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A Gravity and Magnetic Investigation of the Long Valley Caldera, Mono County, California

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Gravity studies show that the subsurface part of the Long Valley caldera is a coincident steep-sided depression filled with porous epiclastic and volcanic materials to a depth of as much as 3 km. The depression contains two major basins, a larger and deeper one making up much of the eastern part and a somewhat smaller, more shallow one to the west; a positive feature underlying the central part of the depression separates the two basin areas. The east side of this feature is linear in plan and coincides with the extension of the Hilton Creek fault which is mapped within and beyond the south edge of the caldera. The indicated relief on the postulated subsurface Hilton Creek fault together with difference in depth of the eastern and western basinal areas indicates that the eastern basin is downdropped in relation to the western one. Gentle gravity gradients outside the caldera but sloping towards it are interpreted as evidence of a low-density mass located below the caldera fill. We conclude that it is probably related to the magma source. Aeromagnetic data indicate that a northwest-trending belt of metasedimentary rocks on the south flank of Long Valley may extend into the caldera proper and form much of the bedrock floor of the western part of the caldera. A magnetic low of shallow source in the hot spring region in the southwest is thought to be caused by hydrothermal alteration of the ferrimagnetic minerals in the underlying rocks. A broad positive magnetic anomaly near the center of the caldera may be caused by a thick section of magnetic volcanic flow lying east of the projected Hilton Creek fault and underlying much of the eastern basin.

INTRODUCTION

Gravity and aeromagnetic surveys were conducted in Long Valley, California, during 1954–1957 as part of a regional geophysical study of the Owens River drainage basin. The results of these surveys were reported in a comprehensive paper by *Pakiser et al.* [1964]. Since that study was completed, more detailed and different kinds of geophysical and geological surveys have been made in Long Valley, and improved techniques for interpreting gravity and magnetic data have been developed. In addition, further insights into the nature of caldera fill have come to light as a result of extensive studies of ash flow-related calderas, for example, *Smith et al.* [1961, 1970]. We have therefore re-examined the gravity and magnetic data in an attempt to refine and extend the earlier interpretations, placing particular emphasis on features that relate to the potential geothermal resources of the valley.

As interest in geothermal resources has increased, a need has emerged for reconnaissance geophysical techniques suitable for identifying target areas for more intense exploration. In this regard, regional gravity and magnetic data are available for many areas and, where they are not available, can usually be obtained more economically than other geophysical data. In the case presented here, distinctive gravity and magnetic anomalies are shown to be associated with the Long Valley caldera and appear to reflect to some extent the geothermal system which is thought to underlie the caldera.

The geology of Long Valley is described elsewhere [*Bailey et al.*, 1976] and is discussed herein only as it relates directly to the gravity and magnetic anomalies. On geological grounds alone, two major anomalous masses with associated gravity anomalies might be anticipated as being approximately coextensive with the valley: (1) the porous volcanic and epiclastic rocks filling the caldera and (2) a postulated intrusive body or magma chamber located at some depth below the caldera fill. Both of these features would be expected to represent relatively negative mass anomalies and would therefore produce gravity lows. In addition, density variations within the caldera fill and shallow intrusive bodies penetrating the fill might cause intracaldera gravity variations. The sum of the local gravity anomalies associated with the Long Valley caldera is superimposed on a relatively complex regional anomaly consisting of two parts: (1) decreasing Bouguer anomaly values toward the west, reflecting isostatic compensation of the Sierra Nevada, and (2) somewhat more localized bedrock anomalies due to the density contrast between the granitic rocks of the Sierra Nevada batholith and the denser older metasedimentary and metavolcanic rocks [*Oliver et al.*, 1961].

Most of the magnetic highs or lows observed in the area can be related to the volcanic rocks of Cenozoic age in which remanent magnetization is probably the predominant factor. Magnetic anomalies are also associated with igneous units within the Sierra Nevada batholith and with some terrains underlain by metasedimentary and metavolcanic rocks.

The gravity map of Long Valley (Figure 1) is based primarily on the data from *Pakiser et al.* [1964] as shown on the Mariposa sheet of the gravity map of California [*Oliver and Robbins*, 1973]. The procedures for the gravity survey and data reduction are described in the work by *Pakiser et al.* [1964]. A second more detailed map was prepared from the data of *Pakiser et al.* [1964] by addition of new data measured by D. L. Peterson of the U.S. Geological Survey in 1973. From the latter map we prepared a residual map (Figure 2) by passing an approximately plane surface through the field such that the residual was zero at a distance of about 6 km beyond the valley margin.

Two separate aeromagnetic surveys were made by the U.S. Geological Survey [*Pakiser et al.*, 1964; *U.S. Geological Survey*, 1974]. The first was a low-level reconnaissance of the valley area made along east-west flight lines 1–1.5 km apart and 0.7 km above the land surface. The data were compiled as a total intensity map relative to an arbitrary datum (Figure 6). The second survey (Figure 7) was part of a high-level regional study with flight lines 1.7 km apart and 4 km above sea level. The data from this survey were compiled as a residual map by

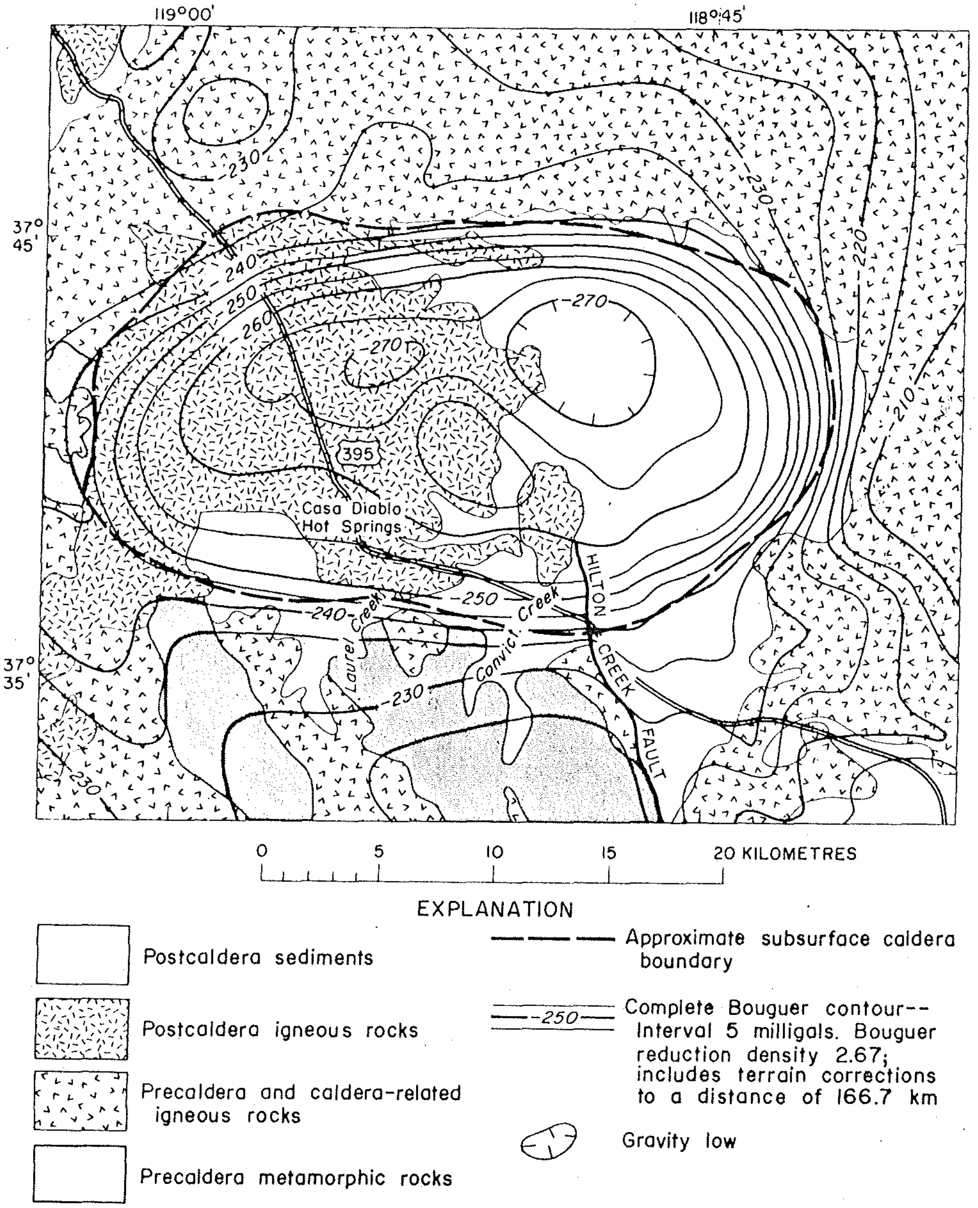

Fig. 1. Combined generalized geology and complete Bouguer gravity map of Long Valley caldera and vicinity. Geology is generalized from R. A. Bailey (written communications, 1974). Gravity is modified from *Oliver and Robbins* [1973].

removing the 1965 international geomagnetic reference field (IGRF) updated to 1973.

GRAVITY

A major gravity low with a relative amplitude of more than 50 mGal coincides with the Long Valley caldera (Figure 1). As reported by *Pakiser et al.* [1964], much of the low is undoubtedly caused by the density contrast between the porous caldera fill and the compact enclosing crystalline rocks. Judging from the bedrock exposed around the valley the bulk of the rock enclosing the caldera probably approaches granite in composition with a corresponding average density of about 2.7 g/cm^3. The average density of the caldera fill depends on many poorly known factors and can only be estimated with considerable uncertainty. Much of the porous sediment probably has a density of about 2.0 g/cm^3, but some of the volcanic units have densities that equal or exceed the density of the enclosing crystalline rocks. Pumiceous sediments may be extremely anomalous in density with values considerably less than 2.0 g/cm^3. We estimate that the average density of the caldera fill is about 2.25 g/cm^3, yielding a density contrast of 0.45 g/cm^3. This estimate may be as much as 50% in error on the average and even more in local areas. But, as will become clear in the following discussion, many other uncertainties in the models derived from the gravity data make the assessment of a more accurate value unwarranted.

Using the assumed average density of 0.45 g/cm^3, we inverted the residual gravity anomaly (Figure 2) to a corresponding distribution of caldera fill (Figure 3) by using the method of *Cordell and Henderson* [1968]. Two constraints were imposed in the technique that was used, namely, that the top of the fill was at the surface and that the sides were within the boundary formed by the zero isogal; i.e., the walls of the caldera dip vertically or inward from within the zero isogal. As might be predicted, the thickness contours of the fill are like those of the gravity map but with considerable detail added in the central (deeper) part of the fill. A cursory inspection suggests that the northern and eastern walls of the caldera are steeper than those to the south and west. An apparent maximum thickness (depth) of 5.5 km is reached in the tight

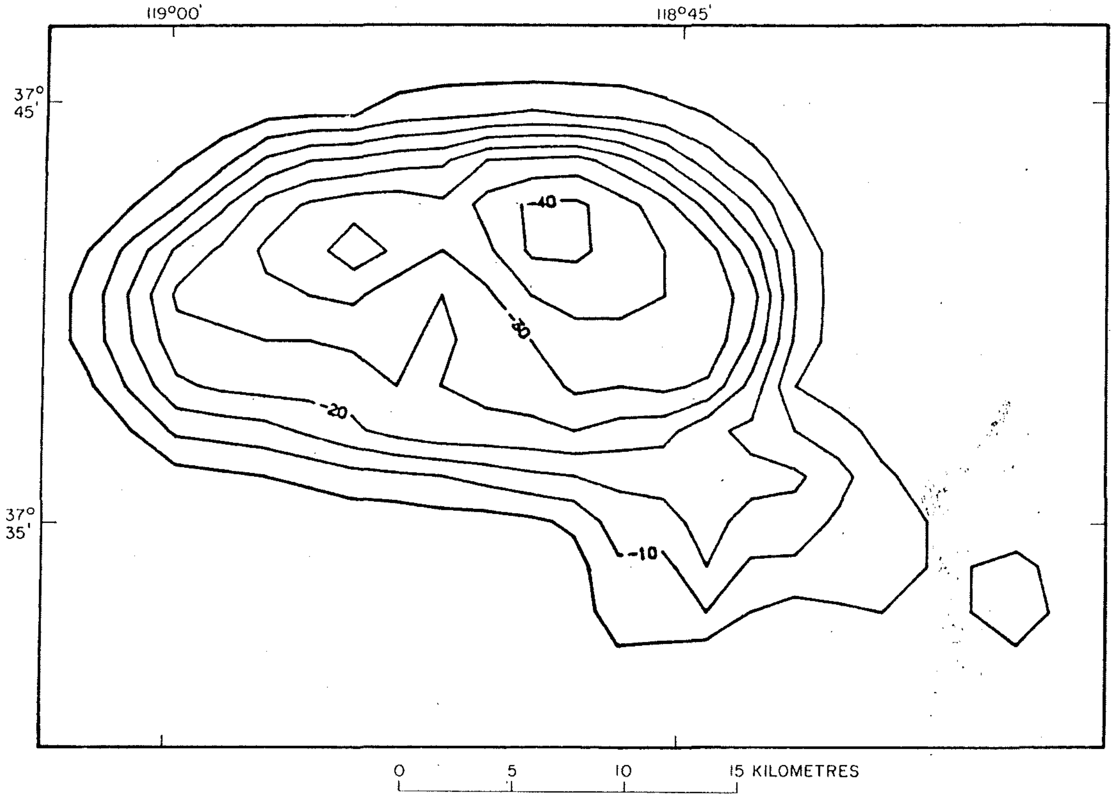

Fig. 2. Residual Bouguer gravity map of Long Valley area. Contour interval is 5 mGal.

gradient closure in the northwest part of the caldera, and a nearly equivalent thickness (depth) occurs in the broader closure just to the east. A series of apparent deeps occur along the west, east, and north rim of the basin; two apparent deeps of lesser magnitude are present in the south central part of the caldera. A central area of relatively positive relief, or platform, in the caldera floor divides the model into what might be regarded as separate eastern and western basinal areas. A well-defined peak in the central part of the platform reaches to within 1 km of the surface and forms the shallowest part of the

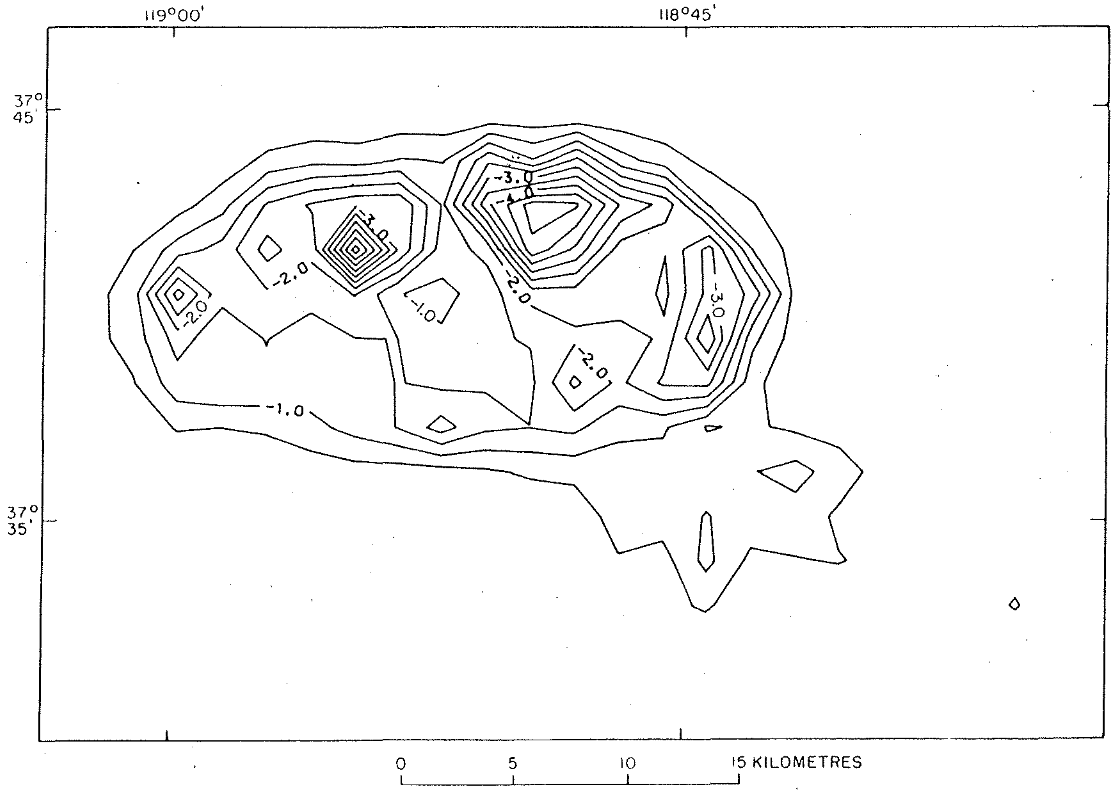

Fig. 3. Model of caldera fill showing depth to bottom of structure, Long Valley area. Interval is 0.5 km.

interior of the caldera. The eastern side of the platform is linear in plan and is approximately coincident with the mapped extension of the Hilton Creek fault in the caldera proper. An apparent shallow area is indicated in the vicinity of the Casa Diablo hot spring.

The shallow lobe southeast of the caldera proper indicates a bedrock trough attaining depths as great as 1 km. A somewhat shallower extension (indicated by the secondary lobe on the gravity contour map of Figure 2) must extend farther southeast to enclose the small isolated closure but is not shown because it is less deep than the contour interval of 0.5 km.

In the preceding discussion, two principal sources limit the validity of the quantitative conclusions. First, the selection of the regional surface is somewhat arbitrary. *Pakiser et al.* [1964] chose a surface such that the residual amplitude was higher, thereby leading to a greater average thickness for the fill. Second, in general, it is not possible to locate with any precision the bottom of models derived from gravity data alone, owing to problems of density contrast and to the separation of the anomaly from fields arising from other sources. Our choices, we believe, are reasonable but are certainly subject to revision if further relevant data, particularly on density contrast, become available. The model is most valid perhaps for the comparison of intracaldera features. Even the latter picture, however, is affected by lateral density variations in the fill, and we discuss these in the following paragraphs.

Variations in the density of caldera fill result mainly from three factors: (1) mode of deposition and degree of compaction of sedimentary units, (2) emplacement of igneous units of contrasting density, and (3) induration and alteration produced by hydrothermal alteration. The density of the epiclastic sediments will be determined largely by the degree of sorting, with coarse poorly sorted materials (less porous, more dense) near the source areas and finer ones (more porous, less dense) in the centers of depressions. The sediments will be compacted and therefore denser with depth. Both extrusive and intrusive rocks occur in the caldera and represent positive mass anomalies, except for pumiceous sediments. The density of the latter can be extremely low. Hot solutions bearing dissolved minerals and moving horizontally and vertically through porous zones can deposit minerals in pore spaces, thereby increasing the density.

When lateral sorting effects on clastic sediments are not accounted for in gravity-derived models of intermontane basins, it can be shown [*Kane and Pakiser,* 1961] that the walls of the model must dip less and be displaced somewhat more basinward than the actual subsurface walls of the basins. Thus to the extent that sorting affects the sediments of Long Valley, the walls of the model of Figure 3 can be considered to have dips equal to or less than actual dips and to have locations at or inside the valley walls.

Direct evidence of an intracaldera density variation—the second factor—is shown in the plot of the difference in values between the measured gravity field (Figure 2) and the field calculated for the model (Figure 4). The 2-mGal negative difference shown in the northeastern part of the caldera represents a steep gradient local anomaly which cannot be accounted for by adding a mass deficiency at the base of the model. The anomaly reflects the presence of a shallow mass which has a density contrast (porosity) higher than the model density (0.45 g/cm^3). This clearly identified area of relatively low density raises the possibility that most, if not all, of the apparent deeps shown by the model have an equal probability of being caused by local increases in the porosity of the fill. The model contours in these areas may therefore also be considered as qualitative indications of possible variations in fill porosity.

The third factor variation which needs to be considered is related to the effect of the percolation of hydrothermal waters through porous sediments. Detailed geophysical measurements in the Raft River area of Idaho [D. R. Mabey, personal communication, 1974] indicate that the passage of water of this type through porous sediments can result in the deposition of minerals in the pore spaces, leading to an effective increase in density. This type of density variation may be the cause of the apparent thin part of the model in the southwest region of the caldera where Casa Diablo hot spring is located.

The model of caldera fill as modified conceptually in the preceding paragraphs has four salient features. (1) It confirms the earlier interpretation [*Pakiser et al.,* 1964] that the caldera is bounded by high-angle faults. The faults may have an equal or steeper dip and may lie somewhat outside those shown by the model. (2) If allowance is made for the suggested porosity variations in basin fill, the maximum thickness of the fill is more probably that shown by the contours exclusive of the local deeps, that is, about 3 km. This depth is appreciably less than that given by *Pakiser et al.* [1964], but the difference is due to the smaller residual that was chosen and the identification of the probable local concentrations of high-porosity fill. The lesser thickness is also in better agreement with the interpretation by *Hill* [1976]. (3) Two basinal areas are defined, the eastern one being estimated as about 3 km deep and the western one about 2 km deep. (4) The shallow region in the southwest part of the caldera may be deeper than shown if an allowance is made for an increase in fill density caused by pore deposition of minerals from percolating hydrothermal waters.

Two geological inferences may be drawn from the modified model. The first is that the local accumulations of high-porosity fill may be pumiceous sediments. Moreover, the locations of these accumulations about the margin of the caldera may mark volcanic centers; i.e., the deeps shown by the uniform density model (Figure 3)—at least the major deeps—may be the manifestation of these centers. The second geological inference is that even when allowance is made for local variations in fill porosity, two basinal areas divided by a relatively high central platform are present. The platform may represent a basement ridge between two areas where the basement has collapsed over separate magma chambers. It should be pointed out, however, that there is positive three-dimensional relief on the platform suggesting either the presence of a coincident igneous feature or residual relief left by erosion at some time prior to collapse of the caldera. The eastern side of the platform is linear and coincides with the location of the Hilton Creek fault. It seems reasonable to assume that the linear part of the model reflects subsurface throw on the fault. This feature together with the difference in depth of the two basins indicates that the eastern basin may have been downdropped relative to the western one along the Hilton Creek fault and the faults which bound the eastern part of the caldera.

The southeast lobe of the model is underlain primarily by Bishop tuff. The most direct interpretation is that the anomaly reflects pre-Bishop tuff topography and gives a measure of the thickness of the tuff. An alternate source for the lobe is a deeper intrabedrock mass, perhaps a lobe of intrusive rock whose emplacement is related to the formation of the caldera.

As will be shown below, the evidence of a gravity source that is significantly deeper than the caldera fill must be sought well outside the caldera boundary. The evidence should take the

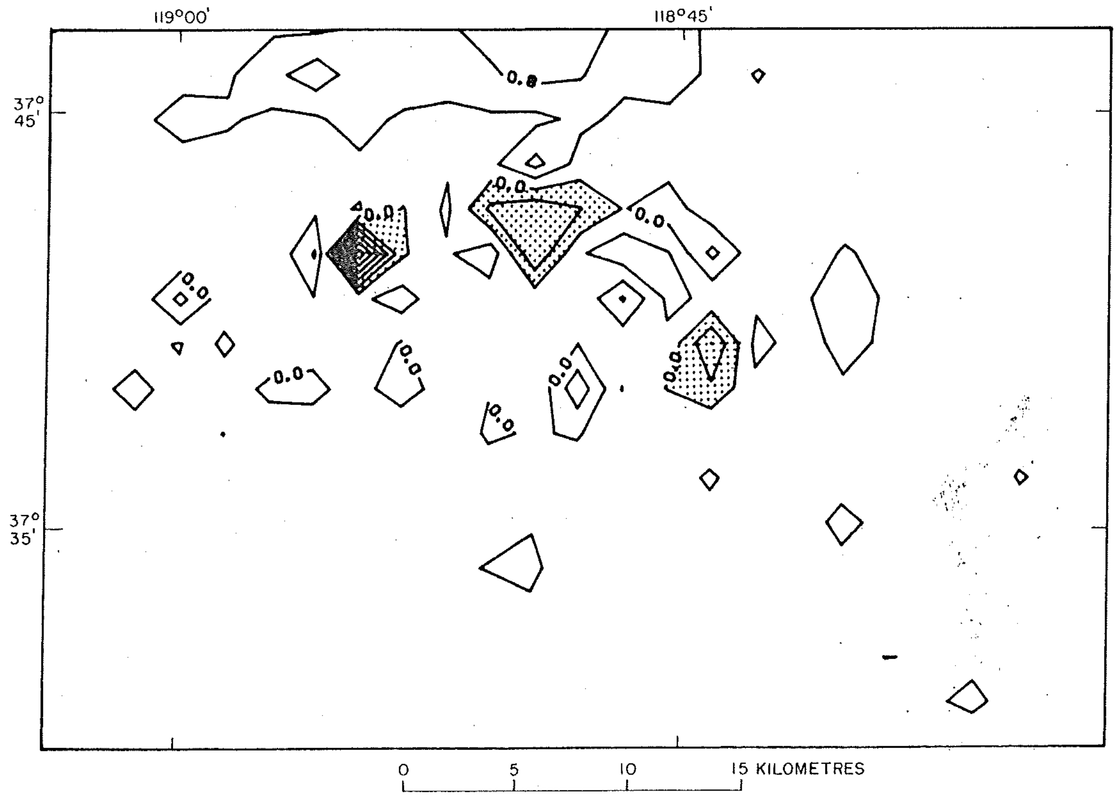

Fig. 4. Difference between measured and calculated values for the model of caldera fill (Figure 3). Interval is 0.4 mGal. Dotted areas are negative.

form of a gradient which persists beyond the region where it could reasonably be attributed to a shallow source, namely, the caldera fill. Because the dip of the regional trend is dominantly westward, the most likely areas to seek a manifestation of the deep-source gradient are north and south of the caldera. Figure 1 shows that a gentle gradient does exist to the north and south of the caldera and that it has an average value in excess of 1 mGal/km.

In order to examine the quantitative aspects of the gradients more closely we have plotted measured gravity profiles over the south edge of the caldera (Figures 5*a* and 5*b*) from the gravity map by *Pakiser et al.* [1964, Plate 1]. We chose the south edge for two reasons. First, north of the caldera the considerable thicknesses of alluvial and volcanic rock which overlies the granitic and sedimentary bedrock might substantially perturb the regional gradient. Second, the juxtaposed belts of metasedimentary and igneous rocks south of the caldera parallel the profile direction so that gravity effects due to bedrock density contrasts tend to be minimized. For comparison we show calculated profiles for a sequence of disc-shaped bodies [*Nettleton*, 1942] in Figures 5*c*, 5*d*, and 5*e*. The point of common reference is the edge of the caldera.

Figure 5*c* is the gravity profile over two concentrically arranged discs where the top of the upper disc coincides with the ground surface; the upper disc is 8 km in radius and 1.2 km thick, and the lower is 6 km in radius and 1.2 km thick. The representation of the caldera fill by the discs is sufficiently accurate for a close quantitative examination of the gradients outside the caldera boundary. Figures 5*d* and 5*e* are profiles of discs with radii of 8 km and maximum gravity amplitudes of about 10 mGal, tops being located at 6- and 10-km depth, respectively.

Comparing the profiles discloses that the interval 6–12 km of the measured profiles (Figures 5*a* and 5*b*) matches the same interval of profile *c* much more closely than that of profiles *d* and *e*; in fact, the gradients of the measured profiles are somewhat more steep than that of profile *c*. This comparison demonstrates that a major part of the observed anomaly must be caused by a shallow source as simulated by the discs of Figure 5*c*, in other words, the caldera fill. The overwhelming effect of the shallow caldera fill precludes separating the effects of deep and shallow sources in the interval 0–10 km, that is, from the center of the caldera to about 2 km beyond its boundary.

Apparently, the critical interval in which to seek evidence of a deep source for a feature of the size and geometry of the Long Valley caldera is 10–12 km, or 2–4 km beyond the caldera boundary. As shown in Figure 5*c* (the disc model of caldera fill), the calculated gradient for a shallow source in the interval 10–12 km is about 1 mGal/km; moreover, the amplitude at 12 km is 1.5 mGal, or roughly 4% of the maximum amplitude. The gravity gradients in the interval 10–12 km for the deep sources of the model profiles *d* and *e* are both about 0.6 mGal/km, but the amplitudes at 12 km are about 30% and 50% of maximum for *d* and *e* respectively.

In the uppermost measured profile (Figure 5*a*) the apparent gradient from 10 to 12 km is nearly 7 mGal, or about 3.5 mGal/km. The dashed part of the profile, however, is estimated from nearby stations, and the well-established part of the profile centered around 10 km is along a moderately wide valley where alluvial fill may be significantly affecting the gradient. We therefore view the gradients of this profile as possibly suspect. The second measured profile along Laurel Creek has a gravity change of 3 mGal between 10 and 12 km, yielding a gradient of about 1.5 mGal/km. This value is 50% larger than that calculated for a shallow source (profile *c*) and is considered to be significant.

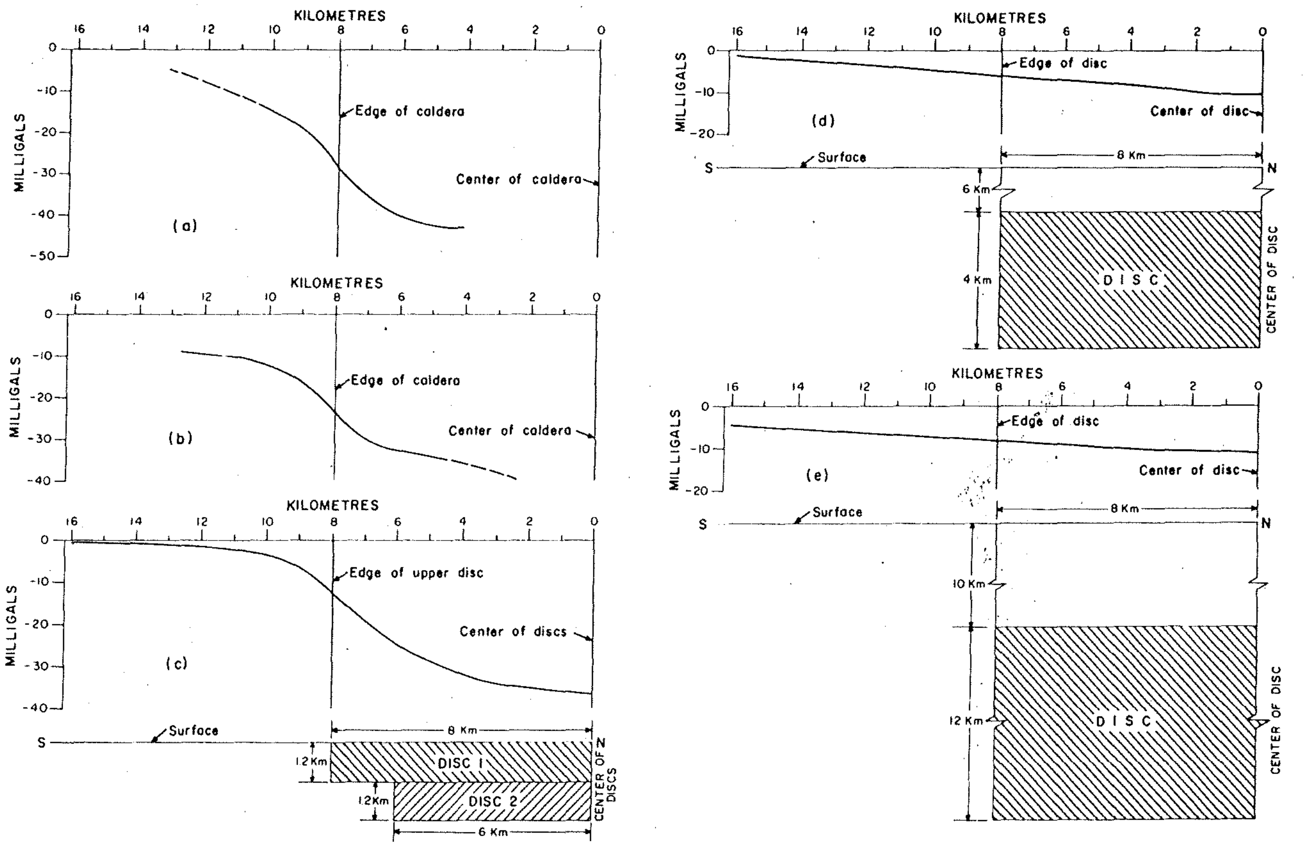

Fig. 5. Measured and calculated gravity profiles over edge of caldera: (*a*) measured gravity profile over south edge of caldera along Convict Creek, (*b*) measured gravity profile over south edge of caldera along Laurel Creek, (*c*) calculated gravity anomaly over edge of two circular, concentrically arranged discs centered at zero (both discs have a density contrast of 0.45 g/cm^3), (*d*) calculated gravity anomaly over edge of circular disc centered at zero (disc has density contrast of 0.45 g/cm^3), and (*e*) calculated gravity anomaly over edge of circular disc centered at zero (disc has density contrast of 0.45 g/cm^3).

From these observations we draw four conclusions. (1) A source about 8 km in radius constrained above 3-km depth and with an amplitude of about 40 mGal should not exhibit a gradient steeper than about 1 mGal/km in the interval 2–4 km beyond the boundary of the source. (2) When the shallow-source steep gradients are integrated over the length of the profile inside and near the caldera boundary, they account for most of the amplitude, and so only a small fraction of that part of the anomaly can be attributed to a deep source, say, less than 10 mGal. (3) Because of the limit on amplitude for a deep source the corresponding deep-source gradient should not exceed 0.6–0.9 mGal/km in the interval 2–4 km beyond the caldera boundary. (4) Therefore a well-established gradient of 1.5–2.0 mGal/km in the interval 2–4 km beyond the caldera is evidence of a deep source. As shown by profiles *d* and *e*, a more direct measure of a deep source would be the observation of a persistent gradient of about 0.5 mGal/km in the interval 12–16 km, or a one-half to full radius beyond the caldera edge. Data in this region were not available for measured profiles *a* and *b* (Figure 5).

Profiles *a* and *b*, if taken at face value, indicate a deep source, although the dashed gradient for measured profile *a* is obviously much too large. The gradient of profile *b* is what would be predicted for a combined shallow source of about 35-mGal amplitude and a deep source of 10-mGal amplitude. Both profiles, however, should be viewed with some caution because they were measured along valleys underlain by an undetermined amount of alluvial fill. Terrain corrections were made for both profiles, but the stations are in relatively high terrain where accuracy of the terrain correction tends to fall off. Despite these reservations we feel that it is reasonable to conclude that the data indicate a deep source perhaps centered at a depth of 8–16 km causing an anomaly of about 10 mGal. Because of the depth, the thickness and density contrast parameters of the body cannot be separated with any precision.

In reviewing Figure 1 in light of the comments about profiles *d* and *e* (Figure 5) it can be seen that a definite gradient appears to persist beyond 4 km from the caldera boundary, particularly on the north. If bedrock density variation is not a factor, this gradient may also be taken as evidence of a deep low-density mass which might be a magma chamber or a pluton.

In general, the gravity evidence of a deep source is sketchy but affirmative. Additional field measurements in key areas outside the caldera and a fuller evaluation of the effect of variable density in the bedrock are needed to substantiate fully the tentative conclusions drawn here.

If it is assumed that all of the caldera fill originates from the immediate vicinity of the caldera (including volcanic material derived from the subsurface), then the porosity volume causing the negative gravity anomaly is an approximate measure of absent subsurface mass. Using Gauss' theorem, we calculate that the mass corresponding to the integrated negative anomaly (Figure 2) is 3.33 × 10^{17} g. For a rock density of 2.67 g/cm^3 we calculate 125 km^3 for empty pores and 200 km^3 for pores filled with water. Our estimate of absent subsurface material is much less than *Pakiser*'s [1961] because we have restricted our integration to the anomaly in the immediate vicinity of the caldera. Much of the difference between the two figures would be attributed by us to the deep source.

MAGNETICS

The low-level magnetic survey (Figure 6) defines two major magnetic anomalies in Long Valley, a broad magnetic high present over much of the northeastern part of the valley and a rather complex magnetic low in the southwest in the vicinity of Casa Diablo hot spring. *Pakiser et al.* [1964, p. 41] estimated that a broad magnetic mass approximately outlined by the 1750 gamma contour underlies the area at a depth of about 1 km. In commenting on the two positive closures superposed on the broader high, they postulate two possible causes: The first is 'rock of intermediate magnetic susceptibility into which have been intruded, or from which have been segregated, the two smaller bodies composed of more highly magnetic rock.' The second, 'an alternative interpretation, which is preferred by the writers and is more consistent with the gravity data, would regard the smaller more highly magnetic masses as volcanic necks that were sources of a sequence of flows that express the broader feature.' In general we would agree with *Pakiser et al.* [1964] in their preference of the latter alternative and would further add that the magnetic mass appears to be bound on the west by the projected Hilton Creek fault.

Pakiser et al. [1964] did not interpret the low at Casa Diablo hot spring. The tightened contours in several places show gradients that indicate a near-surface source. The source could be reversely magnetized volcanic rock or possibly rock in which the magnetite has been altered by hydrothermal solutions. Because of the proximity of the anomaly to known hot springs and an approximately coextensive resistivity low [*Stanley et al.*, 1976] the interpretation as a zone of alteration is thought to be the more likely one.

The higher level of the regional survey (Figure 7) provides a somewhat different perspective of the magnetic anomalies. The outlines of the caldera are indicated by a change in magnetic gradients across the caldera boundary, lower gradients being present over the caldera where the magnetic rocks are farther below the flight level of the survey. The magnetic high in the northeast part of the valley has a similar form on both surveys

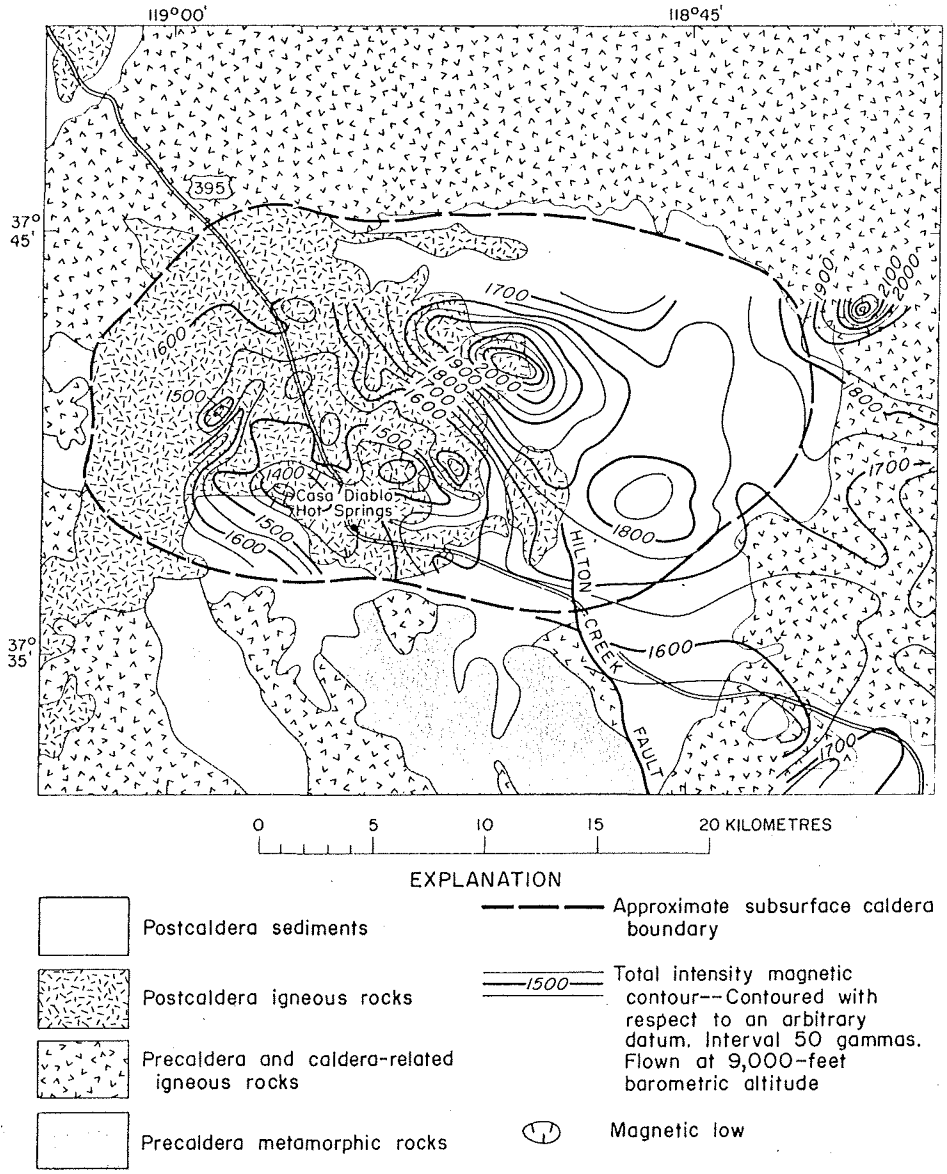

Fig. 6. Combined generalized geology and low-level total magnetic intensity map of Long Valley caldera. Magnetic contours from *Pakiser et al.* [1964].

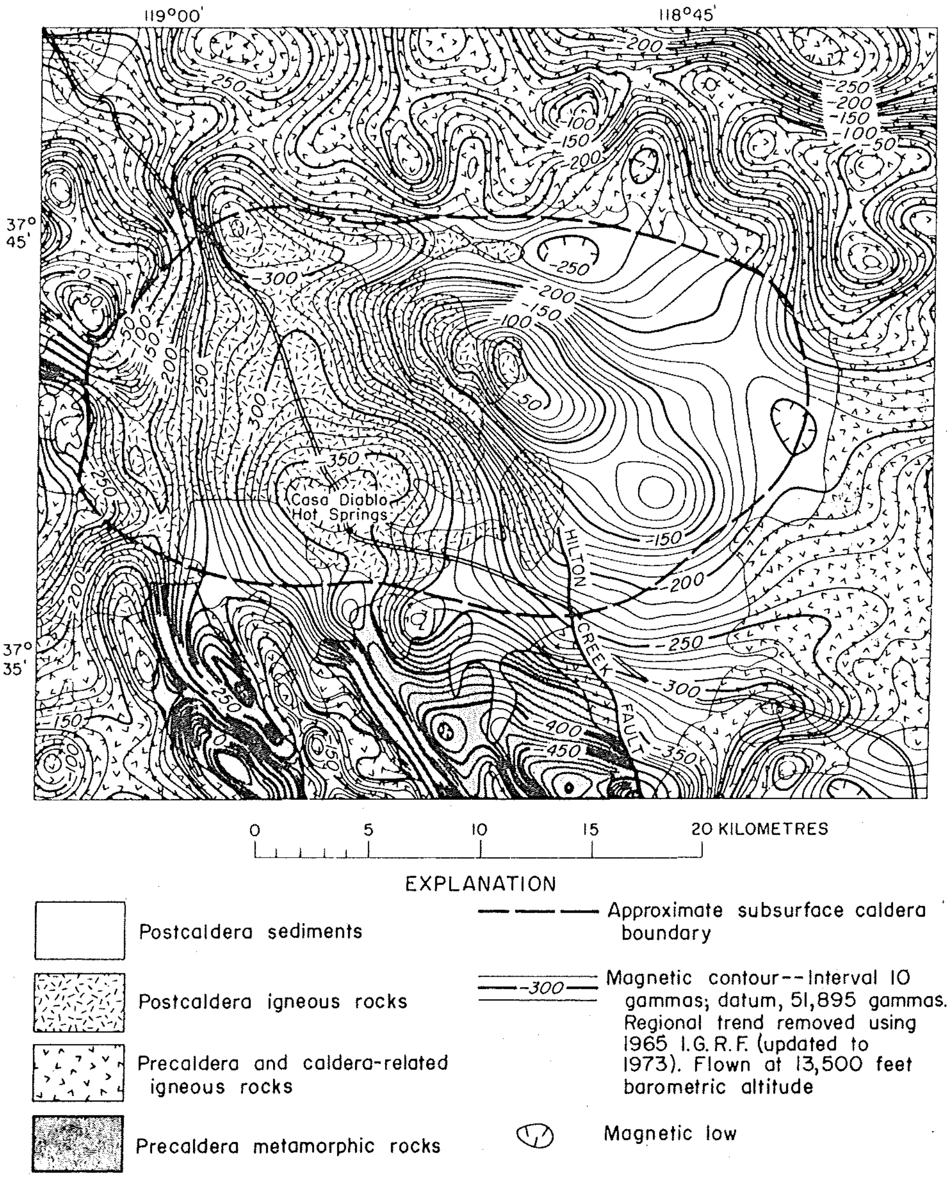

Fig. 7. Combined generalized geology and high-level residual magnetic intensity map of Long Valley area [*U.S. Geological Survey*, 1974].

because the dimensions of the source are large in comparison with the aircraft height above source. The near-surface anomaly at Casa Diablo hot spring, in contrast to the magnetic high, merges into a more intensive regional low on the higher-level survey. The regional feature, in contrast with the local low shown on Figure 6, extends to the north and south beyond the margins of the valley. To the south the regional low coincides with the belt of metasedimentary rocks enclosed within the granitic rocks of the Sierra Nevada batholith, suggesting that the western floor of the caldera may be underlain primarily by a belt of metasedimentary rocks.

SUMMARY

The regional gravity and magnetic surveys of Long Valley illustrate a type of reconnaissance exploration for geothermal systems in the western United States. They show that large features, like calderas, are clearly identified and that much information about the structure of the features can be derived from the geophysical data. The calculated anomalies reveal that evidence for deep sources, perhaps more directly linked to a primary geothermal source such as a magma chamber, must be sought in a region well outside any surface feature. The evidence for a deep source at Long Valley is marginal but affirmative and indicates that a deep source may be detectable by the gravity method under the right conditions, that is, where near-surface gravity variations do not mask the somewhat subtle but persistent gradients caused by the deep source. The calculations also show that the depth of the source is related to the extent of the gradient; i.e., a deeper source will cause the gradient to persist over a larger area. For sources deeper than several kilometers it is probably not possible to separate the thickness and density contrast parameters of a body with any degree of precision. The mass contrast of the body, however, is calculable from Gauss' theorem if the anomaly is reasonably well defined. If the density contrast can be estimated from theoretical or experimental data, then the volume of the postulated magma can be derived. Perhaps the most important point to be made from the calculations is that careful gravity surveys must be conducted over a broad region around a postulated deep source before substantive conclusions are made about its presence.

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