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GRAVITY MODELLING OF THE VALLES CALDERA

D.A.G. NOWELL
2 Tudor Road, New Barnet, Herts, EN5 5PA, United Kingdom

Abstract—Published gravity data have been used to reinterpret the structure of the Valles caldera in the Jemez Mountains of New Mexico. Three 2½D gravity profiles were modelled across the Valles caldera and show a combination of uneven collapse and trapdoor subsidence of up to 3600 m deep, hinged on the west with a volume of 750 km^3 and some faulted basement blocks. A geological interpretation of one of the profiles suggests that the Toledo embayment to the northeast of the Valles caldera was the site of an earlier "Rubio volcano" (4 Ma to 1.78 Ma). This volcano may have erupted the San Diego ignimbrites (1.78 Ma) to the southwest of the caldera and formed the center of a depression that grew southwestward and then collapsed to form first the Toledo caldera (1.61 Ma) and then the Valles caldera (1.22 Ma).

INTRODUCTION

The Valles caldera lies in the Jemez Mountains of New Mexico (106½°W, 36°N), in the southern Rocky Mountains of the western U.S.A. The Jemez Mountains are located at the intersection of the northeast-trending Jemez lineament (first defined by Mayo, 1958) with the western margin of the north-south Rio Grande rift (Self et al., 1986). To the north the rift is displaced eastward, and the Valles caldera is located amid young volcanic strata on the northwestern side of this offset (Fig. 1). The area was mapped by Smith et al. (1970), who also provided a stratigraphic framework (Bailey et al., 1969). Structurally the Jemez Mountains volcanic field is progressively faulted downward to the east by many north-south trending faults (Smith et al., 1961).

The Jemez Mountains range in elevation from 1646 m above sea level near San Felipe to the south, to the 3509-m-high Tschicoma Peak, just to the northeast of the Toledo embayment. Drainage from the central caldera is to the southwest, through Cañon de San Diego, where the northern San Antonio creek and the southern Jemez river meet below Battleship Rock. The drainage pattern off the outer margins of the caldera is radial. Within the Valles caldera the highest point is Redondo Peak, toward the south of the central area, at 3430 m. The lowest ground, 2134 m, is found below Battleship Rock on the southwestern edge of the caldera at the head of Cañon de San Diego. Other low points within the caldera are Valle Grande, 2591 m in the southeast, and Valle San Antonio, 2560 m to the north. The caldera ring-fracture is inferred to coincide with a ring of volcanic domes that range in elevation from 3149-m-high Cerros del Abrigo in the northeast to 2682-m-high Banco Bonito, which at 59–53 ka (Toyoda et al., 1995) is the most recent eruptive unit in the complex. The rim of the Valles caldera is between 183 m high at Sierra de Los Valles in the southeast and 549 m high at Cerro de la Garita in the north. The edge of the Toledo embayment cross-cuts the topography on the northeastern side, but has a rim between 213 m and 305 m high on its northern side.

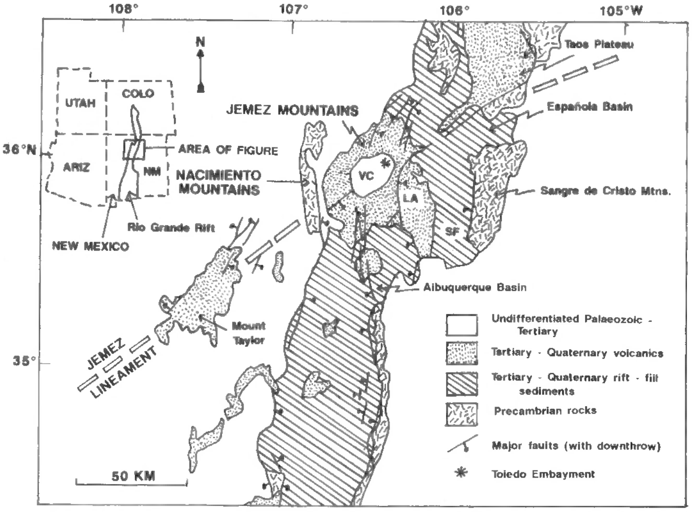

FIGURE 1. Location map showing the basins of the north-central Rio Grande, Precambrian rocks, Tertiary-Quaternary volcanic fields and major faults. VC is the Valles Caldera, LA is Los Alamos and SF Santa Fe. Based on Self et al. (1987).

The Valles caldera is a classic example of a resurgent caldera and has an active high-temperature, volcanic-hosted, geothermal system, fed by a magmatic heat source. This may be an approximately cylindrical low-velocity body below the southern part of the Valles caldera at depths of 1500 m to 10,000 m below sea level (Ankeny et al., 1986). The Jemez Mountains have been drilled intensively as part of the Continental Scientific Drilling program (CSDP), because of their high heat flow, geothermal groundwater and similarities to ancient volcanic-hosted ore deposits. The Valles caldera, including the Toledo embayment to its northeast, is approximately 20 km (NW-SE) by 25 km (NE-SW) across. The whole depression was formed by a succession of catastrophic eruptions that occurred in the middle of the Jemez volcanic field, during which more than 600 km^3 of rhyolitic pyroclastic material were deposited to form the Bandelier Tuff (Smith, 1979). The Bandelier Tuff is an extensive ash-flow deposit extending up to 30 km from the center of the present caldera. It is named after the Anasazi pueblo ruins in Bandelier National Monument, discovered by Adolf Bandelier, a Swiss-born anthropologist (Guest, 1994). At least two major caldera-forming deposits are recognized within the Bandelier Tuff: the Otowi Member (lower Bandelier Tuff) (1.61 Ma) and the Tshirege Member (upper Bandelier Tuff) (1.22 Ma) (Izett and Obradovich, 1994). Their eruption caused the successive collapse of first the Toledo caldera (1.61 Ma) and then the Valles caldera (1.22 Ma). Heiken et al. (1986) considered these calderas to be a pair of approximately coincident trapdoor calderas, hinged on the west. A trapdoor caldera is shallow at one side and slopes consistently downward toward the opposite side which is much deeper. Following the eruption of the Tshirege Member, resurgent doming occurred in the center of the caldera and rhyolitic domes erupted from a ring of vents that coincided with the caldera ring fracture (Smith et al., 1961, 1970). Subsequently a complex geothermal system has evolved within the caldera (Goff and Gardner, 1994).

In the text, grid references are quoted in brackets after locations in the text, and are based on the kilometer grid shown on the 1:125,000 geologic map of the Jemez Mountains (Smith et al., 1970).

TECTONIC SETTING

The Jemez Mountains are located in a region that from 32 Ma onward has undergone regional extension as part of a back-arc basin (Zoback et al., 1981), at first in an ENE-WSW direction and then, some time after 23 Ma, the extension vectors rotated clockwise to the present east-west or WNW-ESE direction (Aldrich et al., 1986). This clockwise rotation of the orientation of regional extension is probably due to the subduction of the Farallon plate under North America being replaced by dextral transform motion between the North American and Pacific plates and the consequent movement of the associated triple junction northward as North America has over-ridden the Pacific (Zoback et al., 1981). The mid-Tertiary back-arc magmatism in the Rio Grande area resulted from this subduction and weakened the lithosphere, allowing it to break apart in the subsequent Basin and Range regional extension (Baldridge et al., 1991). However, since its inception about 31 Ma, east-west spreading of the Rio Grande rift has been controlled by a pre-existing structural grain (Aldrich et al., 1986). Indeed, it is a northward embayment of the main Basin and Range stress province to the west which, itself, was the result of relaxation in the lithosphere after the Farallon plate ceased to be subducted below the southern Rocky Mountains (Park, 1988).

PREVIOUS GRAVITY WORK ON THE VALLES CALDERA

Segar (1974) conducted a gravity survey in the Valles caldera; 730 stations were surveyed. A density of 2450 kg/m^3 was used for Bouguer and terrain corrections. Regional gravity effects due to isostatic conditions were removed by approximating them to an increasingly negative regional field of one mGal (equal to 10 gravity units) per 3.2 km toward the NNW with an overall value of between -220 mGal and -230 mGal, resulting in the residual Bouguer gravity anomalies shown in Figure 2 (Nielson and Hulen 1984). A constant correction throughout the area of 15 mGal was subtracted from all readings in order to bring everything to a zero datum, since most of the areas of Paleozoic outcrop had a value of about +15 mGal. A profile across the center of the caldera was modelled by Segar (1974) to estimate the density contrast. The data were then iteratively modelled in 3D with a simple single -350 kg/m^3 density contrast.

The resulting plot of depth to the base of the caldera fill (Fig. 3) shows that the caldera is asymmetrical, with only 760 m of low density caldera fill in the extreme west and over 4500 m under Valle Toledo (1830 m below sea level) in the east. Nielson and Hulen (1984) proposed, on the basis of this asymmetric fill, that the Valles caldera is of the trapdoor type. The other features of Segar's (1974) model of the Valles caldera (Fig. 3) are a ring fault running between 3 and 5 km inside the present topographic rim with a downthrow toward the center of between 305 m in the northwest and 3050 m in the southeast; three NE-SW trending faults about 3 km apart centered on Redondo Peak (59 70) with downthrows of between 305 m and 1525 m; a maximum basement dip of 37° northeastward (66 74) and 48° southeastward (67 79).

Similar results were obtained by Wilt and Vonder Haar (1986), based on Segar's (1974) data with two 2D gravity profiles using the densities of 2120 kg/m^3 for near-surface caldera fill, 2400 kg/m^3 for the underlying volcanics, and 2650 kg/m^3 for basement rocks, though the maximum depth to the basement is 1000 m less than in Segar's (1974) model. These models are limited, because in a 2D gravity profile the half strike width is assumed to be infinite. This differs from a 2½D gravity profile, where the half strike of each body can be varied. Furthermore the Paleozoic rocks below the Valles caldera were not modelled and the two profiles have a 25% (850 m) difference in thickness of the caldera fill at their intersection, not 10% as stated by Wilt and Vonder Haar (1986). A few additional unpublished gravity readings (National Geophysical Data Center) have been made in the Valles caldera since 1974 that may help define it more precisely, but should not affect the general shape of the Bouguer gravity field. Only Segar's (1974) data have been remodelled here using more sophisticated software than was available in 1974.

2½D GRAVITY PROFILES ACROSS THE VALLES CALDERA

Three 2½D gravity profiles were modelled for this work using GRAVMAG (Pedley, 1991). The gravity values were derived from published maps of Segar (1974). The densities Segar (1974) used to produce the plot of depth to the Paleozoic basement (Fig. 3) were 2100 kg/m^3 for the caldera infill and 2450 kg/m^3 for the normal near-surface densities of pre-caldera rocks, a density contrast of 350 kg/m^3. Compared to other densities obtained for rocks in the Valles caldera (Nowell, 1994), these are

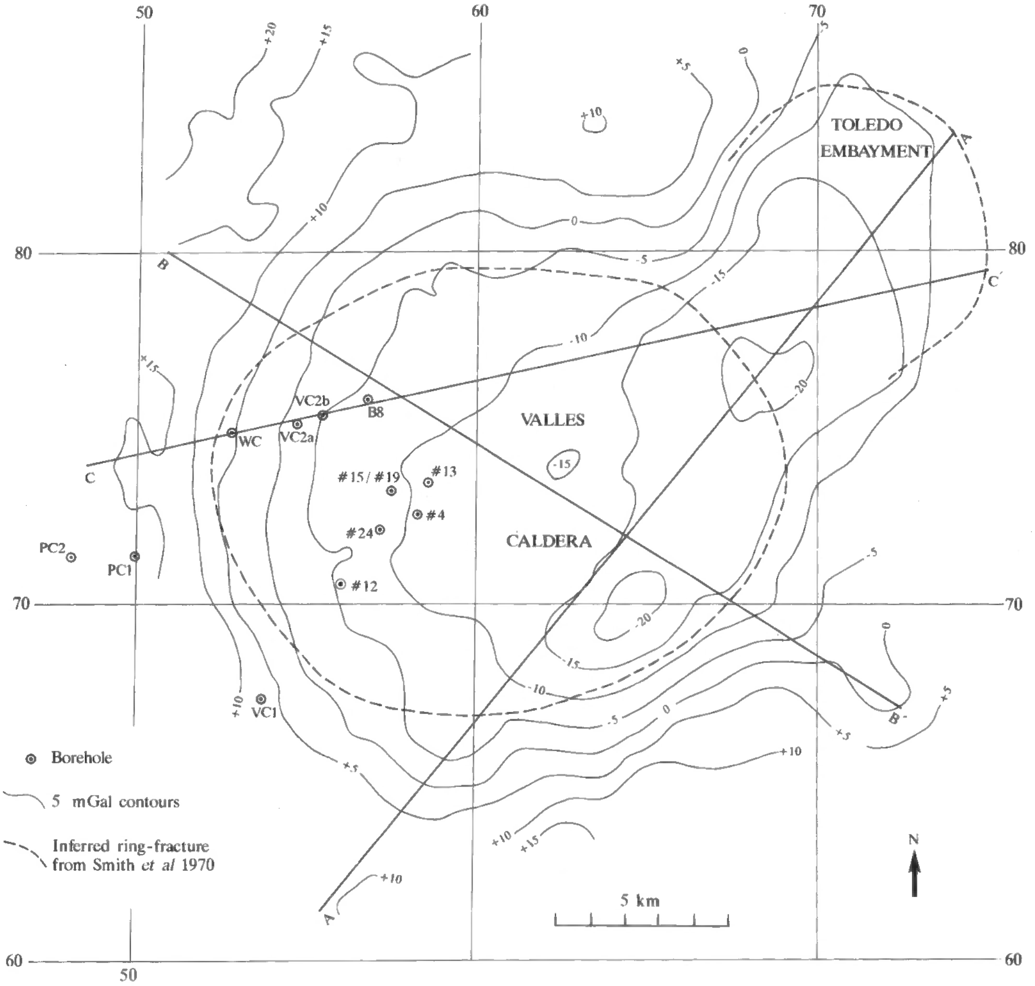

FIGURE 2. Bouguer gravity anomalies after the removal of the regional gravity field due to isostatic conditions, from Segar (1974), before the removal of 17 mGal to model the data. Locations of the 2½D gravity profiles and the geothermal boreholes in and around the Valles Caldera are shown.

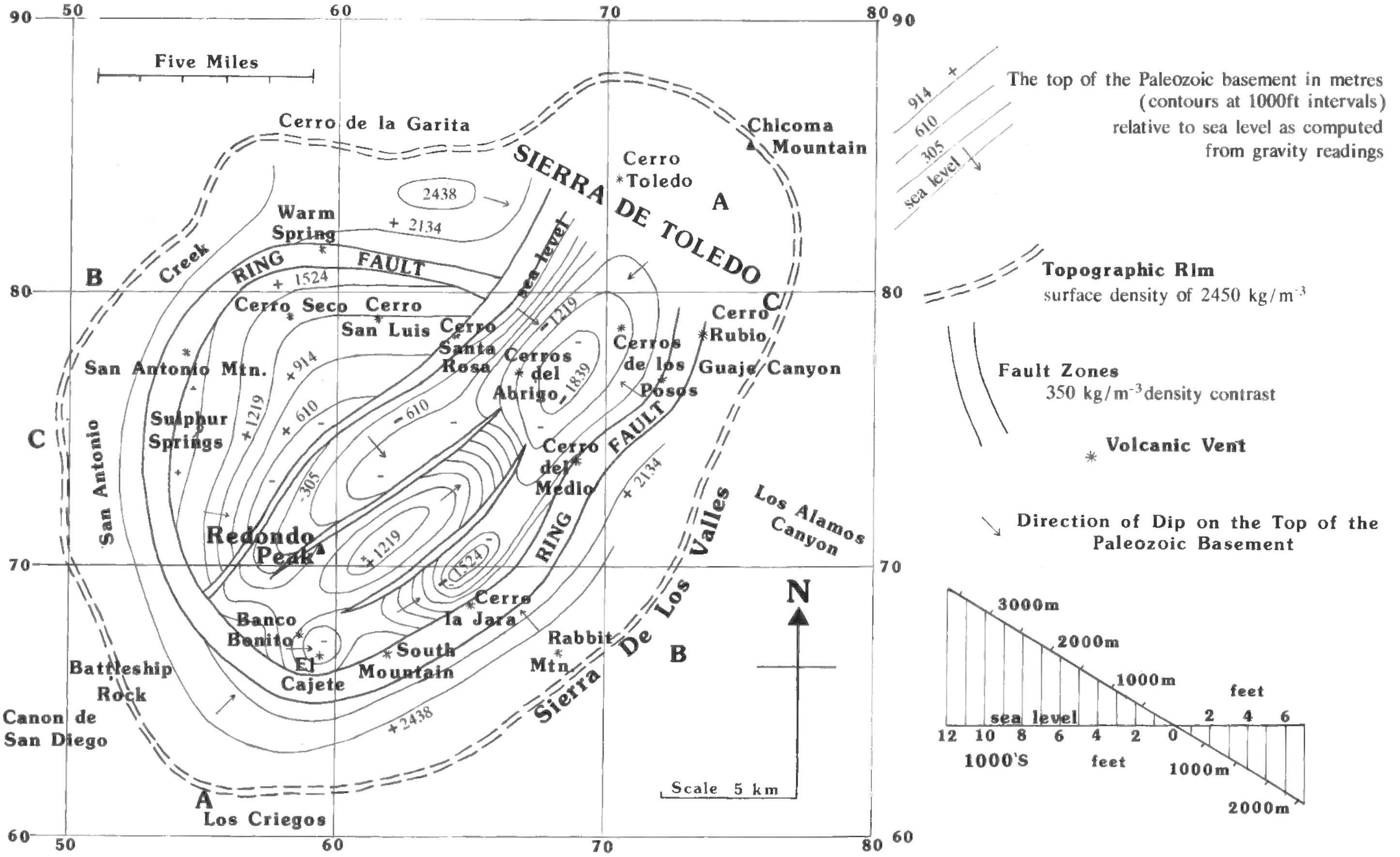

FIGURE 3. Plot of depth to Valles caldera basement in meters relative to sea level; however, contours are at 1000 ft (305 m) intervals, based on Segar (1974).

rather low, and so higher densities were used for the 2½D gravity profiles. The density of 2350 kg/m³ for caldera tuffs and rhyolites in the new profiles, fits in with the average dry bulk density of 2240±220 kg/m³ and 10–30% porosity for tuffaceous caldera fill in VC-2A and VC-2B given by Goff and Gardner (1994), assuming that water fills on average half the porosity, giving an extra 100 kg/m³ to the dry bulk density. The uncertainty in modelling the caldera fill due to alteration in places increasing the dry bulk density of the fill (Goff and Gardner, 1994), is partly offset by the resulting decrease in porosity. Below the water table any decrease in dry bulk density is balanced by the mass of water filling the increased pore space, resulting in a more uniform density distribution than would be expected, for the varying states of alteration in the caldera fill.

Ideally the Bouguer gravity should have been recalculated using the higher background density of 2650 kg/m³, which would have resulted in differences in the residual anomalies, but the original gravity readings were not available. In the 2½D gravity profiles not only was the density contrast with the background density modelled, but the half strike or the width of the causative bodies at right angles to the profile were modelled. A model was constructed from a series of user-defined interlocking polygons, each with a unique density and half strike length. As the elevation of each gravity value along a profile is entered, the terrain is defined. GRAVMAG models the polygons in terms of their density contrast with a chosen background density and is a highly interactive program, allowing the shape, density and half-strike of individual polygons, and thus the calculated gravity, to be changed easily.

The densities (Fig. 4) and half strikes of the main bodies in the profiles were as follows: 2200 kg/m³ and 2 km for alluvium and fan deposits; 2350 kg/m³ and 10 km for caldera tuffs and rhyolites; 2550 kg/m³ and 10 km for Paleozoic rocks such as the Madera and Sandia formations; and a background density of 2650 kg/m³ for Precambrian rocks beneath the caldera. The half strikes for the modelled bodies were chosen with regard to the widths of the relevant formations on the geologic map of the Jemez Mountains (Smith et al., 1970). The background density is 200 kg/m³ higher than the density at which the data were originally reduced, but since it is applied to all the data this makes no difference to the final model as GRAVMAG models the density contrasts with the background density and not the actual densities of the model. Segar (1974) had removed the regional gradient on his map (Fig. 2), and for all three profiles a further constant regional anomaly of 17 mGal was also removed from the data before modelling. As the structure of the western end of the profile C-C' (Fig. 2) was constrained by geothermal boreholes, it was modelled first and then the other two profiles B-B' and A-A' were modelled so that they were in agreement to within 100 m at intersections between them.

Profile C-C' (Fig. 5) is a west-east section from Barley Canyon (485 741) to Cerro Rubio (756 794). The western end of the profile is constrained by boreholes. From VC-2B and other boreholes the Paleozoic sediments below the caldera are known to be over 800 m thick and are modelled as between 1000 m and 500 m thick in the profiles; otherwise the caldera fill (tuffs and rhyolites) would have to be up to 330 m thicker.

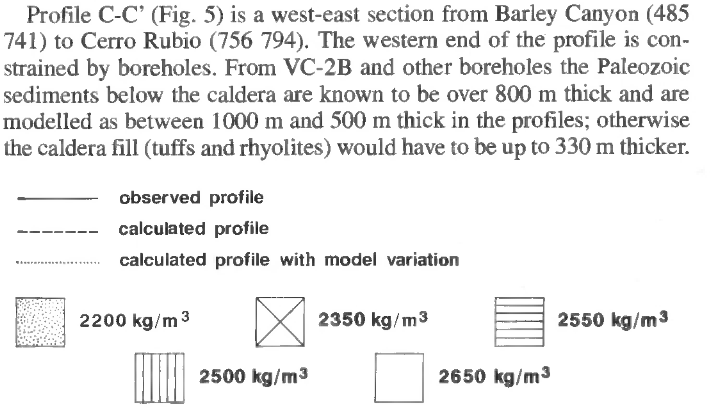

FIGURE 4. Key to the 2½D gravity profiles, see Figure 2 for their location, Figure 5 for profile C-C', Figure 6 for profile B-B' and Figure 7 for profile A-A'. The densities of the bodies in the profiles are 2200 kg/m³ for alluvium and fan deposits; 2350 kg/m³ for caldera tuffs, rhyolites and hydrothermally altered granite below the caldera; 2550 kg/m³ for Paleozoic rocks; 2500 kg/m³ for an intrusion below the caldera; and a background density of 2650 kg/m³ for Precambrian rocks. For the half strikes of these bodies see the figure captions for each profile.

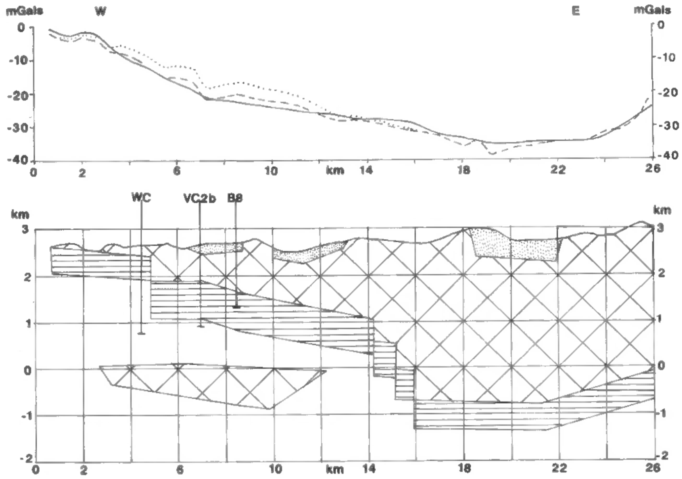

FIGURE 5. Profile C-C' west 485 741 to east 756 794. Solid line is observed profile, dashes are calculated profile, dots are calculated profile without deep body, horizontal and vertical scales in km. Dots density 2200 kg/m^3 half strike 2 km; cross-hatching 2350 kg/m^3 half strike 10 km, deep body half strike 4 km; horizontal lines 2550 kg/m^3 half strike 10 km; background density 2650 kg/m^3. See Figure 4 for visual key.

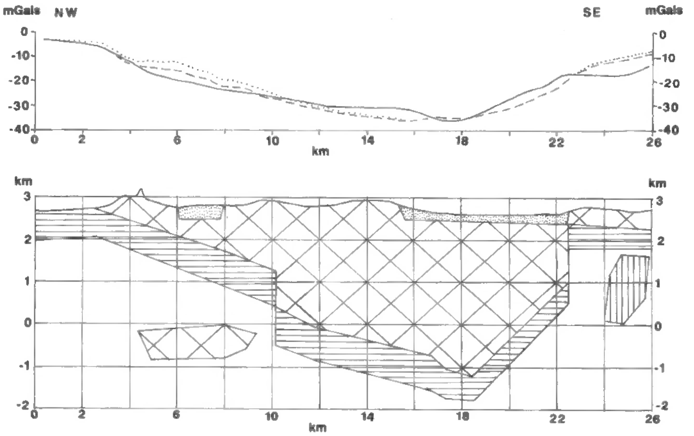

FIGURE 6. Profile B-B' northwest 507 800 to southeast 732 666. Solid line is observed profile, dashes are calculated profile, dots are calculated profile without deep bodies, horizontal and vertical scales in km. Dots density 2200 kg/m^3 half strike 2 km; cross-hatching 2350 kg/m^3 half strike 10 km, far right half strike 5 km, deep body half strike 5 km; horizontal lines 2550 kg/m^3 half strike 10 km; vertical lines 2500 kg/m^3 half strike 1 km; background density 2650 kg/m^3. See Figure 4 for visual key.

In order to better fit the observed and calculated anomalies by about 3.5 mGal, over part of the profile, an intrusion of hydrothermally altered granite with a density of 2350 kg/m^3, half strike of 4 km, and volume of about 40 km^3 is inferred just below sea level. This may be a pod of silicic magma that solidified before reaching the surface and was later altered by the action of subcaldera geothermal solutions. As this is the only part of the three profiles to be constrained by boreholes, this 3.5 mGal anomaly could be added to the profiles to remove it. Thus, instead of removing a 17 mGal regional anomaly, or a 15 mGal regional anomaly as Segar (1974) did, only 13.5 mGal need be removed. If this were done the thickness of the caldera fill along the profiles using the Bouguer slab formula would be reduced by an average of 280 m in the large areas of the caldera not constrained by boreholes.

In the middle of profile C-C' is a series of faults (or a steep slope) with eastward downthrows of about 500 m each; these offsets coincide with the SW-NE fault zone in Segar's (1974) model. For the modelling process faulting was assumed to be more likely in a volcanic setting than steep slopes, which could have been used in the profiles. The caldera-filling tuffs and rhyolites reach a maximum depth of 800 m below sea level (compared with nearly 2000 m below sea level in Segar's (1974) model) and have a thickness of over 3500 m. These large differences between the models are the result of the different density contrasts used and the types of model employed, giving a different emphasis to the modelling of the gravity data. The eastern end of profile C-C' would suggest that either the Toledo-Valles caldera complex extends farther east, which is unlikely, or a regional gravity gradient needs to be added to the observed values at this end of the profile. Such a regional anomaly might be due to the lower densities of the rock in the Rio Grande rift toward the east. Without better borehole or other geophysical controls, the problem of what magnitude regional anomaly to remove from the gravity data before modelling remains unconstrained and shows the ambiguity and limitations of gravity interpretation.

Profile B-B' (Fig. 6) is a NW-SE section from the Jemez Plateau (307 800) across the resurgent dome to the southeastern caldera rim (732 666) over the Sierra de Los Valles. The model has a simple southeastward dip of about 11° from the northwestern end with a 800 m fault half way down the slope. The profile reaches a maximum depth of over 3500 m about 1200 m below sea level, similar to that of Segar's (1974) model, but does not have a 3-km-wide, 1500-m-high fault block in the middle of the profile as there is no evidence for this from the observed gravity profile. Southeast of its low point the caldera floor dips about 29° northwestward—this may in fact be a series of small faulted blocks—and the margin of the caldera is marked by a 1400 m throw fault. The Paleozoic sediments below the caldera are modelled as being between 850 m and 500 m thick. As the northwestern end of the profile is near the boreholes along profile C-C', the thickness of caldera fill cannot be increased. So an intrusion of hydrothermally altered granite with a density of 2350 kg/m^3 and a half strike of 5 km is modelled. Again this may be an intrusion of silicic magma with a volume of about 30 km^3 that fed the rhyolite ring domes. A lower density contrast would necessitate a larger body to produce the same anomaly. At the southeastern end of the profile a small intrusive body with a density of 2500 kg/m^3, half strike of 1 km, and volume of about 4 km^3 is modelled. Such a body could be related to the Rabbit Mountain rhyolite on the caldera rim to the west; alternatively it could represent thicker Paleozoic sedimentary rocks in the subsurface. The levelling out of observed gravity values at the southeastern end of the profile may be due to a regional anomaly related to low density sediments in the Rio Grande rift.

Profile A-A' (Fig. 7) is a SW-NE section from near Los Griegos (555 614) to near Tschicoma Mountain (743 832) on the rim of the Toledo embayment. The profile assumes that the caldera is shallow in the southwest and drops in a series of fault blocks down to a depth of 3000 m, some 500 m below sea level. The maximum depth to the base of the intracaldera tuffs and rhyolites (3600 m) is over 1000 m shallower than in Segar's (1974) model. The largest fault, in a similar position to Segar's (1974) ring fault, has a downthrow to the northeast of 1000 m compared to Segar's 1500 m. The other faults have downthrows of between 200 m and 600 m and could be replaced by a slope with an average dip of 9°. At the northeastern end of profile A-A' a 1000-m-high, 3-km-wide fault block is modelled, without which the calculated profile would be 3 mGal farther below the observed values. The top of this fault block may mark the base of the hypothetical "Rubio volcano", which did not collapse further during the formation of the younger calderas.

The northeastern end of profile A-A' ends in the Sierra de Toledo, and the modelled depth of the caldera at this point would suggest that either the Toledo-Valles caldera complex extends farther northeastward, which is unlikely, or a regional gravity gradient should be removed from the observed values at this end of the profile. The caldera may be slightly shallower toward the middle, since the calculated profile is up to 4.5 mGal below the observed values, or the densities of the caldera fill may be locally greater than assumed. Reducing the thickness or increasing the density of the thin layer of alluvium and fan deposits would have only a small effect in reducing this difference between the observed and calculated profiles. Using the Bouguer slab formula, a 4.5 mGal anomaly is equivalent to the caldera fill being 360 m shallower. This is about 10% of the caldera's depth of 3150 m at this point.

These new 2½D gravity profiles suggest that the Valles caldera is filled by up to 3600 m of tuffs with up to 1000 m of Paleozoic rocks below

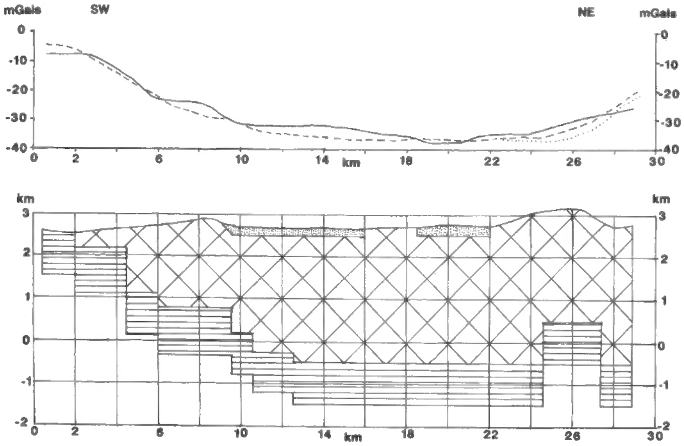

FIGURE 7. Profile A-A' southwest 555 614 to northeast 743 832. Solid line is observed profile, dashes are calculated profile, dots are calculated profile with no upward step in the formations, horizontal and vertical scales in km. Dots density 2200 kg/m^3 half strike 2 km; cross-hatching 2350 kg/m^3 half strike 10 km; horizontal lines 2550 kg/m^3 half strike 10 km; background density 2650 kg/m^3. See Figure 4 for visual key.

that. These models were used to plot the depth to the top of the Paleozoic basement (Fig. 8), which shows that the caldera is asymmetrical with less than 1000 m of low-density caldera fill in the west and up to 3600 m under the northern Valle Grande (66 71) (1000 m below sea level) in the east. The northern and eastern margins of the caldera appear to be fault-bounded with, in the center, two faults each downthrowing over 500 m to the southeast. These new model profiles tend to fit the observed data better and are smoother than Segar's (1974) profiles, generally with lower dips and a short series of faulted blocks. The three NE-SW trending faults centered on Redondo Peak (59 70) in Segar's (1974) model do not exist in profile B-B' (Fig. 6), which as a result gives a better fit, especially to the east. The maximum depth of the tuffs filling the Valles caldera is up to 1000 m less in the new profiles, though in other places along the profiles the tuffs are over 1000 m thicker than in Segar's (1974) model. When Segar's (1974) model and densities are modelled along profile A-A' as a 2½D profile, the profile is in places over 10 mGal below the observed line (Nowell 1994), suggesting that his maximum thickness of tuff is too large. The new profiles have numerous faults with downthrows of up to 1000 m but often less than 500 m, which cannot be traced from one profile to another. This would suggest that the floor of the Valles caldera is a series of disconnected fault blocks. This is consistent with uneven caldera collapse and violent eruption of large volumes of magma.

The total volume of the caldera may be calculated by dividing the whole area into a kilometer grid and finding the average height of the topography and basement, to within 100 m, in each kilometer square. From this the difference in height is used to find the volume of the caldera fill in each compartment. These are then added together. For Segar's (1974) model, the Toledo embayment was added by projecting the model into this area, resulting in an extra volume of 110±6 km^3. The total volume turned out to be 740±40 km^3 for Segar's (1974) model and 750±40 km^3 for the new model. The average 800 m thickness of Paleozoic rocks below the new model are equivalent to an extra 100±5 km^3 of caldera fill. To this must be added the 74±4 km^3 of small intrusions modelled below the profiles, if the volumes of the two models are to be compared. Thus the equivalent volume of the new model is 924±49 km^3. The equivalent volume of the new model should be greater as the main density contrast was only -300 kg/m^3, not the -350 kg/m^3 of Segar's (1974) model, and a lower density contrast will take up a larger volume.

GEOLOGICAL INTERPRETATION AND DISCUSSION

Profile A-A' was used as the basis for a geological cross section (Fig. 9); it passes east of the resurgent dome and through the Valle Grande and the Toledo embayment. On the southwestern side of the caldera is the El Cajete vent, which erupted the El Cajete sequence of lavas and tuffs. The older Valles rhyolite domes and fan deposits, which form a ring around the resurgent dome, fill the uppermost part of the middle of the section. Below are up to 1400 m of Tshirege Tuff erupted during collapse of the Valles caldera (1.22 Ma). On the northeastern side of the section is the Cerro Toledo rhyolite, erupted after collapse of the Toledo caldera. I assume that similar deposits are buried below the southwestern side of the caldera as the later post-Valles domes are found on both sides of the caldera. The bottom of the caldera is filled by up to 1400 m of Otowi Tuff erupted by the collapse of the Toledo caldera (1.61 Ma).

The Toledo embayment is probably the site of a rhyolite vent that was initially similar to those in the older volcanic units of the Jemez Mountains, even if most of the rocks in the Toledo embayment, including the Cerro Toledo rhyolite, are younger and have been dated (Stix et al., 1988) to the interval between the collapses of the Toledo and Valles calderas. Weakened crust at the intersection of the Jemez lineament and faults on

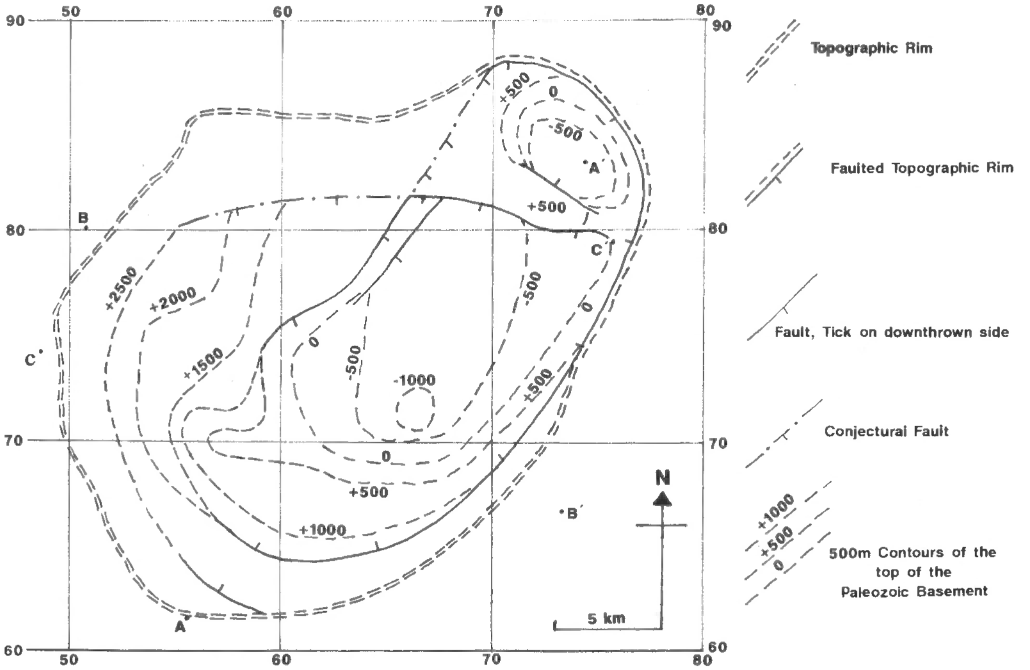

FIGURE 8. Plot of depth of the Valles caldera basement in meters relative to sea level, based on the new 2½D gravity profiles.

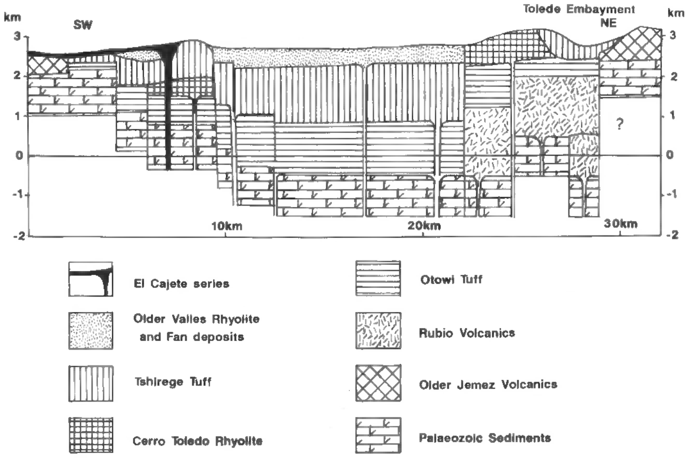

FIGURE 9. Possible geological cross section across the Valles caldera and Toledo embayment based on Profile A-A'.

the western flank of the Rio Grande rift allowed the "Rubio volcano" (4 Ma to 1.78 Ma) to form in the area of the Toledo embayment. These volcanic rocks are part of the Tschicoma and consist of the Cerro Rubio quartz latite (dacite), dated at 3.59±0.36 Ma, and a compositionally related intrusion, dated at 2.18±0.09 Ma (Heiken et al. 1986). But in the modelled profiles these Tschicoma dacites are assumed to have a lower density (2350 kg/m^3) than normal, as they crop out within the area of the gravity low associated with the Valles caldera and Toledo embayment area. The center of the "Rubio volcano" depression migrated southwestward as it grew, until its western margin hit a major rift fault, with thicker crust to the west (Nowell, 1994). At its maximum, it was a downwarped area about 24 km in diameter, bounded by the Cerro de la Garita, Toledo embayment, Rabbit Mountain and the main western ring fracture of the later Valles caldera. The center of this topographic depression collapsed about 1.61 Ma ago to form the Toledo caldera, about 20 km east-west by 15 km north-south, slightly larger with less well developed ring fractures than those of the Valles caldera (16 km by 13 km). The Warm Springs, Cerro Traquilar and Los Poses domes represent ring-fracture volcanism along one of the main Toledo caldera ring fractures. This sequence of events would help to explain the formation of the faulted and slumped ground in the Cerro de la Garita area and the northeastward location of the Toledo embayment.

Below the Toledo embayment on the northeastern side of the section it is postulated that there are between 1500 m and 2500 m of low density Tschicoma Formation volcanics, about 100 km^3 in volume. These rocks were erupted between about 4 Ma and the eruption of the San Diego ignimbrites at 1.78 Ma. The Tschicoma volcanics are exposed on the side of the Toledo embayment 2 km to the southeast of the section. Thus, the Tschicoma volcanics may be at a shallower depth than the 1000 m shown on the section and the Otowi Tuff much thinner or absent at this point. The "Rubio volcano" may have had explosive eruptions, which in its last stages deposited the San Diego ignimbrites 20 km to the southwest. These deposits are up to 80 m thick and have been dated (Spell et al., 1990) at 1.78 Ma and are regarded as a precursor of the Otowi Member of the Bandelier Tuff deposited by the collapse of the Toledo caldera. If this is the case, the Tschicoma Formation volcanics may form a layer including the 69 to 396 m thick lower tuffs (Nielson and Hulen 1984) at the base of the caldera complex. The lower tuffs are believed to be equivalent in part to the San Diego ignimbrites (Hulen et al., 1991), but this can only be proved by dating the lower tuffs. The thickness of the lower tuffs under the western Valles caldera complex was plotted by Hulen et al. (1991) and this shows that the unit thickens to the northeast, which would fit a "Rubio volcano" origin for the lower tuffs, though the pattern is not simple, due to the pre-eruption topography and the present structure of the area. As the Tschicoma formation volcanics were erupted the area beneath them probably collapsed so that the volcano did not stand up above the surrounding country, and it is possible that the center of the "Rubio volcano" may have migrated southwestward toward the center of the Toledo caldera by the time of the eruption of the San Diego ignimbrites. At the time of their eruption the surface of the "Rubio volcano" had sunk at most a few hundred meters, as had the area that would later be the Toledo caldera. Since then, parts of the Toledo embayment have not sunk much farther during the subsequent collapses of the Toledo and Valles calderas, and this explains why the older Tschicoma formation volcanics are exposed in places within the Toledo embayment. Indeed, as each formation in the caldera has been erupted there has tended to be an equal amount of collapse, as a result of the space left by the erupted material (Fig. 10).

The new models presented here, like Segar's (1974) model, show the Valles caldera to be much deeper on the eastern side than in the west. This asymmetry in fill thickness led Nielson and Hulen (1984) and Heiken et al. (1986) to call the Valles caldera a trapdoor caldera. The present work shows, however, that the floor of the caldera is uneven, in that it is broken by a series of discontinuous faults with downthrows often less than 500 m and not smooth like a perfect trapdoor. This is similar to, though less extreme than, the mechanism suggested for funnel-shaped calderas, which involve a process of chaotic collapse, with greatest subsidence toward the center (Scandone, 1990). Caldera collapse has been modelled in experiments using inflatable balloons and a medium of fused alumina power (Marti et al., 1994). Inflation (tumescence) followed by deflation of the balloon resulted in depressions with an outer set of concentric ring fractures surrounding a central funnel. Deflation alone re-

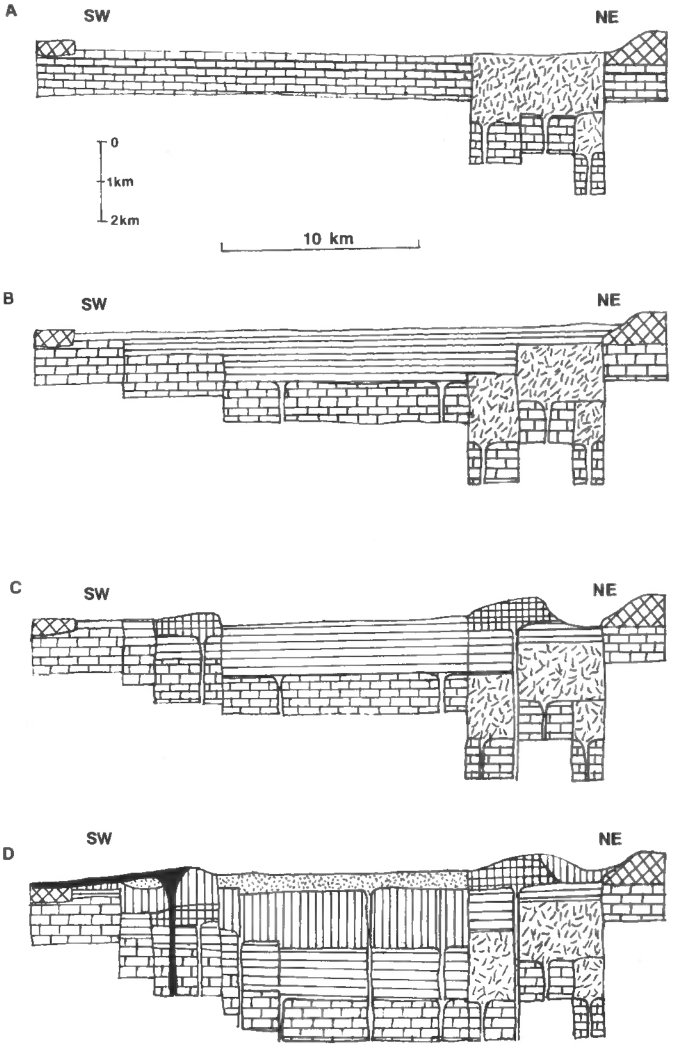

FIGURE 10. Development of the Valles caldera: **A**, Rubio volcano (4 Ma to 1.78 Ma); **B**, Collapse of the Toledo caldera (1.51 Ma); **C**, Intra-caldera volcanics (1.51 Ma to 1.14 Ma); **D**, Collapse of the Valles caldera and postcaldera volcanics (1.14 Ma to 53 ka). See Figure 9 for key to formations.

sulted in an outer set of nearly vertical ring faults surrounding a flat central depression due to collapse of a coherent block. As the floor of the Valles caldera appears to be a series of uneven blocks, but not funnel shaped, its origin may be intermediate between these two extremes.

Boreholes along profile C-C' constrain the thickness of the western caldera fill and thus the model has a positive residual anomaly. This suggests that 70 km^3 of low-density silicic intrusion up to 900 m thick exists beneath the western part of the Valles caldera. Similarly, a positive residual anomaly just outside the eastern margin of the Valles caldera can be modelled as silicic intrusion associated with the eruption of the Rabbit Mountain rhyolite. The Toledo embayment is inferred to have been occupied by an early "Rubio volcano" which erupted 100 km^3 of rhyolite domes and tuffs as one of the possible origins of the Toledo embayment. If the 100 km^3 volume of the Tschicoma volcanics is removed from the 750 km^3 total volume of the Toledo-Valles complex, the remaining 650 km^3 of caldera fill is similar to the 600 km^3 volume of the surrounding Bandelier Tuff deposits. This suggests that, when the Otowi and Tshirege tuffs were ejected by the collapses of the Toledo and Valles calderas, an equal volume of material was left in the caldera. Thus a tuff deposit ejected by an eruption of the Toledo-Valles volcanic complex represents about half the total volume of the material produced in a given eruption.

It is clear that the Toledo caldera and the later Valles caldera had similar centers because the Otowi Member and the Tshirege Member have similar distribution and volume. This suggests that the earlier Toledo caldera occupied a similar area to the later Valles caldera with the "center" offset slightly to the southwest leaving the Toledo embayment outside the later Valles caldera ring fracture. Because the fill in the Toledo embayment is of the same density as that in the later Valles caldera it cannot be separated on gravity profiles. The profiles suggest that the Toledo and Valles calderas are nested, nearly coincident, trapdoor calderas with irregular floors due to uneven collapse. The only part of the Toledo caldera not occupied by the later Valles caldera is the Toledo embayment on the northeastern side of the caldera, which was the site of an earlier "Rubio volcano".

CONCLUSIONS

Gravity data from the Valles caldera area were modelled interactively in 3D with a single density contrast (Segar, 1974). The results suggest that the caldera is asymmetrical with only 760 m of caldera fill in the west and over 4570 m in the east, though the only way the thickness of the caldera fill in the east of the caldera could be proved would be by drilling a borehole in the area. The original corrected data from this gravity survey were here used to model three 2½D gravity profiles across the Valles caldera. Better results would have been obtained if the Bouguer gravity had been recalculated at a higher density of 2650 kg/m^3, a different regional isostatic gravity field removed, and the relatively dense Paliza Canyon and Tschicoma Formations modelled below and to the east of the caldera. In places these profiles indicate that the caldera floor is up to 1000 m shallower than shown by the earlier 3D model with a 3600 m maximum depth, but with a similar shape. Locally faults in one model are not found in the other. Small bodies with different density contrasts are postulated along the 2½D profiles, which could not be modelled previously. The proposed model is that the caldera collapsed in a series of uneven blocks. In agreement with previous models, the Valles caldera appears to be a trapdoor caldera hinged on the west, with a volume of approximately 750 km^3. The earlier Toledo caldera had approximately the same area and extent as the Valles caldera. The 2½D profiles extend to the Toledo embayment and show that this is an area of low density rocks, suggesting that the embayment was the site of the earlier "Rubio volcano". A high-standing fault block in this area possibly represents a segment of "Rubio volcano" that failed to sink farther during the formation of the younger calderas. The San Diego ignimbrites may mark the last stage of the "Rubio volcano" before the collapse of the Toledo caldera.

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