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Interpretation of Gravity Data in a Complex Volcano-Tectonic Setting, Southwestern Nevada

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This regional gravity study, based on an irregular 2-km data grid, was conducted during the past few years at Yucca Mountain, southern Nye County, Nevada, as part of a program to locate a suitable repository for high-level nuclear waste. About 100 surface rock samples, three borehole gamma-gamma logs, and one borehole gravity study provide excellent density control. A nearly linear increase in density of 0.26 g/cm^3 per kilometer of depth is indicated in the thick tuff sequences that underlie the mountain. Isostatic and 2.0-g/cm^3 Bouguer corrections were applied to the observed gravity values to remove regional gradients and topographic effects, respectively. The Bare Mountain gravity high, with an isostatic anomaly maximum of 48 mGal, is connected with a greater gravity high over the Funeral Mountains, to the southwest; together, these highs result from a continuous block of dense, metamorphosed Precambrian and Paleozoic rocks that stretches across much of the Walker Lane from the east edge of Death Valley to Bare Mountain. The Calico Hills gravity high appears more likely to originate from a northeast trending buried ridge of Paleozoic rocks that extends southwestward beneath Busted Butte, 5 km southeast of the proposed repository, where two- and three-dimensional modeling indicates that the pre-Cenozoic rocks lie less than 1000 m beneath the surface. Tuff, at least 4000 m thick, fills a large steep-sided depression in the pretuff rocks beneath Yucca Mountain and Crater Flat. The gravity low and the thick tuff section lie within a large collapse area that includes the Crater Flat–Timber Mountain–Silent Canyon caldera complexes. Gravity lows in Crater Flat itself are interpreted to coincide with the source areas of the Prow Pass Member, the Bullfrog Member, and the Tram Member of the Crater Flat Tuff; these source areas add nearly 350 km^2 to the previously recognized extent of the local caldera complexes. Southward extension of the broad gravity low associated with Crater Flat into the Amargosa Desert is evidence for sector graben-type collapse segments related to the formation of the Timber Mountain caldera and superimposed on the other volcanic and extensional structures within Crater Flat.

INTRODUCTION

This gravity study is concentrated in southwest Nevada near the California border and Death Valley (Figure 1) and on the southwest side of the southwestern Nevada volcanic field (Figure 2*a*). This volcanic field includes the Timber Mountain caldera complex [*Byers et al.*, 1976] and the Crater Flat–Prospector Pass caldera complex [*Carr et al.*, 1984], the sources of numerous, voluminous eruptions from about 16 to 10 Ma ago. A general understanding of the near-surface structure of this volcanic field has existed for more than a decade. In the last few years and as a result of exploration at Yucca Mountain for a repository to hold high-level nuclear waste, geologic and geophysical studies have outlined the complex crustal structures and tectonic history of the region in greater detail.

Gravity investigations play an important role in the characterization of Yucca Mountain as a possible nuclear waste repository. In and near the mountain Cenozoic sedimentary and volcanic rocks obscure the more complex pre-Tertiary geology, and therefore obtaining information about subsurface rock geometry is critical to fully characterize the water flow patterns in the area. The candidate repository site (Figure 1) lies within tuff composing the northern part of Yucca Mountain, a relatively coherent block of rocks within a stratigraphically and structurally complex region. This study explores and interprets the three-dimensional structure and geometry of the rocks surrounding the candidate site; it updates a preliminary report [*Snyder and Carr*, 1982] and earlier work by *Healey and Miller* [1971].

Numerous deep (750–1830 m) holes have been drilled at Yucca Mountain; most have a full suite of geophysical logs. All but three of the holes (Figure 1) are in or near the candidate site area and include USW-G1 [*Spengler et al.*, 1981], USW-G2 [*Maldonado and Koether*, 1983], USW-G3, UE25P-1, and USW-H1. Other holes drilled a little farther outside the site area include J-13 near Fortymile Wash, UE25a-3 in the Calico Hills [*Maldonado et al.*, 1979], and USW-VH-1 [*Carr*, 1982] and USW-VH-2 in Crater Flat. Geologic, geophysical, and hydrologic data have been obtained from these holes, and this information has been used both directly and indirectly in interpreting the structure of the area. Drill holes UE25a-3 and UE25P-1 reached pre-Tertiary rocks, at depths of 1 and 1240 m, respectively, but several holes in the area (G1, G2, G3, and H1) were drilled to depths of about 1830 m without reaching the base of the volcanic rocks (Figure 3). Alteration was especially notable in the lower part of the section penetrated by these deep holes [*Waters and Carroll*, 1981], and metamorphic effects, including density change, increase steadily downward.

Four aeromagnetic surveys are encompassed by the area of the gravity study. Constant-barometric-elevation surveys [*Boynton and Vargo*, 1963; *U.S. Geological Survey*, 1971], flown at 2440 and 2740 m, respectively, indicate a strong gradient across northern Yucca Mountain that increases in total intensity to the north. The breadth and slope of this gradient suggest that the source lies at a minimum depth of

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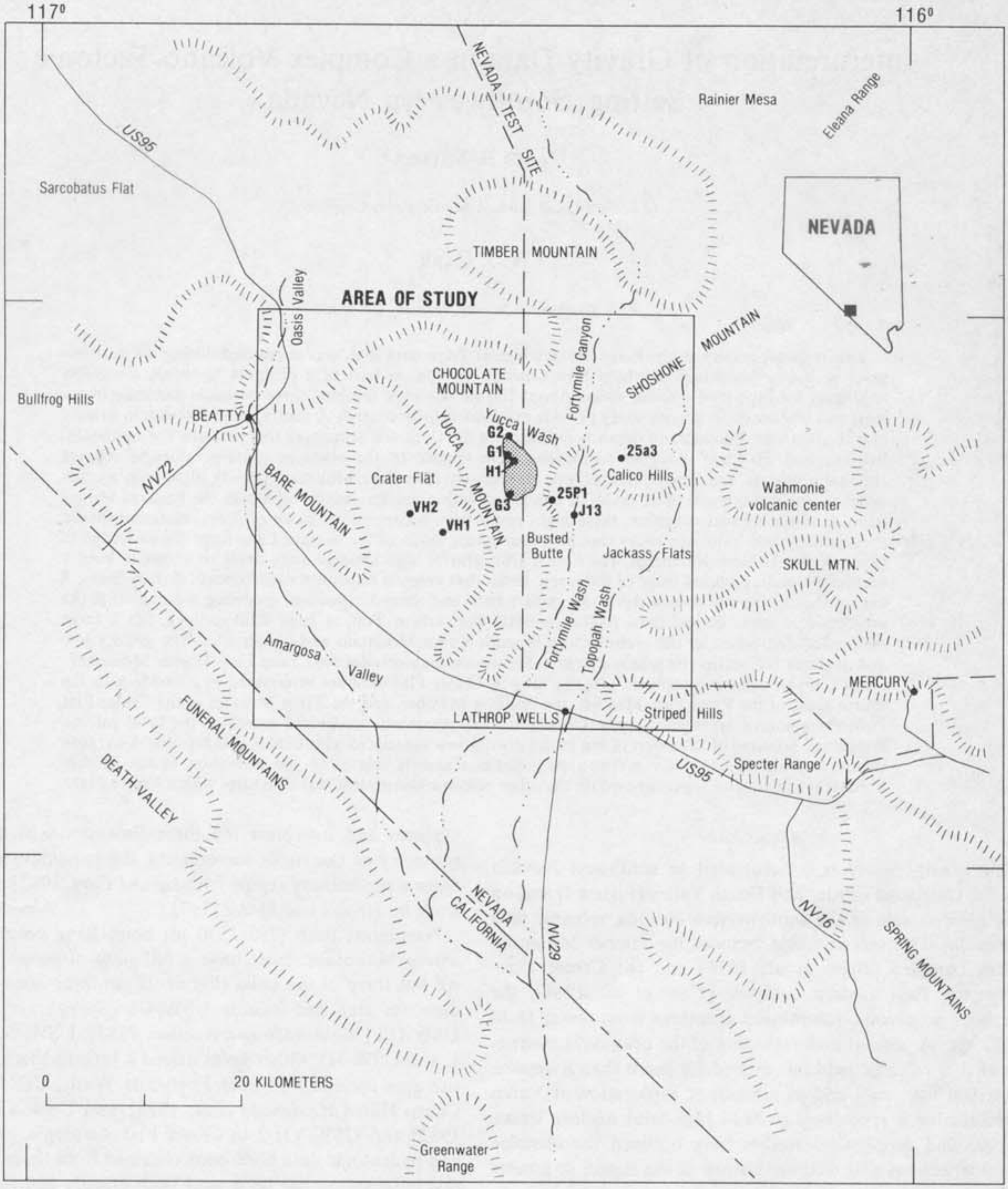

Fig. 1. Index maps showing location of study area (also area of Figures 2 and 4), local physiography, and cultural landmarks. Shaded area represents the potential repository site area. Numbers, such as G1, represent drill hole locations; the USW and UE prefixes of the full designations have been omitted for simplicity.

2200 m (G. D. Bath, written communication, 1980). Two later surveys, flown at constant terrain clearance of 120 m, also covered the study area [*U.S. Geological Survey*, 1978, 1979].

Seismic and electrical techniques thus far have been only partly successful; no clear characterization of the rocks below 500 m has been obtained as yet by these methods. Seismic refraction experiments are testing the gravity model presented here [*Mooney et al.*, 1982]; one unreversed east-west profile produced a velocity cross section compatible with the gravity model and indicated additional structures within the Precambrian and Paleozoic rocks at depths greater than the resolution range of the gravity study.

GEOLOGY OF YUCCA MOUNTAIN AND VICINITY

Yucca Mountain lies in the southern part of the Great Basin section of the Basin and Range physiographic province and within the Walker Lane [*Locke et al.*, 1940; *Carr*, 1974]. Much of the Great Basin is characterized by typical basin-and-range topography, with alternating north trending ridges and valleys. The Walker Lane exhibits more diverse topography of generally lower relief and, locally, arcuate mountain trends; it has been described as a belt of sigmoidal bending and right-lateral faulting [*Albers*, 1967]. The area around Yucca Mountain shows even less relief than most of the

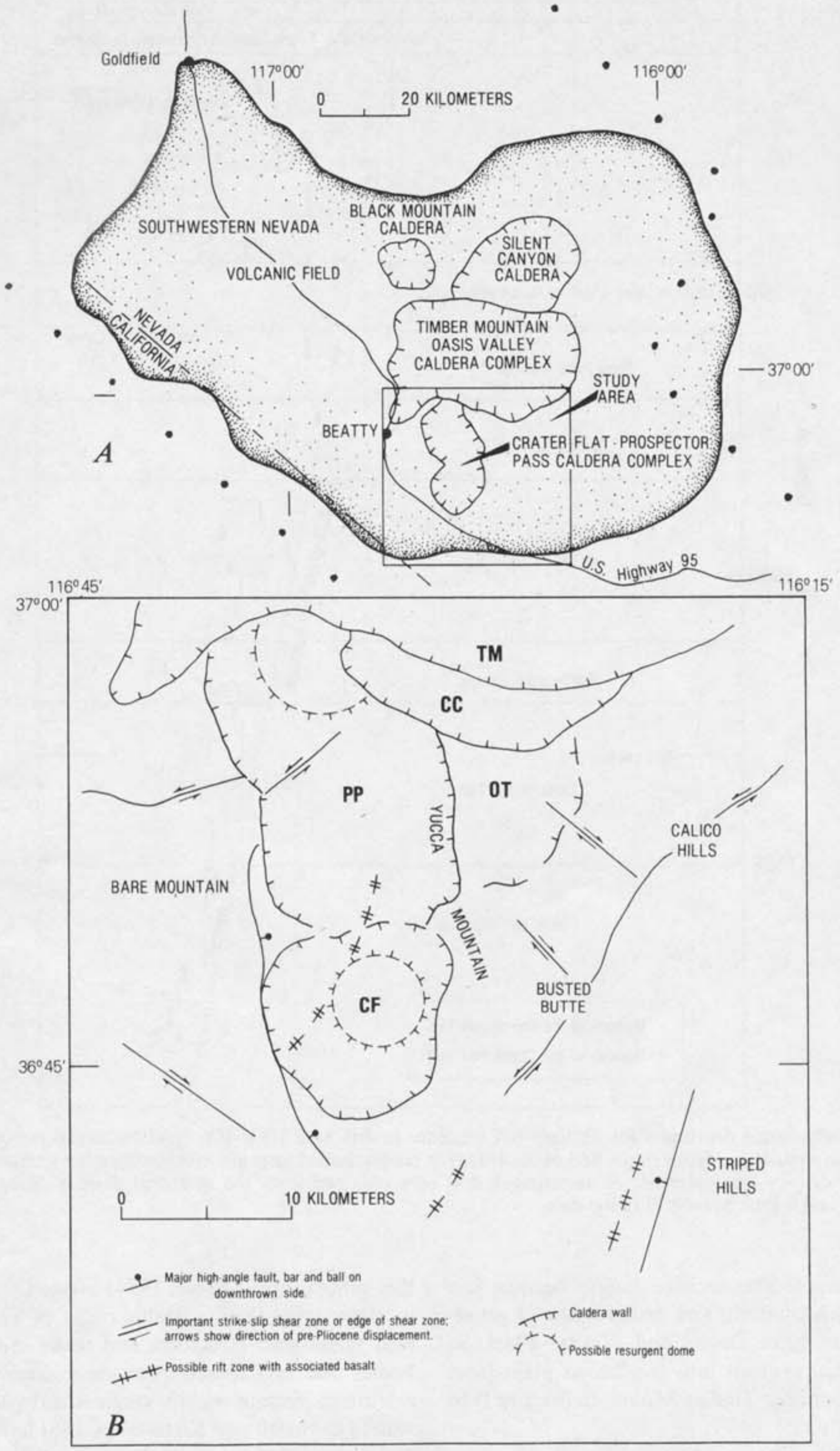

Fig. 2. (*a*) Map of the southwestern Nevada volcanic field and its component calderas. Dotted lines denote approximate boundary of the Walker Lane. (*b*) Tectonic-structural diagram of the study area. The location and size of the diagram is indicated by the rectangle in Figures 1 and 2*a*. Letters identify volcanic structures: TM, Timber Mountain–Oasis Valley caldera complex; CC, Claim Canyon caldera segment; CF, caldera associated with the Bullfrog Member and Prow Pass Member of the Crater Flat Tuff; OT, possible collapse feature filled by older tuff; PP, Prospector Pass caldera segment associated with the Tram Member of the Crater Flat Tuff. Many caldera walls are located with the aid of gravity interpretation.

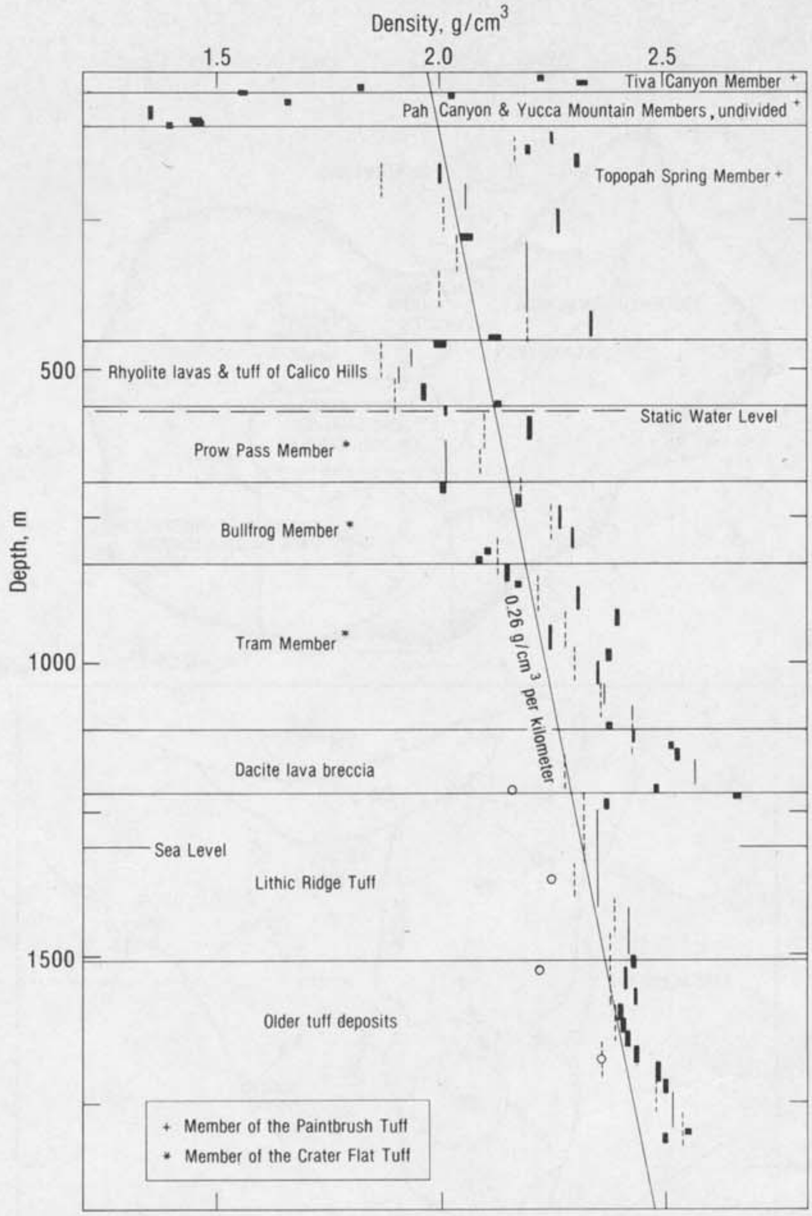

Fig. 3. Density versus depth plot for Tertiary tuff sequence in drill hole USW-H1. Solid rectangles indicate borehole gravity meter determination, depth range, and estimated error range; dashed lines are averaged gamma-gamma log values; circles indicate density measurements of unsaturated drill core obtained from the saturated zone in Yucca Mountain (Table 2). Solid line is least squares fit of the data.

Walker Lane; the characteristic arcuate ranges become less prominent near Yucca Mountain, and broad areas of generally low relief, the Amargosa Desert and Jackass Flats, lie nearby. Yucca Mountain projects into this broad plain from the higher terrain surrounding Timber Mountain (Figure 1) to the north.

Stratigraphy

Table 1 is a simplified stratigraphic column of the geologic units in the Yucca Mountain area pertinent to the gravity study. Pre-Tertiary rocks (Figure 4) consist of upper Precambrian and Cambrian clastic units, lower and middle Paleozoic carbonate rocks, and upper Paleozoic detrital rocks. Locally, these rocks are intruded by Mesozoic or Tertiary granitic plutons. Several ancient structural features and depositional zones of Precambrian and Paleozoic age are thought to cross this general area [*Poole*, 1974; *Stewart*, 1980, pp. 40–52], but in many areas thick volcanic rocks of Tertiary age have covered these older structures and rocks. Although the intrusive bodies that crystallized from the magma feeding the Tertiary extrusions remain mostly concealed, hydrothermal alteration zones [*Cornwall and Kleinhampl*, 1961], dikes and small plugs, and domical structures [*Cornwall and Kleinhampl*, 1961; *Carr and Quinlivan*, 1968; *Maldonado et al.*, 1979] suggest the presence of buried intrusive rocks.

Quartzite and other clastic rocks, which predominate within the upper Precambrian and lowermost Paleozoic assemblage, crop out mainly in the western part of the study area, where they are mildly metamorphosed. A thick sequence of limestone and dolomite of Cambrian through Devonian age crops out mostly on Bare Mountain and in the Striped Hills (Figure 1). Thrust or slide masses of Devonian rocks are also present in

TABLE 1. Density and Thickness of Selected Geologic Units in the Yucca Mountain Area

Age	Unit	Approximate Thickness, m	Average Density, g/cm³
Quaternary and Tertiary	alluvium	0–300	1.6–2.0
	basalt	0–200	2.9
Tertiary	rhyolite lava flows of Shoshone Mountain	0–100	2.2
	rhyolite lava flows of Fortymile Canyon	0–200	2.2
	Timber Mountain Tuff		
11.3 Ma*	Ammonia Tanks Member and Rainier Mesa Member, undivided	0–150	1.9
	Paintbrush Tuff		
12.6 Ma*	Tiva Canyon Member	120	2.1
	Yucca Mountain Member	0–60	1.9
	Pah Canyon Member	0–70	1.9
13.1 Ma*	Topopah Spring Member	300	2.2
13.4 Ma*	rhyolite lavas and tuff of Calico Hills	10–200	1.9
	Crater Flat Tuff		
	Prow Pass Member	100	2.1
14.0 Ma*	Bullfrog Member	150	2.1
	Tram Member	300	2.25
	rhyodacitic lavas	0–200	2.35
	Lithic Ridge Tuff	300	2.35
	ash flow and bedded tuff	300+	2.45
Tertiary and Mesozoic	granitic intrusive rocks	unknown	2.4?
Late Paleozoic	Tippipah Limestone, Eleana Formation	2000	2.62
Middle and early Paleozoic	Devils Gate Limestone, Ely Springs Dolomite, Eureka Quartzite, Pogonip Group, Nopah Formation, Bonanza King Formation	4000	2.72
Early Paleozoic and Precambrian	Carrara Formation, Zabriskie Quartzite, Wood Canyon Formation, Stirling Quartzite, Johnnie Formation	3500+	2.65

*Radiometric ages from *Marvin et al.* [1970].

the Calico Hills. Mississippian and Pennsylvanian rocks, principally argillite, quartzite, and limestone, form the lower plate of low-angle faults from Bare Mountain to the Calico Hills and northeastward through the Eleana Range (Figure 1).

Granite crops out at only one locality within the study area. An altered east-west trending granite dike occurs near Beatty at the northwest end of Bare Mountain (Figure 1); a zircon fission track age of 25.4 ± 1.3 Ma (C. W. Naeser, unpublished data, 1983) and geologic relations suggest that the dike is older than known Tertiary volcanism in the region. Granite of Mesozoic age occurs at several localities in the northern part of the Nevada Test Site, and granodiorite of Tertiary age crops out at the Wahmonie volcanic center, just east of the study area [*Ekren and Sargent*, 1965; *Ponce*, 1981]. The presence of an extensive caldera complex suggests that granitic rocks underlie much of the northern part of the study area.

The exposed Cenozoic stratigraphic sequence of the area has been well studied. Several volcanic centers within and adjacent to the Timber Mountain–Oasis Valley caldera complex [*Marvin et al.*, 1970; *Byers et al.*, 1976] extruded the Cenozoic tuff and lava flows. some of which are listed in Table 1. Potassium-argon dates indicate that most of the tuff was deposited between 15 and 7 Ma ago; however, the oldest units recently encountered in deep drill holes have not been dated. The great thickness of this tuff indicates the close proximity of its sources. The degree of welding and the density of the tuff vary greatly both laterally and vertically.

Alluvium is widespread and thick in Crater Flat, Jackass Flats, and the Amargosa Valley. The alluvium consists mostly of detritus from weathered and eroded tuff, but adjacent to Bare Mountain and the Striped Hills it contains considerable quartzite and carbonate rock clasts. Locally, caliche cement is conspicuous in the alluvium. Basalt crops out and intertongues with the alluvium, principally in southern Crater Flat, around Jackass Flats, and in the moat of the Timber Mountain caldera. The basaltic activity spans most of the alluvial depositional history but has had pulses about 3.75, 1.1, and 0.3 Ma ago [*Vaniman et al.*, 1980].

Rock Densities

In the Yucca Mountain area, density data from surface samples are augmented by both gamma-gamma and borehole gravity measurements in several drill holes. This combination of sample and borehole measurements provides a much better constraint on the rock densities than is available in most gravity studies. The densities of six core samples from drill holes USW-G1 and USW-VH-1, and of 95 surface samples, were measured (Table 2).

Surface samples provide the only density control on the lower Paleozoic rocks modeled in this study. Pre-Tertiary rocks beneath Crater Flat, Yucca Mountain, and Jackass Flats have been sampled only by drill hole UE25P-1, and their exact lithology and density remain largely unknown. Drill hole UE25P-1 penetrated middle Paleozoic dolomite at a depth of 1240 m; preliminary density logs from 1240- to 1800-m depths indicate a bulk density of about 2.75 g/cm³.

A.

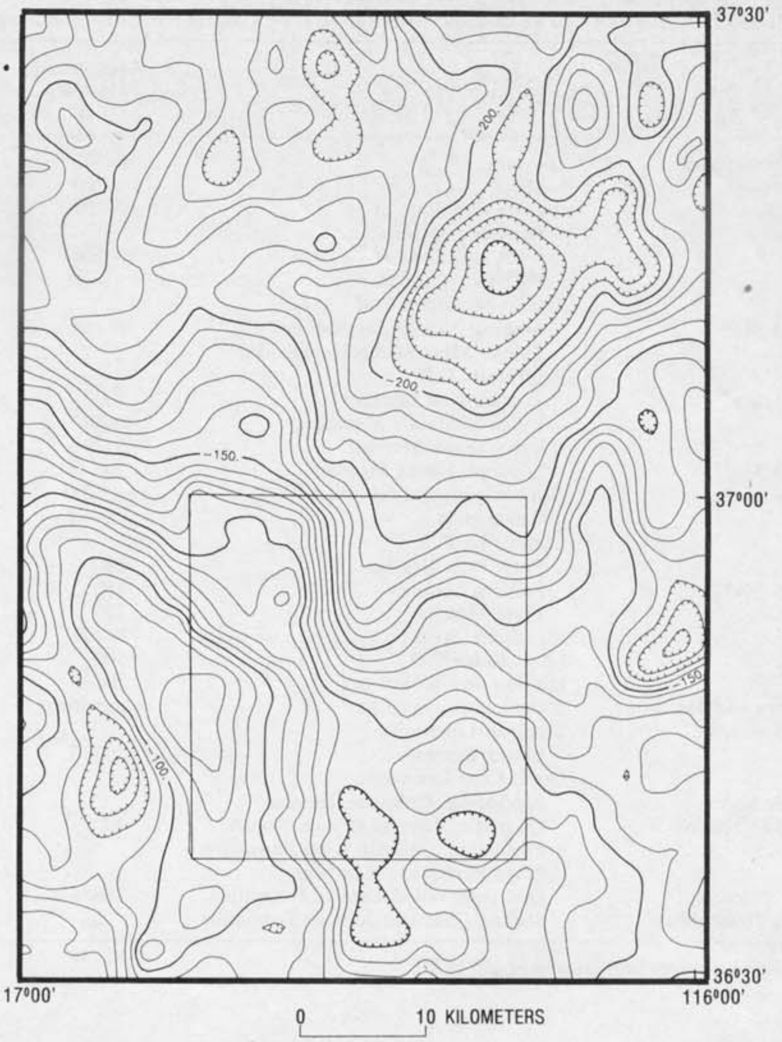

Fig. 4*a*. Complete Bouguer anomaly map of the region surrounding Yucca Mountain. Area of Figures 4*b* and 4*c* is indicated by the rectangle.

The density of saturated pre-Tertiary rock samples ranges from 2.60 to 2.82, with a mean of 2.66 ± 0.06 (1σ) g/cm^3, on the basis of samples taken from outcrops at Bare Mountain and the Striped Hills (Table 2); values in Table 1 are averages of the samples from each rock group listed.

Gamma-gamma density logs were obtained in drill holes USW-G1, H1, and VH-1. These logs have been borehole compensated; that is, any variations in hole diameter caused by wall collapse or the drilling process have been accounted for in the density determinations. The compensated density log curves were then integrated within specified depth intervals to produce an average value for each interval. This analysis further smoothed irregularities caused by fractures in the drill hole walls. The observed downward increase in density (Figure 3) appears to be related to the closing of pore space due to alteration and compaction rather than to primary density variations in the tuff. Nearly linear density increases within individual tuff units (for example, Tram Member in Figure 3) are clearly attributable to the degree of welding and cooling history of the tuff at the time of emplacement.

A downhole gravity study was made in drill hole USW-H1 [*Robbins et al.*, 1982]. Values agree well with the gamma-gamma measurements (Figure 3). This agreement is significant, because borehole gravity measurements sample a much greater lateral volume than do the density logs and include fractures, cavities, and other large irregularities in the rock.

The three drill holes with gamma-gamma logs provide excellent constraints on the densities of the Cenozoic tuff, basalt, and alluvium. The linear gradient of 0.26 g/cm^3 per kilometer of depth, if it is indeed due to alteration and lithostatic loading, is applicable to all the thick tuff sequences within the study area.

Structure

The area of this study is near the axis of the Walker Lane and near the southern margin of the southwestern Nevada volcanic field (Figure 2*a*; *Carr et al.* [1984]). The nearly linear basins and ranges of central Nevada are interrupted in southwestern Nevada by several northwest striking right-lateral fault zones; these fault zones combine with northeast striking fault zones and structures related to numerous nearby calderas to produce a 50- to 100-km-wide northwest trending zone of diverse topography and structure here included in the Walker Lane [*Carr*, 1974]. Large-scale drag folds or oroclinal bends [*Albers*, 1967] are associated with parts of the Walker Lane, but in the study area these structures are obscured by

B.

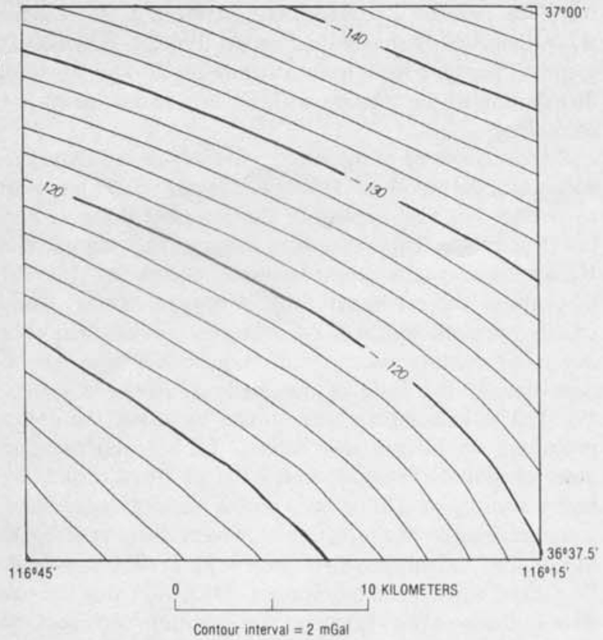

Fig. 4*b*. Map of isostatic correction applied to the Bouguer anomalies to produce the isostatic residual gravity map. See text for parameters used in the calculation of the correction.

Tertiary volcanic rocks and structures. One exception is Bare Mountain (Figure 4) where large-scale right-lateral drag is observed in the pre-Tertiary rocks. The region was also intruded by east trending Mesozoic granitic plutons while being subjected to crustal shortening caused chiefly by eastward or southeastward directed thrusting and folding [*Stewart*, 1980]. The study area is also within the Death Valley–Pancake Range belt of *Crowe et al.* [1983], a zone slightly more tectonically active than adjacent areas during latest Miocene to Holocene time. This belt is the locus of basalts less than 8 Ma in age and relatively dense Quaternary faulting [*Carr*, 1974; *Carr and Rogers*, 1982, pp. 12–14].

Five main structural elements are recognized within the study area (Figure 2*b*): (1) the high-standing block of Bare Mountain exposing metamorphism, thrust faults, and folds [*Cornwall and Kleinhampl*, 1961; *Monsen*, 1983]; (2) northwest trending valleys, such as the Amargosa Valley and Yucca Wash (Figures 1 and 2*b*), that represent the location of fault zones of that trend; (3) northeast trending structural zones in the northwest and southeast quadrants of the study area (Figure 2*b*); (4) north to northeast striking basin-range faults and grabens mostly in the Lathrop Wells area, on Yucca Mountain, and in Crater Flat; and (5) large volcano-tectonic features related to and including the Timber Mountain–Oasis Valley and Crater Flat–Prospector Pass caldera complexes [*Carr et al.*, 1984]. These caldera and collapse features are largely superimposed on, but partly controlled by, the other structural elements.

At Bare Mountain the Late Precambrian and Paleozoic rocks are separated from the Tertiary volcanic rocks by a major fault that dips northward at angles of 10°–20° [*Cornwall and Kleinhampl*, 1961]. Within the Paleozoic rocks, north striking, east dipping normal faults are slightly older or contemporaneous [*Monsen*, 1983] with silicic dikes that are about 13.9 Ma old (R. F. Marvin, unpublished data, 1980). Low-angle normal faults or glide blocks on Bare Mountain postdate the north striking dikes and faults.

In nearby areas where Tertiary rocks are relatively thin, fault trends in the Paleozoic rocks are similar or coincident with those in the overlying Tertiary rocks, and the displacements in the Paleozoic rocks are distinctly larger [*Sargent and Stewart*, 1971; *Byers and Barnes*, 1967]. High-angle faulting was well established prior to the volcanism that began in this area about 16 Ma ago [*Marvin et al.*, 1970]. These relationships suggest that at least some of the extensive faulting in the Tertiary rocks represents reactivation of older structures.

The age of major displacement that is observed on high-angle faults varies within the study area. On Yucca Mountain and in Crater Flat, surface exposures and drill holes provide evidence that most of the displacement on the north trending faults took place between 12.5 and 11.5 Ma ago, that is, between deposition of the Tiva Canyon Member of the Paintbrush Tuff and the Rainier Mesa Member of the Timber Mountain Tuff. The Rainier Mesa Member was deposited across faults bounding structurally elevated blocks of older tuff [*Lipman and McKay*, 1965]. Much Miocene normal faulting thus took place during a period of voluminous volcanism.

Volcano-Tectonic History

Because most of the study area contains thick sequences of tuff and lava and the candidate site area is underlain by more than 2000 m of tuff, a summary of the volcanic history of the study area is warranted.

TABLE 2. Density Measurements of Surface and Drill Hole Samples

Rock Unit	Density, g/cm³ Unsaturated	Saturated
Older tuff	2.37	...
Older tuff	2.22	...
Older tuff	2.25	...
"Tuff of Lithic Ridge"	2.16	...
Tiva Canyon Member*	2.40	...
Basalt	2.88	...
Rainier Mesa Member†	2.00	2.08
Rainier Mesa Member†	1.86	2.26
Basalt	2.76	...
Basalt cinder	1.39	1.55
Basalt cinder	1.90	2.04
Basalt	2.77	2.78
Basalt	2.88	2.89
Tiva Canyon Member*	2.27	2.30
Tiva Canyon Member*	2.34	2.35
Tuff, undifferentiated	2.84	2.85
Tiva Canyon Member*	2.14	2.36
70 samples of rhyolite of Calico Hills	2.12 ± 0.26	2.26 ± 0.17
Argillite, Eleana Formation	2.59	2.63
Carboniferous argillite	2.59	2.61
Carboniferous argillite	2.58	2.61
Devonian limestone	2.81	2.82
Devonian limestone	2.64	2.67
Devonian dolomite	2.68	2.69
Limestone	2.68	2.70
Limestone, Bonanza King Formation	2.66	2.67
Limestone, Bonanza King Formation	2.59	2.62
Zabriskie Quartzite	2.64	2.65
Zabriskie Quartzite	2.59	2.60
Zabriskie Quartzite	2.70	2.72
Zabriskie Quartzite	2.61	2.63
Zabriskie Quartzite	2.64	2.64

*Member of the Paintbrush Tuff.
†Member of the Timber Mountain Tuff.

The stratigraphy of the lower part of the volcanic rock sequence in this area has been studied in detail [*Carr et al.*, 1984], and some revisions in earlier concepts [*Byers et al.*, 1976] have been made. The oldest tuff units at Yucca Mountain, those stratigraphically below the Lithic Ridge Tuff (Table 1), are known from drill holes [*Spengler et al.*, 1981]. The great thickness (more than 600 m) of this older tuff and its position well below sea level suggest accumulation in a sag or collapse feature, possibly a caldera (Figure 2*b*). The Lithic Ridge Tuff is the oldest extensively exposed volcanic unit in the study area. Its source is unknown, and although penetrated by several drill holes on Yucca Mountain, it is not especially thick in that area. Local occurrences of petrographically similar rhyodacite lava flows above and below the Lithic Ridge Tuff, however, suggest that the source is nearby [*Carr et al.*, 1984].

Next to be deposited in the site area were the three members of the Crater Flat Tuff: in ascending order, the Tram Member, the Bullfrog Member, and the Prow Pass Member. The Crater Flat Tuff has no characteristics in the drill holes at Yucca Mountain which would suggest it was deposited in a caldera there, although the three members have a total thickness of more than 450 m. The source areas or calderas, and greater thicknesses of the Crater Flat Tuff, are thought to lie to the west and northwest of Yucca Mountain, mostly beneath Crater Flat itself (Figure 2) [*Carr*, 1982; *Carr et al.*, 1984].

The rhyolite lavas and tuff of Calico Hills were emplaced on top of the Crater Flat Tuff in the area between northern Yucca Mountain and the Calico Hills. The main source areas were in the western Calico Hills–Fortymile Canyon area, but some lava reached as far southwest as the northeast edge of Yucca Mountain, where the section consists mostly of about 100 m of bedded air fall and thin ash flow tuff units.

After deposition of the lavas and tuff of the Calico Hills unit, eruptions began from the Timber Mountain–Oasis Valley caldera complex, including the Claim Canyon cauldron segment just north of Yucca Mountain (Figure 2*b*). These eruptions produced voluminous, widespread ash flow tuff sheets assigned to the Paintbrush Tuff and Timber Mountain Tuff. Regional tumescence or doming is thought to have immediately preceded formation of the complex [*Christiansen et al.*, 1977], and the edge of that uplift may have been near the north end of Yucca Mountain. Very thick sequences of the Paintbrush Tuff and Timber Mountain Tuff accumulated in parts of the caldera complex. During the waning stages of activity at the Timber Mountain center, voluminous lavas and minor tuff were extruded around the edges of the complex. Nearly all the basaltic eruptions followed this stage of activity and have continued into Quaternary time, although volumes have been very small.

GRAVITY DATA

More than 2500 gravity measurements have been made in the study area (Figure 1). Each is generally about 2 km from its nearest neighbor. The complete data set analyzed in this report, both new and previously published data, is described by *Jansma et al.* [1982]. Analysis of the complete Bouguer gravity anomalies reduced at the average crustal density of 2.67 g/cm^3 (Figure 4*a*) was deemed inadequate for the detailed study of the Yucca Mountain area [*Snyder and Carr*, 1982]. Density measurements discussed previously indicate that rocks making up much of the topographic relief in volcanic terrane of this area have densities between 1.7 and 2.3 g/cm^3, averaging 2.0 g/cm^3. The complete Bouguer anomalies were, therefore, reduced a second time, according to the method of R. W. Saltus (written communication, 1980), at a density of 2.0 g/cm^3. Thus gravity effects attributable to the topographic distribution of the stations within volcanic terrane have been eliminated.

To remove some of the effects attributable to lateral density variations deeper than 5 km within the crust, an isostatic correction was also applied to the complete Bouguer anomalies (Figure 4*b*). This correction assumes that complete Airy-Heiskanen isostatic compensation occurs at the Moho throughout the earth; although Airy-type isostasy may not strictly apply to southern Nevada, the gravitational effect of any compensating mass is indistinguishable from Airy compensation at the scale of this study [*Jachens and Griscom*, 1983]. The calculations were made by using the computer procedure of *Jachens and Roberts* [1981] and assuming a mean crustal thickness at sea level of 25 km, a surface topography density of 2.67 g/cm^3, and a density contrast of 0.4 g/cm^3 across the Moho within a 167-km distance from Yucca Mountain [*Jachens and Griscom*, 1983]. Preliminary work (H. W. Oliver, written communication, 1983) adjusting the parameters in the isostatic correction computations indicates that in central Nevada a more appropriate reference mean crustal thickness at sea level may be 16–18 km; calculated crustal thicknesses between 25 and 35 km result for those parts of Nevada where average elevation is 1–2 km. However, in the present study, the purpose of this isostatic correction was not to estimate the deep crustal structure beneath Yucca Mounatin, but to filter out long-wavelength gravity effects related to the compensation of surface topography.

The final product of all these corrections and reductions is a model with rocks of 2.0-g/cm^3 density above the lowest gravity station elevation in the study area, rocks of 0.4-g/cm^3 density contrast across the Moho within its vertical range at depths of about 30 to 40 km locally [*Johnson*, 1965], and rocks of homogeneous lateral densities elsewhere. Further modeling begins with this simple and basic model and, drawing on geologic and geophysical evidence, attempts to further characterize the rocks near the earth's surface by comparing the gravity field in the models with that actually observed.

INTERPRETATION OF THE GRAVITY FIELD

Three analytical tools aided the interpretation of the gravity field at Yucca Mountain: a 2-mGal contour map (Figure 4*c*; *Snyder and Carr* [1982]) reduced at 2.00 g/cm^3 and corrected for perfect isostasy, a two-dimensional modeled cross section extending east-west across the study area (Figures 4*c* and 5), and a three-dimensional multiple-polygon gravity model (Figures 5 and 6). The three-dimensional model [*Plouff*, 1975], using simple flat polygonal source bodies, provided more accurate depth estimates; it consisted of eight bodies of prevolcanic rocks, three bodies of the dense tuff of Chocolate Mountain, two bodies composed of the Crater Flat Tuff, and one alluvial body along Topopah Wash. This simple model approximates the observed gravity field to within 3 mGal in the area near Yucca Mountain and Crater Flat.

Bare Mountain Gravity High

The most distinctive gravity feature within the study area is the approximately rectangular anomaly along the western border of the area, which generally coincides with Bare Mountain and the Funeral Mountains, interrupted by the northwest trending Amargosa Valley (Figures 1 and 4*c*). Residual gravity values greater than 14 mGal delimit the anomaly. The rocks

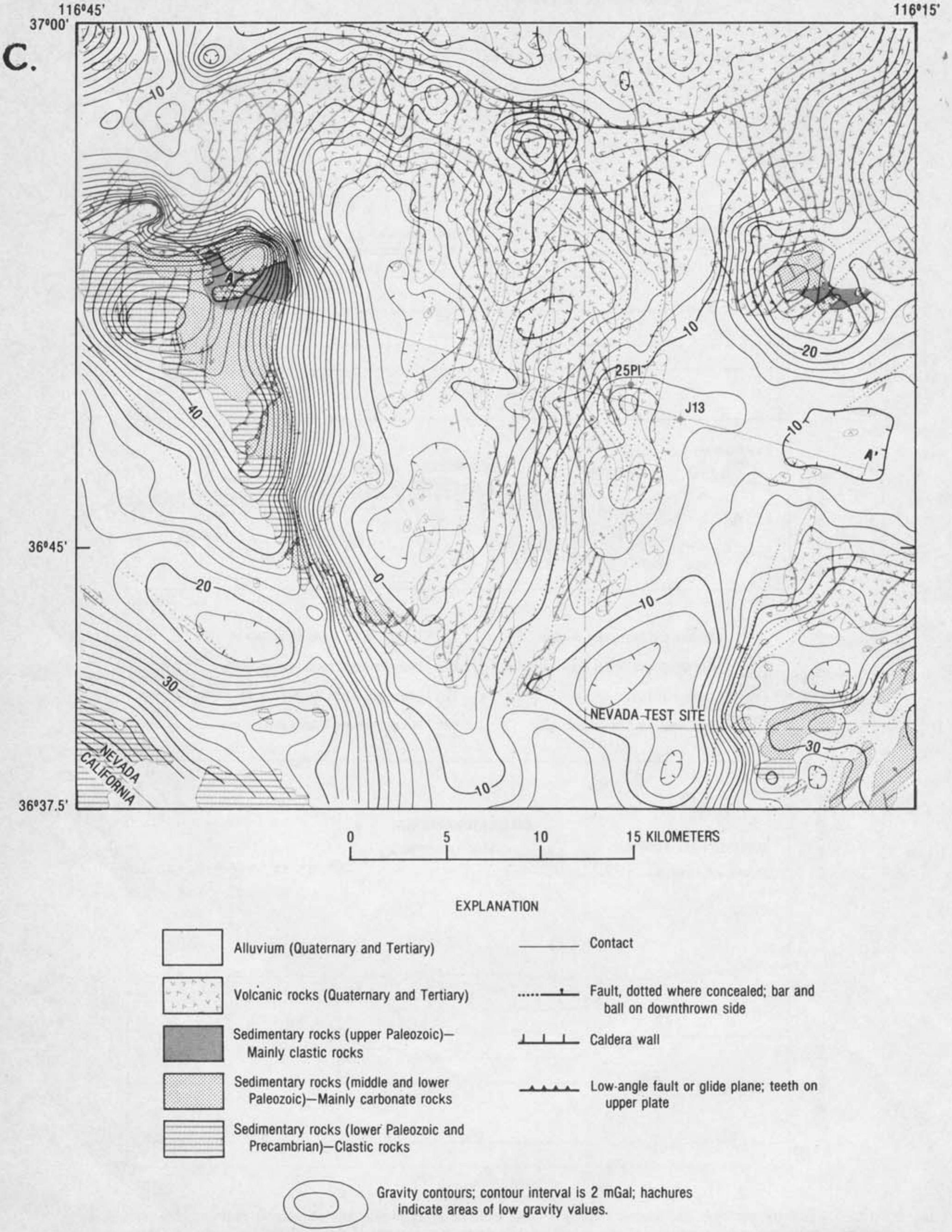

Fig. 4*c*. Isostatic residual gravity and geologic map of the Yucca Mountain–Crater Flat area (Figure 1). Gravity values are isostatically corrected and reduced at 2.0 g/cm^3. A-A' is profile of Figure 5.

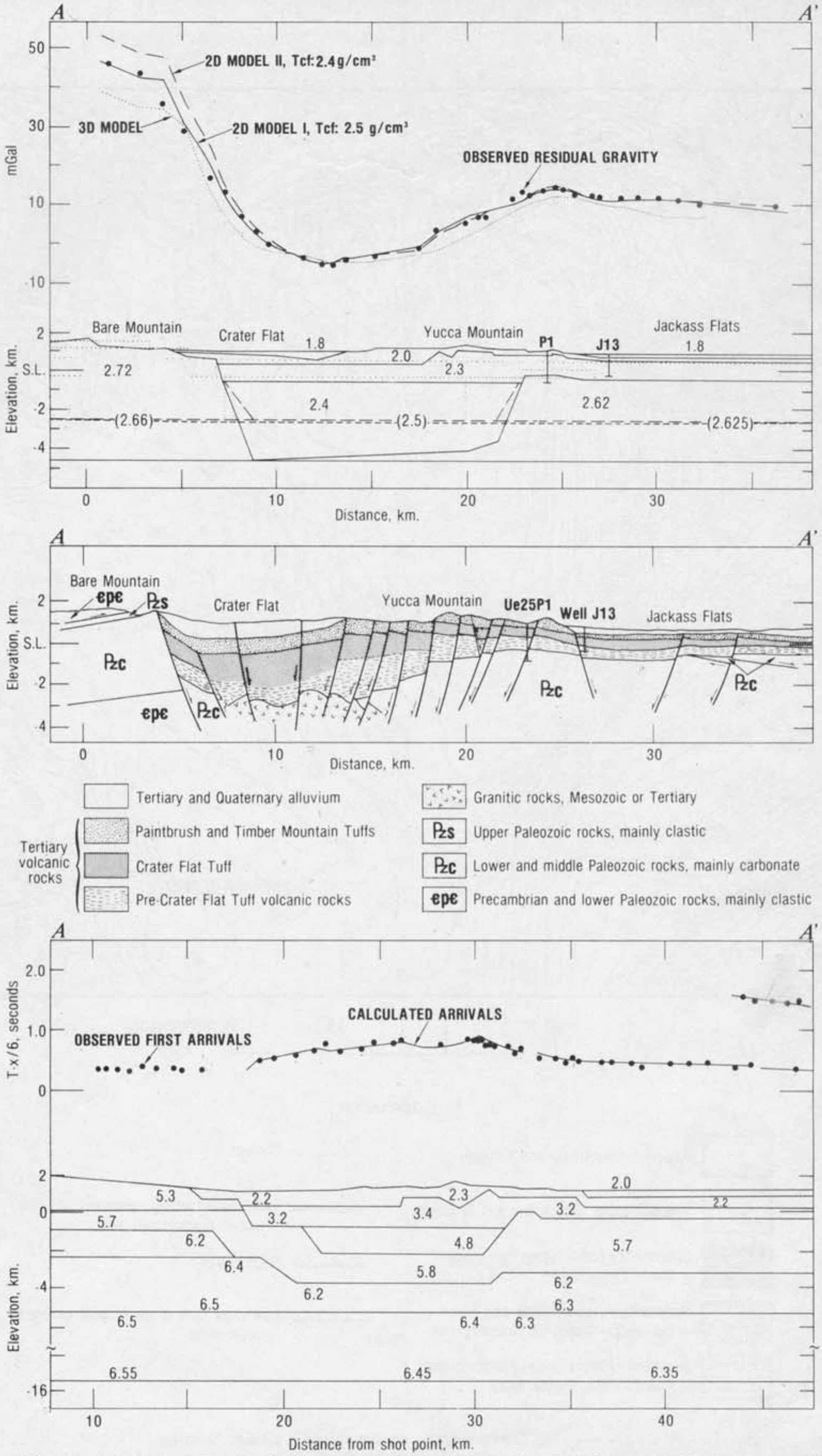

Fig. 5. Gravity, geologic, and seismic refraction cross sections along profile A-A′ (Figure 4). Numbers represent bulk densities (grams per cubic centimeters) and velocities (kilometers per second) of the modeled bodies in the gravity and seismic cross sections, respectively. The three-dimensional model densities are the same as those of two-dimensional model II. Two two-dimensional gravity models are indicated: the density and thickness of the buried Crater Flat Tuff were varied; densities in parentheses were used in model I. The thrust shown near A′ on the geologic cross section is an interpretation based upon the regional distribution of the Eleana Formation and the thick middle and lower Paleozoic carbonate rocks. Seismic section modified from *Hoffman and Mooney* [1983].

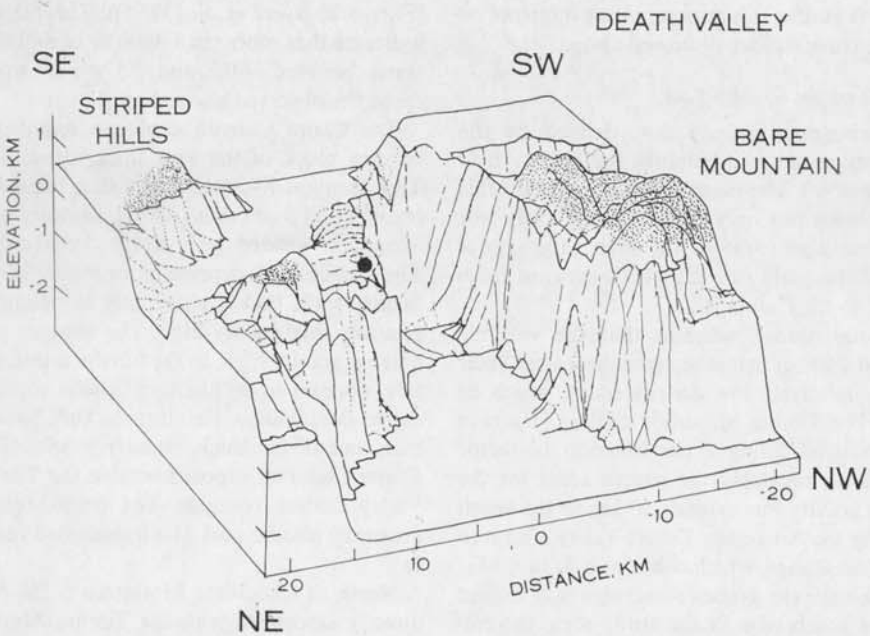

Fig. 6. Mesh perspective of prevolcanic rock unit bodies in the three-dimensional gravity model. The mesh surface represents the pretuff surface beneath the topographic surface. Stippling shows where these surfaces coincide at Bare Mountain, at the Striped Hills, and at the Calico Hills (in left center). Flat surface at elevation of −2.5 km is due to lack of resolution of the gravity method at this depth and greater depths. Repository site on the east side of Yucca Mountain lies about 1 km above shaded circle.

of Bare Mountain and the Funeral Range are Precambrian and Paleozoic limestone, dolomite, argillite, and quartzite; some are locally recrystallized. These rocks have some of the highest densities in the study area. As a result, the observed anomaly (Figures 4 and 5) is accentuated an additional 10 mGal by the reduction density of 2.00 g/cm^3 because the rock densities of measured surface samples actually range from 2.59 to 2.70 g/cm^3.

The gravity feature indicates a continuous block of Precambrian and Paleozoic rocks stretching from the eastern edge of Death Valley, across the Amargosa Valley, to the northern edge of Bare Mountain. The gravity saddle coincident with the Amargosa River is not deep enough to result from an absence of dense rock at depth but probably results from a thick accumulation of Tertiary volcanic and sedimentary rocks underlying the alluvium of Amargosa Valley, possibly augmented by dip-slip faults and extensional grabens related to the Walker Lane. These faults may have created structural downwarps or basins that collected sufficient alluvium from Bare Mountain to account for the lower gravity values. The detailed shape of the gravity curve over the east flank of Bare Mountain in profile (Figure 5) suggests that the Paleozoic rocks extend several kilometers farther eastward beneath Crater Flat than the surface contacts indicate.

The unusually high gravity values at the Funeral Mountains and Bare Mountain complicate the use of Bare Mountain as a reference area against which to compare the gravity over the rest of the study area. After adjustment is made for the surface geology in the three-dimensional modeling, the calculated gravity values at Bare Mountain still are not great enough to match the observed values; this disagreement indicates an underlying mass excess relative to the gravity model. The bulk density of about 2.72 g/cm^3 used in the model may be somewhat low; the Funeral Mountains consist largely of Precambrian rocks, most of which are metamorphosed, and Bare Mountain may contain a low-angle fault underlain by more strongly metamorphosed rocks [*Monsen*, 1983]. Preliminary seismic refraction results (*Hoffman and Mooney* [1983]; Figure 5) confirm density-velocity heterogeneity within the Bare Mountain block. Rock densities as high as 2.8 or 2.9 g/cm^3 are possible based on the seismic velocities modeled within Bare Mountain and velocity-density relationships in southern Nevada [*Hill*, 1978, Figure 7-11].

Calico Hills Gravity High

If defined by the local 22-mGal contour (Figure 4*c*), the Calico Hills gravity anomaly may be interpreted to support the structural dome hypothesis of *Maldonado et al.* [1979]. If expanded to include the 14-mGal contour, the anomaly is no longer closed and extends farther to the northeast. Further, the gravity high enclosed by the 14-mGal contour to the southwest of the Calico Hills near Busted Butte (Figure 1) appears to extend this trend of gravity highs in that direction. Data from the UE25P-1 drill hole further support this observation, as pre-Tertiary rocks similar to those exposed at the Calico Hills were penetrated at depths of about 1250 m. Buried high topography on Paleozoic rocks along the eastern borders of the Timber Mountain and Crater Flat–Prospector Pass caldera complexes could explain the local gravity highs along this trend. The lesser thickness of volcanic rocks in the Busted Butte–Calico Hills area, as suggested by the gravity modeling, may have resulted in the faulting of a different trend and intensity than that observed in the central part of Yucca Mountain, where the volcanic rocks are over twice as thick.

The 10-mGal gravity saddle between the Calico Hills high and the Busted Butte high (Figure 4*c*) is on the trend of Yucca Wash (Figure 1), a conspicuous northwest trending valley bounding northeastern Yucca Mountain. A fault zone, pre-Paintbrush Tuff in age, is suspected along Yucca Wash on the basis of rock unit distributions; this structure may interrupt or offset the buried prevolcanic surface discussed above.

Crater Flat–Yucca Mountain Gravity Low

A large, roughly triangular gravity low, defined by the 8-mGal residual gravity contour, dominates the gravity field in the study area (Figure 4*c*). The most striking feature of this anomaly is that it includes not only the topographically low area of Crater Flat but also some of the high ramparts of Yucca Mountain. The anomaly extends northeastward from Bare Mountain nearly to the Calico Hills.

The three-dimensional model indicates that the volcanic rocks extend to at least 2500 m below sea level beneath Crater Flat (Figure 6). These relatively low density rocks, which lie about 10 km south of the Timber Mountain caldera [*Byers et al.*, 1976], may be material filling a combination of sector grabens and old calderas, probably the source areas for the Crater Flat Tuff. This gravity low extends 50 km to the south of the study area, along the Amargosa Desert Valley, and into the northern Greenwater Range, which contains a 4- to 8-Ma-old volcanic field. Although the graben structures may extend southward beyond the south edge of the study area, the caldera features do not.

Estimates of the tuff thickness beneath Crater Flat are minima. Tuff density below 2000-m depths, as indicated by the log measurements in the deep drill holes at Yucca Mountain, is greater than 2.5 g/cm^3, probably greater than 2.6 g/cm^3 if the linear increase in density continues beneath the drilled depths (Figure 3). Neighboring caldera wallrocks are thought to be mostly Paleozoic sedimentary rocks; metamorphism or hydrothermal alteration may have either increased or decreased the bulk density of these rocks. Surface sample measurements on the Paleozoic rocks indicate densities between 2.6 and 2.7 g/cm^3; densities may be slightly increased by 3 km of overburden. As a result of these uncertainties, the density contrast between intracaldera rocks and the caldera wallrocks may range from -0.2 to $+0.1$ g/cm^3 at 4.0 km below sea level, the estimated floor of the caldera fill. Floor elevation uncertainties of ± 2.0 km or greater (Figure 5) are possible from this range of density contrast. The seismic refraction model achieved the best match between observed and calculated delay times by assuming the caldera floor rocks (5.8-km/s body in Figure 5) to lie between 2 and 4 km below sea level.

The -2-mGal closures in the northern and southern parts of the Crater Flat anomaly are separated by a narrow band of higher gravity values anchored by protruding positive anomalies. This configuration of the gravity field suggests a septum or ridge of higher density rocks cutting across the depression at this point. Relations in the Crater Flat Tuff and associated volcanic rocks suggest that Crater Flat may contain the source areas for this tuff and related lavas [*Carr*, 1982]. The septum suggested by the slight gravity deflections may separate two source and collapse areas. The 0-mGal closure to the northeast of the Crater Flat gravity low correlates with a postulated "older tuff" caldera or sag feature (Figure 2).

Chocolate Mountain Gravity High

A narrow band of gravity highs (Figure 4*c*), peaking at 14, 12, and 16 mGal, separates the large negative anomalies associated with Crater Flat and those associated with the Timber Mountain caldera to the north. The most prominent gravity high along this band coincides with Chocolate Mountain (Figure 1) and the Claim Canyon cauldron segment (Figure 2; *Byers et al.* [1976]). The three-dimensional model indicates that more than 4000 m of material with density contrasts between $+0.2$ and 0.3 g/cm^3 would be necessary to cause the observed anomalies.

The Claim Canyon cauldron segment is an eccentric resurgent block of the very thick, densely welded intracaldera Tiva Canyon Member and other related parts of the Paintbrush Tuff [*Byers et al.*, 1976]. Samples collected at Chocolate Mountain yielded an average density of 2.32 ± 0.12 g/cm^3. The absence of a depression or moat, filled with relatively low density rock, that is commonly associated with a caldera emphasizes this gravity high. The western part of this relatively narrow gravity high, in the northwestern part of Yucca Mountain, appears to be due largely to a combination of the thick, dense intracaldera Paintbrush Tuff, as at Chocolate Mountain, and of the thick, densely welded Tram Member of the Crater Flat Tuff exposed outside the Timber Mountain–Oasis Valley caldera complex. The tram Member exposed in this area may also be part of a fragmented resurgent dome (Figure 2).

North of Chocolate Mountain is the edge of a gravity low directly associated with the Timber Mountain caldera [*Kane and Webring*, 1981]. This gravity low, which is related to the Timber Mountain and Silent Canyon calderas, is the most conspicuous one in southern Nevada (Figure 4*a*).

DISCUSSION

The present gravity study clearly defines the proposed waste repository site as lying adjacent to one of the most voluminous Tertiary caldera complexes in the western United States. The central gravity low on the residual gravity map (Figure 4*c*) represents a large tuff-filled hole or depression in the pre-Tertiary rocks beneath both Crater Flat and parts of Yucca Mountain (Figure 6). A minimum thickness of 1830 m of tuff beneath Yucca Mountain is confirmed by drill holes. Reference gravity values above known Paleozoic rocks at drill hole UE25P-1, and at outcrops in the Calico Hills and the Striped Hills, give a modeling estimate of at least 4000 m of tuffaceous fill in the Crater Flat–Yucca Mountain depression.

In addition to the gravity evidence, surface geologic relations and information from drill holes strongly suggest that Crater Flat is the source area for all three members of the Crater Flat Tuff. The gravity saddle separating the northern and southern minima in Crater Flat may indicate two structures: a caldera associated with the Tram Member in the northern part of Crater Flat and a caldera associated with the Bullfrog Member and Prow Pass Member in the southern part of Crater Flat. These two collapse areas may be separated by a narrow septum of Paleozoic rocks, or possibly lava flows, beneath central Crater Flat. It is unlikely, however, that the lobe of the gravity low extending northeastward beneath Yucca Mountain is part of the collapse area related to the Crater Flat Tuff. The Crater Flat Tuff is nearly as thick in well J-13 as it is in drill hole G1 within the gravity low lobe. Therefore the northeastern lobe of the gravity low at Yucca Mountain is unrelated to the Crater Flat Tuff and is related to either a structural depression, possibly a caldera, within which thick units older than the Crater Flat Tuff accumulated or altered upper Paleozoic rocks with densities of 2.5–2.6 g/cm^3 underlying the tuff in this location.

The recognition of the Crater Flat–Prospector Pass calderas adds nearly 350 km^2 to the total 1500-km^2 area of caldera collapse associated with the southwestern Nevada volcanic field. Considered together, the Timber Mountain caldera complex and its satellite calderas form one of the largest caldera systems in the western United States. Only the Long Valley caldera [*Kane et al.*, 1976] and the Yellowstone caldera [*Eaton et al.*, 1975; *Lehman et al.*, 1982] compare in areal extent, 550 and 3300 km^3 versus 1800 km^2, and in magnitude of the associated negative gravity anomaly, 50 and 60 mGal versus 60 mGal, with the Timber Mountain complex.

The gravity high that extends southwestward from the northeast corner of the study area is interpreted to reflect a shallowly buried, Paleozoic rock surface. Indeed, Paleozoic rocks crop out at several places along this high, for example, in the Calico Hills and the Eleana Range (Figure 1). The Eleana Range, the Calico Hills, and the Paleozoic rocks beneath Busted Butte may all be part of a topographically high pre-Miocene surface, underlain predominantly by argillite of the Eleana Formation, that was partly covered by Tertiary tuff. This ridge of Paleozoic rocks could also be viewed as an eroded escarpment facing the Crater Flat–Timber Mountain–Silent Canyon caldera complexes. We suggest that the down-to-the-east faults, unusual near Yucca Mountain, in the area of Busted Butte [*Lipman and McKay*, 1965] are the result of drag and shear of the tuff near the intersection of northwest and northeast trending shear zones (Figure 2). The expression of this structure may be enhanced by the thinner tuff cover in this area.

An important question is the possible existence of a large east-west trending intrusive body beneath the area. Evidence for such a body includes a distinct east-west trending lineament of several parallel contours on the 2440-m constant-barometric-elevation aeromagnetic map of the area [*Boynton and Vargo*, 1963] that coincides roughly with the southeast border of the northeastern lobe of the central gravity low. Very little difference in the upper part of the tuff section occurs across this lineament, as shown by the similarity of the units encountered in drill holes north and south of it, but significant magnetic property changes may occur in the middle part of the section which includes a Bullfrog Member variable in thickness and local dacitic lava flows. The distribution of these changes in units, however, does not appear to correspond closely with the aeromagnetic lineament. The gravity modeling is ambiguous with regard to a deep intrusive body. All the gravity anomalies can be adequately accommodated by density contrasts at the Paleozoic-Tertiary unconformity, assuming that all the pre-Tertiary rocks are nonigneous. Part of the gravity low in the center of the study area could also be produced by a large shallow intrusive mass, a possibility favored by the relative paucity of major faults in this vicinity if a large intrusive body acted as a structurally stabilizing mass for overlying units at Yucca Mountain.

The depth and extent of an intrusive body beneath the nearby Calico Hills remain unresolved [*Snyder and Oliver*, 1981]. Extensive hydrothermal and contact-metamorphic alteration of the rocks in drill hole UE25a-3 [*Maldonado et al.*, 1979], the high heat flow of 3.2 HFU [*Sass et al.*, 1980], and topographic uplift (D. L. Hoover, written communication, 1982) all suggest, but of course do not prove, the existence of an intrusive body beneath the Calico Hills. At Bare Mountain, metamorphism [*Monsen*, 1983] and a granitic dike of probable Mesozoic age similarly suggest the presence of plutonic rock at depth.

Estimates based on the aeromagnetic contours between the Calico Hills and Yucca Mountain [*Boynton and Vargo*, 1963] indicate that the source of the anomaly, possibly a granitic pluton with a magnetite replacement halo, is 2200 m or more deep (G. D. Bath, unpublished data, 1981). These depths are near the bottom of the gravity models and would require differentiation between carbonate rocks, argillite, and intrusive rocks beneath a thick tuff overburden. At that depth, these rocks have similar densities and would be difficult to distinguish without precise thickness estimates and density control of the overlying rocks; this gravity study cannot independently determine whether the tuff grades downward into a crystallized magma body or rests atop a downdropped block of pre-Tertiary rocks.

Both seismic refraction studies (Figure 5; *Mooney et al.* [1982]) and teleseismic experiments [*Monfort and Evans*, 1982] have shown that high-velocity rocks underlie the Yucca Mountain region. Velocities as high as 6.55 km/s are tentatively inferred to lie at depths as shallow as 15 km. The high velocities here may be caused by either mafic sills, dikes, or diapirs that were involved in the extensive Miocene volcanism of the area and the more recent basaltic eruptions in Crater Flat or by metamorphosed sedimentary and crystalline rocks such as those exposed at Bare Mountain and in the Funeral Mountains. The mafic intrusives may be related to the riftlike graben structure of Crater Flat and be part of an extensional zone accommodating right-lateral movement within the Walker Lane [*Wernicke et al.*, 1982]; the regional metamorphism may have resulted from heat associated with the eruptions of the Timber Mountain caldera complex [*Monsen*, 1983]. Without density measurements from depths greater than 2–3 km, gravity modeling cannot independently resolve rock configurations at the base of the intracaldera fill. Simultaneous inversion of velocity and density data to match gravity and seismic observations could better resolve structural-tectonic questions related to the subsidence history of the calderas, questions concerning the existence of mafic intrusive or metamorphosed wall rock within the collapsed area, and the possibility that low-angle faults separate brittle rock cut by numerous high-angle faults from plastically deformed metamorphosed basement rock beneath Crater Flat, Bare Mountain, and to the west toward Death Valley.

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