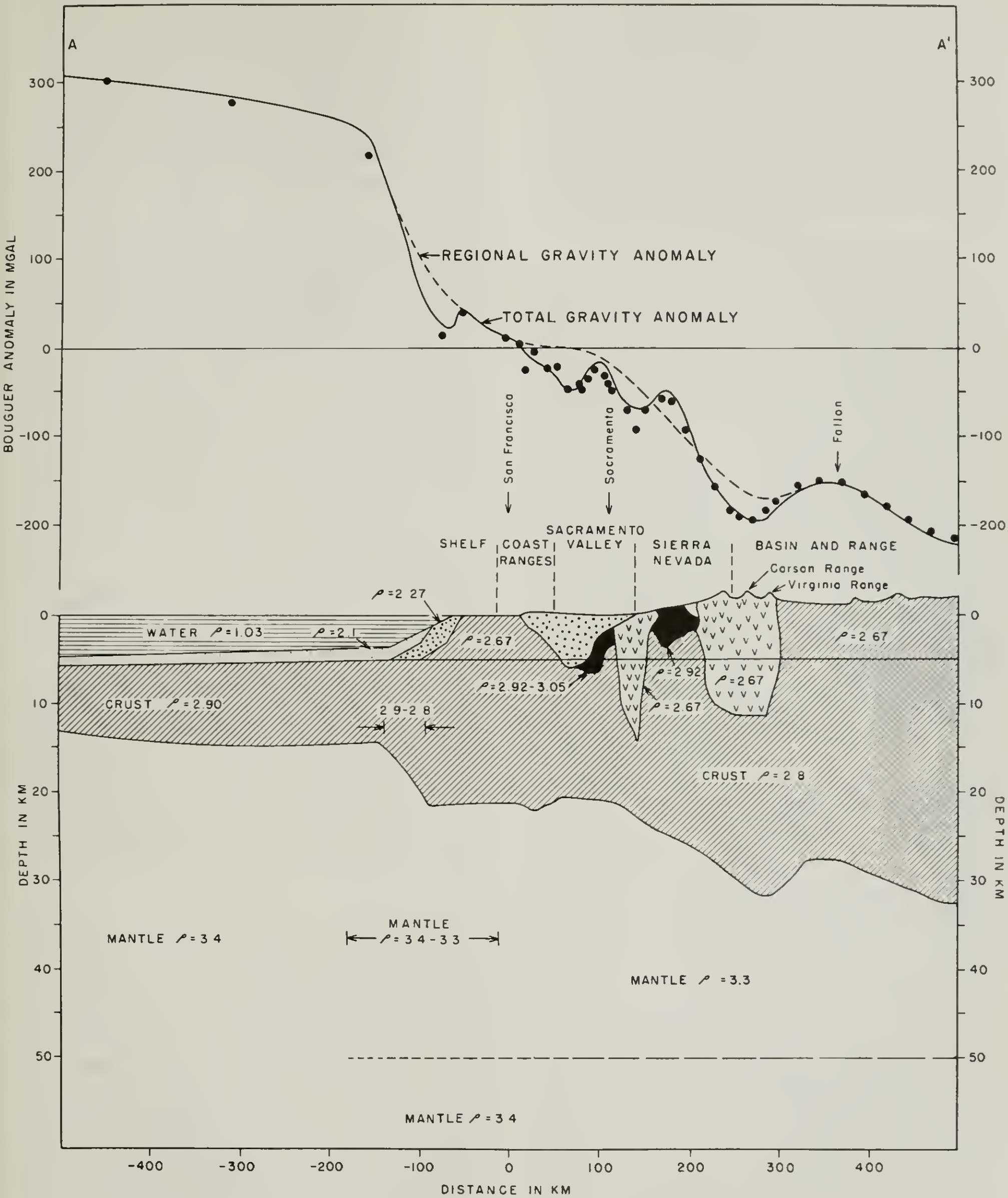

Figure 2. Section of crust and upper mantle along A-A', figure 1, showing gravity anomaly computed from section compared with observed points. Dotted patterns represent sedimentary rocks; checks, granitic rocks; shading, greenstone (after Thompson and Talwani, 1964, fig. 4).

on figures 1 and 2 by numbers. Three of the more prominent northwest-trending anomalies that can be seen on the map include a gravity minimum (No. 1) associated with the Sierra Nevada, a gravity high (No. 2) extending along the length of the Great Valley on its east side from near Redding to Bakersfield, and a gravity minimum (No. 3) located on the east side of the Coast Ranges and west side of the Great Valley. The local anomalies will be discussed in more detail in the following sections on the individual geologic provinces.

COAST RANGES PROVINCE AND OFFSHORE AREAS

In many parts of the Coast Ranges of California there is only a small amount of gravity data available. The Coast Ranges in the area north and south of San Francisco have received the most attention. Figure 1 shows that in general the gravity field decreases from between +20 and 0 mgal at the coast to as low as −80 mgal in rhe eastern part of the Coast Ranges and western part of the Great Valley.

Local studies have usually found gravity lows associated with large thicknesses of Cretaceous and Cenozoic rocks and almost normal or high gravity values over the more dense Franciscan Formation and granitic basement rocks of the Coast Ranges. Thicknesses of the sedimentary rocks have been estimated in some areas from the gravity data. These estimations depend critically on the density contrasts selected unless independent seismic data are available, and for many areas the densities are not well established.

In the Salinas Valley-San Antonio Hills area northwest of King City, P. E. Byerly (1966, fig. 2) found a negative anomaly of about −30 mgal (fig. 1, No. 4) which he attributes largely to a 6,000-foot-thick section of Miocene shale. Farther north in the Salinas Valley, J. W. Fairborn (1963, student project, Stanford Univ., p. 17) analyzed a −38 mgal anomaly (fig. 1, No. 5) south of the city of Salinas. He concluded that this is caused by a thickness of approximately 9,000 feet of Tertiary sediments bounded on the east by granitic basement rocks of the Gabilan Range and on the west by the King City fault and basement rocks in the Sierra de Salinas.

Parts of the south San Francisco Bay and northern Santa Clara Valley area have been studied by S. G. Taylor (1956) and G. M. Greve (1962). Additional work has also been done recently in this area by the California Division of Mines and Geology and the California Department of Water Resources (California Dept. Water Resources, 1965) and near San Jose by Stephens Robbins (oral communication, 1964). These studies have revealed steep gravity gradients and large gravity lows of up to −30 mgal in parts of the valley, and these indicate the presence of faults separating several major structural blocks. The gravity evidence suggests that younger sediments with thicknesses up to 5,000 feet may overlie the basement of Franciscan rocks in parts of the valley.

In the vicinity of San Pablo Bay, northeast of San Francisco, Clement (1965, p. 4) has outlined another major gravity low (fig. 1, No. 6) which he believes is caused primarily by a downfaulted and folded block of Tertiary rocks bounded by Jurassic and Cretaceous rocks on the west and east. In addition, C. F. Petersen (1962, student project, Stanford Univ., p. 3) found a negative anomaly with a westerly trend and an amplitude of about 30 mgal over a thick accumulation of sediments in the Livermore Valley, east of the San Francisco Bay area (fig. 1, No. 7).

Gravity highs in the Coast Ranges are often related to exposed basement rocks, particularly greenstone masses in the Franciscan Formation and intrusive granitic, mafic, and ultramafic bodies. Examples are highs over the granitic rocks of Montara Mountain and Point Reyes in the San Francisco Bay area (Greve, 1962, p. 21; Clement, 1965, p. 5) and a high east of the San Andreas fault in Marin County caused by a belt of greenstone and ulrramafic rocks (Clement, 1965, p. 5). A surprisingly large positive anomaly of approximately 50 mgal (fig. 1, No. 8) found in a survey of the Mount Diablo area by Wood (1964, p. 33) indicates by its size that the diabase exposures northwest of the central peak of Mount Diablo represent a very large deepseated mass. Another prominent broad gravity high (fig. 1, No. 9) in the Coast Ranges, east of Cape Mendocino, is based on very few measurements but corresponds in general to a wide belt of Franciscan Formation rocks.

Masses of ultramafic rock in the Coast Ranges are believed to be largely serpentinized. The range of densities for dunite, peridotite and pyroxenite is about 3.1 to 3.3 g/cm^3 (Birch, 1942, p. 14), but for serpentine it is about 2.2 to 2.8 g/cm^3. Thus, an ultramafic body in contact with Franciscan graywacke which has an average density between 2.60 and 2.65 (Bailey and others, 1964, p. 141) might cause either a gravity high or low depending on the proportion of serpentine present.

Gravity surveys of several ultramafic masses in the Coast Ranges have been made to determine the nature of these bodies at depth. For example, P. E. Byerly (1966), using a reduction density of 2.67 g/cm^3, found a negative anomaly over a serpentinized laccolith or thick sill north of Coalinga in the Diablo Range. He concluded that there could be no large amount of unaltered ultramafic rock in the core of the mass. Studies of exposed dunite bodies at Cazadero, in Sonoma County, and Burro Mountain, in Monterey County, reveal relatively small gravity anomalies that indicate "shallow depths of dunite and a probable abundance of concealed serpentine" (Thompson, 1963, p. 228). A possible exception to these findings is the ultramafic mass in the eastern Klamath Mountains discussed in a later part of this article.

Published offshore gravity data in northern California are meager. Profile A-A′, shown in figure 2, makes use of sea pendulum stations by Harrison and others (1957) and Vening Meinesz (1948) and a station on Farallon Island. This profile shows a 40 mgal negative residual anomaly in the vicinity of the continental slope, which Thompson and Talwani (1964, p. 4829) suggest is caused by a thickness of about 3 km of sedimentary rocks. A survey offshore in the San Francisco area by the U.S. Coast and Geodetic Survey (Jones, 1963, p. 32) revealed a gravity low bounded by steep gravity gradients (fig. 1, No. 8) between the Farallon Islands and the mainland. This suggests a fault-controlled basin, or graben, filled with sediments.

In the vicinity of the Mendocino fracture zone off northern California some gravity stations have been occupied by Worzel and others (1955) and Harrison and others (1957). A more detailed investigation of this area was recently completed by geophysicists of Oregon State University, using a shipborne gravity meter (Peter Dehlinger, written communication, 1965).

An interpretation of the structure across the Mendocino fracture zone based on the gravity data available at that time has been presented by Talwani and others (1959, p. 55). According to this interpretation, which assumed that the crust consists of a single homogeneous layer overlain by sediments and water, the crust was found to be about 3 km thicker north of the fracture zone than south of it in the area studied. There is also an indication of a mass deficiency under the escarpment which may represent a local thickening of the crust. Limited data obtained by Bowers (1958) in the Cape Mendocino area east of the Mendocino and Gordo escarpments does not provide evidence for the shoreward continuation of these structural features.

San Andreas fault. Many of the gravity anomalies in the Coast Ranges are related to faulting, which has brought rocks of contrasting densities into contact. Where rock types on each side of the faults are similar, or have similar densities, there may be no associated anomaly. It is conceivable, however, that a major fault zone, such as the San Andreas, could displace the base of the earth's crust or layers deep within the crust and have a characteristic anomaly related to this relatively deepseated displacement even though the surface rocks have similar densities.

If we examine gravity maps of the area along the San Andreas fault zone we find in some areas anomalies associated with the fault, but in others essentially no anomalies. P. E. Byerly (1966), for example, found northeast of King City, a negative anomaly (fig. 1, No. 11) of about 40 mgal just southwest of and parallel to the San Andreas fault zone. This anomaly is probably caused by a thick section of Miocene and Pliocene sedimentary rocks, which lies between the fault and the exposed crystalline rocks of the Gabilan Range to the southwest. A Bouguer anomaly profile across the Coast Ranges and San Joaquin Valley (P. E. Byerly, 1966, pl. 1) which has been corrected for near-surface geologic effects shows no evidence of an anomaly related to the San Andreas fault.

In the San Francisco Bay area there are both negative and positive anomalies found close to the San Andreas fault, but these are also clearly related to near-surface geologic features. In the vicinity of Tomales Bay, for example, there are no local anomalies to distort the smooth regional surface, and Clement (1965, p. 5) has concluded that there is no characteristic anomaly associated with the fault. A study of the regional magnetic data leads to a similar conclusion with respect to the San Andreas fault according to Griscom (this bulletin, p. 408).

GREAT VALLEY PROVINCE

The Great Valley of California, which includes the Sacramento Valley on the north and the San Joaquin Valley on the south, is a broad alluviated depression near sea level in elevation. Structurally, it is an asymmetrical synclinorium containing on its western side 30,000 feet or more of Cretaceous and Cenozoic sediments (Kilkenny, 1951, p. 215). As would be expected, the western side of the valley and the eastern side of the Coast Ranges are characterized by a prominent gravity low (fig. 1, No. 3) owing to this great thickness of sedimentary rock. A surprising gravity feature in the Great Valley, however, is a nearly continuous gravity high (fig. 1, No. 2) that trends down the length of the valley and is nearly in the middle from east to west, except for a southernmost segment which is nearer the eastern side. On profile A-A′ (fig. 2), for example, the gravity values increase from less than −50 mgal along the western edge to about −20 mgal near the center of the valley. Both of these major gravity anomalies extend throughout the length of the valley.

The gravity high in the Great Valley has been tne subject of great interest and speculation, partly because it tends to obscure smaller effects of possible oil-bearing structures (Ivanhoe, 1957, p. 64). Associated with the gravity anomaly is a prominent magnetic high (Grantz and Zeitz, 1960, p. B346), and both anomalies probably result from the same geologic feature. Several explanations for this high have been suggested. Woollard (1943, p. 778) observed this gravity anomaly and the related magnetic high in the Bakersfield area, and he pointed out that it is one of three major positive anomalies encountered on a transcontinental traverse. He suggested a gabbro intrusive as a possible cause. Bowers (1958, p. 20–23) attributed the gravity high near Marysville in the Sacramento Valley to a combination of a buried basement ridge and an upwarp of the earth's crust. The results of drilling in the Great Valley, however, show that basement topography is probably not an important factor in the cause of the anomaly. The Cenozoic intrusive and volcanic rocks at Sutter Buttes, near Marysville, suggest another possible cause for the anomaly in this area, but similar volcanic rocks are not found in other parts of the valley.

Ivanhoe (1957, p. 62) interpreted the positive anomaly belt as only a relative maximum located between the negative anomaly associated with the valley sediments and a negative anomaly caused by isostatic compensation of the Sierra Nevada. This explanation, however, does not account for the associated magnetic anomaly.

Bayoumi (1961, p. 32) concluded that the positive anomalies in an area generally between Merced and Fresno in the San Joaquin Valley are caused mainly by lithologic variations in the basement rocks. He supports this idea with a large number of density and magnetic susceptibility measurements from drill cores and outcrops. Similarly, Thompson and Talwani (1959, p. 1688) concluded that the positive anomaly belt is "directly associated with the greenstone belt, partly exposed and partly concealed beneath the Great Valley sediments." However, according to Griscom (this bulletin, p. 410), the results of recent aeromagnetic surveys by the U.S. Geological Survey do not support this explanation because no positive magnetic anomaly is associated with the exposed greenstone in the central Sierra foothills belt.

Grantz and Zietz (1960, p. B346) suggest igneous rock masses, at a depth of from 5 to 10 miles, as a cause of the aeromagnetic anomaly in the Great Valley. As a result of a study of gravity and magnetic data in the San Joaquin Valley, Oliver and Mabey (1963, p. 1293) conclude that the mass responsible for the anomaly is in the lower part of the earth's crust at a depth of 5 to 10 miles, and is conceivably related to the more mafic rocks of the earth's upper mantle. Seismic data suggest that the crust may thin to less than 20 km or 12 miles in this area, possibly as a result of an isostatic adjustment to balance the thick section of low-density sediments. Bailey (1964) has suggested that the anomalous zone represents a Mesozoic sphenochasmic rift in the continental crust caused by westward drifting of a crustal block. This rift might represent the boundary between Sierran granitic and Coast Range Franciscan basement rocks, and could also explain a rise of dense, magnetic upper mantle rocks below the Great Valley.

Oil companies have conducted extensive gravity surveys of the Great Valley in the search for possible oil- and gas-bearing structures. Although few results

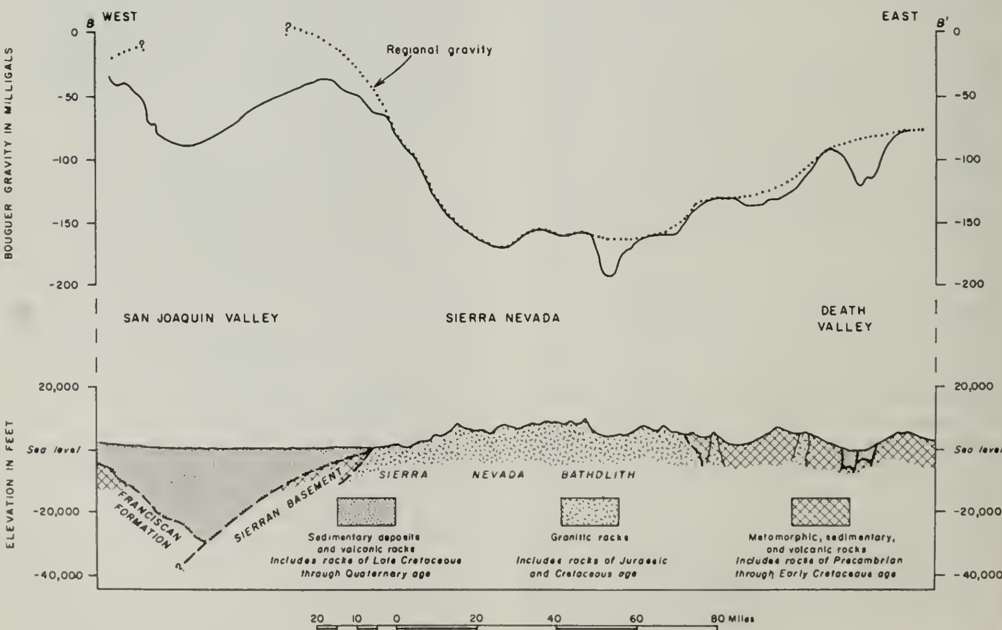

Figure 3. Bouguer gravity profile and geologic cross section along B-B', figure 1. Dotted curve marked "regional gravity" has been corrected for the effect of sedimentary deposits and volcanic rocks of late Cretaceous through Quaternary age (after Oliver and Mabey, 1963, fig. 1).

of these studies are available, some examples of the more unusual features and difficulties encountered in interpreting local anomalies have been published. Born (1956, p. 302) described a positive gravity anomaly near Dinuba in Tulare County that is caused by a buried topographic feature, which was also detected by other geophysical methods. Boyd (1949, p. 523–528) shows how a gravity high at the Kettleman Hills domes, southeast of Coalinga, becomes a gravity minimum along the same structural trend at the Lost Hills anticline. This effect is apparently caused by a transition in the sedimentary rocks from clays and shales at Kettleman Hills to light, diatomaceous shales at Lost Hills.

SIERRA NEVADA AND GREAT BASIN PROVINCES

Gravity values decrease rapidly eastward in the western foothills of the Sierra Nevada. The total decrease from the foothills to the vicinity of the High Sierra is as much as 200 mgal and gravity gradients are as high as 7 mgals/mile (Oliver and Mabey, 1963, p. 1295). In the Central Sierra Nevada this decrease culminates just west of the crest of the mountain range (profile B-B′, fig. 3). Farther north, according to Thompson and Sandberg (1958, p. 1278), the gravity minimum is reached just east of the Carson Range in western Nevada (profile A-A′, fig. 2). East of the Sierra Nevada low, gravity values tend to increase in an eastward direction in the mountain blocks of the Great Basin province, but the intermontane basin areas are characterized by local lows.

A large part of the negative gravity anomaly associated with the Sierra Nevada is believed to be caused by isostatic compensation, indicating a root composed of relatively light rocks extends downward into the earth's mantle (Oliver, 1960, p. B314; Oliver and others, 1961, fig. 3). A portion of this anomaly is probably caused by the difference in density between the granitic rocks of the Sierra Nevada batholith and the bordering basement rocks (Thompson and Sandberg, 1958, p. 1280; Oliver and Mabey, 1963, p. 1296). Whether the thickness of the granitic rocks actually is greater under the Sierra Nevada than elsewhere, however, cannot be determined from gravity data alone.

Oliver and others (1961, p. 4268) estimated from gravity data that in the central Sierras a root of crustal material may extend to a depth of 50 km. On the basis of seismic data obtained subsequently by the U.S. Geological Survey, Eaton (1963, p. 5805) estimated that the earth's crust is more than 40 km thick beneath the crest of the northern Sierra Nevada near Lake Tahoe. This does not agree well with Section A-A′ (fig. 2) where the base of the crust is shown to be at a depth slightly greater than 30 km. Thompson and Talwani (1964, p. 4832) suggest, however, that the calculated thickness would be increased and the gravity interpretation brought into accord with the seismic results if the lower part of the crust under the Sierra Nevada batholith is unusually dense. This condition is not unreasonable; the batholiths are lighter than normal, and if they were formed by differentiation within the crust the rocks remaining below them should be heavier than normal.

The Great Basin province east of the Sierra Nevada has been the subject of several gravity investigations. Gravity augmented by some seismic control has been found very useful in this province in the study of some structures, particularly in learning the depth of Cenozoic deposits and in locating hidden high-angle faults. As might be expected, the gravity field tends to be low in the valleys and basins containing relatively low-density sediments and volcanic rocks of

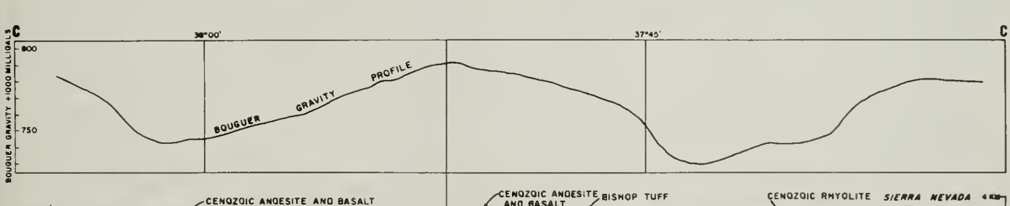

Figure 4. Bouguer gravity profile along C-C′, figure 1, across Mono Basin and Long Valley, showing assumed subsurface structure (after Pakiser and others, 1964, fig. 9).

Cenozoic age and high in the ranges where pre-Tertiary rocks predominate. A study of Mono Lake basin (fig. 1, No. 12) by Pakiser and others (1960) revealed a remarkable volcano-tectonic basin structure bounded by steep faults and containing a maximum thickness of 18,000 feet of Cenozoic deposits. Similar studies of Long Valley (fig. 1, No. 13) (Pakiser, 1961, p. B252) and southern Owens Valley (fig. 1, No. 14) (Kane and Pakiser, 1961, fig. 7) yielded estimates for the maximum thicknesses of Cenozoic deposits of 12,000 and 8,000 feet, respectively. Figure 4 (after Pakiser, 1964, fig. 9) shows the gravity anomalies and the assumed subsurface structure on a profile (profile C-C′, fig. 1) crossing Long Valley and Mono Lake. The gravity low over Long Valley, superimposed on the low regional value in this area, results in a value of less than −270 mgal, and is the largest negative Bouguer gravity value in California.

Gravity and seismic data at Indian Wells Valley (fig. 1, No. 15) and Searles Lake (fig. 1, No. 16) indicate maximum thicknesses of Cenozoic deposits of over 7,000 and 3,400 feet, respectively, according to Healy and Press (1964, fig. 10), von Huene (1960, pl. 3), and Mabey (1956, fig. 6). In the Death Valley region, according to a gravity survey by Mabey (1963), the Cenozoic fill reaches a thickness of about 10,000 feet in Mesquite Flat (fig. 1, No. 17).

Farther north in Honey Lake Valley (fig. 1, No. 18) in southeastern Lassen County, a gravity study suggests a thickness of about 5,000 feet of Cenozoic deposits in the basin bounded by granitic basement rocks (California Department of Water Resources, Bull. 98, 1963, p. 210). A study of Sierra Valley (fig. 1, No. 19), in parts of Sierra and Plumas Counties near the north end of the Sierra Nevada, indicates a minimum from 2,500 to 3,000 feet of Cenozoic fill (Jackson and others, 1961, p. B254). On the basis of the gravity data and outcropping volcanic rocks, Pakiser (1960, p. B413) has suggested that Sierra Valley may be a volcano-tectonic depression similar to Mono Basin and Long Valley.

CASCADE MOUNTAINS AND MODOC PLATEAU PROVINCES

Regional gravity surveys now extend over the entire southern Cascade Mountains and the western part of the Modoc Plateau, which consist almost entirely of sequences of Cenozoic lava and include the well-known eruptive centers of Mount Shasta and Lassen Peak.

A large gravity low in the Lassen Peak area was discovered by Bowers (1958, p. 24) while making a regional gravity survey in northern California. This survey was later extended by the U.S. Geological Survey to obtain more detail and more regional data (Pakiser, 1964). These studies have revealed that the gravity low in this area (fig. 1, No. 20) has a maximum amplitude of 70 mgal and an area of about 2,000 square miles. Although analysis of the anomaly is made difficult by the fact that the entire area is covered by Cenozoic volcanic rocks, Pakiser (1964, p. 617) suggests as possible causes for the anomaly the following geologic structures: (1) a batholith of silicic rock beneath the volcanic rock, (2) a thick buried accumulation of low-density sedimentary rocks of Cretaceous(?) age, (3) a low-density mass caused by thermal expansion of crustal rocks by heat from igneous activity, as originally suggested by Bowers (1958, p. 26), and (4) a volcano-tectonic depression filled with volcanic rock of low-average density.

Because subsidence in major volcanic source areas is very common and may be a characteristic condition, Pakiser (1964, p. 619) concludes that "* * * volcano-tectonic subsidence was a major element contributing to formation of the large mass of low density material buried in the Lassen Peak area." However, some of the other suggested causes may also contribute to the anomaly. Figure 5 shows a gravity profile (profile D-D′, fig. 1) across the Lassen Peak area with an assumed cross section and calculated anomaly based on the volcano-tectonic subsidence theory.

Farther north in the Cascade Mountains, in the Mount Shasta area (fig. 1, No. 21) LaFehr (1965a, 1965b) found a negative anomaly of from -35 to -50 mgal, which is very similar in amplitude, gradients, and general size to the Lassen Peak anomaly. Both anomalies are found within a broad gravity low with a width of about 50 km and a length of 75 km following the axis of the southern Cascades (LaFehr, 1965a, p. 11). Thus, it is reasonable to suppose that both the Mount Shasta and Mount Lassen anomalies have a similar cause: a large volume of low-density material at a shallow depth. LaFehr (1965b, p. 5581) calculated that this anomalous mass cannot be wholly below a depth ranging between 4 and 10 km in the Mount Shasta area, and he suggests that part of this low may be caused by the presence of shallow magma chambers containing silicic intrusive rocks. It is also possible that a part of the anomalies could be caused by a thickening of the crust below the volcanic province, but the largest part must have a relatively shallow source.

Both Pakiser (1964, p. 616) and LaFehr (1965b) applied Gauss' theorem to determine the mass deficiencies represented by the residual gravity lows, and compared this figure with the mass excesses represented by the mountains. The results at both Mount Shasta and Lassen Peak are that the mass deficiencies and mass excesses have the same order of magnitude. This significant result indicates that compensation of these large mountain masses must be largely a local rather than a regional phenomenon. LaFehr (1965a, p. 13) notes that the average free air gravity anomaly in the western portion of the Modoc Plateau is nearly zero, suggesting that the Modoc Plateau region is in nearly complete isostatic equilibrium.

KLAMATH MOUNTAINS PROVINCE

The gravity contours shown in figure 1 for the Klamath Mountains area in northwestern California are based on only a few stations. A part of the eastern side of this area, however, has now been covered by LaFehr (1965a) in his regional survey of the Mount Shasta and southern Cascade Mountains, but these data have not been incorporated into the map.

The rocks of the eastern portion of the Klamath Mountains range from pre-Silurian to Jurassic in age and consist predominantly of metasedimentary and metavolcanic rocks intruded by Mesozoic ultramafic, mafic, and granitic rocks (Irwin, 1960, p. 14–15).

The recent survey by LaFehr (1965a, p. 10) revealed a major north-trending positive gravity anomaly with a width of about 25 km and an amplitude of about 50 mgal centered near the high peaks of the Scott Mountains, the easternmost uplift of the Klamath Mountains. This anomaly is not properly shown by the contours on figure 1 but its position is indicated by number 22. LaFehr (in press) points out that this is evidently one of the few large positive gravity anomalies associated with a structural uplift on the North American continent.

The anomaly appears to be associated with an ultramafic intrusive mass, perhaps a thick sill occupying the crest of an anticlinal structure, although the surface geology and density samples do not provide conclusive evidence for this. The anomaly could also be caused by mafic intrusive rocks which have been mapped in the same general area. Calculations indicate that the maximum possible depth to the anomalous mass is 4 km (LaFehr, in press); thus, the source is shallow and may actually crop out. If the ultramafic mass is largely serpentine, as suggested by surface samples, rather than unaltered ultramafic or mafic rock, it is doubtful that there would be sufficient density contrast with the normal basement rocks to account for the anomaly. Therefore, if an ultramafic sill is actually the cause of the anomaly, serpentinization must decrease with depth in the sill.

The broad gravity low (fig. 1, No. 23) northwest of Redding and centered in the vicinity of the Trinity Alps, is based on few gravity stations. It corresponds in general to an area of Mesozoic ultramafic and mafic rocks intruded by large Mesozoic granitic batholiths, but additional gravity data are needed to better define the anomaly.

SUMMARY AND CONCLUSIONS

Our knowledge of the regional geology of northern California has been enhanced substantially by the information obtained from gravity surveys, as exemplified by some of the structures described in the preceding sections of this article. Additional gravity data in parts of the State not now covered adequately will further increase our knowledge of many of its major structures. A few examples of the many diverse projects in progress might include: (1) a study in the Burro Mountain area in Monterey County, by the U.S. Geological Survey, expected to yield new information on the nature of ultramafic intrusions, (2) a survey in the vicinity of Mount Konocti and Mayac-

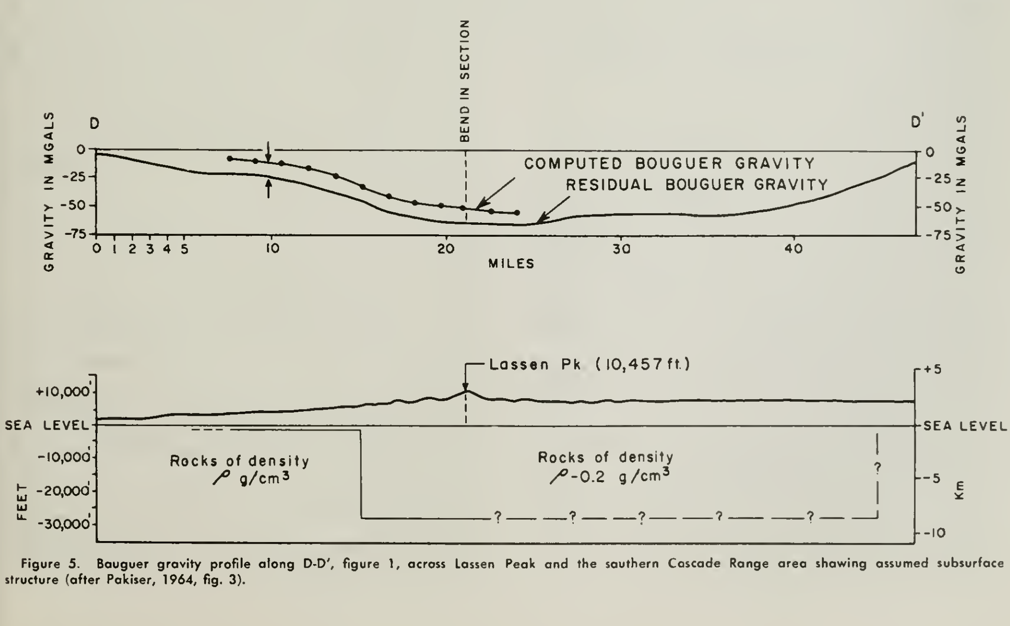

Figure 5. Bouguer gravity profile along D-D', figure 1, across Lassen Peak and the southern Cascade Range area showing assumed subsurface structure (after Pakiser, 1964, fig. 3).

mas uplift in Lake and Sonoma Counties, by the California Division of Mines and Geology, will add to our knowledge of Quaternary structure and volcanism in the Coast Ranges, and (3) sea gravity investigations off northern California, by Oregon State University, leading to better knowledge of the offshore geologic structure.

Detailed gravity surveys in areas now covered only by regional data will be justified in many cases because of the evidence they will bring to bear on local problems. One of the goals of the Division of Mines and Geology is to publish gravity maps of California on the state map scale (1:250,000), as sufficient data become available, in the belief that maps on this scale will prove to be useful for many relatively local problems.

Additional gravity studies both on land and offshore are needed for an understanding of such broad problems as the nature of the transition from oceanic to continental crust, the differences in the crust and upper mantle in different areas, and the nature of isostatic compensation. Specific major problems identified but not solved include: (1) the Great Valley anomaly, (2) the degree of isostatic compensation of the Coast Ranges and Great Valley, (3) the possible shoreward continuation of the structures represented by the Mendocino and Gordo escarpments.

Because of the nature of the gravity field, structure cannot be determined from gravity data alone. Thus, there is a need for not only seismic and other geophysical data, but for geologic mapping, drilling information, and measurements of physical properties of rocks underlying northern California in order that the full benefit of both present and future gravity surveys may be realized.

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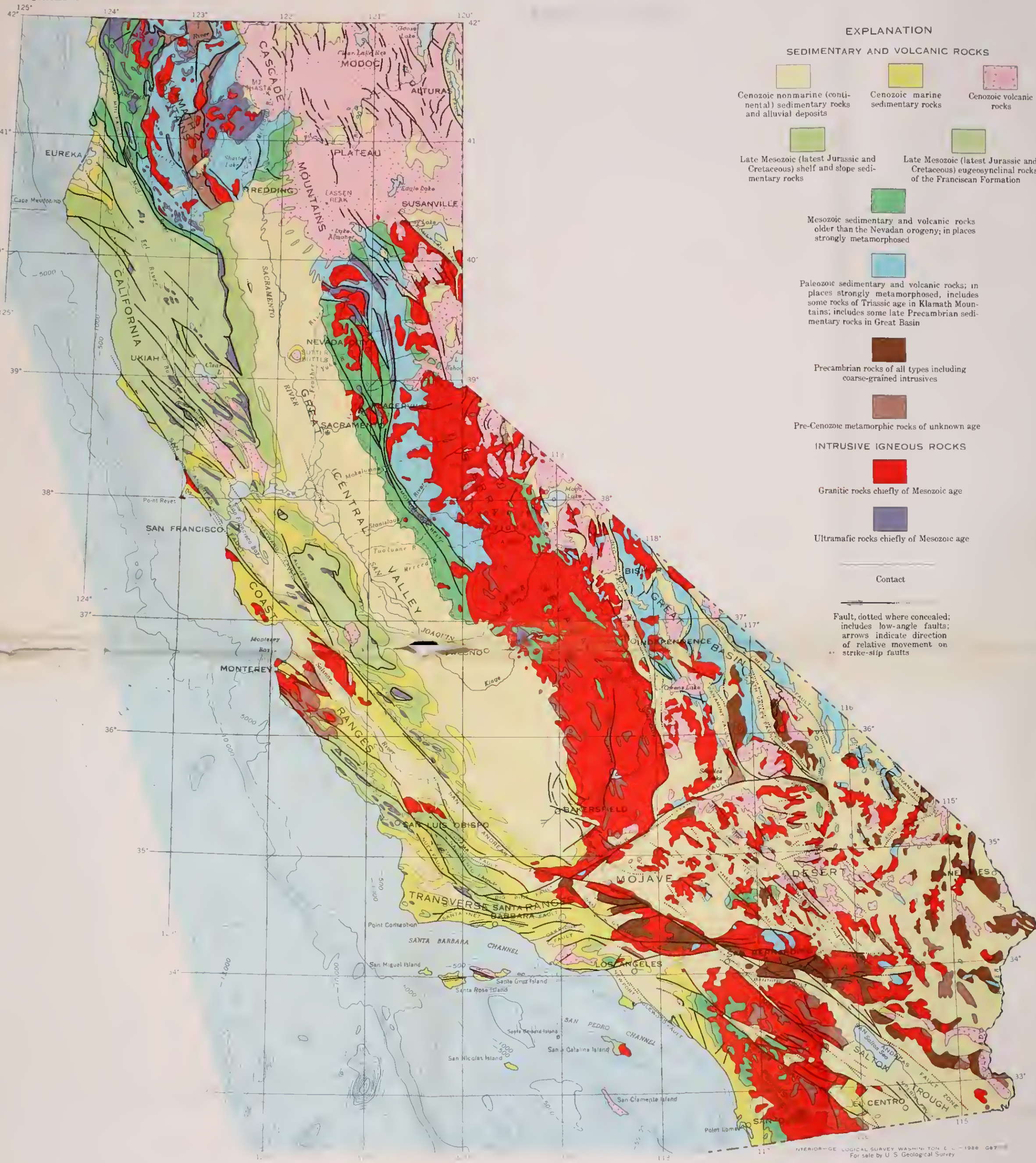
DEPARTMENT OF INTERIOR
UNITED STATES GEOLOGICAL SURVEY

MISCELLANEOUS GEOLOGICAL INVESTIGATIONS
MAP I-512



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

INTERIOR—GEOLOGICAL SURVEY, WASHINGTON, D.C.—1966
For sale by U.S. Geological Survey

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