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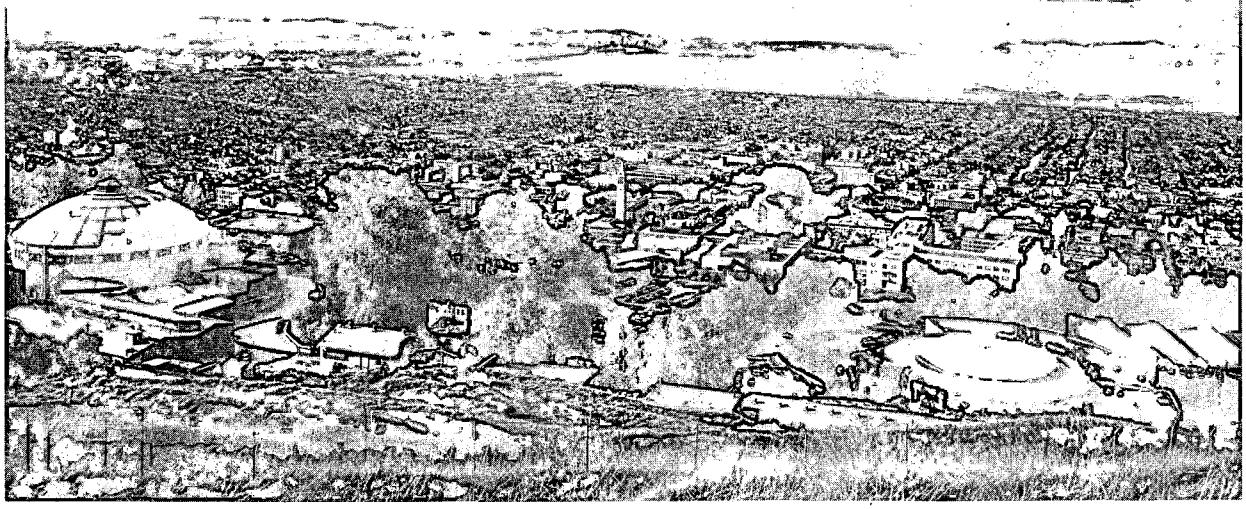

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A Three-Dimensional Gravity Model of the Geologic Structure of Long Valley Caldera

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Introduction

Long Valley caldera originated around 0.73 Ma upon the eruption of the Bishop Tuff, an extensive ash-flow tuff (Bailey et al., 1976). Collapse of the roof over the magma chamber associated with the Bishop Tuff and subsequent volcanic resurgence have formed what is now an elliptical caldera measuring 29 km west-east by 15 km south-north, and having a maximum subsidence of 3.5 km. In addition to the Bishop Tuff, the caldera has been filled with the flows, dikes, and tuffs of resurgent volcanism, which has continued episodically up to recent time. Significant volumes of lake sediments, glacial till, alluvium, and reworked volcanics have been deposited in the caldera. The rocks of the caldera fill attain a maximum thickness of about 2.8 km, and because most of these rocks are less dense than the pre-caldera "basement" of granitics, metasediments, and metavolcanics, a gravity low of -50 mGal coincides with the caldera.

Several attempts to define and interpret this anomaly have been made in the past using 2-D and 3-D models (Kane et al., 1976; Abers, 1985). None of the previous interpretations have yielded definitive results, but in fairness, the interpretation here has benefited from a larger gravity data base and more subsurface control than available to previous workers. All published 3-D models simplistically assumed constant density of fill. All 2-D models suffered from the inherent three-dimensionality of the complicated density structure of Long Valley caldera. In addition, previous interpreters have lacked access to geological data, such as well lithologies (Benoit, 1984; Farrar et al., 1985; Smith and Rex; Suemnicht, 1986) and density logs, seismic refraction interpretations (Hill et al.,1985), surface geology (Bailey and Koeppen, 1977), and structural geology interpretations (Hill et al., 1985; Bailey et al., 1976). The purpose of this study is to use all available gravity data and geological information to constrain a multi-unit, 3-D density model based on the geology of Long Valley caldera and its vicinity. Insights on the geologic structure of the caldera fill can help other geophysical interpretations in determining near-surface effects so that deeper structure may be resolved. With adequate control on the structure of the caldera fill, we are able to examine the gravity data for the presence of deeper density anomalies in the crust.

Defining the Gravity Anomaly Associated with the Caldera

The gravity data set consists of 2026 stations from the U.S.G.S. and 473 stations contributed by Unocal Geothermal. All gravity measurements were reduced to Bouguer gravity (see Figure 1) using a terrain density of 2.67 g/cm^3, a good approximation of the average density of the crystalline

basement rocks in the region. About 900 of these stations are located within the model region, between 119° 9' W and 118° 35' W and between 37° 32.25' N and 37° 49.25' N, and the rest provide regional control. The regional gravity is strongly influenced by isostatic thickening of the crust associated with the Sierra Nevada mountains. The gravitational effect of a best fitting Airy isostatic model, having the parameters of sea level crustal thickness of 18 km and Moho density constrast of 0.55 g/cm^3, accounts for the regional gravity (see Figure 2). A range of Airy parameters were tried. The criteria for best fit was based on removal of the regional gravity trend correlated with regional topography and convergence of the residual gravity (see Figure 3) towards zero over outcropping basement rocks of density near 2.67 g/cm^3 (H. W. Oliver, written commumication, 1987; Blakely and McKee, 1985).

The Modelling Technique

All of the gravity modelling was done three-dimensionally because of the complex geological structure. The model consists of a grid of rectangular prisms with a horizontal cross section of about 1.4 km on a side and bounded vertically by the surface topography and the subsurface model structure. The model consists of 23 constant density units corresponding to the major geological units. Some geologic units defined by Bailey and Koeppen (1977) were combined for lack of resolution or simplicity. Each prism consists of a stack of the units with non-zero thickness. The vertical gravitational field at each grid point is computed using a cylindrical approximation to calculate the contribution of each prism (Kane, 1962). By comparing the observed and calculated residual gravity, the thickness of any number of the units may be iterated by a technique modified from the method of Cordell and Henderson (1968), so that the difference between observed and calculated gravity approaches zero. Also, the unit thicknesses may be adjusted manually (forward modelling).

The density constrasts chosen for the model units were based on well log information, laboratory analysis of core samples, and surface rock specimens (Abers, 1985; H. W. Oliver, written communication, 1987; S. J. Maione, written communication), and P-wave velocities (E. Kissling, written communication, 1986). Although the assumption of discrete density contrasts for individual geologic units is by no means exact, it is necessitated by the limited distribution of rock density measurements available, and it is far more realistic than the assumption of a constant density of fill. Because these units vary both in thickness and lateral extent, many of the features in the residual gravity can be accounted for by the distribution of units within the caldera fill, rather than by the total depth of fill, and hence the caldera structure.

The Interpretation

Most of the residual Bouguer gravity low can be accounted for by the Bishop Tuff, early rhyolite flows and tuffs, and lake sediments. Starting from an initial model, we interated the unit thicknesses by means of forward and inverse modelling until an agreeable fit between observed and calculated gravity and *a priori* information was attained. The other units are thin, or not extensive, near-surface layers whose distribution can largely be inferred on the basis of surface geology and well data. These units, including moat rhyolites, basaltic and andesitic flows, till, alluvium, and pumice, contribute to the residual gravity

and cannot be ignored. Some of the subtle features in the residual gravity were accounted for by modelling variations in the thicknesses of these units (see Figures 4,5, and 6).

By integrating the amount of vertical subsidence over the area of the model, obtaining the volume of subsidence in Long Valley caldera, we estimate that the volume of erupted magma associated with the Bishop Tuff and the resurgent volcanics is 900 km^3. Bailey et al. (1976) estimated a volume of subsidence of 800 km^3, of which 600 km^3 volume of magma was attributed to the Bishop Tuff eruption. We estimate that about 100 km^3 more Bishop Tuff is contained within the caldera than Bailey et al.'s (1976) estimate of 350 km^3. Because most of the intra-caldera Bishop Tuff is densely welded, we would add nearly 100 km^3 to Bailey et al.'s (1976) estimate of the volume of erupted magma associated with the Bishop Tuff, making our estimate of the order of 700 km^3. We can attribute most of the remaining 200 km^3 volume of subsidence to the resurgent volcanics, which we estimate corresponds to about 150 km^3 of erupted magma.

Basement Structure

In attempting to account for the residual gravity completely by caldera fill, it became apparent that part of the residual gravity is caused by anomalously low density rocks below the caldera fill, represented by a persistent misfit between observed and calculated gravity in and nearby the west side of the caldera. The required amount of fill rocks at all of the basement penetrating wells (M1, CP, 66-29, and 44-16) except for 66-29 would have to be greater then the well lithologies suggest. Over basement for several kilometers outside the caldera in the southwest and northwest, the observed gravity was consistently less than the calculated gravity, suggesting that the misfit is not due structural or density errors within the fill. Five explanations for this gravity misfit could be made, followed by arguments for or against:

1) A lack of stations outside the caldera. This analysis could benefit from better station coverage outside the caldera, however there appears to be enough data to justify the reality of the misfit. In a line of stations running up Laurel Canyon to the south of the caldera, the misfit persists (see Figure 5, upper). The Unocal data provides good control in the northwest.

2) Incorrect regional gravity. The regional gravity fits the geological data outside the caldera in three areas of geologic control: a region of granitic rocks of density near 2.67 g/cm^3 to the west and southwest of the caldera indicated by extensive surface sampling (H. W. Oliver, written communication, 1987), a region of anomalously high density basement rocks in the Benton Range to the east of the caldera indicated by high P-wave velocities in a 3-D geotomographic model (E. Kissling, written communication, 1986), and surface samples of granitics near 2.67 g/cm^3 collected in the Boundary Peak and Pellisier Flats plutons further to the east (Blakely and McKee, 1985). Within the caldera, the regional gravity is determined by the isostatic model which is consistent with the data outside the caldera. If the misfit were solely due to an error in the regional gravity correction, the crust below the caldera would appear to be isostatically overcompensated with respect to the regional control outside the caldera.

3) Density variations in the basement granitics or metasediments beneath the caldera. Density variations in basement rocks could account for the misfit (see Figure 6). Surface specimens to the immediate southwest of the caldera are consistently 2.55 to 2.65 g/cm^3 (Oliver, written communication, 1987). To explain the misfit completely by basement density variations, the basement

rocks to the south and northwest, which are downdropped within the caldera, would have to be, on the majority, less than 2.67 g/cm^3. Unfortunately, adequate sampling is not available there. Basement rocks further to the south appear to be highly variable above and below 2.67 g/cm^3. Evidence from a line of gravity stations up McGee Creek indicates anomalously dense basement rocks south of the caldera. The metasediments in this region are highly variable in composition, and could certainly be expected be highly variable in density. Thus, there is not overwhelming evidence that the basement rocks beneath Long Valley caldera are consistently less than 2.67 g/cm^3.

4) Presence of a low density silicic melt body beneath Long Valley caldera. Recent geophysical studies have implied that a silicic melt body exists beneath Long Valley caldera (Sanders, 1984; Ryall and Ryall, 1984; Hill et al. 1985; Savage and Cockerham, 1984; Rundle and Whitcomb, 1984; Denlinger and Riley, 1984). High pressure and temperature studies indicate that such a melt could have a density contrast of up to 10% with respect to its solid form (Hargraves, 1980). The computed gravitational effect of a melt body with a density contrast and configuration consistent with the above studies is not enough to account for the misfit.

5) Presence of a large low density pluton that may or may not contain residual melt. A large, silicic magma chamber existed before the eruption of the Bishop Tuff. Conceivably a large portion of this magma chamber remained after the Bishop Tuff eruption, providing the source for subsequent eruptions (Bailey et al., 1976), and may still remain, though extensively crystallized. If this crystallized magma is about 2.50 g/cm^3, a roundish, plutonic body of about 10 km width and 7 km thickness centered at -7 km elevation in the southwest-central part of the caldera can simply account for the misfit (see Figures 4,5 and 6). A residual gravity low centered near Devil's Postpile can similarly be accounted for by a low density (2.40 g/cm^3) plutonic body centered at about -5 km elevation (see Figure 4, lower).

Caldera Structure

Once the misfit was explained within the caldera, the caldera fill structure could be analyzed while maintaining lithological control at the wells and from other information. Although the cross sections (Figures 4,5 and 6) and the thickness of fill (post-caldera rocks including the Bishop Tuff) map (Figure 7) show much fine detail, more attention should be paid to the simpler, extensive features, which are most likely to be real.

Some structural features are very prominent in the thickness of fill map. The caldera area east of the extension of the Hilton Creek fault is the lowest part of the caldera floor, having a fairly uniform thickness of fill of 2-2.8 km, where the surface elevation is about 7000 feet. A trench-like feature surrounds the caldera floor to the west. The thickness of fill shallows in the south-central and southwest-central parts of the caldera.

A possible explanation of these structural features is that the pre-caldera Sierran range front extended within the caldera where the thickness of fill is now shallow. The trenches may have formed as a result of the eruption or northeastward drift of the downdropped block as it settled.

Another notable feature is the thickening of fill below the graben in the northwest near Highway 395, suggesting that the graben is associated with

deep, pre-caldera structure. The main caldera ring fractures are within the topographic boundary. In the northeast the ring fractures appear to step down over 2-3 km from the topographic boundary, consistent with ring fractures mapped on the surface (Bailey and Koeppen, 1977). The main ring fracture in the southwest is conincident with the strike of the Inyo Domes, suggesting that either the the Inyo domes chain lies on a pre-caldera fracture system, or that the Inyo domes fracture system propagated from the ring fracture.

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References

Abers, G., 1985, The subsurface structure of Long Valley caldera, Mono County, California: A preliminary synthesis of gravity, seismic, and drilling information: *J. Geophys. Res.*, v. 90, n. B5, p. 3527-3636.

Bailey, R. A., Dalrymple, G. B., and Lanphere, M. A., 1976, Volcanism structure, and geochronology of Long Valley caldera, Mono County, California, *J. Geophys. Res.*, v. 81, n. 5, p. 725-744.

Bailey, R. A., and Koeppen, R. P., 1977, Preliminary geologic map of Long Valley caldera, Mono County, California, *U.S.G.S. Open-File Map 77-468.*

Benoit, W. R., 1984, Initial results from drillholes PLV-1 and PLV-2 in the western moat of Long Valley Caldera, Phillips Petroleum Company, unpublished report.

Blakely, R. J., and McKee, E. H., 1985, Subsurface structural features of the Saline Range and adjacent regions of eastern California as interpreted from isostatic residaul gravity anomalies, *Geology*, v. 13, p. 781-785.

Cordell, L., and Henderson, R. G., 1968, Iterative three-dimensional solution of gravity anomaly data using a digital computer, *Geophysics*, v. 33, n. 4, p. 596-601.

Denlinger, R. P., and Riley, F. S., 1984, Deformation of Long Valley caldera, Mono County, California, from 1975 to 1982, *J. Geophys. Res.*, v. 89, p. 8304-8314.

Hargraves, R. B., 1980, Physics of Magmatic Processes, Princeton University Press.

Hill, D. P., Bailey, R. A., and Ryall, A. S., 1985, Active tectonic and magmatic processes beneath Long Valley caldera, eastern california: an overview, *J. Geophys. Res.*, v. 90, n. B13, p. 11,111-11,120.

Hill, D. P., Kissling, E., Luetgert, J. H.,and Kradolfer, U., 1985, Constraints on the upper crustal structure of the Long Valley-Mono Craters volcanic complex, eastern California, from seismic refraction measurements, *J. Geophys. Res.*, V. 90, n. B13, p. 11,135-11,150.

Farrar, C. D., Sorey, M. L., Rojstaczer, S. A., Janik, C. J, Mariner, R. H., Winnet, T. L., and Clark, M. D., 1985, Hydrological and geochemical monitoring in Long Valley caldera, Mono County, California, 1982-1984, *U.S.G.S. Water-Resources Investigations Report 85-4183.*

Kane, M. F., 1962, A comprehensive system of terrain corrections using a digital computer, *Geophysics*, v. 27, n. 4, p. 455.

Kane, M. F., Mabey, D. R., and Brace, R., 1976, A gravity and magnetic investigation of the Long Valley caldera, Mono County, California, *J. Geophys. Res.*, v. 81., n. 5, p. 754-762.

Oliver, H. W., 1977, Gravity and magnetic investigations of the Sierra Nevada batholith, California, *Geol. Soc. Am. Bull.*, v. 88, p. 445-461.

Oliver, H. W., and Robbins, S. L., 1982, Bouguer gravity map of California, Mariposa sheet, California Division of Mines and Geology.

Ryall, A., and Ryall, F. D., 1984, Shallow magma bodies related to lithospheric extension in the western Great Basin, western Nevada and eastern California (abstract), *Earthquake Notes*, *55*, p. 11-12.

Sanders, C. O., 1984, Location and configuration of magma bodies beneath Long Valley, California, determined from anomalous earthquake signals, *J. Geophys. Res.*, v. 89, p. 8287-8302.

Savage, J. C., and Cockerham, R. S., 1984, Earthquake swarm in Long Valley caldera, California, January 1983: Evidence for dike injection, *J. Geophys. Res.*, v. 89, p. 8315-8324.

Smith, J. L., and Rex, R. W., Drilling results from the eastern Long Valley caldera, Republic Geothermal, Inc., unpublished report.

Suemnicht, G., 1986, Results of Deep Drilling in the western moat of Long Valley, California, preliminary version, Twelfth Annual Stanford Reservoir Engineering Workshop, Stanford, California.

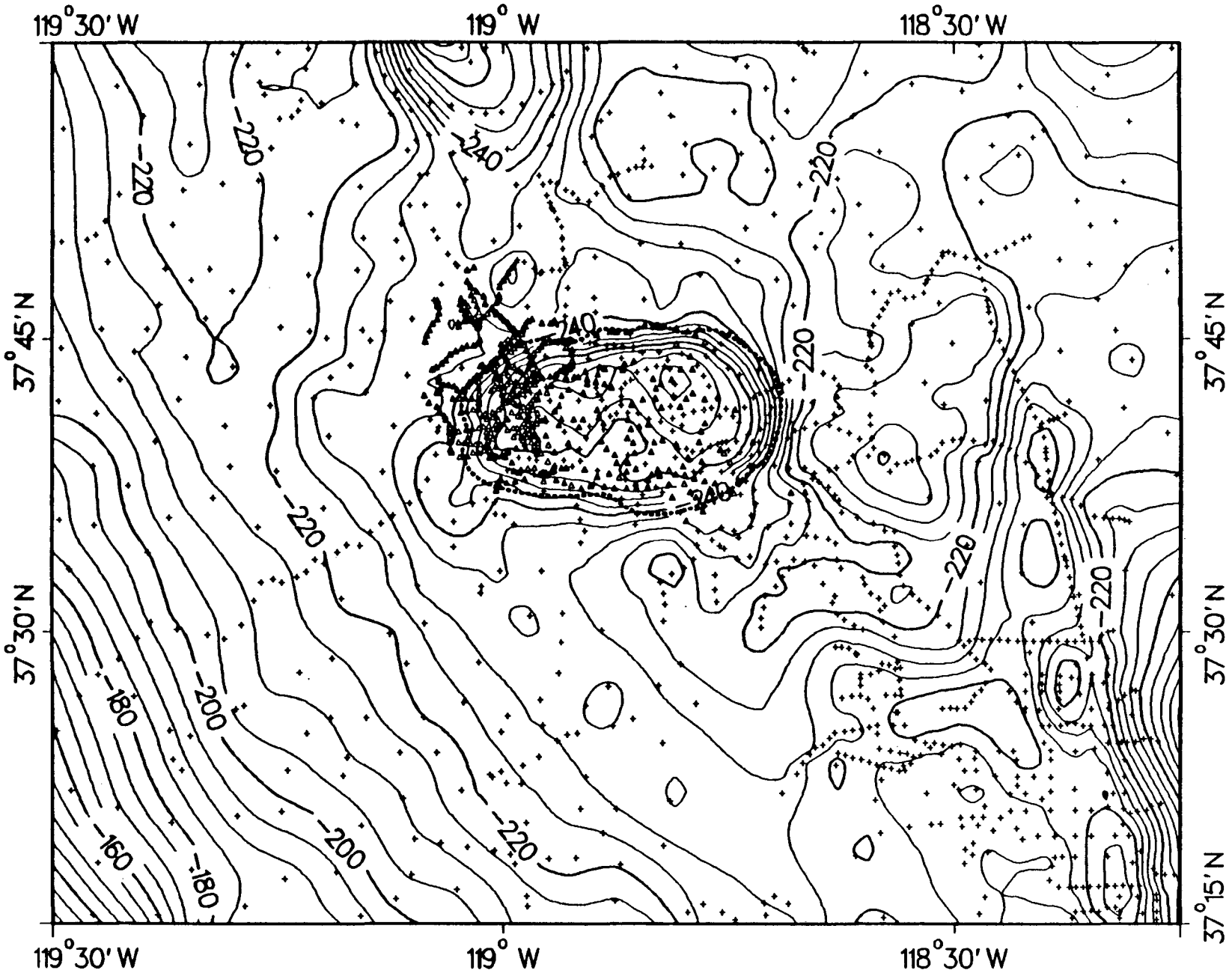

Fig. 1. Bouguer gravity map. The scale is 1:500,000. The contour interval is 5 mGals. Crosses denote U.S.G.S. gravity measurement stations. Triangles denote Unocal Geothermal gravity measurement stations. The dashed line is the topographic boundary of Long Valley caldera.

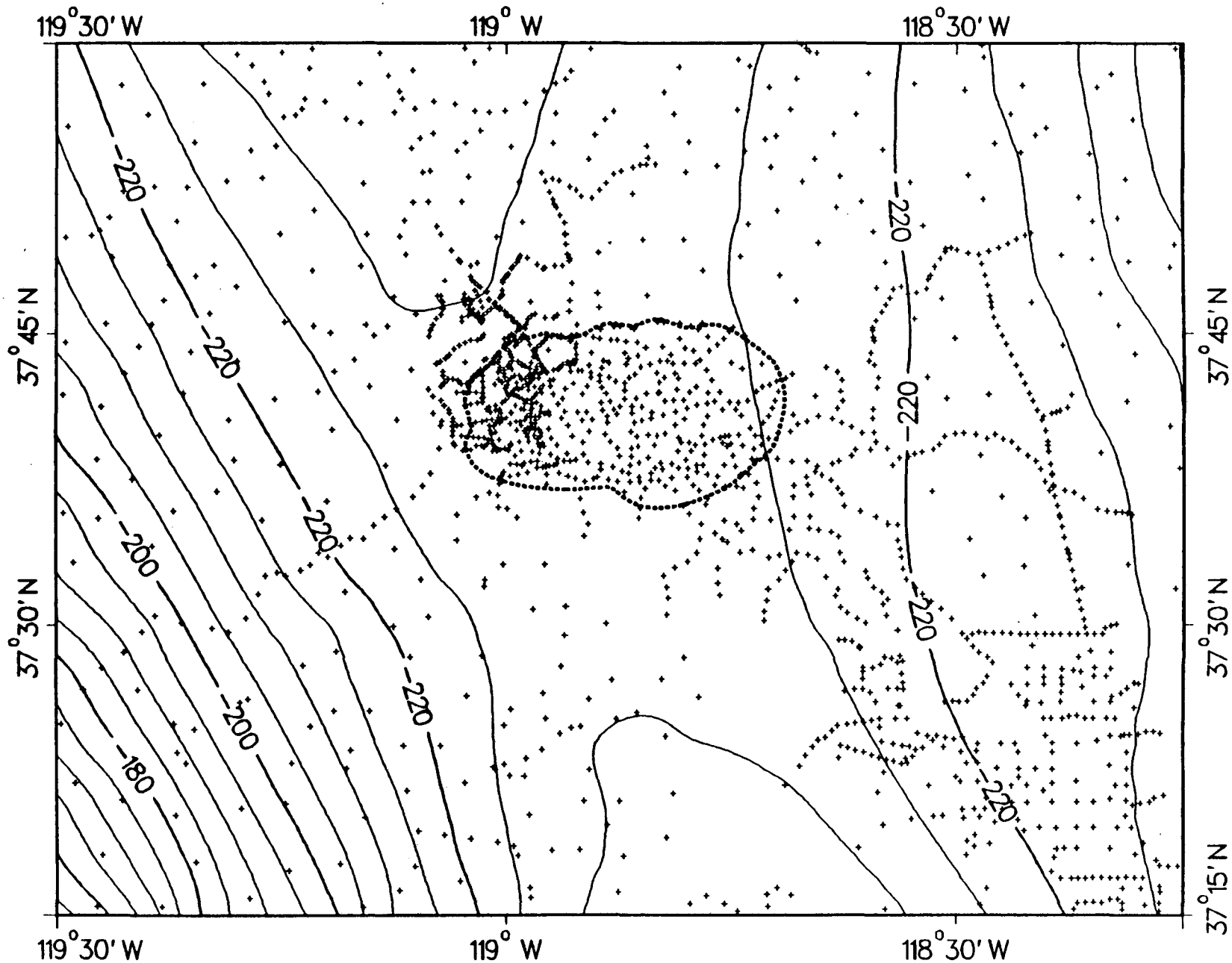

Fig. 2. Regional gravity map calculated from Airy model with sea level crustal thickness of 18 km and Moho density contrast of 0.55 g/cm . The scale is 1:500,000. The contour interval is 5 mGals. Crosses denote U.S.G.S. and Unocal Geothermal gravity measurement stations. The dashed line is the topographic boundary of Long Valley caldera.

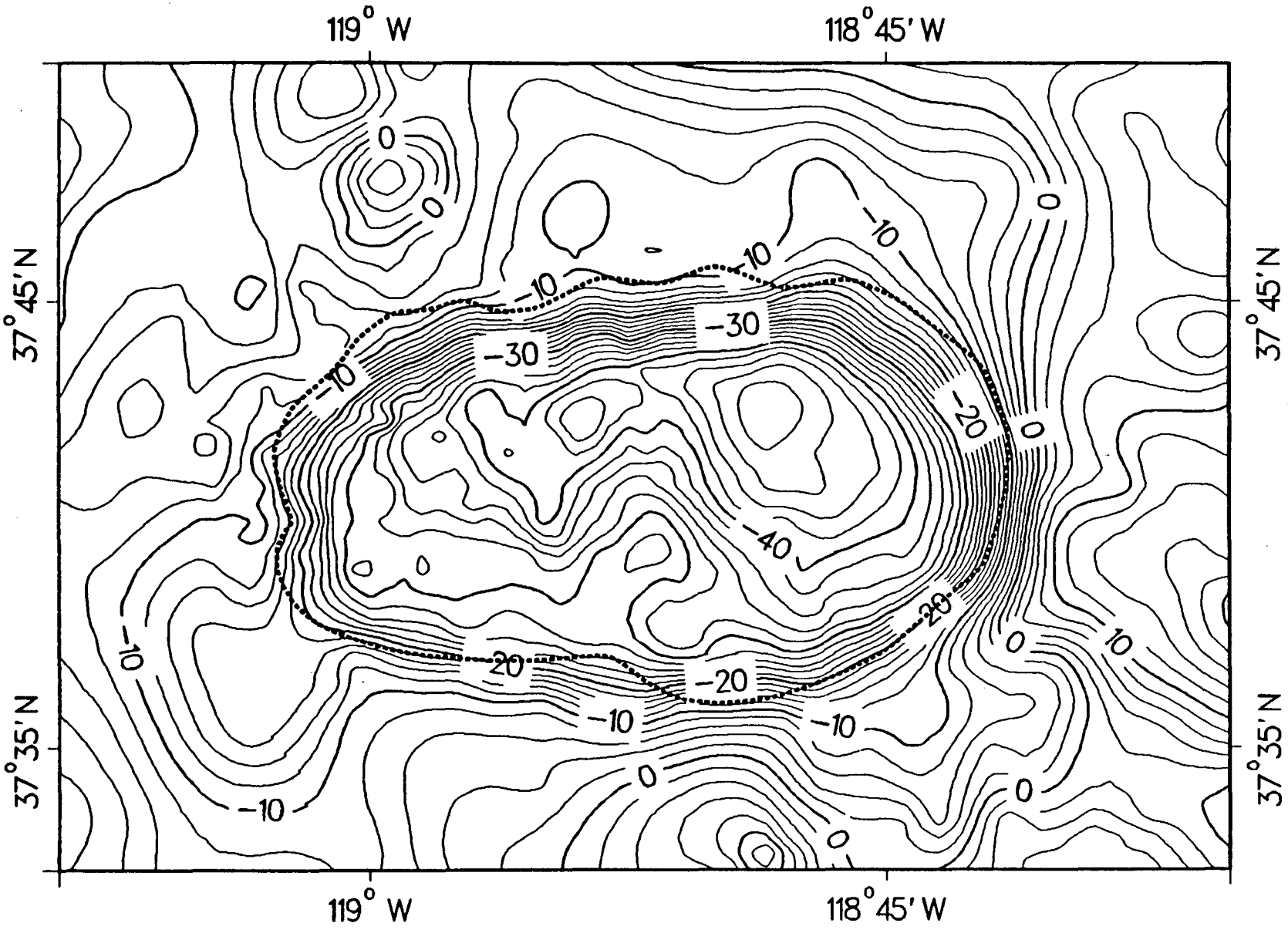

Fig. 3. Residual gravity map in area of model. The scale is 1:250,000. The contour interval is 2 mGals. The dashed line is the topographic boundary of Long Valley caldera.

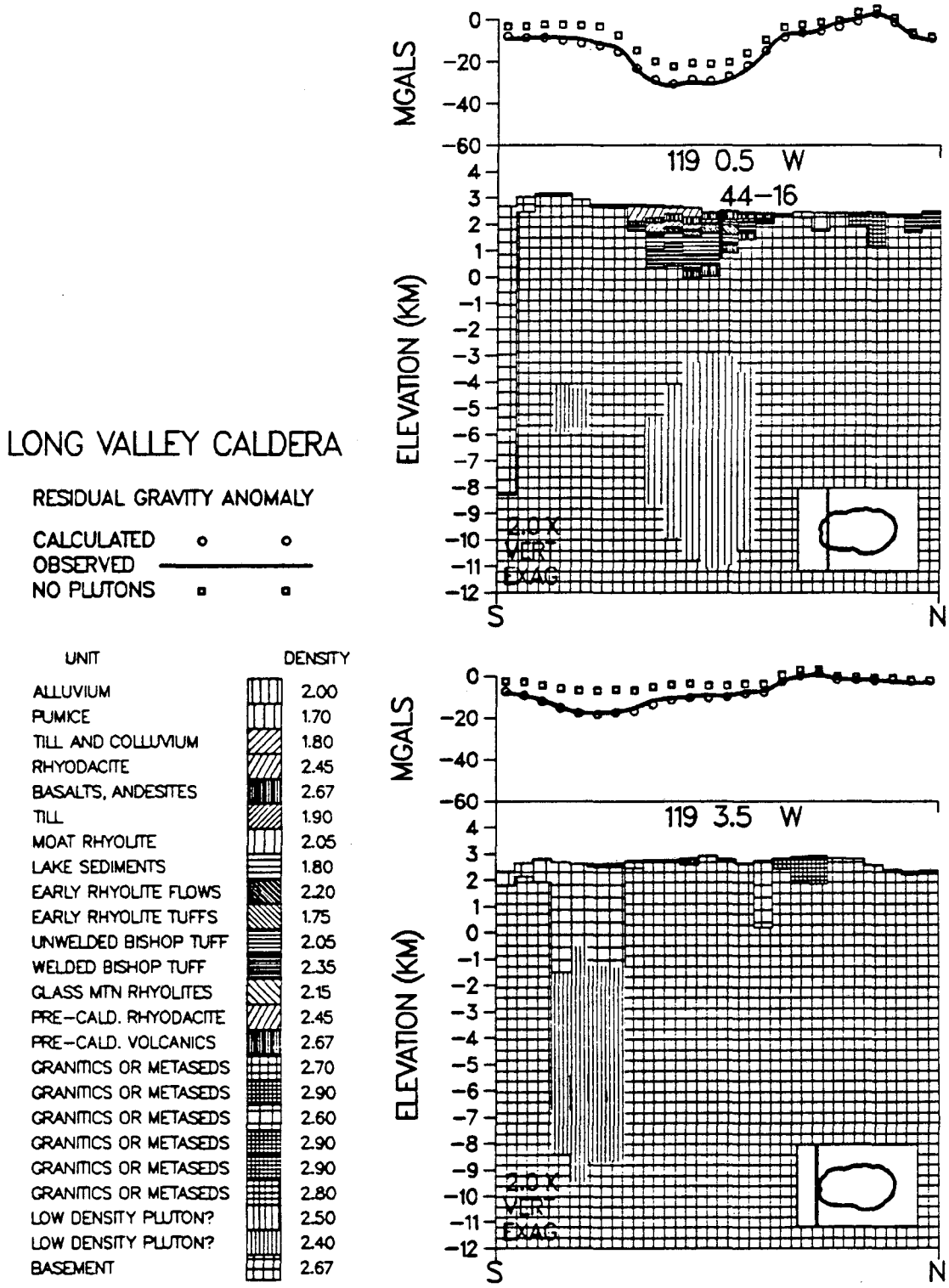

Fig. 4. Cross sections through the three-dimensional model along the indicated longitudes. The horizontal scale is 1:500,000. Cross-section orientation with respect to the topographic boundary of the caldera is shown in the lower right. "NO PLUTONS" indicates the calculated residual gravity if the low density plutons are removed from the model.

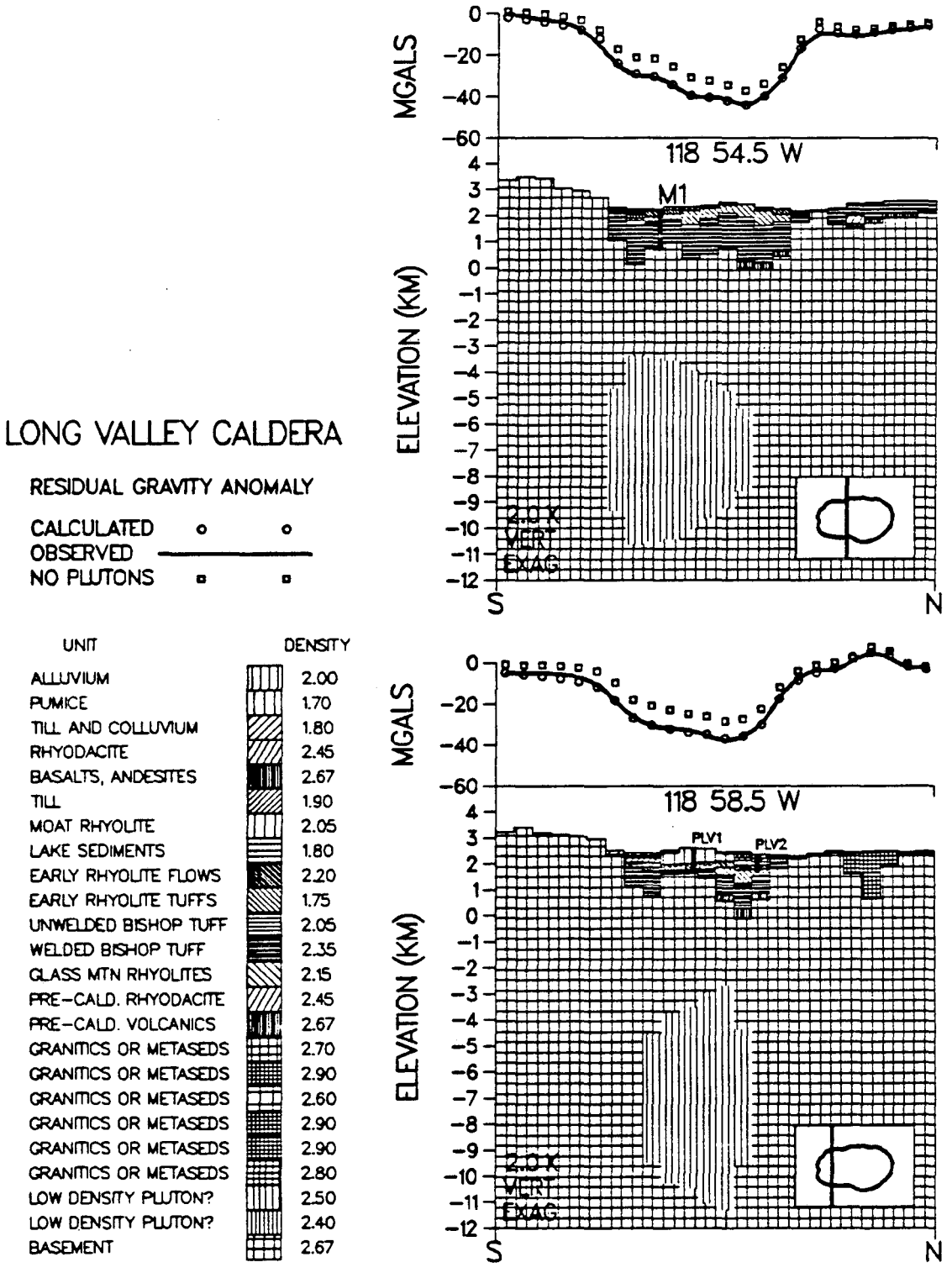

Fig. 5. Cross sections through the three-dimensional model along the indicated longitudes. The horizontal scale is 1:500,000. Cross-section orientation with respect to the topographic boundary of the caldera is shown in the lower right. "NO PLUTONS" indicates the calculated residual gravity if the low density plutons are removed from the model.

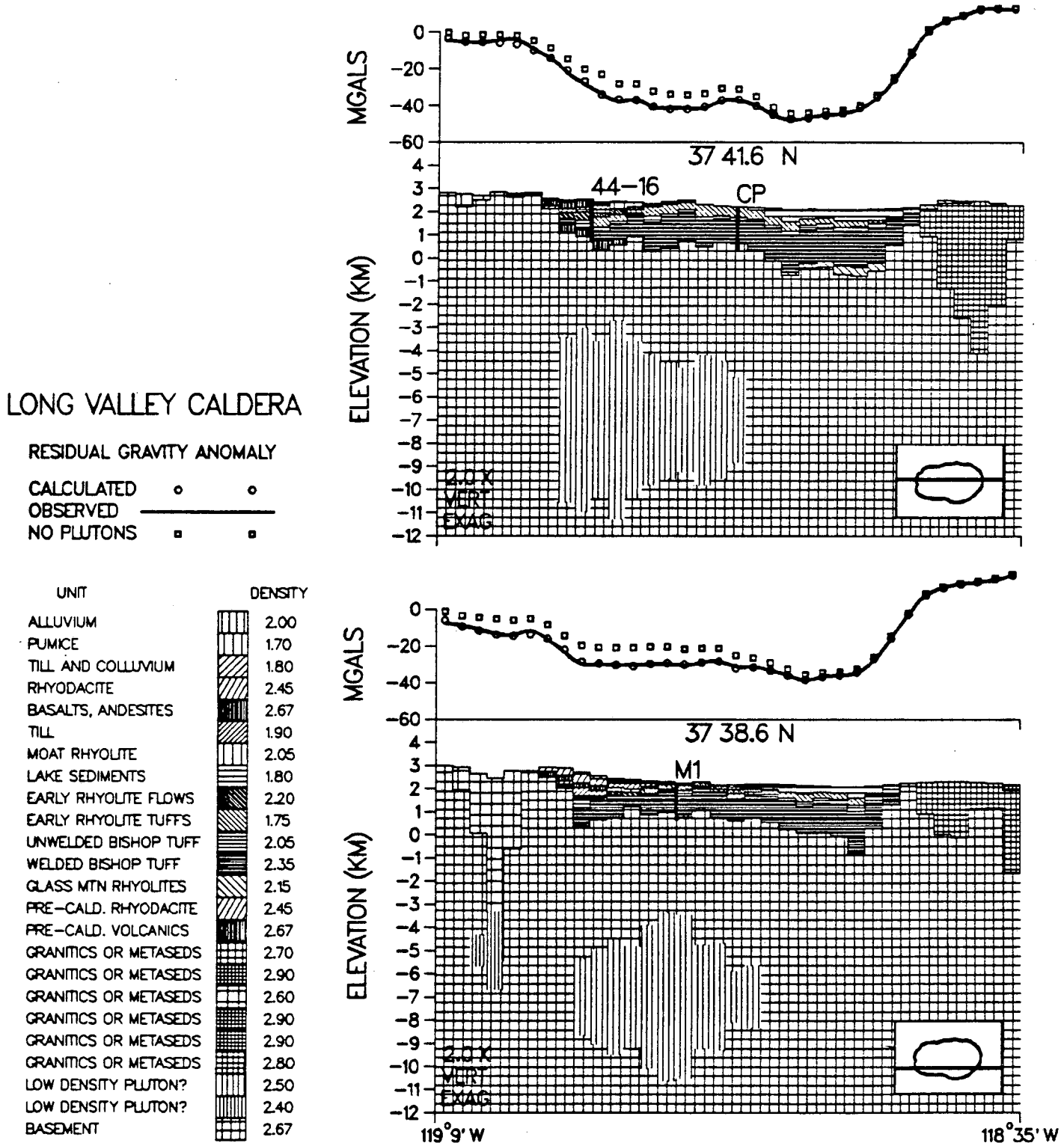

Fig. 6. Cross sections through the three-dimensional model along the indicated latitudes. The horizontal scale is 1:500,000. Cross section orientation with respect to the topographic boundary of the caldera is shown in the lower right. "NO PLUTONS" indicates the calculated residual gravity if the low density plutons are removed from the model.

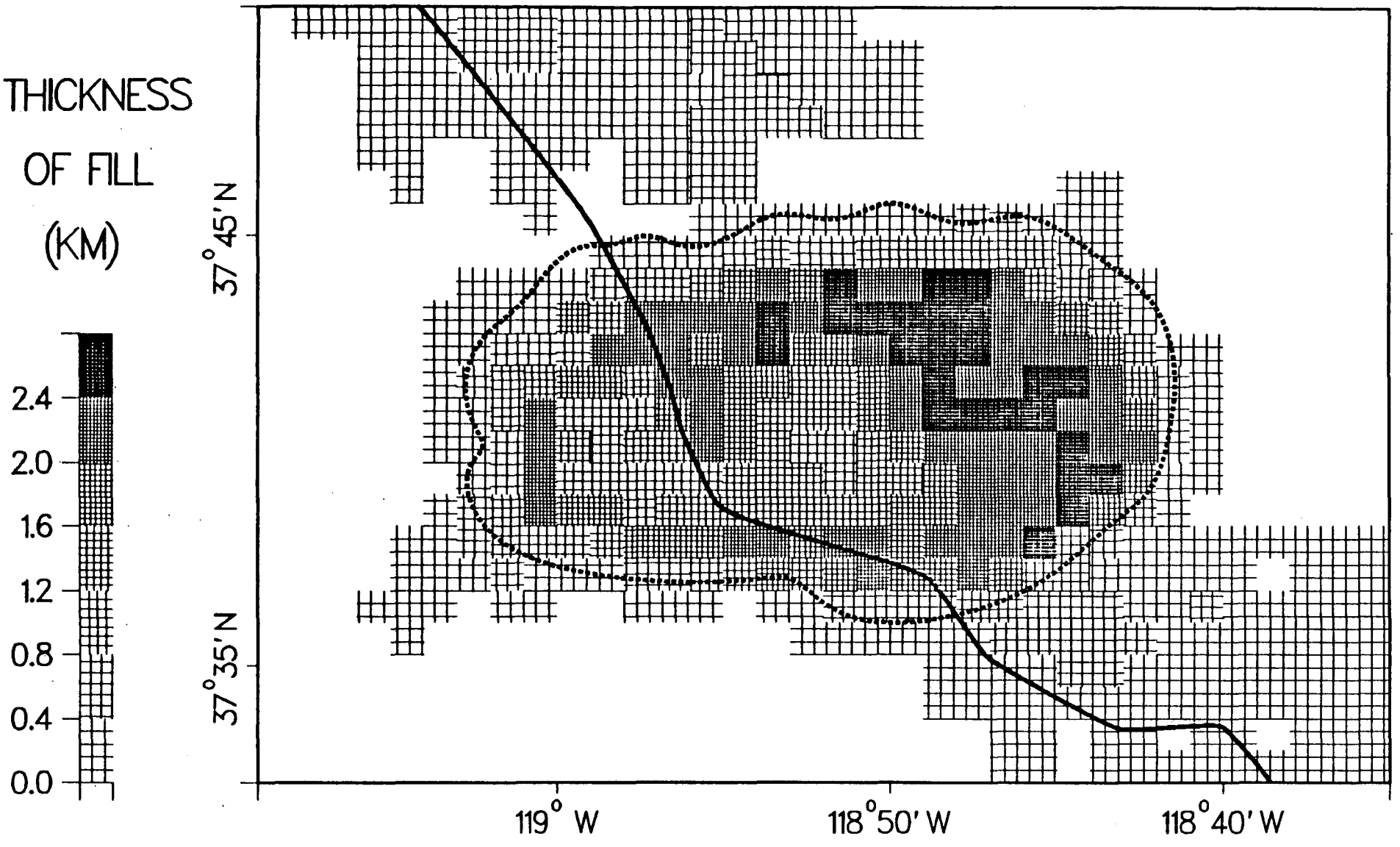

Fig. 7. Thickness of caldera fill, including all post caldera eruption rocks and the Bishop Tuff, according to the model. Scale is 1:250,000.

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