Gravity evidence for a shallow intrusion under Medicine Lake volcano, California

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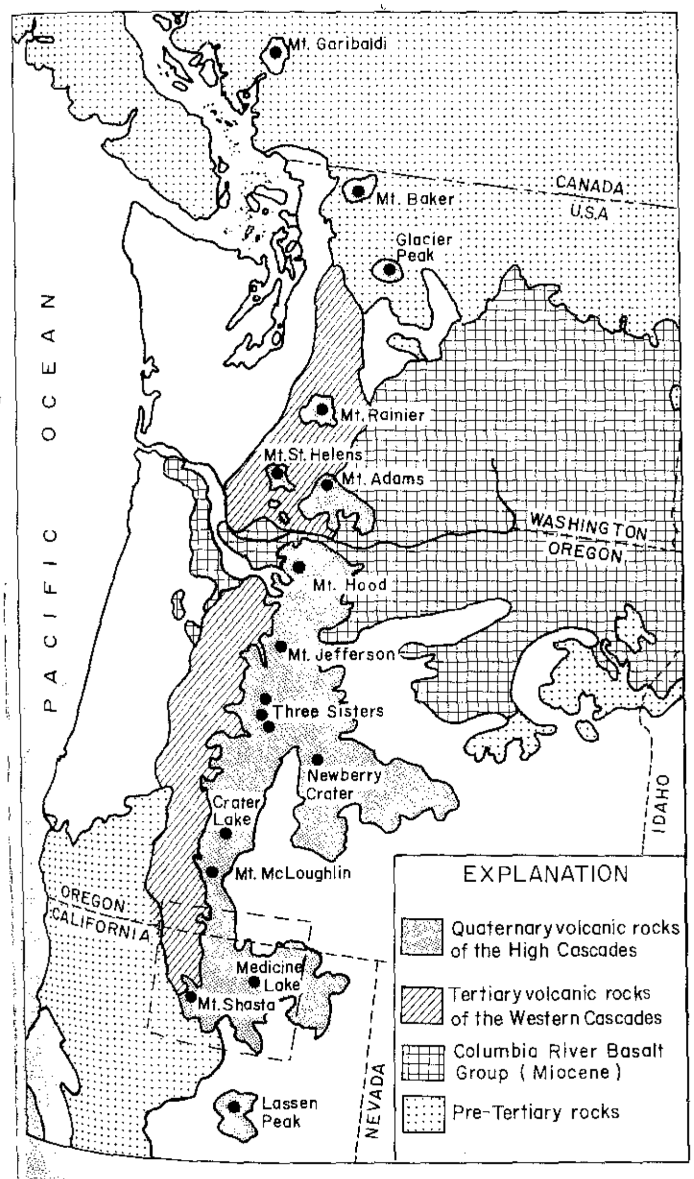


Figure 1. Index map (adapted from McBirney, 1968). Dashed rectangle indicates area of Figure 4.

ABSTRACT

A positive gravity anomaly is associated with Medicine Lake volcano, California. Trials with different Bouguer reduction densities indicate that this positive anomaly cannot be explained by an inappropriate choice of Bouguer reduction density but must be caused by a subvolcanic body. After separating the Medicine Lake gravity high from the regional field, we were able to fit the 27-mgal positive residual anomaly with a large, shallow body of high density contrast (+0.41 g/cm^3) and a thickness of 2.5 km. We interpret this body to be an intrusion of dense material emplaced within the several-kilometres-thick older volcanic layer that probably underlies Medicine Lake volcano.

INTRODUCTION

The complete Bouguer gravity map of California (Alturas sheet; Chapman and Bishop, 1968) shows a positive anomaly associated with Medicine Lake volcano. The volcano, a shield with a central caldera, has erupted basalt, andesite, dacite, and rhyolite over a period of about 1 m.y. (Anderson, 1941; Mertzman, 1981; J. Donnelly-Nolan, 1981, oral commun.). Older, probably Tertiary to early Pleistocene, basalts are exposed in fault scarps (J. Donnelly-Nolan, 1982, written commun.) and appear to make up a 2- to 3-km-thick volcanic layer that partially underlies the flanks of the volcano (LaFehr, 1965; Stanley, 1982). Medicine Lake volcano is located on the boundary between the Basin and Range province and the High Cascades (Fig. 1). Many geologic and petrologic studies have been done in the area (Anderson, 1941; Powers, 1932; Eichelberger, 1975, 1980; Heiken, 1978; Condie and Hayslip, 1975; Mertzman, 1977, 1981; Donnelly-Nolan and others, 1981). Geophysical work includes a regional gravity survey (LaFehr, 1965; Finn and Williams, 1981) and aeromagnetic (unpub. data), heat-flow (Mase and others, 1980, 1982), seismic-refraction (Zucca and others, 1981; Catchings, 1982), and magnetotelluric (Stanley, 1982) studies. Additional geologic work is now being done by Donnelly-Nolan on Medicine Lake volcano (Donnelly-Nolan and others, 1981) and by R. L. Christiansen in the adjacent volcanic terrain to the west. These studies were conducted by the U.S. Geological Survey as part of its Geothermal Program.

Four hundred and seventy-five new gravity stations, including 250 stations collected by Finn (1981a, 1981b), were obtained to fill in critical areas in the regional coverage. The entire data set includes 2,200 stations and covers an area of 2,300 km^2. The average station spacing between gravity readings on the Medicine Lake 15′ topographic quadrangle is less than 1 km.

DENSITY DETERMINATION

A critical problem in reducing gravity data in volcanic terrain with high relief is the choice of the Bouguer reduction density. This density is used to remove the gravitational effects of topography. We believe that the topographic edifice of Medicine Lake volcano has a low average density. At the surface of the volcano are large amounts of pumice and numerous interbedded, commonly blocky flows, of compositions varying from basalt through rhyolite. We do not know whether the entire volcano is made of volcanic rocks proportionately similar to those observed at the surface or whether it may contain significantly more basalt or more rhyolite at depth. In either case, the density of the volcano is further diminished by jointing and spaces between blocks and particles in the flows, by vesiculation, and by the presence of pyroclastic material. Hydrologic evidence suggests that the edifice is porous and therefore of relatively low density: water does not flow off the surface of the volcano but soaks into it and flows out at a distance as springs.

A standard procedure in the reduction of regional gravity data is to use a density of 2.67 g/cm^3 to represent the average topographic density. Most volcanic edifices, however, are composed of rocks of lower average density. The result of using the standard 2.67 g/cm^3 as the Bouguer reduction density is overcorrection for the topographic expression of the edifice, which produces a gravity low mimicking the topography of the volcano, if there are no subsurface density contrasts. In other words, the correct reduction density ought to remove any anomaly and leave a flat Bouguer gravity field in the absence of any subsurface density contrasts. A method to determine the most appropriate Bouguer reduction density for a topographic feature (Nettleton, 1939) selects the reduction density by reducing the data at different densities and choosing the density for which the Bouguer anomaly values have a minimum correlation with topography. It is usually assumed in this method that a correlation does not exist between topography and subsurface density contrasts. Although a gravity high is associated with a subvolcanic source at Medicine Lake volcano, we were still able to apply this technique. The "wavelengths" of the topography and the underlying source are sufficiently different to allow visual separation of the two effects and to observe how the part of the gravity anomaly correlated with topography changes with density. Woollard (1951) used this same "modified" Nettleton method to estimate the density of 2.3 g/cm^3 for Oahu.

Figure 2 shows a topographic profile and a series of corresponding Bouguer gravity profiles reduced at different densities for Medicine Lake volcano. The profile reduced at 2.67 g/cm^3 has a narrow high superimposed on a broad gravity low extending from 22 to 60 km, which correlates inversely with terrain. This indicates that we have overcorrected for the mass of the edifice. The sides of the low almost flatten out at 2.43 g/cm^3 in Figure 2, and the terrain effect of the edifice disappears at 2.2 g/cm^3. At lower reduction densities (2.0 g/cm^3, 1.9 g/cm^3, 1.8 g/cm^3), the effect of the terrain again is evident as a positive correlation between gravity and topography. Applying this method to many profiles, we chose a Bouguer reduction density of 2.2 g/cm^3. Because the amplitude of the high does not change too much within a small range of densities (± 0.1 g/cm^3), other values close to 2.2 g/cm^3 could be used without significantly altering the results. Too great a deviation from this value, however, will lead to a blending of the gravity high with topographic effects, which results in an alteration of the primary shape and amplitude of the anomaly.

ANOMALY SEPARATION

Although the positive gravity anomaly at Medicine Lake volcano is clearly apparent on the complete Bouguer map (Fig. 3), it is superimposed on other anomalies (the regional field) associated with larger scale features. It is necessary for modeling purposes to separate the local Medicine Lake anomaly from these regional ones. The regional field has two major components: a large, roughly circular gravity low near Medicine Lake volcano, perhaps caused, in part, by an older low-density volcanic layer (LaFehr, 1965), and an eastward decrease of the field attributed to thickening of the continental crust in the same direction (LaFehr, 1965). LaFehr (1965) first noted the gravity low; Heiken (1976), in a study of the satellite imagery, recognized a corresponding circular topographic depression. The combined effect of these two sources is seen in Figure 3 as a large, roughly circular low where the gravity values to the east are lower than those to the west. For this study, it is unnecessary to separate these two components, and we have dealt with them as a single regional field. To remove this field, we assume the continuity of the large, circular low through the region of the Medicine Lake gravity high. The regional field was produced by "visually" removing the Medicine Lake gravity high and extending the regional contours through the Medicine

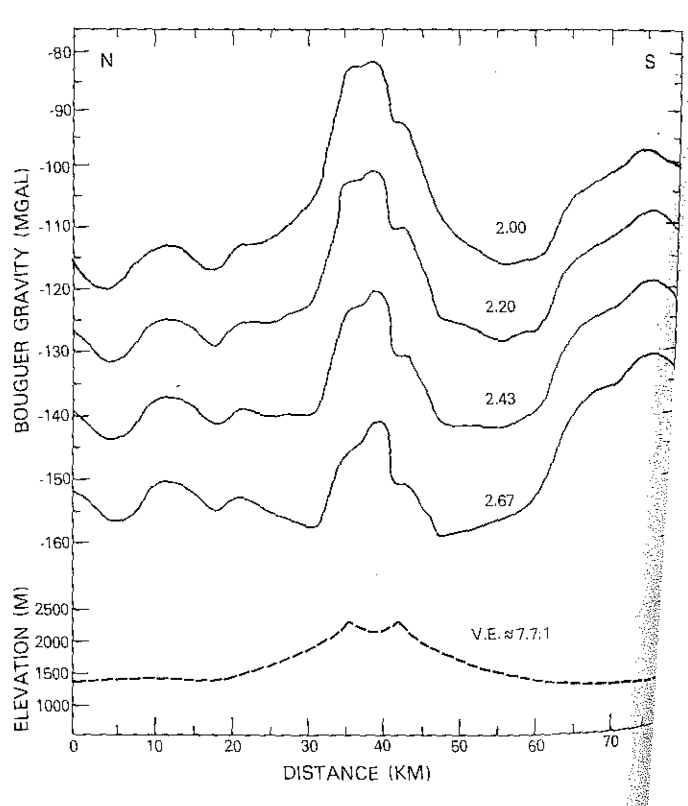


Figure 2. Topographic and Bouguer gravity profiles at Medicine La volcano, California. Dashed line indicates topography (from terrain data digitized from AMS 2° sheets with a 15" grid spacing); solid li indicates Bouguer anomaly. Bouguer reduction densities are marke g/cm^3. V.E. = vertical exaggeration. Topography is generalized. L tion of profile is shown in Figure 3; profile is north-south. Low asso ciated with topography extends approximately from 22 to 60 km a easily seen on 2.67 g/cm^3 profile. From this profile we might selec either 2.43 or 2.2 g/cm^3 as best reduction density.

Lake region. Although this process is subjective and nonunique (Vajik, 1951), removal of alternate regionals, such as one produced by a second-order polynomial surface fitted to the data, does not change the basic shape of the Medicine Lake residual.

In addition to removing this regional field, we also separated the northeastern positive gravity anomaly (marked Mammoth Siding in Fig. 3) from the gravity high directly over Medicine Lake volcano. We believe that this other anomaly is too far away from Medicine Lake volcano to be associated with it. It may be related to basalt volcanism in the area (LaFehr, 1965), or to intrusive rocks underlying the surface lavas, or to lateral density changes within the volcanic rocks (Chapman and Bishop, 1968).

Subtracting the regional from the complete Bouguer gravity field (Fig. 3) gives the Medicine Lake volcano residual anomaly shown in Figure 4a. It is important to note that all the assumptions made about the regional field have a geologic implication. By drawing the edges of the large low through the Medicine Lake high, we imply that the edge of the source of the regional low partially underlies Medicine Lake volcano. Geologically, this means that the older low-density volcanic layer that may be the source of

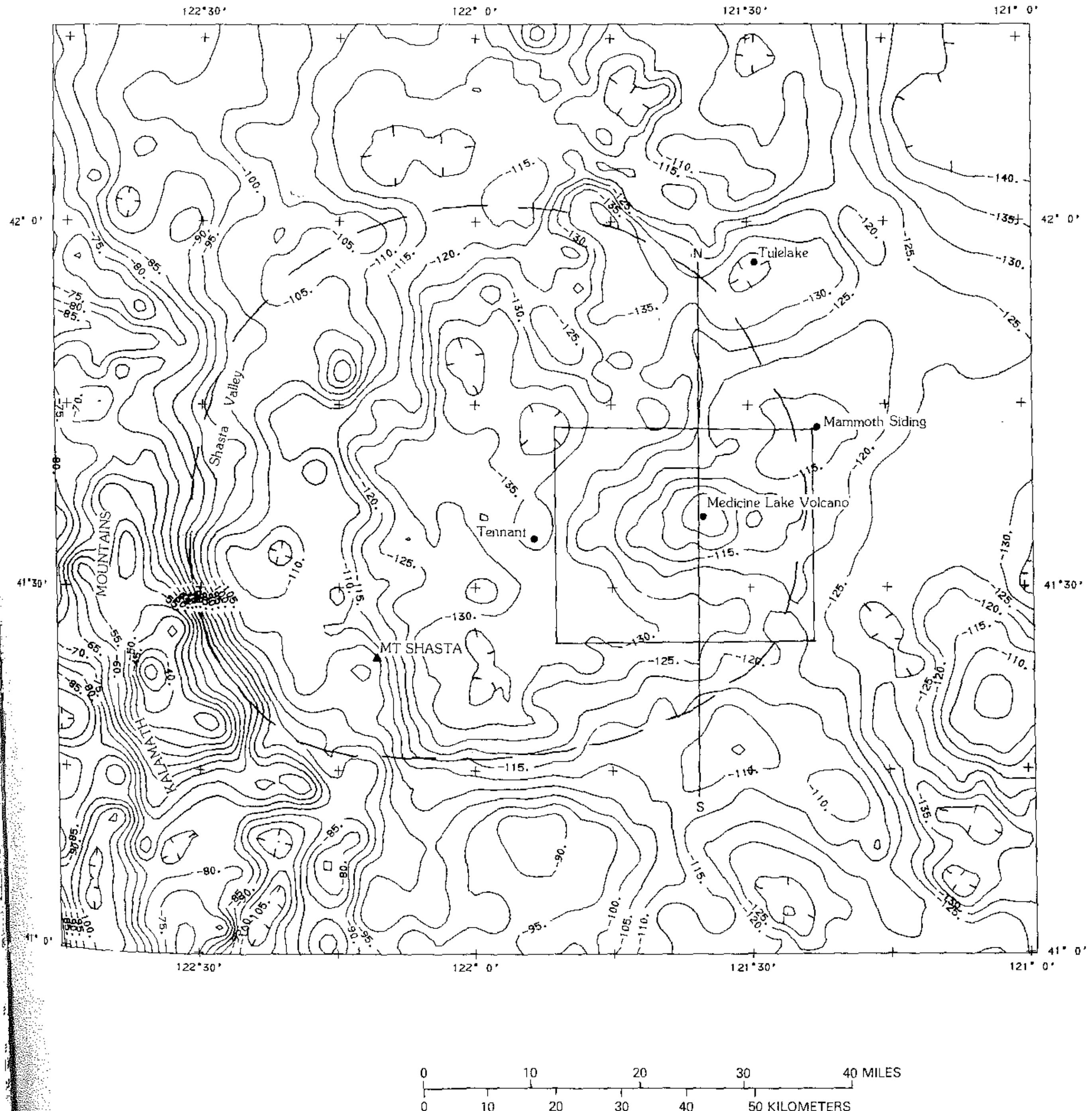


Figure 3. Complete Bouguer gravity map of area near Medicine Lake and Mt. Shasta, California, reduced at density of 2.2 g/cm^3, and contoured at 5-mgal interval. Hachures indicate gravity lows. Dashed circle outlines shape described by LaFehr (1965) and Heiken (1976). North-south line indicates profile in Figure 2; rectangle is area shown in Figure 4.

the regional gravity low (LaFehr, 1965) partially underlies Medicine Lake volcano. This layer, which we will call the volcanic layer, may be composed of older (Tertiary to Pleistocene) basalt flows. It is electrically more conductive (Stanley, 1982), has a higher seismic velocity (around 4.5 km/s, estimated by us, by Zucca and others [1981], by Catchings [1982]), and probably a higher density (about 2.4 to 2.5 g/cm^3 [LaFehr, 1965]) than the material in the edifice. The bottom of the volcanic layer in the area enclosed by the large gravity low was estimated to be about 1.5 to 2 km below sea level by LaFehr (1965, p. 5593–5594), using gravity data. He chose a density contrast for his model based on field observations and put the top of the body at sea level; these restrictions led to his depth for the bottom. Stanley (1982) derived the same depth using magnetotelluric data. The top of the layer was modeled by Stanley (1982) to be 0.5 to 1.0 km above sea level for the same region. The Medicine Lake caldera floor is at an elevation of 2.1 km.

MODELING

Before quantitatively estimating a source for the Medicine Lake residual anomaly, we employed constraints from other methods because gravity data cannot be used to uniquely define structures. Although gravity data can yield useful information about the source, more than one source configuration can produce a similar gravity anomaly at the surface. To minimize this ambiguity we used magnetotelluric data available for Medicine Lake volcano which may bear on the geometry of the gravity source body.

Magnetotelluric soundings (Stanley, 1982) show that a resistive body (> 100 ohm/m) lies 1.5 km below the caldera in a position that makes it a plausible source body for the gravity anomaly. The location of a source at that depth implies that the body lies within the volcanic layer described above. Because we assumed that the body lies within this layer, we inferred that the principal density contrast causing the gravity anomaly is associated with the body and this volcanic layer. Therefore, we fixed the bottom of the modeled source at an elevation of -2 km, or 4 km below the surface (approximately the bottom of the volcanic layer) and assumed that the density contrast below this was negligible. In other words, the intrusive body may continue to greater depth (indicated by question marks in Fig. 4b), but it cannot be observed in the gravity data. The magnetotelluric and geologic data allow us to estimate the vertical extent and possible thickness (about 2.5 km) of the source body, thereby allowing us to constrain the model and to determine other parameters of the body such as its mass. In order to determine a mass distribution that fits the residual gravity anomaly and satisfies the constraints, we used a three-dimensional computer modeling program (Cordell and Henderson, 1968). The resulting model (Fig. 4b) has a density contrast of +0.41 g/cm^3, and lies between elevations of 0.5 and -2 km. Because we constrained the top and bottom of the model, the density contrast had to be 0.41 g/cm^3. The body in plan view has a diameter of about 9 km at the top and broadens at the base to a 20- by 36-km ellipse elongated east-west. The mass excess represented by the model is 2.0×10^{17} g. The vertical dashed lines on the cross section in Figure 4b indicate our guess at the location of the edges of the major source of the gravity high. For this study, we restricted our interpretation to the main features of this source and did not analyze the "short-wavelength components" of the residual gravity field.

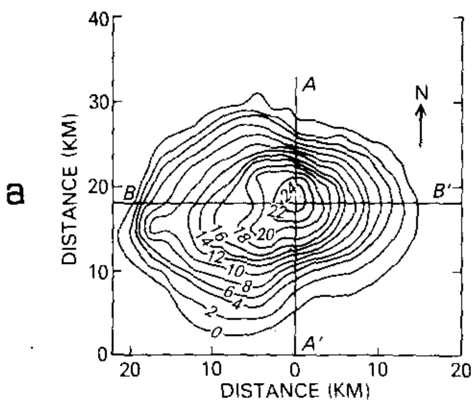
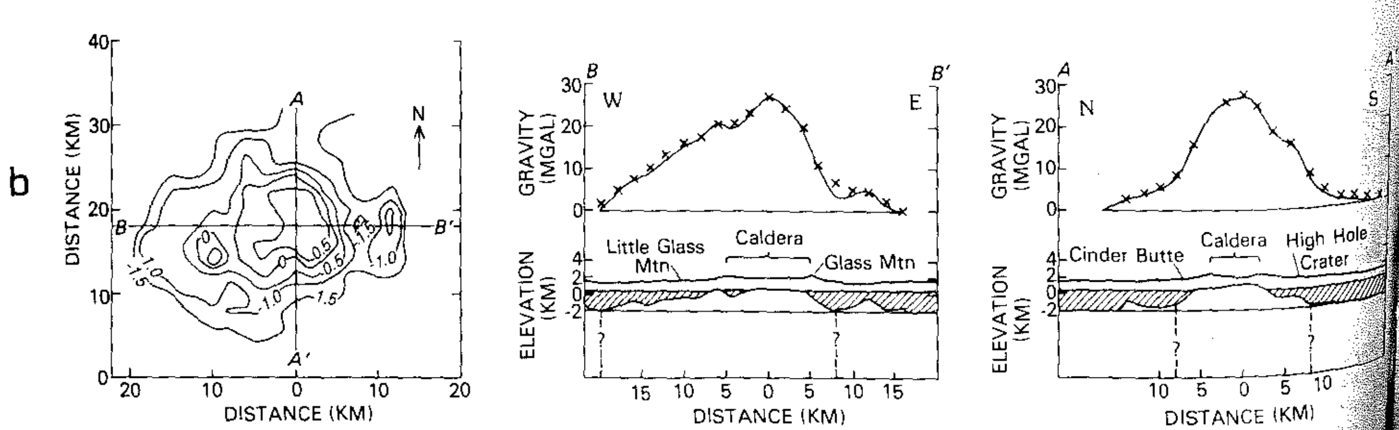


Figure 4. a: Residual gravity anomaly obtained by subtracting regional gravity contours from original complete Bouguer gravity map (Fig. 3). Contoured at 2 mgal. A–A' and B–B' are locations of profiles in b. b: Modeled body in plan and profile view and calculated versus observed gravity in profile. Plan view of body is contoured at 0.5-km interval. Depths are relative to sea level (caldera is at 2 km above sea level). A–A' and B–B' are topographic and residual gravity profiles. Stippled pattern marks edifice of Medicine Lake volcano. Striped pattern marks volcanic layer. Solid line on gravity profile indicates observed residual gravity, Xs indicate calculated gravity. Bottom of model is shown by solid horizontal line at 2 km depth. Inferred edges of intrusion are marked by vertical dashed lines. High Hole Crater and Cinder Butte, sources of large basaltic flows, are projected onto north-south profile. Cinder Butte lies 2 km west of profile, and High Hole Crater is 2 km east of it. Glass Mountain and Little Glass Mountain are rhyolitic flows.



INTERPRETATION OF THE MODEL

We suggest that the major source of the gravity high is intrusive material within the volcanic layer. This is supported by the magnetotelluric data, which indicate the presence of a resistive body; young intrusions are often very resistive. We have given the modeled body a shallow bottom, which can be explained in one of two ways: (1) the intrusive material may not extend below the bottom of the volcanic layer but may dwindle off to small feeder dikes below it; (2) alternatively, the body may extend deeper but with a very small density contrast with the country rock, resulting in no detectable gravity anomaly.

The intrusive material under Medicine Lake volcano could be the result of a single intrusive episode but more likely was built up throughout the history of the volcano by the addition of some of each new magma injection to older ones. Another interpretation of the modeled body would include other material besides intrusions—for example, dikes combined with a metamorphosed part of the volcanic layer. The metamorphism would be related to the intrusion of dikes and would increase the density of the volcanic layer. However, the high resistivity of the body probably indicates that it is mostly intrusive material, because extensive metamorphism and hydrothermal alteration would increase the conductivity of the body.

We could have also fit the residual anomaly with a layered body, representing a differentiated magma chamber, but the gravity data do not allow us to discriminate between a homogeneous and a heterogeneous body or bodies.

Seismic refraction studies, which include work by us as well as Zucca and others (1981) and Catchings (1982), show a travel-time advance over Medicine Lake volcano indicating the presence of a shallow, high-velocity body with approximately the same dimensions and shape of the modeled gravity source body. No large low-velocity zones that might be associated with magma are seen in the data. Electrical studies (Stanley, 1982) do not show a conductive anomaly that would typically be associated with a partially molten body, implying that the intrusive material is mostly solidified. It is reasonable, however, to assume that part of the body is still hot, possibly molten, because of the presence of several young (about 1,000 yr old) silicic domes and basaltic flows and a fumarole with a near-boiling temperature (J. Donnelly-Nolan, written commun.) near the caldera rim.

From the gravity data alone it is difficult to determine whether the intrusive material is mafic, intermediate, silicic, or some combination of these. If the volcanic layer has a density of 2.4 or 2.5 g/cm^3 (LaFehr, 1965) and if the intrusion has a density contrast of 0.41 g/cm^3, we obtain a density of 2.81 to 2.91 g/cm^3 for the intrusion. These values are too high for felsic rocks but are appropriate for mafic or intermediate rocks.

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