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GEOPHYSICAL STUDY OF THE CLEAR LAKE REGION, CALIFORNIA

By

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ABSTRACT

Results of geophysical studies in the Clear Lake region of California, north of San Francisco, have revealed a prominent, nearly circular negative gravity anomaly with an amplitude of more than 25 milligals (mgal) and an areal extent of approximately 250 square miles and, in addition, a number of smaller positive and negative anomalies. The major negative gravity anomaly is closely associated with the Clear Lake volcanic field and with an area characterized by hot springs and geothermal fields. However, the anomaly cannot be explained by mapped surface geologic features of the area.

Aeromagnetic data in the Clear Lake region show no apparent correlation with the major negative gravity anomaly; the local magnetic field is affected principally by serpentine. An electrical resistivity low marks the central part of the gravity minimum, and a concentration of earthquake epicenters characterizes the Clear Lake volcanic field area.

The primary cause of the major negative gravity anomaly is believed to be a hot intrusive mass, possibly a magma chamber, that may underlie the Clear Lake volcanic field and vicinity. This mass may serve as a source of heat for the geothermal phenomena in the area. Other smaller gravity anomalies in the Clear Lake region are apparently caused by near-surface geologic features, including relatively dense units of the Franciscan Formation and less dense Cenozoic sedimentary and volcanic rock units.

GEOPHYSICAL STUDY OF THE CLEAR LAKE REGION, CALIFORNIA

by Rodger H. Chapman

INTRODUCTION

The area designated in this report as the Clear Lake region is located in the northern Coast Ranges of California about 75 miles north of San Francisco (figure 1). The region comprises about 1900 square miles and includes parts of Lake, Colusa, Sonoma, Napa, Yolo, and Mendocino Counties. It extends from the western edge of the Sacramento Valley on the east to the vicinity of Ukiah on the west and from near Upper Lake on the north to Mt. St. Helena on the south. This area is one of moderately rugged relief; elevations vary from a few tens or hundreds of feet above sea level along the Russian River and in the Sacramento Valley to almost 5000 feet at peaks along the crest of the Mayacmas Mountains.

The Clear Lake region is of special interest both because of a complex local geologic setting and because it includes a major geothermal area. This area, The Geysers geothermal field, is the site of the only commercially successful geothermal power facility presently operating in the United States. At The Geysers, southwest of Clear Lake, steam is produced from reservoirs in fractured and faulted graywacke of the Franciscan Formation.

In 1963, a gravity study of the area in the vicinity of Clear Lake was begun by the California Division of Mines and Geology in conjunction with the mapping of the geology of the Kelseyville quadrangle by James R. McNitt (1968a). This work led to the discovery of a large negative gravity anomaly centered in the vicinity of the Clear Lake volcanic field, south of Clear Lake and northeast of The Geysers. A preliminary gravity map of the area and tentative interpretation of the data were published in *Mineral Information Service* (California Division of Mines and Geology, 1966). Additional gravity data were obtained in this area from 1965 to about 1970 in connection with the preparation of the Santa Rosa and Ukiah sheets of the *Gravity map of California* (Chapman and Bishop, 1974; Chapman and others, in press).

Other geophysical data in the Clear Lake region available to the writer include: an aeromagnetic survey flown by the Division of Mines and Geology in 1968, using a Varian proton-precession magnetometer mounted in a light aircraft; recently released U.S. Geological Survey open-file reports which include the results of deep resistivity measurements in the vicinity of the Clear Lake volcanic field (Stanley and others, 1973); and an aeromagnetic map of the Clear Lake region (U.S. Geological Survey, 1973). Still other data include microearthquake studies near The Geysers by Lange and Westphal (1969) and Hamilton and Muffler (1972) and a seismic noise study by Iyer (1973).

Much of the field work on which this report is based, and interpretation of the data, was done with the assistance of James R. McNitt.

Figure 1. Index map showing the location of the Clear Lake region in California.

GEOLOGY

The geology of parts of the Clear Lake region has been discussed in recent years by a number of investigators including Anderson (1936), Bailey (1946), Yates and Hilpert (1946), Brice (1953), Irwin (1960), Bailey and others (1964), Hodges (1966), McNitt (1968a, 1968b), Swe and Dickinson (1970), Rich (1971), Garrison (1972), Blake and others (1971), and McLaughlin (1974). The discussion of the geology of the Clear Lake area in this report will be brief and will emphasize those aspects bearing on interpretation of the geophysical anomalies.

Franciscan Formation rocks and Great Valley sequence sedimentary rocks, both of Mesozoic age, and Clear Lake volcanic rocks of Quaternary age underlie much of the Clear Lake region. Other abundant rock units present in the area include masses of serpentinized ultramafic rocks, marine sedimentary rocks of Paleocene and Eocene ages, nonmarine sedimentary rocks of Pliocene and Pleistocene ages, the Sonoma Volcanics of Pliocene age, and Quaternary alluvium, terrace deposits, and landslide debris.

The geology of the Clear Lake region is summarized on the Santa Rosa and Ukiah sheets of the *Geologic map of California* (Jennings and Strand, 1960; Koenig, 1963). A generalized version of parts of these maps is shown in figure 4.

Stratigraphy

The Franciscan Formation of Late Jurassic and Cretaceous ages in the Clear Lake area consists of a thick eugeosynclinal sequence of graywacke with interbedded shale, basalt ("greenstone"), and minor beds of chert. Serpentine and diabase bodies, some of which may be intrusive, are frequently associated with the Franciscan rocks. Bailey and others (1964) have discussed the Franciscan rocks of western California in great detail.

In some parts of the Coast Ranges, the Franciscan Formation rocks are highly deformed and chaotic. In fact, it has been suggested that the Franciscan Formation originated from ocean floor materials either scraped off or carried along as the oceanic plate slid beneath the continental North American plate along a Mesozoic Benioff seismic zone (Hamilton, 1969, p. 2409; Ernst 1970, p. 886). In the Kelseyville quadrangle, however, McNitt (1968a) was able to subdivide the Franciscan rocks into two distinct units which he believes are generally conformable. The lower unit has a minimum thickness of 15,000 feet and consists of a dense graywacke interbedded with chert and basalt and intruded by, or interbedded with, basic igneous rocks. The upper unit consists of interbedded sandstone and shale and has a thickness of 10,000 feet. Other authors (for example, Raymond and Berkland, 1973) strongly disagree with this relatively simple conception of the Franciscan stratigraphy in the Clear Lake region and stress the presence of melange units and a complex internal structure.

Clastic marine sedimentary rocks of the Great Valley sequence which range in age from Late Jurassic to Late Cretaceous are found south, southeast, and northwest of Clear Lake (McNitt, 1968b; Brice, 1953). These rocks are lithologically similar to the miogeosynclinal rocks of the same ages found at the western edge of the Great Valley. Swe and Dickinson (1970, p. 165) report approximately 35,000 feet of Great Valley sequence rocks in the area south and southeast of Clear Lake. These rocks are believed to be a part of a thrust fault complex that structurally overlies the Franciscan Formation rocks in the Clear Lake region.

Brice (1953, p. 28) also described Lower Tertiary marine sedimentary rocks of Paleocene and Eocene age exposed southeast of Clear Lake. These rocks consist of a conformable succession of sandstone, mudstone, and conglomeratic sandstone with a total thickness of about 5500 feet. They comprise one of the stratigraphic components of the thrust complex which overlies the older Jurassic and Cretaceous rocks (Swe and Dickinson, 1970, p. 165).

Up to 2000 feet of moderately well consolidated nonmarine sedimentary rocks which unconformably overlie pre-Tertiary rocks are found along the course of Little Sulphur Creek on the southwestern flanks of the Mayacmas Mountains (McNitt, 1968a). McNitt has tentatively correlated these rocks with the late Pliocene Merced Formation which crops out about 4 miles to the southeast.

Rock units of the Sonoma Volcanics of Pliocene age are exposed in the southern part of the map area near Mt. St. Helena. The volcanic rocks consist of a succession of flows and pyroclastic deposits up to 2000 feet thick which range from basalt to rhyolite in composition. These rocks are interbedded with sands and gravels that are principally of volcanic origin.

The Cache Formation locally overlies the Mesozoic and Tertiary rocks unconformably in the vicinity of Clear Lake. This rock unit is a locally thick sequence of lacustrine and fluviatile beds ranging from silts to gravels. The largest exposure of these rocks east of Clear Lake (designated QP on the Ukiah and Santa Rosa sheets of the *Geologic map of California)* is about 40 square miles in area. Rocks of the Cache Formation have been dated as late Pliocene on the basis of fossil diatoms (McNitt, 1968a).

A series of volcanic flows and domes, tuffs, and pyroclastic rocks, varying from Pleistocene to Holocene in age, covers an area of approximately 85 square miles mostly immediately south of Clear Lake. These Clear Lake volcanic rocks include obsidian, rhyolite, dacite, andesite, and olivine basalt, of which dacite and andesite constitute the greatest volume (Brice, 1953, p. 47).

The Clear Lake volcanic rocks form a number of prominent landforms in the Clear Lake area, including Mt. Konocti, a composite volcano, and Mt. Hanna, Cobb Mountain, Boggs Mountain, and Siegler Mountain, some of which probably represent volcanic vents and plugs. It is probable that these rocks were extruded onto an erosion surface which exhibited several thousands of feet of local relief. Thus, the thicknesses of the various volcanic units may vary considerably within the area, because of irregularities in both the surface of deposition and the superimposed volcanic features. It is also probable that both tectonic movements (folding, faulting, and uplift) during Pleistocene and Holocene times, as well as erosion, have had a pronounced effect on the volcanic terrane, as well as on the older rocks.

Deposits of Quaternary alluvium, terrace, and lake deposits are common in the valley portions of the Clear Lake region. Recent landslide debris is also common, particularly in and near fault zones.

Structure

Major northwest-trending fault zones dominate the geologic structure of the Clear Lake region. This region is also on the northern extension of the Diablo antiform, which is described by Bailey and others (1964, p. 154) as an arch on a regional scale in the Franciscan rocks. The numerous faults present include examples of normal, strike-slip, and thrust faults. The effect of the normal faults, in particular, has been to produce a series of parallel horst and graben structures in the region. For example, McNitt (1968a) has described the Mayacmas Mountains as "a large horst bounded on the northeast and southwest by structural as well as topographic depressions."

McNitt (1968a) estimates the throw on the steeply dipping faults which bound the Mayacmas horst to be in the range of 10,000 to 20,000 feet each. Within the large horst, McNitt has described a pattern of differential fault movement which has resulted in a progressive increase of fault throw from the southwest to the northeast which is reflected in the topographic asymmetry of the Mayacmas Mountains. Thus, according to McNitt, "the fault block bordering the northeast side of the Mayacmas Mountains is the highest topographically and has undergone the greatest amount of uplift, and exposes a stratigraphic section lower than is seen in any of the fault blocks to the southwest." Also, according to McNitt's interpretation, the Great Valley sequence miogeosynclinal sedimentary rocks bordering the Mayacmas Mountains on the southwest and northeast are found in structural depressions bordering the uplifted mountain block.

Based on work throughout the Coast Ranges, Irwin (1960) and Bailey and others (1964, 1970) have proposed that the Great Valley sequence has been emplaced above the Franciscan rocks by thrusting on a regional scale. The exposures of Great Valley sequence rocks within the Franciscan terrane, according to this interpretation, are believed to be klippen. The serpentine masses which are commonly found between the Franciscan Formation rocks and the Great Valley sequence rocks in this area may have served as a lubricant at the base of the overriding thrust sheet. Bailey and others (1970, p. C77) believe that the serpentine is also the base member of an ophiolite sequence of mafic and ultramafic rocks which represents the Mesozoic sea floor upon which the Great Valley sediments and Franciscan Formation sediments were both deposited.

Swe and Dickinson (1970) have described a number of major thrust faults in the area south and southeast of Clear Lake which they believe have been instrumental in that area in emplacing the Great Valley sequence rocks above the Franciscan Formation rocks. Presumably, the major sole thrust, named the Soda Creek fault by Swe and Dickinson (1970, p. 179) corresponds to the "Coast Range Thrust," described by Bailey and others (1970, p. C77), along the western margin of the Great Valley where these two major rock units are also in contact.

Arcuate fault patterns obtained from photogeologic interpretation in the Mayacmas Mountains and adjacent Clear Lake volcanic field have been described by Garrison (1972, p. 1453) and Austin and others (1971, p. 30). It is conceivable that these fault patterns could be related to either uplift or subsidence of Cenozoic age in the Clear Lake area. Although Clear Lake is believed to occupy a Cenozoic structural depression (Hodges, 1966, p. 117; Berkland, 1972, p. 12-15), it is also thought that the Mayacmas Mountains in this area were characterized by uplift during Quaternary time (Hodges, 1966, p. 145; McNitt, 1968a).

That the Clear Lake region is still tectonically active is attested to by the present-day seismic activity. Figure 2 shows the location of epicenters of minor to moderate shocks in the area between 1910 and 1973 (California Division of Mines and Geology unpublished data). This map shows a number of epicenters — most of which are located along a northwest-trending zone which passes through the Clear Lake region. There is also an apparent concentration of epicenters in the vicinity of the main part of the Clear Lake volcanic field, although the location errors of some epicenters may be as much as 10 km or more. In addition to the data from larger earthquakes, Lange and Westphal (1969) and Hamilton and Muffler (1972) have reported concentrations of microearthquakes in the vicinity of The Geysers geothermal field.

GEOPHYSICAL DATA

Gravity Survey

Approximately 575 gravity stations are located within the Clear Lake region map area (figure 2); this yields an average density of about one station per 3 square miles. The gravity stations are located chiefly at points of known elevation such as U.S. Geological Survey and U.S. Coast and Geodetic Survey bench marks and spot elevations from U.S. Geological Survey topographic maps and manuscripts. The maximum elevation errors vary from 1 foot or less at bench marks to about 4 feet at field-checked spot elevations and to as much as 10 feet at unchecked spot elevations. A few stations (less than 2 percent) in the area are located at points where elevations were estimated from contours on the U.S. Geological Survey 7 1/2-minute topographic maps. The estimated accuracy of these stations is ± 20 feet.

Worden Pioneer model meter no. 558 and LaCoste-Romberg geodetic meters G129 and G65 were used at different times for the gravity survey. The calibrations of these meters were checked on ranges which have recently been established in California (Barnes and others, 1969). Gravity observations at the stations were tied to base stations previously established in this area by the California Division of Mines and Geology (Chapman, 1966a, p. 42-46). LaCoste-Romberg gravity data were corrected for drift and tidal effects; Worden data were given a combined correction. Gravity observations were repeated at a number of the stations, usually with different meters, during the course of the survey. It was found that at least 90 percent of the remeasured values were within 0.2 mgal of the original values.

Values of observed gravity were reduced to Bouguer anomalies for a density of 2.67 grams per cubic centimeter (g/cm^3) by means of a U.S. Geological Survey gravity reduction computer program. Inner zone terrain corrections were made manually for each station by the methods of Hammer (1939) and Hayford-Bowie (Swick, 1942, p. 68) to a radius of 2.29 kilometers (km). The remaining corrections out to a radius of 166.7 km were then computed by the use of a U.S. Geological Survey terrain correction program (Plouff, 1966). The values of the total terrain corrections for stations in this area range from more than 15 mgal at the crest of the Mayacmas Mountains north of The Geysers to about 1 mgal in Big Valley, near Kelseyville.

Figure 2 is the complete Bouguer gravity map of the Clear Lake area with a 5 mgal contour interval. The contours are based both on the stations in the survey area

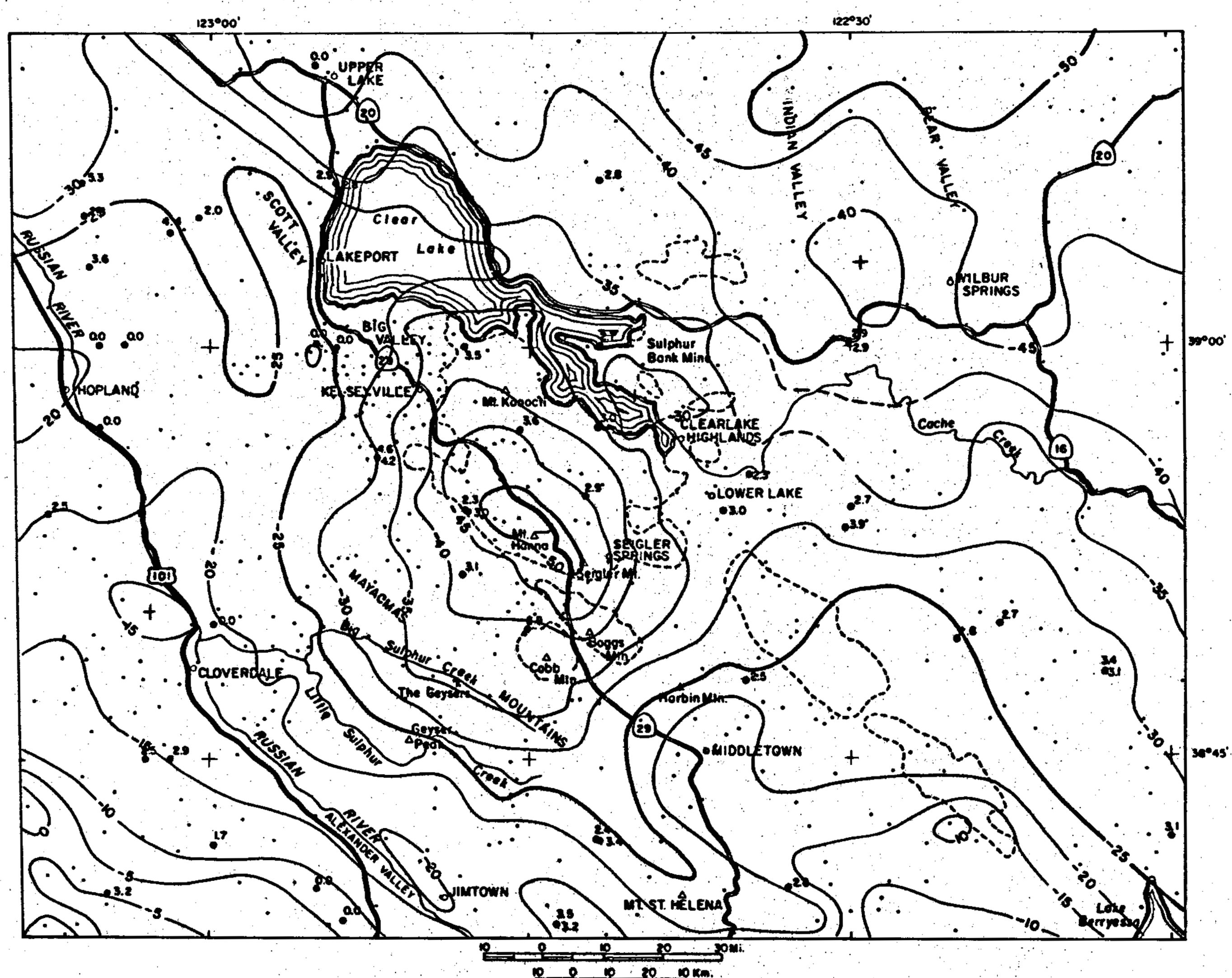


Figure 2. Bouguer gravity map of the Clear Lake region, showing locations of gravity stations and earthquake epicenters. Gravity contour interval: 5 milligals. (• Gravity station, ● 3.0 Earthquake epicenter and magnitude). Short dashes outline surface exposures of Pleistocene and Holocene volcanic rocks.

and on those in the surrounding areas of the Santa Rosa and Ukiah sheets.

Aeromagnetic Survey

An aeromagnetic survey of most of the Clear Lake region was flown using a proton-precession magnetometer installed in a light airplane. The survey consisted of 10 northeast-trending flight lines with an average line spacing of approximately 3 miles. Because land elevations in the area surveyed range from less than 200 feet in Alexander Valley to over 4700 feet at Cobb Mountain, a constant barometric flight elevation of 6500 feet was used for the survey. The total area included in the aeromagnetic survey was about 1000 square miles. The results of the aeromagnetic survey were plotted and contoured (figure 5) on an arbitrary datum, using 50- and 100-gamma contour intervals, after removing an assumed regional gradient of 10 gammas per mile to the northeast.

Rock Density and Magnetic Susceptibility Measurements

The results of density measurements for a large number of samples of graywacke from both the Franciscan Formation and the Great Valley sequence have been discussed by Bailey and others (1964, p. 141). These measurements have been combined with other values obtained for rock samples from the Clear Lake region and vicinity and are summarized in table 1.

The magnetic properties of hand specimens of various types of rock in the Clear Lake region were tested qualitatively in the field. The only rocks in the area which were found to have relatively strong magnetic properties were serpentine and some of the volcanic rocks. Table 2 summarizes in electromagnetic units per cubic centimeter (emu/cm^3) the magnetic susceptibility measurements made by means of a Soiltest model MS-3 magnetic

Table 1. Rock density measurements.

Age	Rock unit and type	Source of data	No. of samples	Density range (g/cm^3)	Average density (g/cm^3)
Quaternary	Clear Lake volcanic rocks	Chapman and Bishop (1974); this report	22	2.16-2.86	2.48
Jurassic-Cretaceous	Upper Cretaceous graywacke	Bailey, Irwin, and Jones (1964, p. 141)	78		2.55 (median value)
	Lower Cretaceous graywacke	Bailey, Irwin, and Jones (1964, p. 141)	71		2.57 (median value)
	Franciscan Formation graywacke	Bailey, Irwin, and Jones (1964, p. 141)	725		2.65 (median value)
	Franciscan Formation graywacke (Clear Lake area)	Chapman and Bishop (1974)	4	2.48-2.75	2.65
	Franciscan Formation greenstone	Clement (1965, p. 2)	--	2.38-2.89	2.78
	Franciscan Formation greenstone	Chapman and Bishop (1974)	3	2.70-3.14	2.95
	Serpentine	Chapman and Bishop (1974)	3		2.53

Table 2. Magnetic susceptibility measurements.

Age	Rock unit and type	Source of data	No. of samples	Susceptibility range (emu/cm^3)	Average magnetic susceptibility (emu/cm^3)
Quaternary	Clear Lake volcanic rocks	This report	13	Negligible-0.0006	~0.0002
Jurassic-Cretaceous	Franciscan Formation greenstone	This report	8	--------	Negligible
	Serpentine	This report	8	0.0011-0.0052	0.0034

susceptibility bridge on crushed samples of these rock types. No measurements of the permanent magnetism of samples of these rocks were made.

INTERPRETATION OF ANOMALIES

Regional Gravity

Bouguer gravity values in the Clear Lake area (figure 2) decrease in general from the southwestern part of the map (0 contour) to the northeastern part (-50 contour). The northeastern decrease in gravity values, which characterizes this part of the Coast Ranges, is probably largely the effect of a thickening of the earth's crust in this direction inland from the continental margin. The area of very low gravity in the northeastern part of the map area, along the western margin of the Great Valley, is approximately over the axis of the Great Valley syncline (Hackel, 1966, figure 1). The low values in this area probably result from the superposition on the regional gravity gradient of a negative anomaly related to the thick section of Cretaceous and younger sedimentary rocks which make up the major Great Valley structure.

Despite the strong regional gravity gradient in the Clear Lake region, a number of relatively local positive and negative anomalies are well defined by the gravity contours. The region is dominated, in particular, by a nearly circular negative anomaly (-50 mgal contour) which is centered near Mt. Hanna (figure 2). The anomaly center is over the southwestern part of the Clear Lake volcanic field; but a large portion of the anomaly is associated with rocks of the Franciscan Formation, the Great Valley sequence, and serpentine, exposed south and southwest of the Clear Lake volcanic field.

Residual Gravity Map

In order to study the local anomalies in more detail, a residual gravity map was prepared by subtracting from the Bouguer gravity values a regional gravity surface (figure 3) that was constructed by graphically "smoothing" parts of the Santa Rosa and Ukiah sheets of the *Gravity map of California* (Chapman and Bishop, 1974; Chapman and others, in press). The resulting values, plotted and contoured with a 5 mgal interval, are shown superimposed on a generalized geologic map of the area (figure 4). The preparation of a graphical residual gravity map is a somewhat subjective procedure, but it is believed to result in a reasonably accurate representation of the data.

The residual gravity map strongly resembles the Bouguer gravity map in general aspects; but it emphasizes local features, some of which are not readily seen on the original map. The major negative anomaly is very similar in shape on both maps, for example; but the small negative anomaly northeast of Clear Lake Highlands is much more apparent on the residual map. The -5 mgal contour which outlines the major negative anomaly encloses an area of approximately 250 square miles; this anomaly has an amplitude of over 25 mgal. The -15 mgal contour (figure 4) which may give a measure of the possible size in plan of the mass that causes the anomaly, includes the area between the southern slopes of Mt. Konocti, on the north, Big Valley, on the west, The Geysers, on the southwest, and Siegler Springs, on the southeast. The fact that this anomaly is centered on the Clear Lake volcanic field suggests a genetic relationship, but the actual cause of the anomaly is not readily apparent. The anomaly does not coincide with any known structural feature.

In addition to the major negative anomaly, the residual gravity map shows more localized anomalies of up to a few milligals in amplitude which are associated with certain near-surface geologic features. Small positive anomalies of up to 5 mgal are associated with mafic volcanic rocks within the Franciscan Formation west of Lakeport, southwest of Big Valley, and north to northwest of Clear Lake Highlands. Relatively large masses of these rocks north and northwest of The Geysers and near Geyser Peak (see McNitt, 1968a) apparently cause deflections of the gravity contours within the major negative anomaly, but no actual closures, at the contour interval used.

Negative anomalies with amplitudes of up to about 5 mgal are associated with the Sonoma Volcanics near Mt. St. Helena in the south part of the area, and with alluvium and possibly Great Valley sedimentary rocks near Upper Lake. Another negative anomaly causes a northwestern deflection of the gravity contours in Big Valley, where the lacustrine deposits (Cache Formation?) are at least 400 feet thick (McNitt, 1968a). Although no gravity stations were located near the top of Mt. Konocti, it might be expected that this large volcanic pile would produce a local negative anomaly in view of the fact that the average density of the Clear Lake volcanic rocks obtained from samples (table 1 - approximately 2.50 g/cm^3) is less than the density used for reduction of the gravity data (2.67 g/cm^3). A negative anomaly of somewhat more than 5 mgal (-5 mgal contour) northeast of Clear Lake Highlands marks the location of a relatively large area of partly downfaulted sedimentary rocks of the Cache Formation. These sedimentary rocks, which are apparently mostly gravels, may be as much as 6500 feet thick in this area according to Brice (1953, p. 33). Although no density measurements have been made on samples of these rocks, if we assume a contrast of 0.20 g/cm^3 between Cache sedimentary rocks and the Mesozoic "basement" rocks in the area, an anomaly with an amplitude at least twice as large as the one observed would be expected, if the Cache rocks were actually 6500 feet thick over at least part of the outcrop area. Thus, gravity data suggest a maximum thickness of about 3000 feet for these rocks.

A part of a positive gravity anomaly (+10 mgal contour) is located in the southeastern part of the map area. This anomaly is associated with Franciscan Formation rocks, serpentine, and Great Valley sedimentary rocks west of Lake Berryessa (Chapman and Bishop, 1974), but the anomaly may be caused primarily by metamorphosed Franciscan rocks which are believed to underlie much of this area.

Aeromagnetic Map

The aeromagnetic map (figure 5) shows a dominant northwest regional trend, similar to both the regional

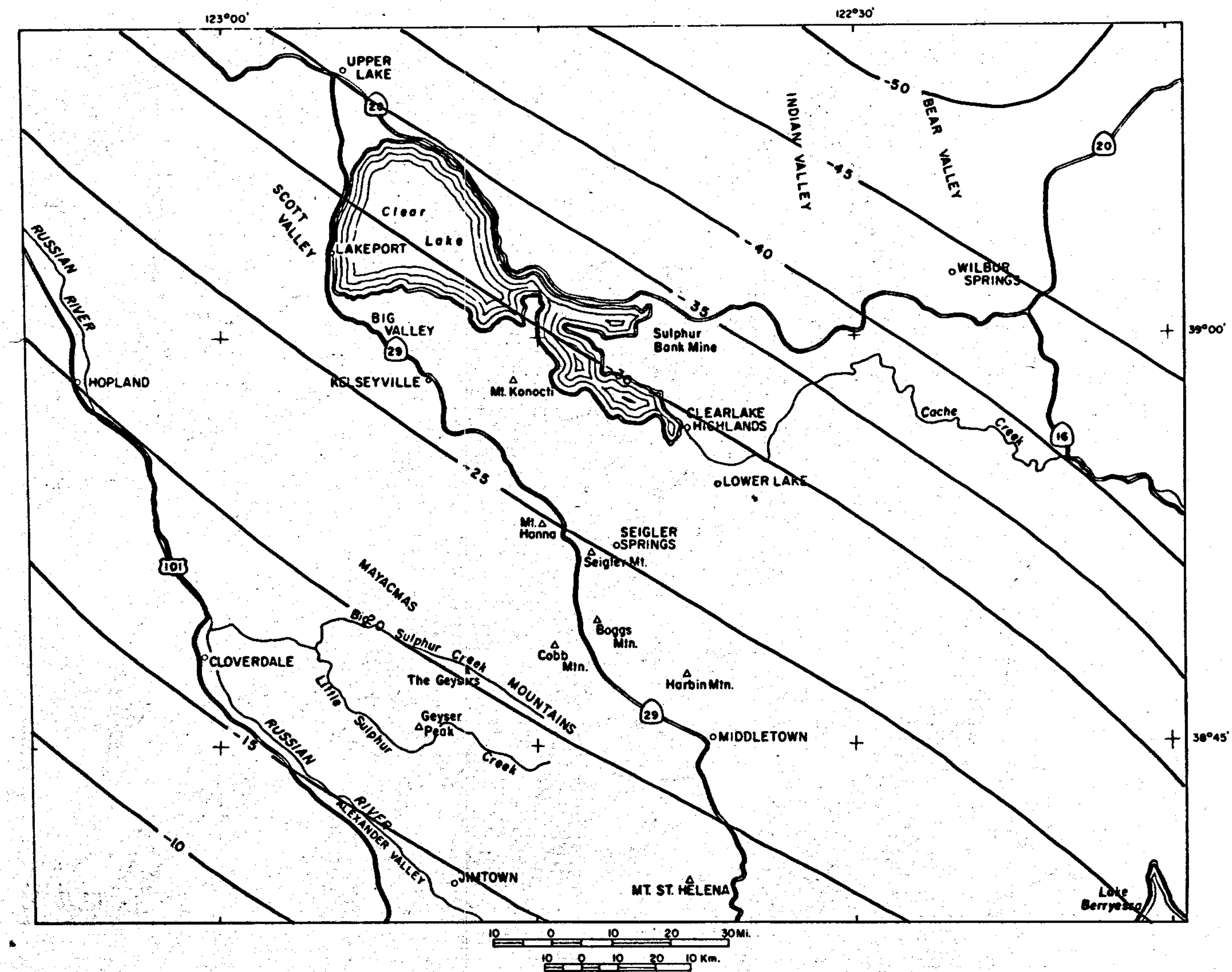


Figure 3. Regional gravity map of the Clear Lake region. Gravity contour interval: 5 milligals.

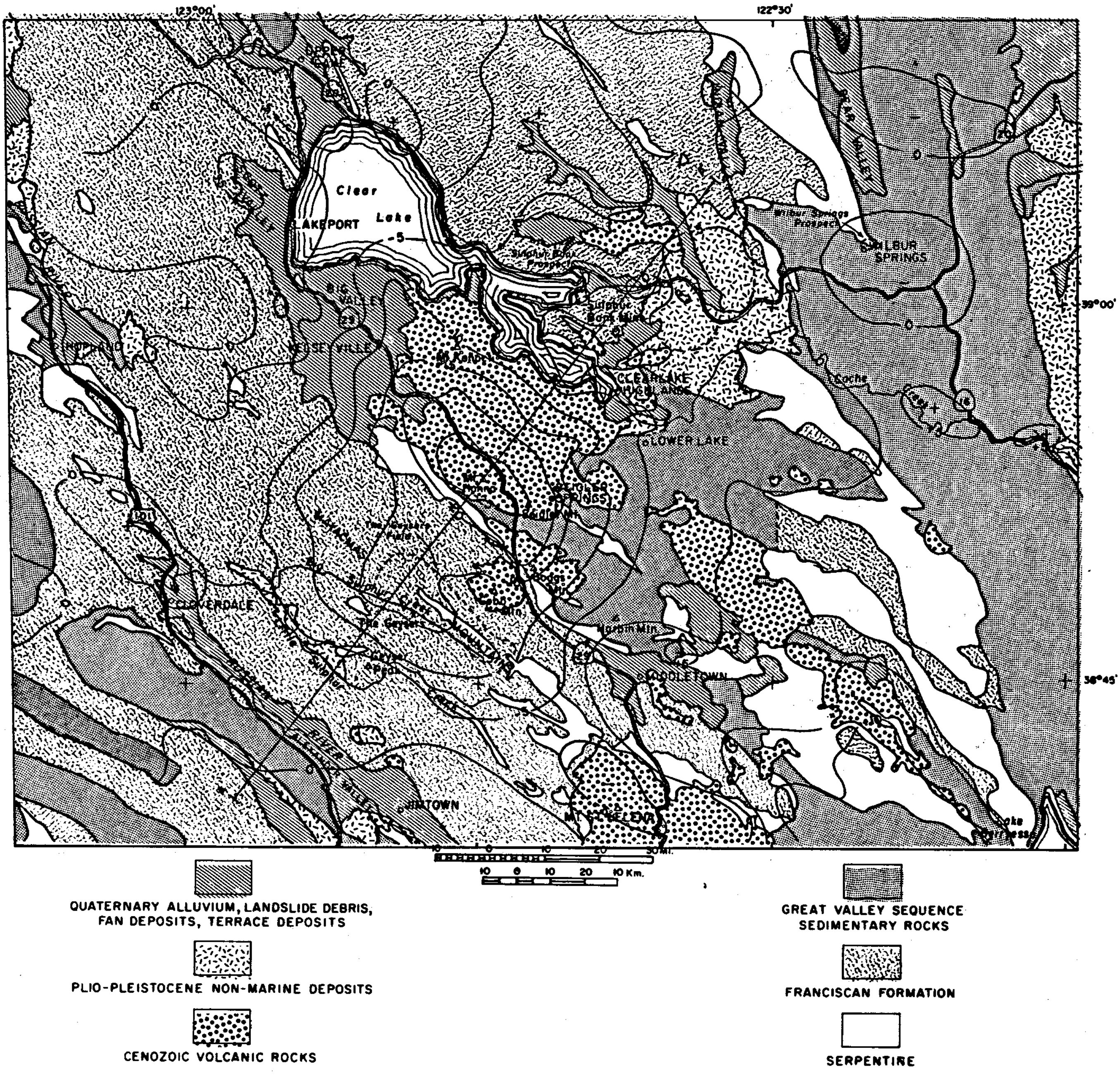


Figure 4. Residual gravity map of the Clear Lake region, showing generalized geology (after Jennings and Strand, 1960; Koenig, 1963) and location of geothermal fields and prospects. Gravity contour interval: 5 milligals.

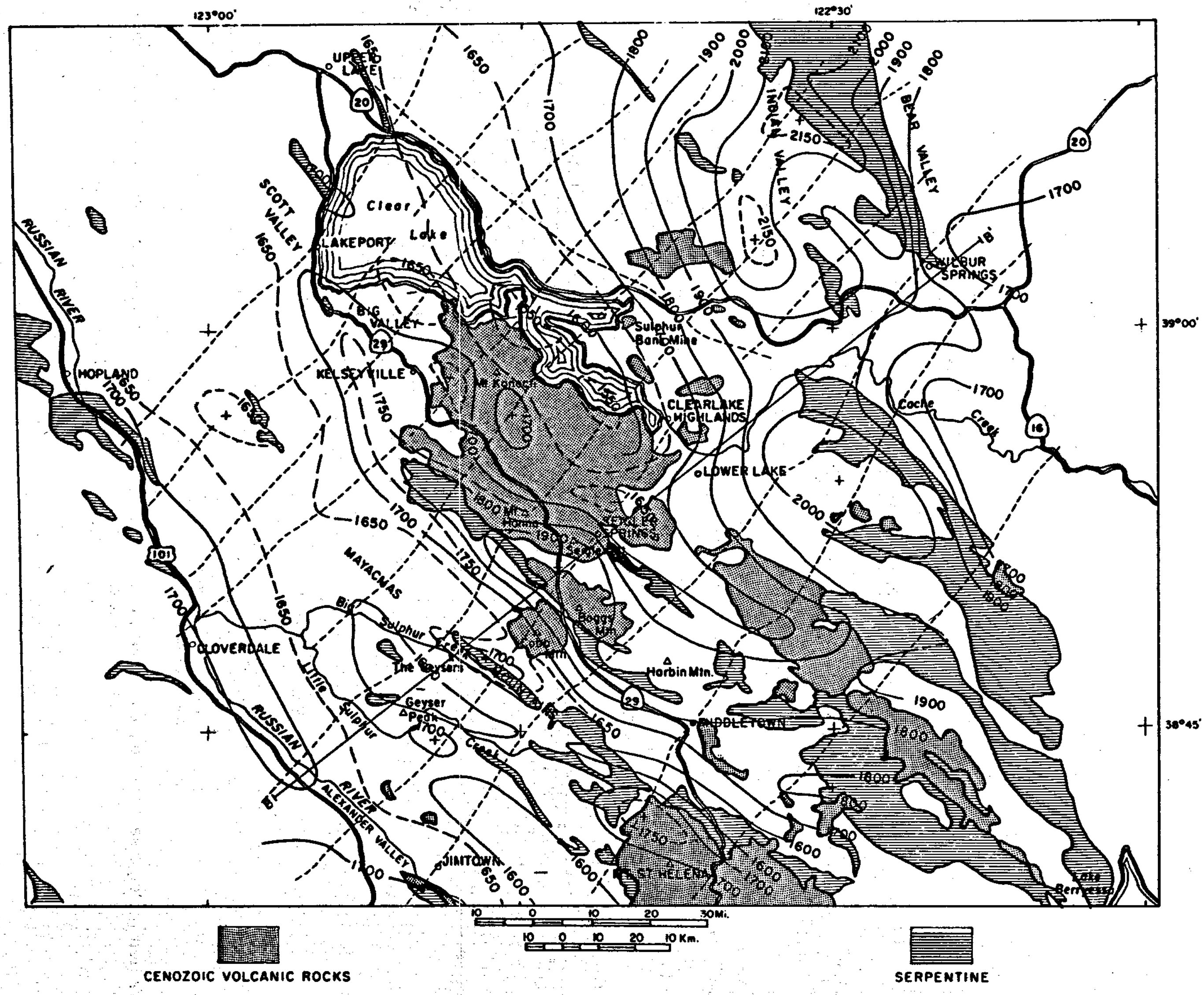
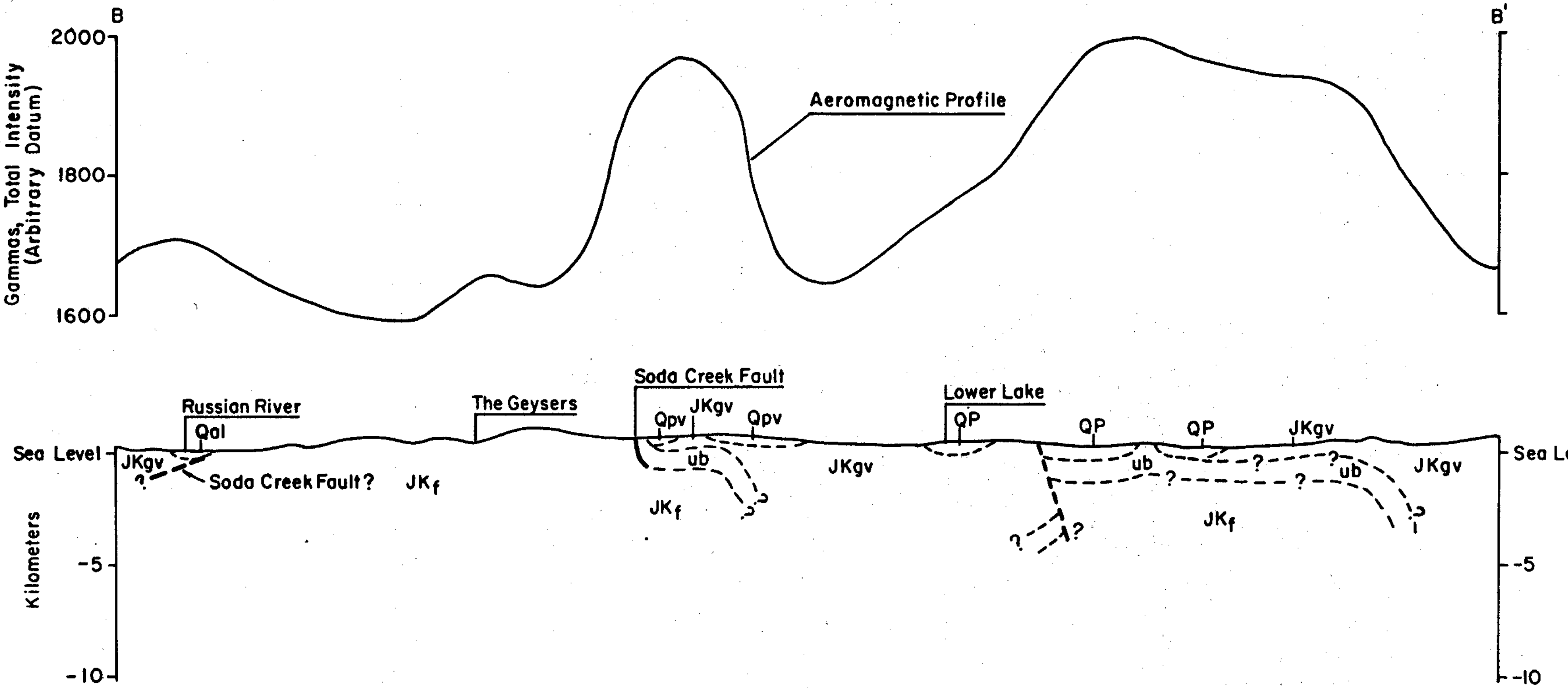


Figure 5. Aeromagnetic map of the Clear Lake region, showing generalized geology (after Jennings and Strand, 1960; Koenig, 1963) and contours after the regional magnetic gradient of about 10 gammas per mile has been removed from the data. Contour interval: 100 and 50 gammas, total intensity.



EXPLANATION

JKf = Franciscan Formation
ub = Serpentine
JKgv = Great Valley Sedimentary Rocks
QP = Plio-Pleistocene Non-marine
QPv = Cenozoic Volcanic Rocks
Qal = Quaternary Alluvium

Figure 6. Aeromagnetic profile B-B' and generalized geologic section (based on qualitative interpretation of magnetic data and geology after Jennings and Strand, 1960, and Koenig, 1963).

gravity and geologic structural trends in the map area. Locally, the area is characterized by two relatively large positive anomalies, one trending nearly north, east of Clear Lake, the other trending northwest, south and southwest of Clear Lake. These anomalies are evidently associated with discontinuous exposures of serpentine. The two major anomalies and the exposures of serpentine both appear to merge into one in the southeastern part of the map area, northwest of Lake Berryessa.

The measurements given in table 2 indicate that serpentine samples from this area have an average magnetic susceptibility of about 0.003 emu/cm^3, more than 10 times as large as the value of 0.0002 emu/cm^3 given for the average of the Clear Lake volcanic rocks. (Saad, 1969, p. 979, reported a value of approximately 0.0054 emu/cm^3 for serpentine from the Red Mountain area in the Diablo Range). In addition, samples of altered basic volcanic rocks (greenstone) from the Franciscan Formation were found to have a very low magnetic susceptibility, negligible in comparison with serpentine and the younger volcanic rocks. In view of these results, it is not surprising that magnetic anomalies related to serpentine apparently dominate the aeromagnetic map. No measurements of remanent magnetization of the rock samples were made, however.

The southwesternmost magnetic anomaly, which has a maximum amplitude of about 250 gammas, trends nearly west, just north of Middletown, but trends northwest in the vicinity of Boggs Mountain where it reaches its maximum amplitude. The anomaly continues in this direction west of Mt. Hanna for at least 20 miles from Boggs Mountain to the vicinity of Lakeport. North and northwest of Middletown, the width of the anomaly is greater than might be expected from the outcrops of serpentine shown on the geologic map. The anomaly encompasses the entire area between the serpentine exposed east of Cobb Mountain and similar rock exposed in the core of the Howard Springs arch, to the northeast (Swe and Dickinson, 1970, p. 169). This fact suggests that the serpentine may underlie at shallow depth the Great Valley sedimentary rocks and Clear Lake volcanic rocks in this area. Furthermore, the apparent continuity of the anomaly from north of Middletown to the vicinity of Lakeport suggests that the serpentine may be present in the form of a continuous body in this area even though only scattered outcrops of these rocks are found along the trend.

A northeast-trending aeromagnetic profile, B-B′, shown in figure 6, was drawn across the serpentine belt in the vicinity of Boggs Mountain and Harbin Mountain. This profile shows a fairly symmetrical positive magnetic anomaly with an amplitude of about 300 gammas and a width of about 4 miles. If the serpentine in this area can be approximated by a tabular dipping mass, the shape of the profile suggests that these rocks are dipping steeply to the northeast. However, if so, the magnetic anomaly caused by such a large mass of serpentine with a high magnetic susceptibility would be much larger in amplitude than the one observed. Thus, it is likely that the serpentine is in the form of a folded sheet or bed somewhat as shown in figure 6. The northeastern flank of the magnetic anomaly may also be affected by other anomalies, which could be caused by units of the Clear Lake volcanic rocks.

The eastern branch of the positive anomaly is fairly broad and trends nearly north across the eastern side of the map area. This anomaly evidently represents the major serpentine belt located on the west side of the Great Valley in this part of the Coast Ranges. Northeast of Clear Lake, the anomaly has a maximum amplitude of more than 400 gammas. This anomaly crosses the large area of Cache Formation rocks located northeast of Clear Lake, with only a slight decrease in amplitude, which suggests that the serpentine is probably continuous below these surface deposits. Continuing northward, the positive anomaly passes through the vicinity of Indian Valley, at the northern end of which it is again associated with serpentine outcrops. The location of the anomaly in the vicinity of Indian Valley indicates that serpentine almost certainly is buried at shallow depth underneath rocks mapped as Franciscan Formation, or equivalent, in this part of the area. Recent work in the northern Coast Ranges has suggested that the major ultramafic belt on the west side of the Great Valley is the base of the overriding Coast Range thrust. Accepting this conclusion, it may be deduced that the thrust surface is overturned in this area, or some of the rocks mapped as Franciscan Formation are, in reality, rocks of the Great Valley sequence. An alternative might be that Franciscan Formation rocks have been thrust over Great Valley sequence rocks in this local area.

A northwest-trending negative anomaly (160 gammas closure) is centered in the vicinity of the southeast arm of Clear Lake, near the Clear Lake volcanic field. This anomaly includes a number of irregular minor positive and negative closures. It is interpreted to be a relative magnetic low, between the two strong, positive anomalies, discussed above. The Clear Lake volcanic rocks which are present in this area may be the source of the relatively small irregular magnetic features. Figure 6 shows a generalized geologic cross section through the area based on surface geologic data (Jennings and Strand, 1960; Koenig, 1963) and a qualitative interpretation of the magnetic data.

There is no apparent magnetic counterpart to the major negative gravity anomaly in the Clear Lake area and no apparent magnetic anomalies associated with the known geothermal areas. Because a moderately small magnetic anomaly might be hidden by the relatively strong magnetic effects related to serpentine, a trend surface analysis of orders one through six was used in an attempt to isolate any possible anomalies that might correspond in wavelength and location to the major gravity anomaly. However, the results of this analysis did not reveal any such anomalies.

DISCUSSION

The major negative gravity anomaly in the Clear Lake region may have a number of different possible causes. If the area within the boundaries of the gravity anomaly were covered by volcanic rocks, it might be assumed that the anomaly is caused by a buried caldera or volcano-tectonic structure filled with volcanic deposits and possibly related sedimentary deposits. The Clear Lake anomaly is similar to anomalies in other volcanic regions which are known or believed to be caused by calderas (Malahoff, 1969, p. 369-374). Even the presence of the largest volcano in the area, Mt. Konocti, on the north edge of the gravity anomaly, bears a resemblance to volcanoes found near the rims of known (or assumed) calderas, such as Sakurajima on the southern edge of the Aira caldera in Japan (Yokoyama, 1961), and the rim volcanoes around the Medicine Lake Highland caldera in northern California (Anderson, 1941, p. 359-362). Furthermore, arcuate fractures in the vicinity of the Clear Lake gravity anomaly (p. 7) have been mapped in both the Clear Lake volcanic rocks and in adjacent Franciscan Formation rocks. There is, however, no convincing evidence for any major collapse structure associated with these fractures.

Berkland (1972, p. 13) suggested that the Clear Lake basin was formed by Quaternary caldera-type subsidence centered around Mt. Konocti. However, the gravity anomaly does not coincide with the Clear Lake basin as defined either by the present-day lake or by the caldera suggested by Berkland.

In general, the Clear Lake volcanic field apparently does not occupy a depression in the older rocks; rather the volcanic rocks more or less mantle the pre-existing landforms. It is likely that the thickness of volcanic rocks does not generally exceed about 1000 feet except in the vicinity of some of the volcanic vents and volcanoes (McNitt, 1968a). Differential vertical movement during Tertiary or Quaternary time may have resulted in some local depressions, or grabens, which may also contain relatively thick deposits of volcanic and/or Cache Formation sedimentary rocks. The area of Cache Formation gravels northeast of Clear Lake (figure 4) may be one such local depression. Assuming a difference in density of approximately 0.15 g/cm^3 between the Clear Lake volcanic rocks and the average Franciscan Formation graywacke (2.65 g/cm^3 to 2.50 g/cm^3) (see table 1), a 1000-foot thickness of volcanic rocks would cause a maximum gravity anomaly of only about 2 mgal.

Some other plausible causes for the major Clear Lake gravity anomaly include: 1) a buried mass of serpentine, 2) a graben containing Great Valley sedimentary rocks within Franciscan Formation rocks, or 3) either a graben or an intrusive plug within the basalt basement underlying the Franciscan Formation rocks. The average density of serpentine from the Clear Lake area (table 1) is 2.53 g/cm^3 based on three samples. However, because the degree of serpentinization of the samples may vary, this figure may not be representative. Hanna and others (1972, p. C10), for example, assume a wet bulk density range for serpentine of 2.3- to 2.5-g/cm^3 in an area near Cholame in the southern Coast Ranges of California. Regardless of the correct value for the density, it is clear that a very large mass of serpentine would be necessary to cause the observed anomaly (about -25 mgal). It is true, also, that masses of serpentine in other places in the Coast Ranges cause negative anomalies of only a few milligals (Chapman, 1966b, p. 398). Furthermore, serpentine characteristically has a relatively high magnetic susceptibility, so that a large mass of serpentine would certainly cause an observable magnetic anomaly. As mentioned above (p.15), no such magnetic anomaly is apparent in the aeromagnetic data (figure 5).

Sedimentary rocks of the Great Valley sequence may underlie a large part of the anomalous area east of the Soda Creek thrust (figure 4; Swe and Dickinson, 1970, figure 2), and these rocks probably have a lower average density than Franciscan Formation rocks. According to Bailey and others (1964, p. 141) densities of Lower and Upper Cretaceous graywackes average 2.57 g/cm^3 and 2.55 g/cm^3, respectively (table 1). Although the density differences between these rocks and the "unmetamorphosed" Franciscan Formation graywacke are less than 0.1 g/cm^3, a sufficient volume of the lower density rocks could theoretically cause the observed gravity anomaly. However, the mass of Great Valley sequence sedimentary rocks required to satisfy the gravity anomaly would have to be approximately equidimensional in plan, and more than 20,000 feet thick vertically. In addition, a large part of the mass must underlie the Franciscan Formation rocks exposed in the Mayacmas Mountains southwest of the Clear Lake volcanic field. These conditions appear to be unlikely in view of the current interpretations of the geology of the area. Furthermore, other sections of Great Valley sedimentary rocks in this part of the Coast Ranges apparently do not cause large negative gravity anomalies. Drill holes in The Geysers area, some of which were greater than 9000 feet in total depth and were believed to be entirely in Franciscan Formation rocks have failed to encounter either Great Valley sequence rocks or appreciable amounts of serpentine at depth.

Other plausible causes for the Clear Lake anomaly could be either a local depression or an intrusive plug in the basalt basement (ancient sea floor?) which is generally believed to underlie the Franciscan Formation at depth. If this basalt basement rock were at a relatively shallow depth—say within 5 km of the surface—a local mass of lighter rocks in this area (granitic intrusive plug, or a graben of Franciscan rocks, for example) could cause the observed anomaly. In either case, the density contrast would be close to 0.30 g/cm^3. We do not have accurate information regarding the depth to the basalt basement in this area, but the results of seismic refraction work by the U.S. Geological Survey (Eaton, 1966, figure 5) along a line from San Francisco to Fallon, Nevada, suggest that the rocks of the Franciscan Formation may extend to a depth of at least 10 km and probably more in this part of the Coast Ranges. Thus, unless the basalt basement is higher in the crust than expected in the Clear Lake region, a structure within these basement rocks is unlikely to be the cause of the anomaly.

Two other plausible causes for the anomaly include: (1) a hot intrusive mass underlying the Clear Lake region at a relatively shallow depth, and (2) a steam-water reservoir underlying the anomalous area and characterized by porosity on a large scale, possibly caused by fracturing related to faulting in the enclosing rocks.

Intrusive Hypothesis

The presence of numerous hot springs and two developed steam fields in the Clear Lake area (Garrison, 1972, p. 145) suggest that the area may be underlain at some depth by a still-hot intrusive mass of substantial size. Bottom hole temperatures from unsuccessful deep drill holes as much as 3 miles from The Geysers area have generally been over 300° Fahrenheit (F.) and some over 400° F. (Koenig, 1971, p. 32). At the Sulphur Bank mine on Clear Lake, for example, temperatures of over 350° F. were measured in exploration holes.

If the theoretical hot intrusive mass is present, and if its composition corresponds to the average of that of the extrusive rocks in the Clear Lake volcanic field, it would have the composition of diorite or granodiorite. The densities of these rocks at room temperature would be in the range of 2.6 g/cm^3 to 2.8 g/cm^3. Assuming a reasonable value for volume thermal expansivity for these rock types, perhaps 20×10^{-6} per degree Celsius (Skinner, 1966; p. 94), solid rock of this type at a temperature of 1200°C. (Celsius) would show a density contrast with adjoining cold rock of the same type of somewhat less than 0.10 g/cm^3. However, if the intrusive rock should be either in a glassy state or actually molten, calculations indicate that the density contrast could be as much as 0.3 or 0.4 g/cm^3, depending, in part, on the temperature of the mass (Skinner, 1966, p. 93). This large density contrast suggests that a magma chamber could easily account for the observed gravity anomaly.

Using the depth relationship given by Bott and Smith (1958, p. 2-3), $h = 0.86\,\Delta g\ max/\Delta g'\ max$,

where

h = maximum depth to the top of an anomalous 3 dimensional density distribution

Δg = maximum value of the gravity anomaly

$\Delta g'$ = maximum value of the horizontal gradient of the gravity anomaly,

the maximum depth to the top of the source of the Clear Lake anomaly must be no greater than about 4 miles (6.5 km). Of course, the actual depth to the top of the anomalous mass may be less than this figure; it could even be at the ground surface.

A northeast-trending gravity profile (figures 4 and 7) crossing the gravity anomaly was used to calculate possible configurations of the theoretical anomalous mass. Because of the asymmetry of the anomaly shown in the profile, it is clear that a simple geometric shape for the anomalous mass, such as a sphere or vertical plug, does not yield a satisfactory solution; thus it is necessary to assume a more complex configuration, such as a cylindrical mass inclined toward the southwest. Figure 7 shows a comparison of the residual gravity profile and the approximate anomaly which would be caused by an assumed cylindrical mass with a radius of 18,000 feet, a density contrast of -0.4 g/cm^3, depth to the top of about 10,000 feet, a vertical depth extent of 30,000 feet, and an axis inclined about 60° from the vertical toward the southwest. This model is the result of a trial and error process which involves calculating the gravity effects of a series of individual circular discs at different depths (after Nettleton, 1942, p. 304), then summing these effects in different configurations—thus varying the inclinations, depth of burial, and depth extent of the theoretical mass. Finally, the models were checked by the three-dimensional computer method developed by Talwani and Ewing (1960). The radius of the model was selected on the basis of the areal extent of the gravity anomaly, and the depth to the top was based on the results of the model studies and the results of deep drilling in the area. The density (0.4 g/cm^3) is a probable maximum difference selected to represent the case of a magma chamber. The cylindrical mass shown in figure 7 is by no means a unique solution in regard to shape, depth, depth extent, inclination, or density contrast, but it does serve to illustrate the type of solution which appears to be necessary to account for the anomaly under the hypothesis that it is caused by an underlying hot intrusive mass. The intrusive mass probably would be much more complex in shape than this simple model used for purposes of calculation. Drill holes in the Clear Lake area, some of which are deeper than 9000 feet, have not encountered any evidence of an underlying intrusive mass, and they place an upper limit on the depth to such a mass if it exists. The concentration of minor earthquake activity in the vicinity of the Clear Lake volcanic field, as shown in figure 2, is entirely compatible with a possible process of emplacement of an intrusive mass that is still continuing.

The lack of a magnetic anomaly to correspond with the major Clear Lake gravity anomaly is not unfavorable evidence for the presence of such an intrusive body; assuming that this mass is above the Curie point of magnetite (about 800°C.), there would be *no induced* magnetic field in the mass, and no associated magnetic anomaly.

Water-Steam Reservoir Hypothesis

Drilling in The Geysers geothermal field indicates that the major productive zones are generally deeper than about 2000 feet, and range in depth to 9000 feet or more. The steam produced from shallow wells in this area is believed to be from smaller (volumetrically) sources closer to the surface. That a large steam reservoir exists at depth is shown by the high rates of flow of the steam and the relatively rapid recovery of pressure after shutting in a well (Koenig, 1969, p. 128). The limits of the field have not yet been delineated by drilling, however, and whether reservoirs exist in other parts of the anomalous area has not yet been determined.

To test the hypothesis that the gravity anomaly can be accounted for by a large fracture zone (or series of zones) filled with steam and hot water, a three-dimensional iterative gravity interpretation program developed by Cordell and Henderson (1968) was used to construct a model for the hypothetical source. The top of the major reservoir was assumed to be at an average depth below the surface of one km (3200 feet), and a density contrast of 0.2 g/cm^3 was used for a trial calculation. A somewhat "smoothed" version of the residual gravity map shown in figure 4 was used as the basis for the three-dimensional calculation. The resulting anomaly profiles are compared in figure 8 along with a cross section of the computed theoretical mass distribution.

The enormous size of the anomalous zone (reservoir) required to satisfy the observed gravity anomaly is evident in the cross section of figure 8. The greatest thickness of the hypothetical zone, as shown in figure 8, is indicated by the center of the gravity anomaly, which is located near Mt. Hanna. Alternatively, the anomalous zone could be closer to the ground surface near the anomaly center and not necessarily thicker. Shown in figure 4 are the locations of The Geysers steam field and the Sulphur Bank mine prospect. The developed steam field is in the south to southwestern part of the anomalous area. The Sulphur Bank mine prospect is just northeast of the anomalous area.

The assumed density differential of 0.2 g/cm^3, assuming the hypothetical reservoir is filled chiefly with water, would require an average porosity of about 10 percent. If much of the volume were actually filled with steam, this figure may be as little as about 8 percent. This may be an unreasonably high effective porosity for such a large volume of reservoir rock. For example, Koenig (1971, p. 35) suggested an effective porosity of about 2 percent for The Geysers reservoir. However, it is doubtful that such a low value of reservoir porosity (2 percent), and correspondingly small density contrast, could possibly serve as an explanation for the observed gravity anomaly.

It is possible that the gravity anomaly could be caused by a combination of effects: an intrusive mass below, a fracture zone-reservoir in the rocks above the intrusive, and to a minor extent, the volcanic and sedimentary rocks near the surface.

Gauss's theorem was used to estimate the size of the anomalous mass from the "smoothed" residual gravity map (figure 4) for a comparison with the results obtained for the two different geological "solutions" examined in detail above (Hammer, 1945). Utilizing the relationship given by La Fehr (1965a, p. 1913) between the percent of actual mass as a function of area integrated, the anomalous mass was estimated to be approximately 4.0 x 10^{17} grams. For comparison, the inclined "cylinder" solution (page 17) yields a figure of 3.4 x 10^{17} grams, and the iterative three-dimensional calculation (page 17) results in a mass of 3.1 x 10^{17} grams. On the basis of these figures, the volume of the mass would then range from approximately 900 km^3 for the cylindrical "magma chamber" hypothesis to over 1500 km^3 for the near-surface steam-reservoir hypothesis.

The preliminary results of deep electrical resistivity measurements in the vicinity of the Clear Lake volcanic field (Stanley and others, 1973) provide significant new evidence in regard to the possible source of the gravity anomaly. Stanley and others (1973) have mapped a large low-resistivity zone centered around Mt. Hanna with an extension to the southeast, and a depth extent of at least 15,000 feet below the surface. The fact that the location of the resistivity low corresponds well with the inner part of the gravity low strongly suggests that both anomalies may have at least in part the same or closely related causes. Stanley and others (1973, p. 17) suggest that the electrical anomaly could be caused by thick marine sedimentary rocks with warm saline pore waters, and that the center of the low may indicate an area of abnormally high heat flow. These results are not inconsistent with the idea of a heat source (magma chamber) below the Clear Lake volcanic field and a reservoir (or reservoirs) of hot water above.

COMPARISON WITH OTHER CENOZOIC VOLCANIC AND GEOTHERMAL AREAS

McNitt (1965, p. 247; in press) has noted that a large number of the geothermal areas being developed throughout the world are located in regions of Quaternary volcanism or Cenozoic tectonism, or both. It is reasonable to suppose that the source of heat in many of these thermal areas must be related to volcanism and magmatic activity. That is, the heat is probably derived from either buried volcanic rocks or from still-cooling intrusive masses (Bodvarsson, 1970; White and others, 1971, p. 90).

The results of geophysical studies in many geothermal areas as well as in other areas of Cenozoic tectonism and volcanism have been published in recent years (see references below), and these examples can be compared with the present studies in the Clear Lake region. Negative gravity anomalies—generally similar in areal extent and amplitude to the Clear Lake anomaly—are apparently not uncommon in some of these areas. In some particular examples, these negative anomalies are clearly associated with calderas filled with relatively low-density volcanic and sedimentary deposits. Examples of this type in Japan have been summarized by Yokoyama (1963), and in Tanzania, by Searle (1971, p. 350). In Kamchatka, U.S.S.R., and on the Alaskan Peninsula, however, some very similar negative anomalies have been attributed to underlying magmatic material (Erlich and others, 1972, p. 233; Kubota and Berg, 1967, p. 207-211) at depths generally ranging from 4 to 6 km. Evidence tending to confirm the postulated magma chambers has come from the attenuation of transverse seismic waves (Gorshkov, 1971, p. 204-206; Kubota and Berg, 1967, p. 211-212). In some volcanic regions, however, positive gravity anomalies are associated either with calderas, or with volcanoes or volcanic chains. Examples of this are the Avachinsky group of volcanoes in the U.S.S.R. (Steinberg and Zubin, 1965) and the Medicine Lake Highland in northern California (Chapman and Bishop, 1968). These positive anomalies have generally been attributed to underlying dense intrusive masses.

Gravity anomalies associated with the Italian steam producing areas of Larderello and Monte Amiata (Marchesini and others, 1962, p. 525; Mouton, 1969, p. 186,

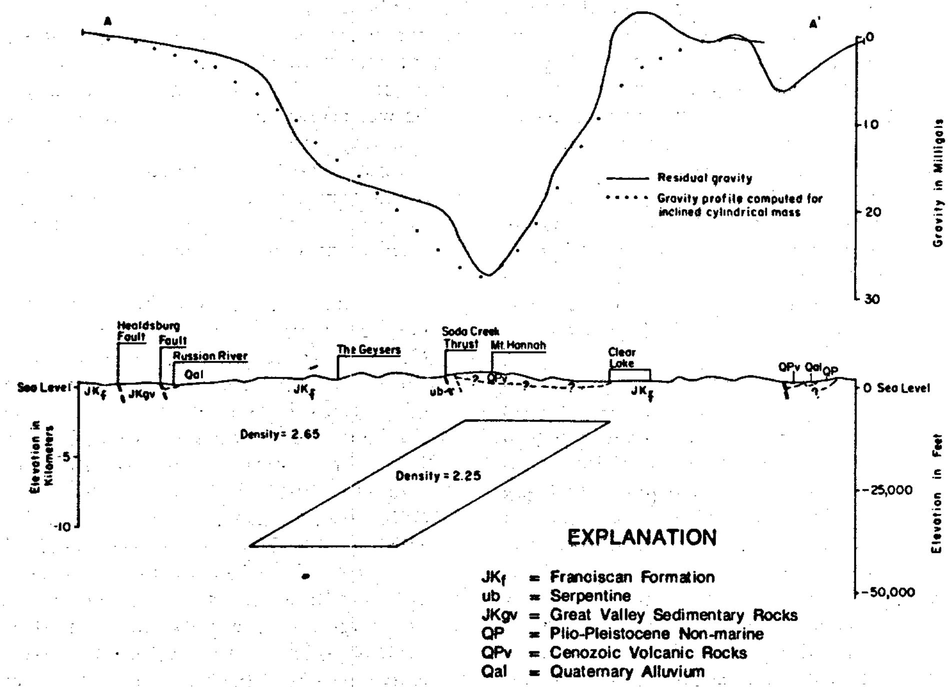


Figure 7. Residual gravity profile A-A′ and generalized geologic section (geology after Jennings and Strand, 1960, and Koenig, 1963), showing cross section of assumed inclined cylindrical mass and calculated gravity profile.

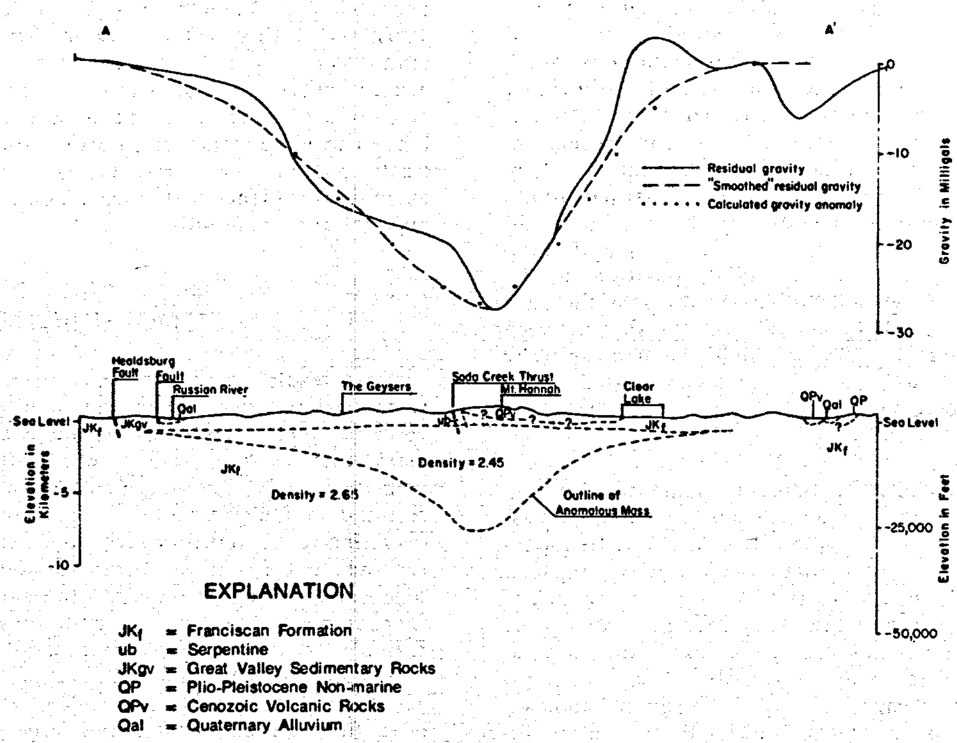


Figure 8. "Smoothed" residual gravity profile A-A′ and generalized geologic section (geology after Jennings and Strand, 1960, and Koenig, 1963), showing a cross section of assumed near-surface anomalous mass and calculated gravity profile.

plate 4) are generally similar but somewhat smaller than the major negative Clear Lake anomaly in areal extent (average 15 x 30 km) and in magnitude (10 to 20 mgal). Marchesini and others (1962, p. 531) note a correlation between curved concentric fractures, the gravity anomalies, and areas of post-Pliocene uplift in both the Larderello and Monte Amiata areas. These authors suggest that these features probably outline the shape and location of the buried sources of heat. Mouton (1969, p. 187) also suggests a sialic intrusive at a depth of 7 to 8 km as the cause of the Mt. Amiata anomaly. Thus, there are apparent geologic and geophysical similarities between the Clear Lake region and these Italian areas.

A number of significant geothermal fields and prospects are found in relatively large areas of late Cenozoic subsidence; namely the central volcanic region of the North Island of New Zealand, the Imperial-Mexicali Valley in California and Mexico, and the Long Valley area in California. These areas are characterized by negative gravity anomalies which serve to outline the major structural depressions; but in contrast to the Clear Lake region, individual geothermal fields are frequently marked by positive gravity anomalies. For example, in the Imperial-Mexicali Valley, the local positive gravity anomalies are attributed both to underlying igneous intrusive rocks and to the metamorphism of sediments by rising plumes of hot water (Meidav and Rex, 1970, p. 1; Biehler, 1971). In the Broadlands geothermal field in New Zealand, Hochstein and Hunt (1970, p. 344) relate positive residual gravity anomalies to hydrothermally altered volcanic rocks and intrusive rhyolite domes. The Wairakei field in New Zealand is also marked by a local positive gravity anomaly that is believed to be caused chiefly by a horst block of dense basement rock which protrudes into the less dense volcanic and sedimentary rocks filling the region of subsidence (Beck and Robertson, 1955). However, on the basis of more recent information from drilling, Modriniak and Studt (1959, p. 667) and Grindley (1965) suggest that at least part of the Wairakei positive gravity anomaly may be caused by an intrusion of rhyolite. Also, in the Long Valley area of Mono County, eastern California, a small, positive gravity anomaly is located a few miles to the northeast of the Casa Diablo thermal area. However, the relationship between this anomaly and the thermal field is unclear. The anomaly may be caused by intrusive rocks located within the structural depression (Pakiser and others, 1964, p. 27).

Magnetic anomalies in general apparently are less characteristic of thermal areas than are gravity anomalies. Banwell (in press) has described the difficulties frequently encountered in attempting to interpret magnetic anomalies in such areas. This is generally due to a lack of subsurface information and the numerous possible causes of magnetic anomalies in volcanic regions. In the Imperial Valley, however, the Buttes area (Salton Sea geothermal field) is characterized by a positive magnetic anomaly (Griscom and Muffler, 1971), probably caused by intrusive rhyolite domes. In other thermal areas, certain negative magnetic anomalies might be related to the destruction of magnetite by thermal fluids as suggested by Modriniak and Studt (1959, p. 669) for areas in New Zealand. This might be the cause of minor negative aeromagnetic anomalies in the vicinity of the Casa Diablo thermal area (Henderson and others, 1963; Stanley and others, 1973, p. 6). The lack of any positive association between aeromagnetic anomalies in the Clear Lake region and the thermal areas or the major negative gravity anomaly has been discussed above (p. 15). A ground magnetometer traverse by the author crossing The Geysers area also failed to reveal evidence of any significant magnetic anomaly.

Large negative gravity anomalies are frequently observed in areas like the Clear Lake region, where late Cenozoic siliceous volcanic rocks are abundant but where direct evidence for Cenozoic subsidence or the presence of calderas is lacking. A few examples of such areas are the southern Cascade Range in California (Pakiser, 1964; La Fehr, 1965b), the Cascade Range in Washington (Daneš, 1964), Yellowstone National Park in Wyoming (Pakiser and Baldwin, 1961; Malahoff and Moberly, 1968, p. 790-791), and possibly the island of Sicily (Medi and Morelli, 1952). In most of these examples, both the volcanic fields and gravity anomalies associated with them are larger in areal extent than at Clear Lake. Nevertheless, these anomalies could have basically the same cause as that of the anomaly in the Clear Lake region. The negative gravity anomalies in these examples have been attributed by various authors to either volcano-tectonic depressions or to underlying siliceous igneous intrusives or a combination of both. However, of these areas, the only one in which pre-volcanic rocks are sufficiently well exposed to eliminate the possibility of a volcano-tectonic depression, or caldera, may be the Clear Lake region. Thus, the results of the work in the Clear Lake region tend to lend support to the idea that at least some of the negative gravity anomalies in Cenozoic volcanic areas may be caused by underlying igneous intrusives rather than by hidden collapse structures. Furthermore, the density contrast apparently required to explain the Clear Lake anomaly is evidence that at least a part of this hypothetical mass of rock may still be molten.

CONCLUSIONS

The results of the geophysical study in the Clear Lake region strongly suggest that the vicinity of the Clear Lake volcanic field is underlain at depth by a hot, intrusive, mass that is the source of heat for the thermal phenomena. The emplacement of this mass may have resulted in faulting and fracturing of the adjacent and overlying rocks that now serve as reservoirs and conduits for the geothermal fluids. If so, the gravity anomaly, together with other geological and geophysical data, can serve to outline the approximate areas in the Clear Lake region that have the greatest possibilities for additional reservoirs of geothermal steam. Other types of geophysical data, particularly deep electrical soundings, heat flow measurements, and seismic data, including studies of possible attenuation of transverse seismic waves and local microseismic characteristics, should eventually result in a more complete understanding of the geology of this region.

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