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PRELIMINARY RESULTS OF GRAVITY INVESTIGATIONS AT YUCCA MOUNTAIN AND VICINITY, SOUTHERN NYE COUNTY, NEVADA

By

D.B. Snyder and W.J. Carr

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ABSTRACT

Exploration for a high-level-nuclear-waste-repository site in the Yucca Mountain area, Nev., resulted in the addition of 423 new gravity stations during the past 2 years to the 934 existing stations to form the data base of this study. About 100 surface-rock samples, three borehole gamma-gamma logs, and one borehole gravity study provide excellent density control. A linear increase in density of 0.26 g/cm^3 per km is indicated in the thick tuff sequences. This steady increase of density within the tuff sequences makes the density contrast across the basal contact of the tuff the only strong source of gravity fluctuations. Isostatic and 2.0-g/cm^3 Bouguer corrections were applied to the observed gravity values to remove deep-crust-related regional gradients and topographic effects, respectively. The resulting residual-gravity plot shows significant gravity anomalies that correlate closely with the structures inferred from drill-hole and surface geologic studies.

Gravity highs over the three Paleozoic rock outcrops within the study area--Bare Mountain, the Calico Hills, and the Striped Hills--served as reference points for the gravity models. The Bare Mountain gravity high, which peaks at 48 mGal, connects with a larger gravity high over the Funeral Mountains to the south; together, these highs may result from a continuous block of mildly metamorphosed Precambrian and Paleozoic rocks stretching from the east edge of Death Valley to Bare Mountain. The Calico Hills gravity high appears more likely to originate from a northeast-trending remanent topographic high of buried Paleozoic rocks rather than from an isolated structural dome. This buried ridge may extend southwestward beneath Busted Butte, 5 km southeast of the proposed repository, where 2 1/2- and 3-dimensional modeling indicates that the pre-Cenozoic rocks may be less than 1,000 m deep.

At least 3,000 m of tuff fills a large steep-sided depression in the prevolcanic rocks beneath Yucca Mountain and Crater Flat. The gravity low and thick tuff section probably lie within a large collapse area comprising the Crater Flat-Timber Mountain-Silent Canyon caldera complexes. Gravity lows in Crater Flat itself are thought to coincide with the source areas of the Prow Pass Member, the Bullfrog Member, and the unnamed member of the Crater Flat Tuff. 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 Timber Mountain caldera and superimposed on the other structures within Crater Flat.

INTRODUCTION

Location

Yucca Mountain is in southern Nye County, Nevada, near the southwest corner of the Nevada Test Site (NTS) (fig. 1). The valleys of Crater Flat and Jackass Flats lie to the west and east, respectively. The study area, here called Yucca Mountain and vicinity, is roughly defined by and includes the edges of Jackass Flats on the east, Timber Mountain on the north, Bare Mountain on the west, and the Amargosa Valley on the south.

Lathrop Wells, 132 km (85 mi) northwest of Las Vegas on U.S. Highway 95, is in the southeast corner of the study area. The climate is arid, and the vegetation sparse. The land is nearly totally devoted to mining and projects of the Nevada Test Site. A well-maintained dirt road leads north from U.S. Highway 95 in the western part of the study area; the eastern portion is accessible from Mercury via Jackass Flats but only by authorized entry on the Nevada Test Site. U.S. 95 is the only paved public thoroughfare within the study area, and land travel is difficult after leaving these established routes. Gold, silver, and tungsten mines are found on Bare Mountain; a cinder quarry operates just west of Lathrop Wells.

Purpose of the gravity study

Gravity investigations play an important role in characterizing Yucca Mountain as a possible nuclear-waste repository. Obtaining subsurface information is critical because thick Cenozoic sedimentary rocks and tuff obscure the complex pre-Tertiary geology in most areas. The candidate site lies within the tuff composing the northern end of Yucca Mountain, a relatively coherent block of rock within a stratigraphically and structurally complex region. This study explores the 3-dimensional structure and geometry of the rocks surrounding the candidate site.

Several other geophysical methods have been employed to explore the Yucca Mountain area. Electrical soundings and magnetic traverses are best suited to characterize the upper few thousand feet of the mountain. The gravity method which commonly is best suited to characterize the relatively deep features of an area, at times surpasses other geophysical techniques in continuity and subsurface definition. Such is the case at Yucca Mountain, where the surface rocks appear to be seismically opaque and magnetically complex. The gravity method also serves as a pioneering exploration tool by proposing structures and geologic concepts to be better defined and established by later work.

Other geophysical investigations at Yucca Mountain

The characterization of Yucca Mountain as a radioactive-waste-disposal site involves a multidisciplinary Earth-science approach. This report is one of the first to integrate geologic and geophysical results but does not necessarily contain final interpretations of the area. The following paragraphs attempt to summarize work done to date; ongoing drilling, seismic, electrical, surface-mapping, and other studies continue to bring new data and facts to bear on the problems. Therefore, this report, though comprehensive as to the gravity studies, is preliminary in its interpretations; future reports will undoubtedly add much to the understanding of Yucca Mountain and vicinity.

Several drill-holes and a full suite of geophysical logs have recently been completed. All but two of these holes are located (fig. 1) in or near the candidate site area and include drill-holes UE25a-1 (Spengler and others, 1979), UE25a-4 through UE25a-b,, USW-G1 (Spengler and others, 1981), and USW-H1. Recently drilled holes outside the site area include drill-hole UE25a-3 in the Calico Hills (Maldonado and others, 1979) and drill-hole USW-VH-1 in Crater Flat. Many geologic, geophysical, and hydrologic data have been obtained from these and older holes (wells J-11 through J-13), and this information has been used both directly and indirectly in the preparation of this report. Only drill-hole 25a-3 reached pre-Tertiary rocks, even though two holes (G1 and H1) were drilled to a depth of 1,830 m (6,000 ft). In these deep holes, especially, alteration was notable in the lower part of the section penetrated, and metamorphic effects, including density change, increase downward nearly linearly.

Four aeromagnetic surveys are encompassed by the area of the gravity study. Constant-barometric-pressure surveys (Boynton and Vargo, 1963; U.S. Geological Survey, 1971), flown at 2,440 m (8,000 ft) and 2,740 m (9,000 ft), respectively, indicate a strong gradient across northern Yucca Mountain rising in total intensity to the north. The breadth of this feature suggests that it arises from deep sources, estimated to lie at a minimum depth of 2,200 m (7,200 ft) (G. D. Bath, written commun., 1980). Later, two 122-m (400 ft) draped surveys also covered the study area (U.S. Geological Survey, 1977, 1978). Zietz and others (1977) included the earlier surveys in a compilation of the aeromagnetic coverage for all of Nevada.

Seismic and electrical techniques thus far have been only partly successful; no clear characterization of the rocks below 500 m (1,640 ft) has been obtained as yet by these methods.

Acknowledgments

H. W. Oliver, U.S. Geological Survey, supervised all phases of the gravity study and provided advice and guidance throughout. P. P. Orkild, also of the U.S. Geological Survey, graciously permitted use of some unpublished geologic data. We are greatly indebted to the many other scientists investigating the suitability of Yucca Mountain as a waste-isolation site, for freely sharing their data and thoughts, particularly to: G. D. Bath, F. M. Byers, Jr., G. L. Dixon, D. L. Healey, D. B. Hoover, and R. W. Spengler, all of the U.S. Geological Survey. Many others assisted with the field operations at Yucca Mountain, including: I. Madin, D. A. Ponce, R. W. Saltus, and R. W. Tang of the U.S. Geological Survey and R. Lahoud, L. Parish, R. Orsak, and S. Waddell of Fenix & Sisson, Inc. W. McQuary drafted most of the illustrations; T. A. Sagara produced figure 13.

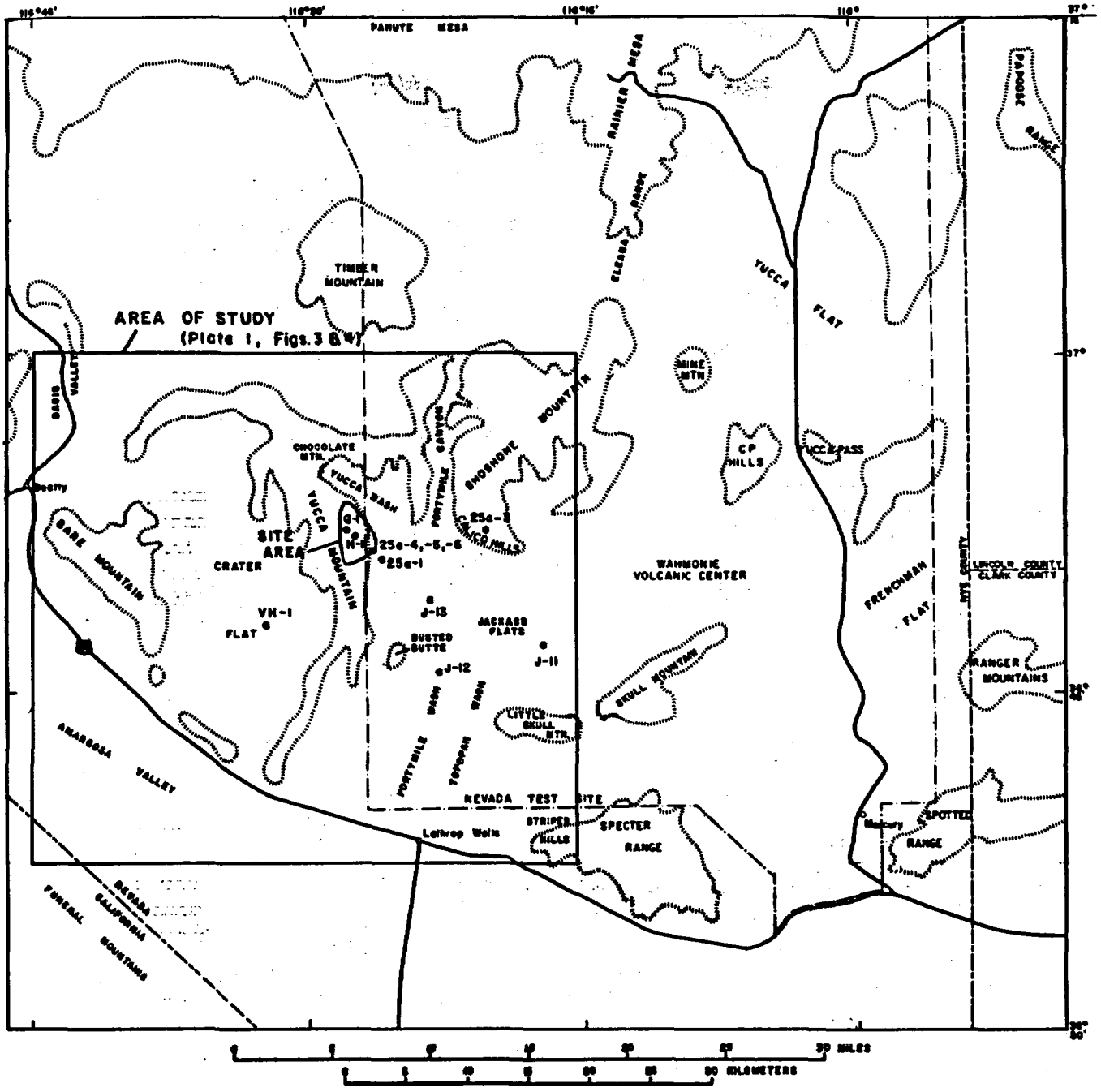


Figure 1. Index map of southern Nevada Test Site area.

GEOLOGY OF YUCCA MOUNTAIN AND VICINITY

Physiography

Yucca Mountain lies near the south edge of the Great Basin section of the Basin and Range physiographic province; further subdivision places the area within the Walker Lane belt (fig. 2) and the southern part of the Lahontan subsection of the Great Basin[1]. Much of the Great Basin is characterized by classic basin-and-range topography, with alternating ridges and valleys oriented nearly due north. The Walker Lane belt exhibits a more diverse topography of generally lower relief and, locally, chaotic or 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 Walker Lane belt; 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 to the north.

The lowest elevation in the study area, approximately 800 m (2600 ft), is along its south border, where the Amargosa Desert decreases in elevation to the south. Crater Flat and Jackass Flats lie between 850 m (2800 ft) and 1220 m (4000 ft), and Yucca Mountain ranges from 1770 m (5800 ft) in the north to 900 m (3000 ft) at its south end. The highest points within the study area are a 1925-m (6316 ft) peak on rugged Bare Mountain and 2043-m (6703 ft) Chocolate Mountain.

Stratigraphy

Table 1 is a simplified stratigraphic column of the geologic units in the Yucca Mountain area, pertinent to the gravity study. The distribution of pre-Tertiary rocks in the vicinity of Yucca Mountain is not well known at present, because in most areas, stratigraphy and structure combine in a very complex way deep beneath volcanic rocks and alluvium. These buried rocks consist of upper Precambrian and Cambrian clastic units, lower and middle Paleozoic carbonate rocks, and upper Paleozoic detrital rocks and local granitic intrusions. Several ancient structural features and depositional zones of Precambrian and Paleozoic age are thought to cross in this general area (Poole, 1974; Stewart, 1980, p. 40-52), but vast amounts of volcanic materials 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 unexposed, thermal-alteration zones, dikes and small plugs, and domical structures (Cornwall and Kleinhampl, 1961; Carr and Quinlivan, 1968; Maldonado and others, 1979) suggest the presence of buried intrusive rocks. Quartzite and other clastic rocks, which predominate within the upper Precambrian and lower Paleozoic assemblage, crop out mainly in the southwestern part of the study area, where they are mildly metamorphosed. A thick sequence of limestone and dolomite predominates in the middle part of the section, approximately Cambrian through Devonian in age; these rocks crop

[1]W. J. Carr (unpub. data, 1982) suggests that the Great Basin can be subdivided into two parts or subsections, the Lahontan on the west and the Bonneville on the east, based on physiography, Neogene tectonism and volcanism, and other characteristics.

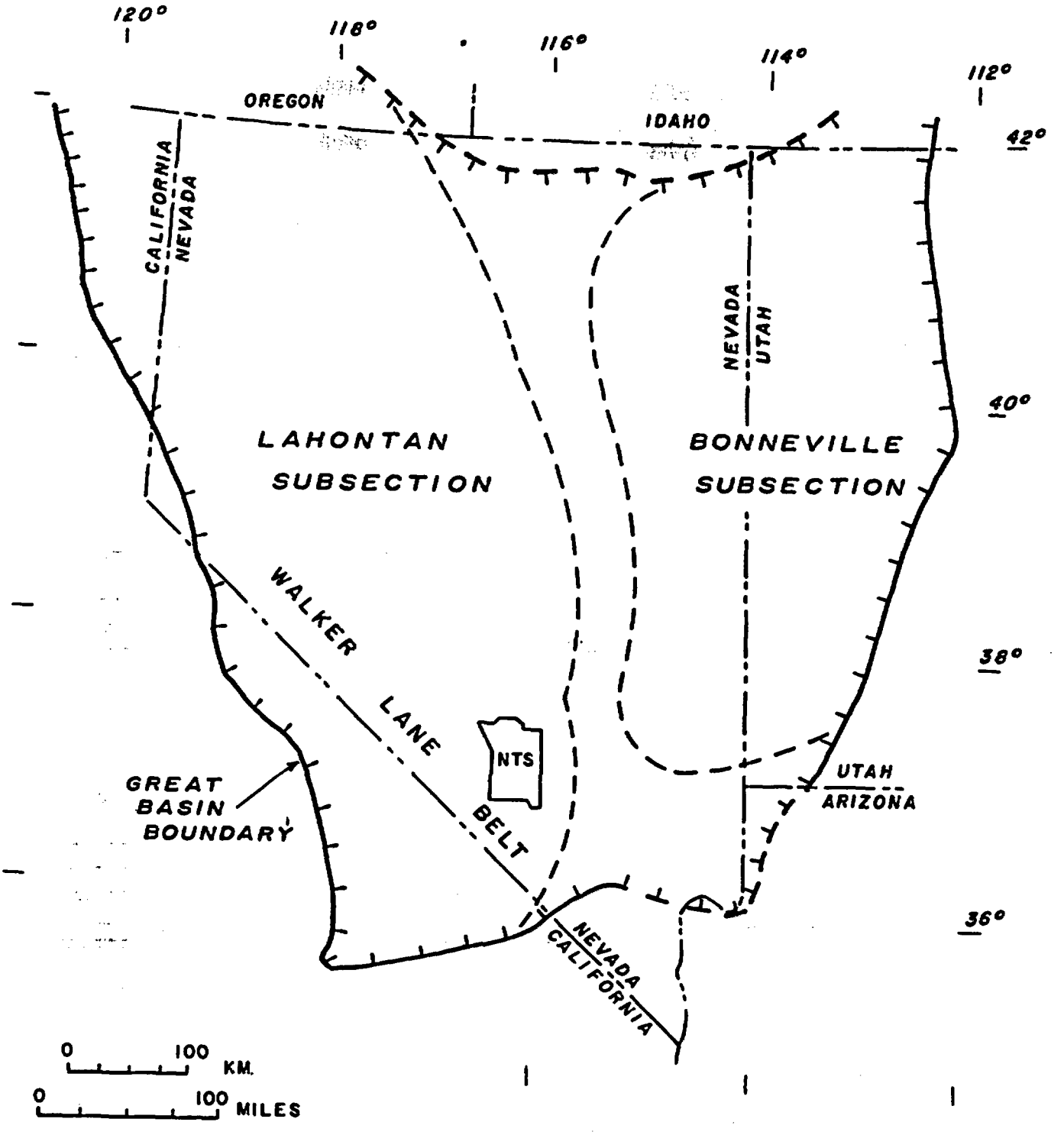


Figure 2. Great Basin, showing location of Nevada Test Site with respect to Walker Lane belt and Lahontan subsection.

Table 1.--Density and thickness of selected stratigraphic units in the Yucca Mountain area

Age	Stratigraphic unit	Approximate thickness (m)	Average density (g/cm^3)
Quaternary and Tertiary	Alluvium	0-300	1.6-2.0
	Basalt	0-50	2.9
Tertiary	Rhyolite lava flows of Shoshone Mountain	0-100	2.2
	Rhyolite lava flows of Fortymile Canyon	0-150	2.2
	Timber Mountain Tuff		
	Ammonia Tanks Member and Rainier Mesa Member	0-100	1.9
	Paintbrush Tuff		
	Tiva Canyon Member	120	2.1±0.4
	Yucca Mountain Member	0-60	1.9
	Pah Canyon Member	0-70	
	Topopah Spring Member	300	2.2±0.2
	Tuff and rhyolitic lavas of the Calico Hills	10-150	1.9±0.1
	Crater Flat Tuff		
	Prow Pass Member	100	2.1
	Bullfrog Member	120	2.1
	Unnamed Member	300	2.25
	Rhyodacitic lavas	0-60	2.35
	"tuff of Lithic Ridge"	300	2.35
	Ash-flow and bedded tuff	300+	2.45
Tertiary and Mesozoic	Granitic intrusive rocks	unknown	2.4?
Upper Paleozoic	Tippipah Limestone and Eleana Formation	1,000	2.6
Middle and Lower Paleozoic	Devils Gate Limestone, Ely Springs Dolomite, Eureka Quartzite, Pogonip Group, Nopah Formation, Bonanza King Formation	1,800	2.7
Lower Paleozoic and Precambrian	Carrara Formation, Zabriskie Quartzite, Wood Canyon Formation, Stirling Quartzite, Johnnie Formation	2,500+	2.65

out mostly on Bare Mountain and in the Striped Hills (figs. 1, 3). Thrust or slide masses of Devonian rocks are also present in the Calico Hills. Mississippian and Pennsylvanian rocks, principally argillite, quartzite, and limestone, form the lower plate of thrust faults from the Calico Hills northeastward through the Eleana Range (fig. 1).

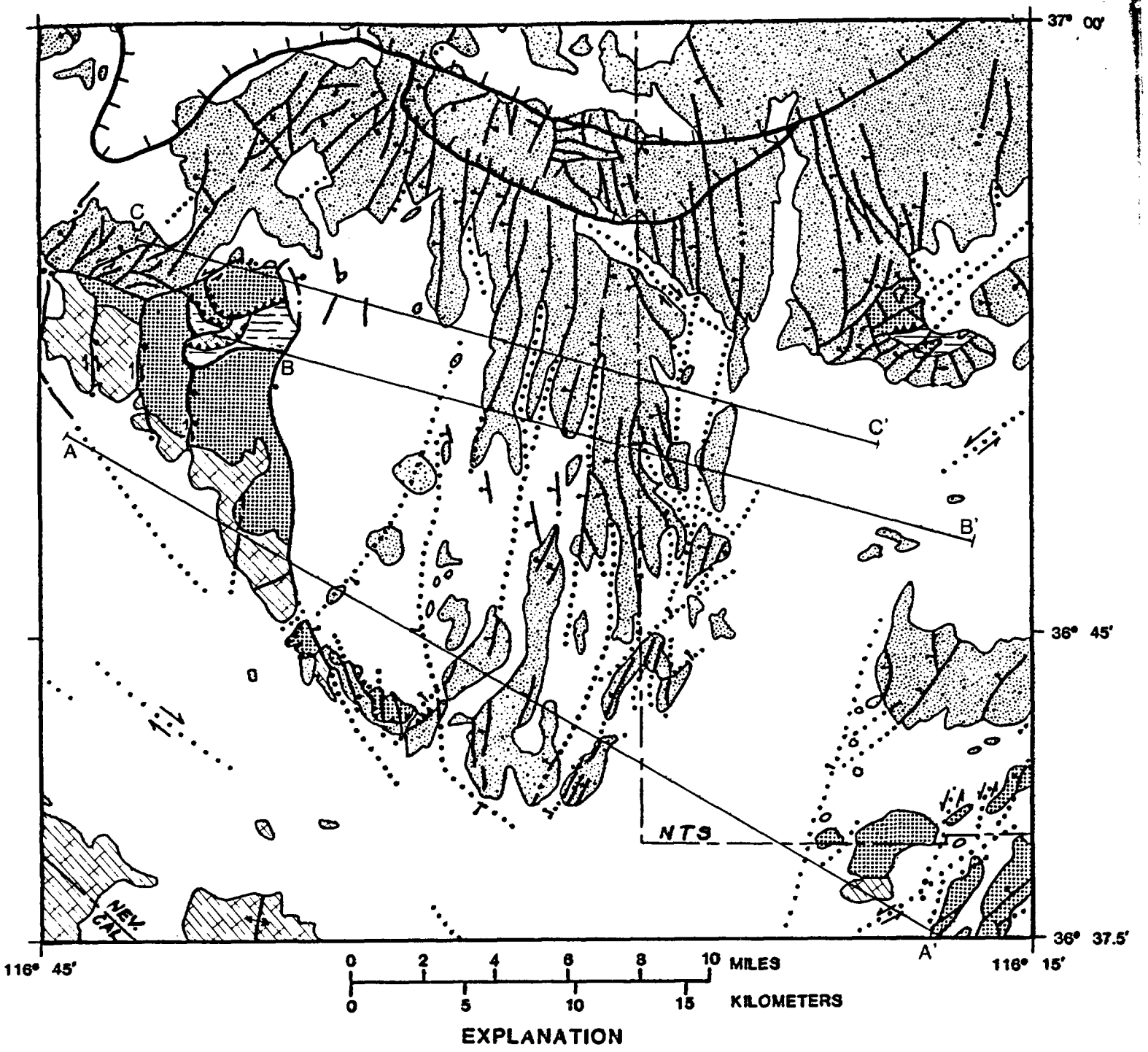
Granite crops out at only one locality within the study area. An altered east-west-trending granite dike occurs near Beatty at the northwest end of Bare Mountain (fig. 1); geologic relations suggest, but do not prove, that it is pre-Tertiary in age. Granite of Mesozoic age occurs at several localities in the northern part of the NTS, and granodiorite of Tertiary age crops out at the Wahmonie volcanic center, just east of the study area (Ponce, 1981).

The exposed Cenozoic stratigraphy of the area has been well studied. Several volcanic centers within and adjacent to the Timber Mountain-Oasis Valley caldera complex (Marvin and others, 1970; Byers and others, 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 m.y. ago, B.P., although the oldest units recently encountered in deep drill holes have not yet been dated. The great thickness of this buried tuff indicates the close proximity of its sources. The degree of welding and the density of the tuff vary greatly both laterally and vertically.

Quaternary alluvium is a significant unit 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 cementation is conspicuous in the alluvium. Basalt crops out and intertongues with the alluvium, principally in southern Crater Flat and around Jackass Flats. The basaltic activity spans most of the alluvial depositional history but has had pulses about 3.75, 1.1, and 0.3 m.y. ago (Vaniman and others, 1980), basalt forms several cinder cones in and near Crater Flat.

STRUCTURAL SETTING

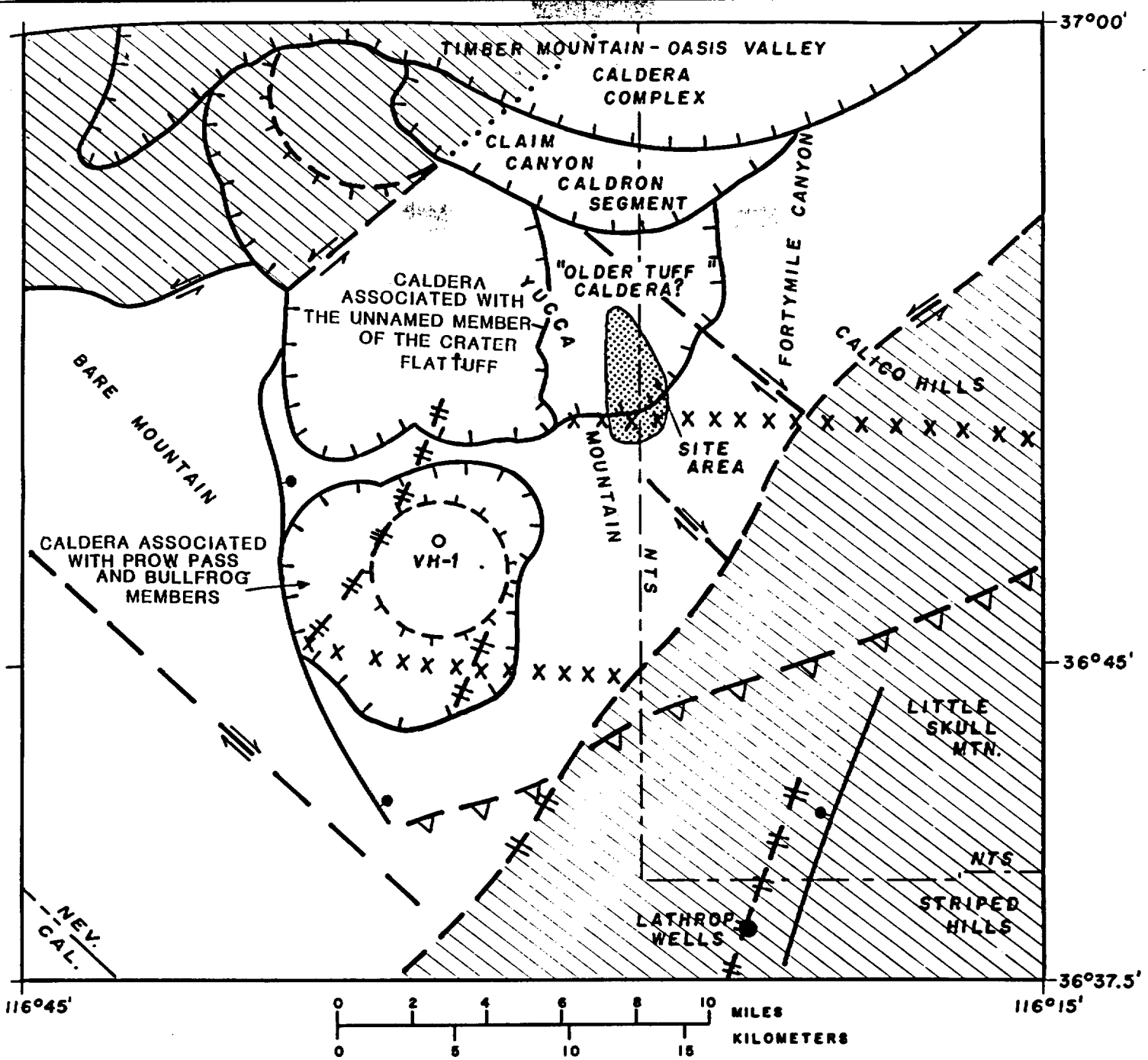
The Nevada Test Site and Yucca Mountain lie within the Walker Lane belt of the southern Great Basin (fig. 2). In most of the study area, however, the northwest-trending shear zones or arcuate mountain ranges commonly associated with this belt are not obvious. Nevertheless, three principal structural elements can be recognized in the area (figs. 3, 4): (1) northwest-trending valleys (Amargosa Valley, Yucca Wash, fig. 1) that probably represent the position of shear zones of that trend; (2) northeast-trending shear zones situated southeast of a line through Busted Butte, well J-13, and the western Calico Hills and northwest of a line from the northeast corner of Bare Mountain to the northwest end of Yucca Mountain; and (3) north-south- to north-northeast-trending basin-and-range faults and possible rifts in the Lathrop Wells area, on Yucca Mountain, and in Crater Flat (fig. 4). Superimposed on these elements and to some extent controlled by them are large volcanotectonic features, such as the Timber Mountain-Oasis Valley caldera complex, and postulated caldera or sector graben-type collapse segments in the Crater Flat area.



EXPLANATION

- Tertiary and Quaternary alluvium
- Tertiary and Quaternary volcanic rocks
- Upper Paleozoic clastic rocks
- Lower and middle Paleozoic carbonate rocks
- Precambrian and lower Paleozoic clastic rocks
- Contact
- Fault, dotted where concealed; bar and ball on downthrown side
- Caldera wall
- Low-angle fault or glide plane; teeth on upper plate

Figure 3 Simplified geologic map of Yucca Mountain and vicinity, showing location of gravity-model profiles (figs. 8-10).



Area dominated by northeast-trending faults

Major high-angle fault zone, bar and ball on downthrown side

Important strike-slip shear zone or boundary of zone, as shown by hatching; arrows indicate direction of lateral displacement in pre-Pliocene time

Possible "rift" zone with associated basaltic volcanism

Approximate buried trace of CP thrust system; teeth on upper plate of predominantly carbonate rocks; Eleana Formation (Devonian and Mississippian) predominant in lower plate to northwest

Caldera wall

Possible resurgent dome

XXXX Aeromagnetic lineament marking southern edge of possible east-west trending granitic bodies

Figure 4 Tectonic-structural map of study area. Caldera locations are based on gravity interpretaions as well as drill-hole and surface geologic evidence.

The tectonic history of the region, and structures mapped in the pre-Tertiary rocks, indicate that all the structural elements mentioned, except for the north-southerly trending faults and caldera structures, were at least partly present before the regional volcanism, and that the structures developed in the Tertiary rocks commonly either are reactivated old faults or are influenced by old fault trends. The north-south- to north-northeast-trending fault set occurs largely in the volcanic terrane of Yucca Mountain and Crater Flat, on the basis of aeromagnetic and gravity evidence, however, a relatively young structural trough of this set is thought to be buried in the valley near Lathrop Wells marked by Fortymile and Topopah Washes (fig. 1). The association of this north-southerly trend with thicker alluvium and Quaternary basaltic eruptive centers and faulting suggests that at times it has been the most active trend tectonically, although Yucca Mountain has persisted as a series of relatively high standing fault blocks between the volcanotectonic depression in Crater Flat and the trough north of Lathrop Wells. Scattered patches of the Rainier Mesa Member of the Timber Mountain Tuff on the flanks of Yucca Mountain indicate however, that most of the basin-and-range-fault displacement occurred there after the Paintbrush Tuff and before the Timber Mountain Tuff were deposited. At the candidate-site area at Yucca Mountain, most faults of the north-southerly trending set decrease markedly in displacement as they approach the site from both the north and south.

VOLCANOTECTONIC HISTORY

Because most of the study area contains thick sequences of tuff and lavas and the candidate-site area is underlain by more than 2,000 m (6,500 ft) of tuff, a summary of the volcanic history of the study area is warranted.

The stratigraphy and nomenclature of the lower part of the volcanic-rock sequence in this area is currently being studied in detail and revised. The oldest tuff units at Yucca Mountain, those statigraphically below the "tuff of Lithic Ridge" (table 1), are known only from drill hole USW G1 (Spengler and others, 1981). The general thickness (more than 600 m [2000 ft]), flat-lying attitudes, abundance of lava lithics, fragments, and absence of structural disturbance suggest accumulation of this older tuff in some sort of sag or collapse feature, possibly a caldera (fig. 4). If correlations are correct, tuffaceous sediment and thin layers of ash-flow tuff were deposited elsewhere in the area during this time. Scattered small exposures of the "tuff of Lithic Ridge" occur on the southeast side of Shoshone Mountain and across the southern NTS area. Local occurrences of rhyodacite lava flows above and below the "tuff of Lithic Ridge" further indicate the proximity of the source.

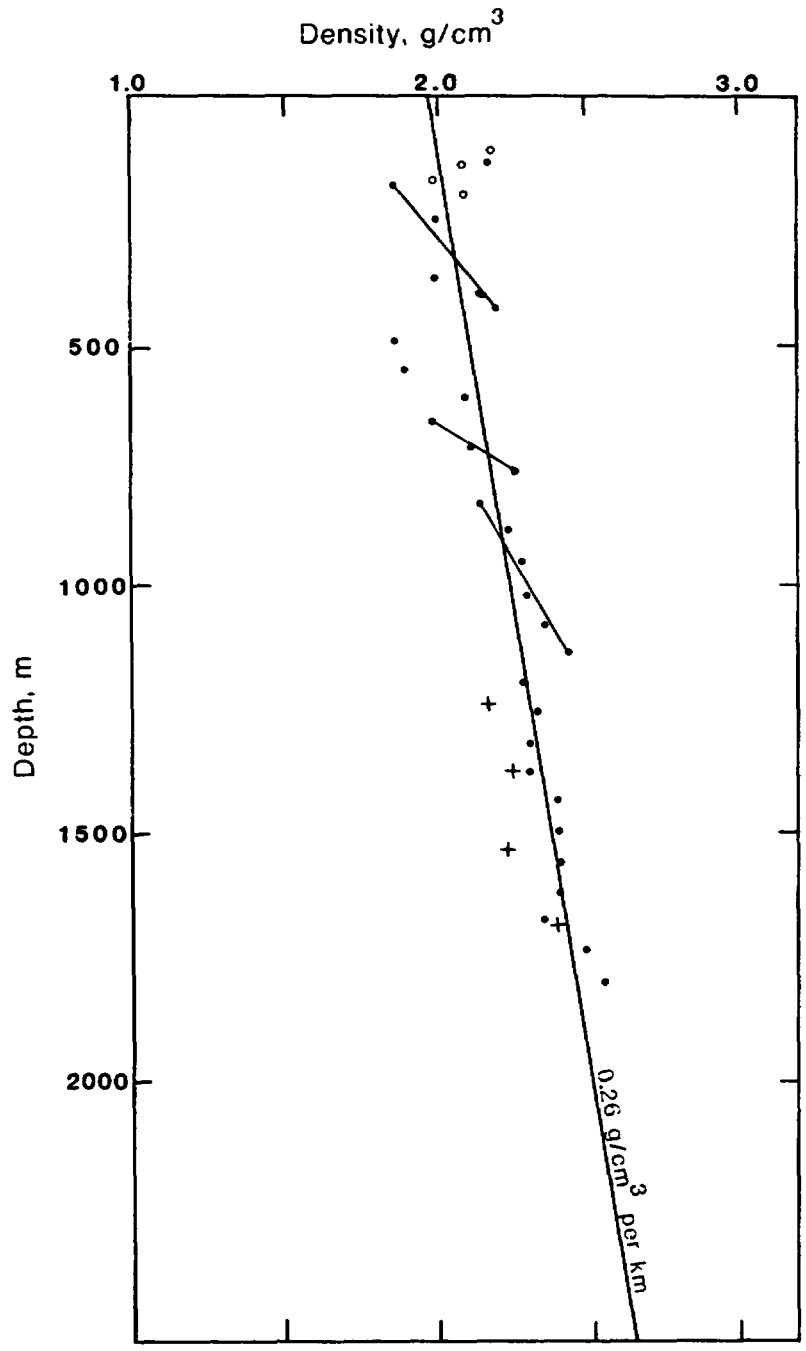
Next to be deposited in the site area were the three members of the Crater Flat Tuff: in ascending order, the unnamed member (= Tram unit), the Bullfrog Member and the Prow Pass Member. The Crater Flat Tuff has no characteristics in the drill holes at Yucca Mountain which would suggest it was deposited in a caldera there, although all three members have a total thickness of more than 450 m (1,480 ft). The source areas or calderas, and greater thicknesses of the Crater Flat Tuff, are thought to lie to the southwest and northwest of Yucca Mountain, mostly beneath Crater Flat itself (fig. 4).

The tuff and lavas of the Calico Hills were emplaced atop the Crater Flat Tuff. The main source areas were in the western Calico Hills-Fortymile Canyon area, but a little lava reached as far southwest as the northeast edge of Yucca Mountain, where the section consists mostly of about 100 m (330 ft) of bedded air-fall and thin ash-flow tuff units. After deposition of the tuff and lavas of the Calico Hills, eruptions began from the Timber Mountain-Oasis Valley caldera complex and the Claim Canyon caldron segment just north of Yucca Mountain. These eruptions produced voluminous widespread ash-flow tuff sheets of the Paintbrush and Timber Mountain Tuffs. Regional tumescence or doming is thought to have immediately preceded formation of the complex (Christiansen and others, 1977), and the edge of that dome may have been near the north end of Yucca Mountain. Very thick layers of the Paintbrush and Timber Mountain Tuffs 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.

ROCK DENSITIES

The density of the rocks within the study area, together with their three-dimensional distribution, are the two characteristics most critical to a gravity study. Collection and laboratory measurement of surface-rock samples is the standard method of obtaining the density or specific gravity of the rocks. If this is the only source of density control available several assumptions become necessary; an excellent discussion addressing these assumptions was given by Mabey (1960). In the Yucca Mountain area, the surface-density data from samples is 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 specific gravities of six core samples from drill holes USW-G1 and USW-VH-1, and of 95 surface samples, were measured, using tapwater at standard temperature and pressure as the reference fluid and an electronic balance accurate to four significant figures. Table 2 summarizes these results.

Gamma-gamma density logs have been completed in drill holes USW-G1, H1, and VH-1. These logs have been borehole compensated; that is, any change in hole diameter caused by wall collapse or the drilling process has been accounted for in the density determinations. The compensated logs provided by the Birdwell logging team were then averaged by dividing the area measured under the density curve by the depth interval considered. This analysis further smoothed irregularities caused by fractures and localized effects in the drill-hole walls. Figure 5 plots these average densities; least-squares-fit line represents the density gradient as a function of depth for the entire length of drill hole USW-H1, extrapolated to about 500 m (1,650 ft) beneath the bottom of the drill hole. The downward increase in density appears to be related to the closing of pore space due to alteration and compaction rather than to primary density variations in the tuff. Four core samples are also shown for comparison, although they represent nonsaturated measurements on tuff obtained from within the saturated zone. Table 3 lists the average density values derived from the gamma-gamma log in drill-holes USW-H1, VH-1, and G1.



• H1 average log densities

o G1 average log densities

+ Specific gravity of core samples

Figure 5 Drill-hole G1 specific-gravity measurements and gamma-gamma log density averages with respect to depth. Line is least-squares-fit of data points. Short segments indicate linear density increases within tuff members. Four core samples represent nonsaturated measurements of tuff obtained from saturated zone in Yucca Mountain.

A downhole gravity study was made at drill-hole USW-H1 (S. L. Robbins, written commun., 1981). Values agree with the gamma-gamma measurements in almost all cases. This agreement is significant, because borehole gravity samples a much greater lateral volume than do the density logs and includes fractures, cavities, and other large irregularities in the rock. The gamma-gamma method surveys the true atomic density of the rocks in the immediate vicinity of the drill hole and is much more sensitive to fractures and irregularities immediately next to the instrument.

The locations of 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 in figure 5, if it is, indeed, due to alteration, compaction, and lithostatic loading, is probably applicable to all the thick tuff sequences within the study area.

Surface samples provide the only real density control on the lower Paleozoic rocks modeled in this study. Other pre-Tertiary rocks beneath Crater Flat, Yucca Mountain, and Jackass Flats have never been sampled, and their composition and density remain unknown. The specific gravity for the pre-Tertiary rocks exposed at the surface ranges from 2.58 to 2.70 g/cm^3, with a mean of 2.64 ± 0.06 g/cm^3, on the basis of samples taken from Bare Mountain and the Striped Hills during this study.

Table 2. Specific gravity measurements of surface and drill-hole samples

Sample	Rock unit	Specific gravity	
		Unsaturated	Saturated
G1 5500	Older tuff	2.37	--
G1 5005	Older tuff	2.22	--
G1 4531	Older tuff	2.25	--
G1 4021	"Tuff of Lithic Ridge"	2.16	--
VH-1 762	Tiva Canyon Member[1]	2.40	--
VH-1 151	Basalt	2.88	--
CF 09	Rainier Mesa Member[2]	2.00	2.08
CF 11	Rainier Mesa Member[2]	1.86	2.26
CF 11	Basalt	2.76	--
CF 39	Basalt cinder	1.39	1.55
CF 39A	Basalt cinder	1.90	2.04
CF 46	Basalt	2.77	2.78
CF 48	Basalt	2.88	2.89
CF 49	Tiva Canyon Member[1]	2.27	2.30
CF 50	Tiva Canyon Member[1]	2.34	2.35
CF 52	Tuff, undifferentiated	2.84	2.85
CF 59	Tiva Canyon Member[1]	2.14	2.36
70 samples of rhyolite of Calico Hills		2.12±0.26	2.26±0.17
C-28	Argillite, Eleana Formation	2.59	2.63
CF 85	Carboniferous argillite	2.59	2.61
CF 86	Carboniferous argillite	2.58	2.61
CF 90	Devonian limestone	2.81	2.82
CF 91	Devonian limestone	2.64	2.67
CF 81	Devonian dolomite	2.68	2.69
CF 82	Limestone	2.68	2.70
CF 62	Limestone, Bonanza King Formation	2.66	2.67
CF 72	Limestone, Bonanza King Formation	2.59	2.62
CF 30	Zabriskie Quartzite	2.64	2.65
CF 31	Zabriskie Quartzite	2.59	2.60
CF 32	Zabriskie Quartzite	2.70	2.72
CF 33	Zabriskie Quartzite	2.61	2.63
CF 61	Zabriskie Quartzite	2.64	2.64

[1] member of the Paintbrush Tuff
[2] member of the Timber Mountain Tuff

Table 3. Average gamma-gamma well-log measurements

Depth interval (ft)[1]	Area under the curve / actual interval length (in.)	Average density (g/cm^3)	Geologic unit[2]
USW-H1			
350- 500	2.93	2.17	Topopah Spring Member[3]
500- 700	2.17	1.87	
700- 900	2.52	2.01	
900-1100	2.60	2.04	
1100-1300	2.50	2.00	
1300-1500	2.99	2.20	Tuff of Calico Hills
1500-1700	2.17	1.87	
1700-1900	2.26	1.90	
1900-2100	2.74	2.10	Prow Pass Member[4]
2100-2250	2.48	1.99	
2260-2400	2.70	2.08	Bullfrog Member[4]
2400-2600	3.12	2.25	
2600-2800	2.82	2.13	Unnamed member[4]
2800-3000	3.04	2.22	
3000-3200	3.19	2.28	
3200-3400	3.26	2.30	
3400-3600	3.39	2.36	
3600-3800	3.57	2.43	Flow breccia
3800-4000	3.92	2.28	
4000-4200	3.31	2.32	
4200-4400	3.29	2.32	"Tuff of Lithic Ridge"
4400-4600	3.25	2.30	
4600-4800	3.48	2.39	
4800-5000	3.46	2.38	
5000-5200	3.44	2.38	Older tuff
5200-5400	3.48	2.39	
5400-5600	3.39	2.36	
5600-5800	3.70	2.48	
5800-6000	3.84	2.54	
USW-VH-1			
50- 100	1.32	1.53	Alluvium
100- 200	3.01	2.20	Basalt and basalt cinders
200- 300	2.31	1.92	
300- 400	2.53	2.01	Alluvium
400- 500	3.07	2.23	Tiva Canyon Member[3]
500- 600	2.36	1.94	
USW-G1			
300- 400	2.98	2.19	Topopah Spring Member[3]
400- 500	2.76	2.10	
500- 600	2.50	2.00	
600- 700	2.76	2.10	

[1] To obtain approximate depth in meters, multiply by 0.305.
[2] Unit contacts are approximate only.
[3] member of the Paintbrush Tuff
[4] member of the Crater Flat Tuff

GRAVITY DATA COLLECTION AND REDUCTION

Field work

A substantial number of gravity measurements already existed in the area before this study as a result of many years of work, mostly by D. L. Healey of the U.S. Geological Survey (Healey and others, 1980). From his work, 934 stations have been incorporated into this study. Though not generally available for many of these stations, accuracy specifications are commensurable with those of later measurements.

Field work to supplement these existing data for the Yucca Mountain area began in autumn, 1979. A helicopter was used to occupy 55 gravity stations on many ridges and hilltops. A detailed profile along an access road in Jackass Flats, as well as a detailed grid in "drill-hole wash," also established at this time, added 28 and 64 stations, respectively. The complete data set of 1,357 stations was completed in autumn, 1980, with the surveying, both geodetic and gravity, of 70 stations along three profiles extending from Bare Mountain eastward to the center of Jackass Flats.

Accuracy of data

An observed gravity precision of ±0.1 mGal was the goal of the data collection in support of this study. LaCoste and Romberg gravity meters G17, G177, and G192 were used, commonly operated in tandem. In addition to the factory calibrations, each gravity meter was recalibrated on either the Mount Hamilton, Calif. (Barnes and others, 1969), or Charleston Peak, Nev. (Ponce and Oliver, 1981), gravity loops before and after each field session. Each day, work was closed on a reoccupied station to check the gravity meter drift during that day, and as many times during the day as was convenient.

Most stations were located on U.S. Geological Survey bench marks, spot elevations, and other previously established standard reference points. The remaining stations were surveyed in by the gravity field parties using Hewlett-Packard Total and Total Electric stations. Surveying precision was checked many times against standard reference marks; this surveying adds an additional uncertainty of ±0.5 m to the published uncertainty of the reference bench mark. Exhaustive accuracy information is available from the senior author upon request.

Standard reductions

All gravity stations have been reduced by a method used by the U.S. Geological Survey, Menlo Park, California utilizing the computer procedures of Plouff (1977) and D.F. Barnes (written commun., 1978), and the formulae of Oliver (1980, p. 50). The gravity datum is IGSN 71 (Morelli, 1974); free-air anomalies are referenced to the Geodetic Reference System of 1967 (International Association of Geodesy, 1971). Terrain corrections to a radial distance of 0.068 km from the station were made in the field; those from 0.068 km to 0.59 km were made by using cylindrical-ring templates (Swick, 1942). The remaining correction for terrain variations out to 167 km were computer generated with the U.S. Geological Survey modification of Defense Mapping Agency digital terrain data. The primary base station, Mercury, has an observed gravity value of 979,518.80 mGal (Ponce and Oliver, 1981, p. 13).

Additional reductions

The analysis of complete Bouguer gravity anomalies reduced at the average crustal density of 2.67 g/cm^3 was deemed inadequate for the Yucca Mountain area. Density measurements discussed previously indicate that rocks making up the topographic relief in 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 commun., 1980), at a density of 2.0 g/cm^3. Thus, gravity effects, difficult to quantify in an obvious way (fig. 6), attributable to the topographic distribution of the stations have been reduced or eliminated.

To remove large-scale effects arising from lateral density variations deeper than 5 km within the crust, an isostatic correction was also applied to the complete Bouguer anomalies (fig. 6). This correction assumes complete Airy-Heiskanen isostatic compensation at the Moho, primarily on the basis of the elevation of the land within a 166.7 km radius of the study area. The actual 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 (Roberts and others, 1981). The purpose of this final correction was not to estimate the deep crustal structure beneath Yucca Mountain but to filter out long-wavelength gravity effects related to the surface topography.

The final product of all these corrections and reductions is a model of 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 (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.

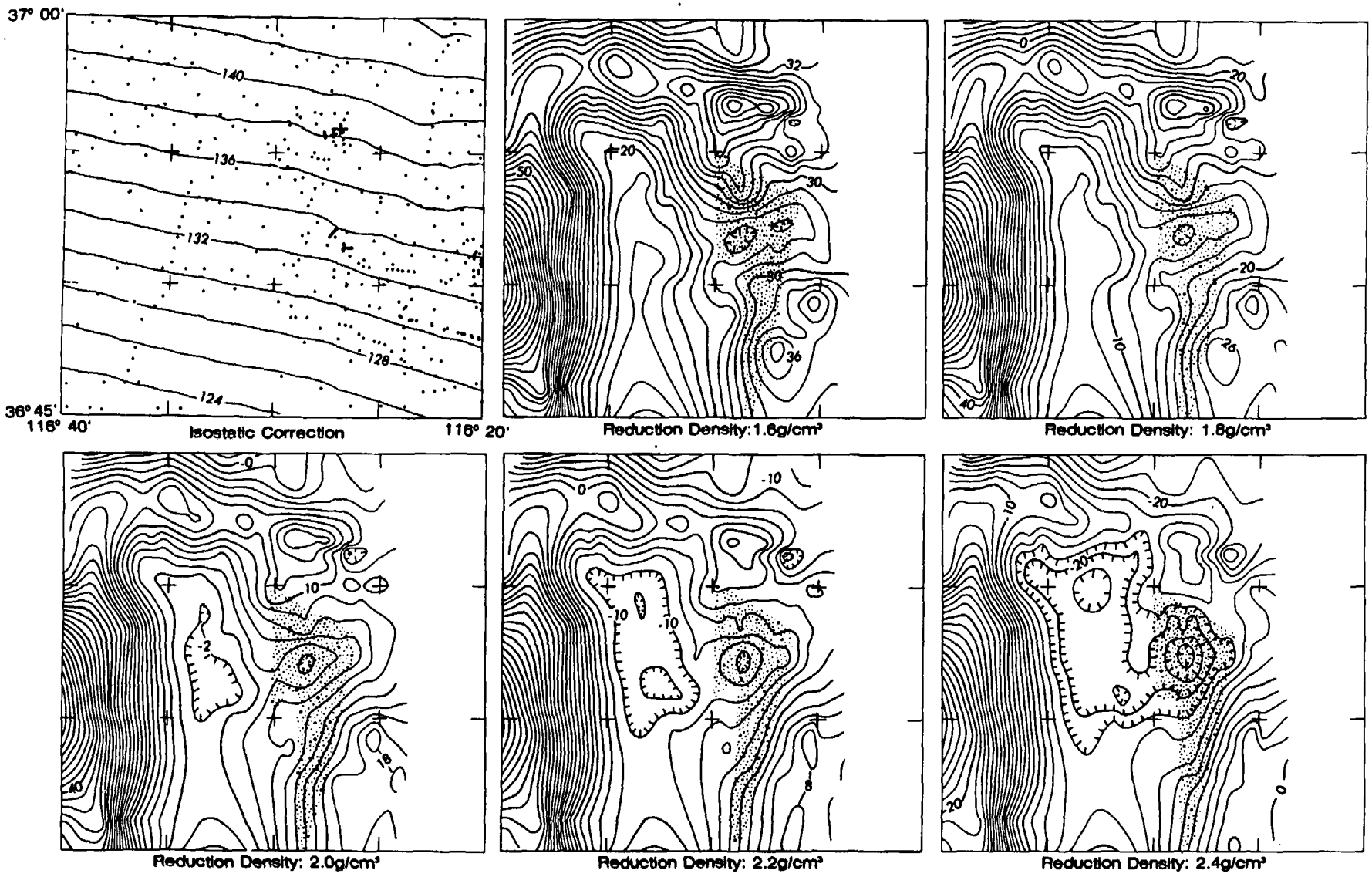


Figure 6 Gravity-contour maps of central part of study area, showing effects of choosing various Bouguer reduction densities. Stippling represents topographically highest part of Yucca Mountain. Upper left-hand map shows isostatic correction applied to data; the correction is nearly planar in character, tilted slightly to north-northeast.

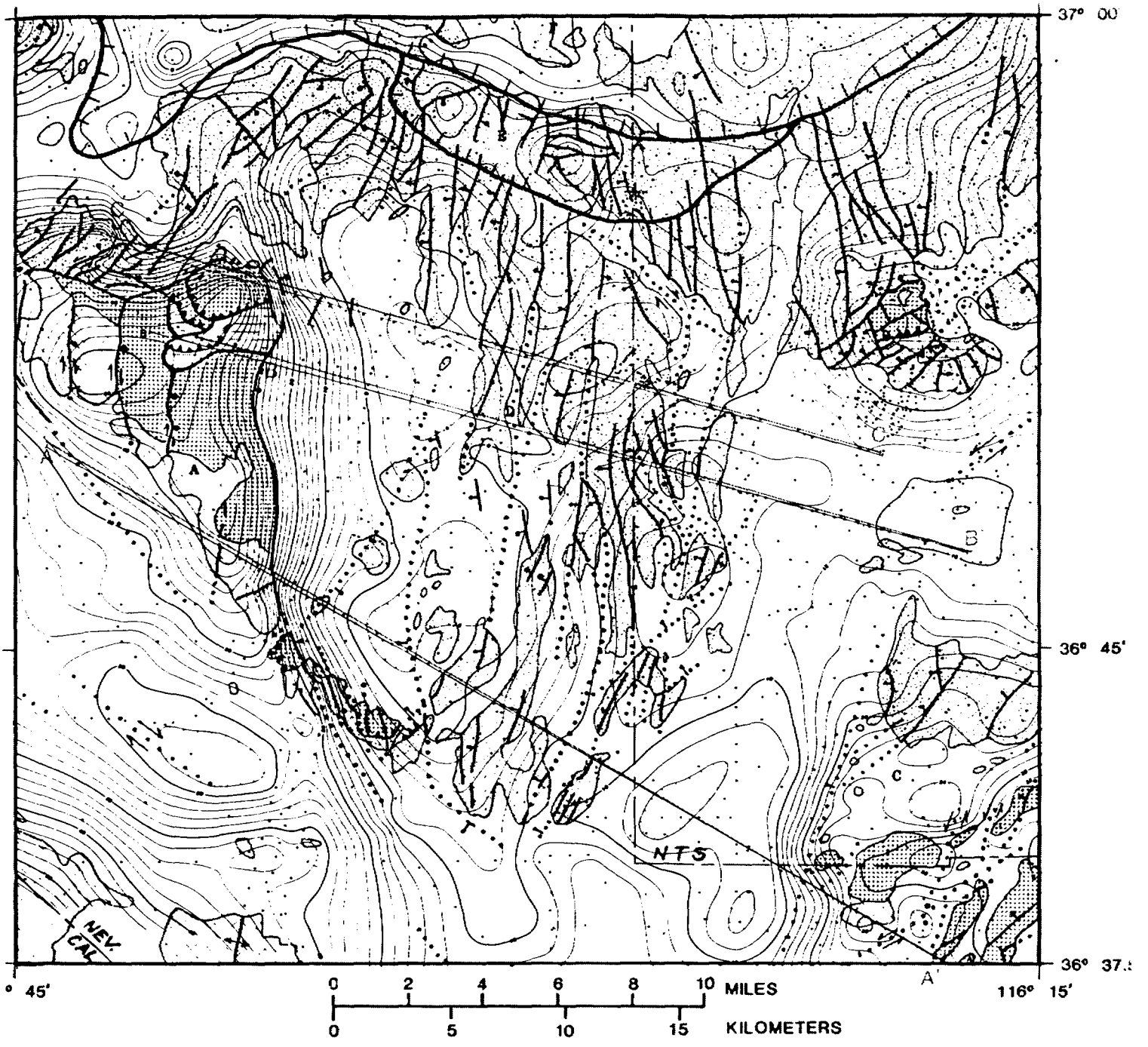
INTERPRETATION OF THE GRAVITY FIELD AT YUCCA MOUNTAIN AND VICINITY

The interpretation of the gravity field at Yucca Mountain uses three analytical tools: a 2-mGal contour map (pl. 1; fig. 7;) reduced at 2.00 g/cm^3 and corrected for perfect isostasy; three 2½-dimensional modeled cross sections extending east-westward across the study area (figs. 8-10); and a 3-dimensional multiple-polygon gravity model (pl. 1). The contour map incorporates three significant refinements not included in previously published gravity maps of the area (for example, Healey and others, 1980). (1) reduction density of 2.00 g/cm^3 appropriate to most of the surface rocks in the area, which removes some gravity features resulting only from surface topography, (2) the 2-mGal-contour interval, which emphasizes many localized gravity features; and (3) the isostatic corrections, which remove broad gravity effects arising from masses near the base of the crust on the basis of their general correlation with broad surface elevation.

The 2½-dimensional modeling utilizes the geophysical theory developed by Cady (1980), in which source bodies remain invariant within a given cross section but may terminate at a specifiable finite distance along strike in either direction. The use of varying extensions along strike and of nested bodies permits much of the generality of 3-dimensional modeling to be retained in this much simpler process. The three models of figures 8 through 10 all incorporate the third dimension by specification of varying extensions of the modeled bodies into the northern and southern half-spaces. The small 2.7-g/cm^3 body at 30 km in figure 8 and the near-surface 2.0-g/cm^3 body at the far left in figure 10 do not exist south of the respective profiles--a geometry critical to obtaining a satisfactory fit of the gravity curves. These models are useful in determining contact dips and small structures within the subsurface rocks. The more generalized three-dimensional model (Plouff, 1975), using flat polygonal source bodies, provides more accurate depth estimates, even though it is limited to eight prevolcanic bodies, three bodies of the dense tuff of Chocolate Mountain (see pl. 1), two bodies of the Crater Flat Tuff, and one alluvial body along Topopah Wash. Figure 11 shows that this simple model approximates the observed gravity field to within 3 mGal in all the central areas of primary interest. The average difference is 3.7 mGal, whereas the root-mean-square mismatches of the models in figures 8 through 10 were 2.8, 2.1, and 1.5 mGal, respectively. Given these modeling errors, the excellent correspondence of the 2½- and 3-dimensional models, as suggested by figure 12, adds confidence to the subsurface geometries estimated by these models.

Bare Mountain-Funeral Mountains 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 (A, pl. 1) and the Funeral Mountains (fig. 1). Residual-gravity values of at least 14 mGal delimit the anomaly. The rocks of Bare Mountain and the Funeral Range--Precambrian and Paleozoic limestone, dolomite, argillite, and quartzite, some metamorphosed, especially in the Funeral Mountains--have some of the highest densities in the study area. As a result, the anomaly is accentuated 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.



EXPLANATION

- Tertiary and Quaternary alluvium
- Tertiary and Quaternary volcanic rocks
- Upper Paleozoic clastic rocks
- **Lower and middle** Paleozoic carbonate rocks
- **Precambrian and lower Paleozoic** clastic rocks
- Contact
- Fault, dotted where concealed; bar and ball on downthrown side
- Caldera wall
- Low-angle fault or glide plane, teeth on upper plate

Figure 7 Residual gravity map of Yucca Mountain and vicinity, superimposed on geologic map in figure 3. Contour interval, 2 mGal; reduction at 2.0 g/cm^3.

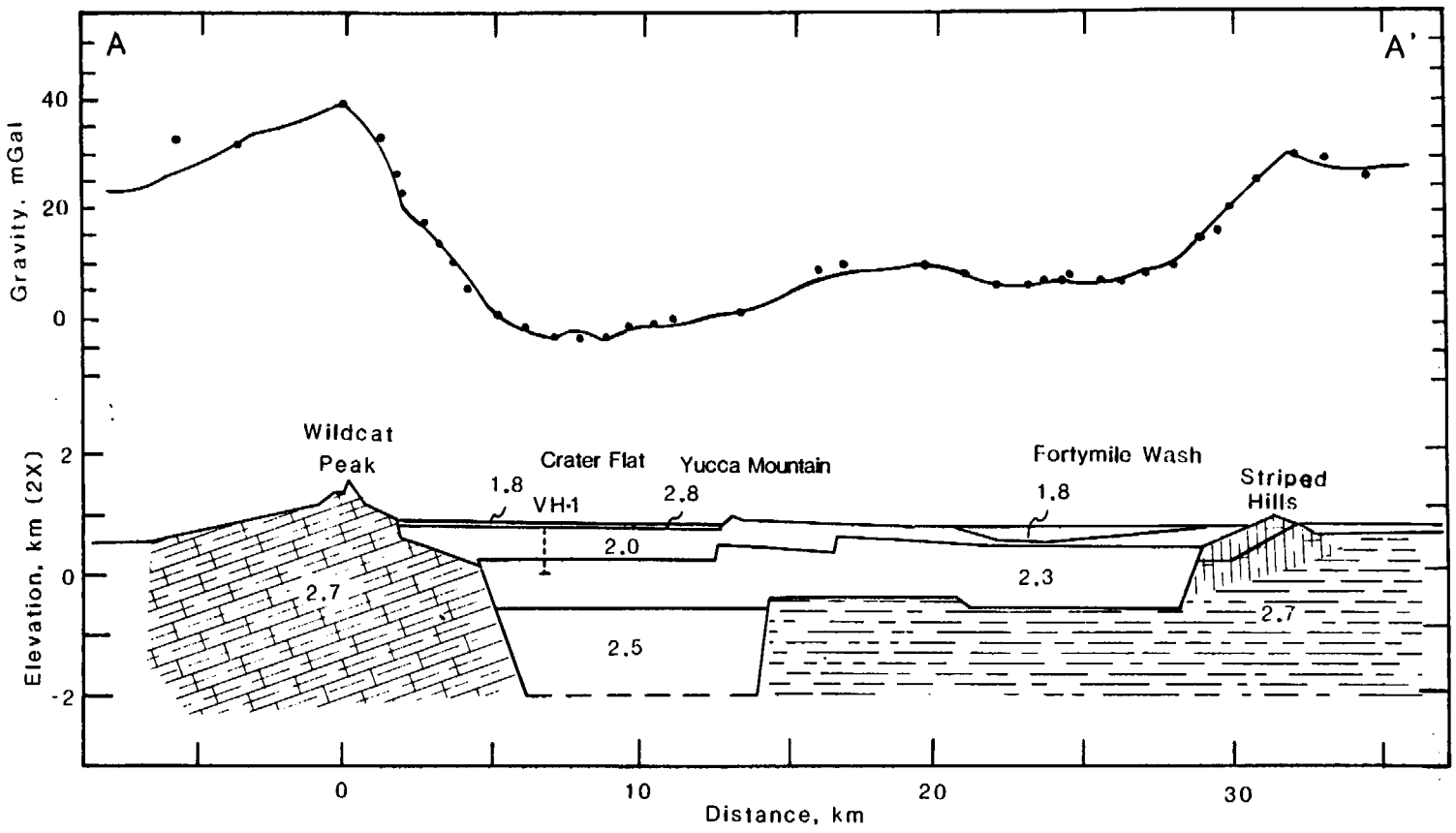


Figure 8 Gravity-modeling profile A-A'. Curve represents calculated gravity values; data points denote observed gravity values(fig. 7); numbers are bulk densities of modeled bodies(in g/cm^3). Drill-hole VH-1 is projected onto profile from 4.5 km. to north. Patterns represent Paleozoic rock at approximate observed attitude. Additional body in striped Hills is a 2.7-g/cm^3 body that exists only in northern half-space.

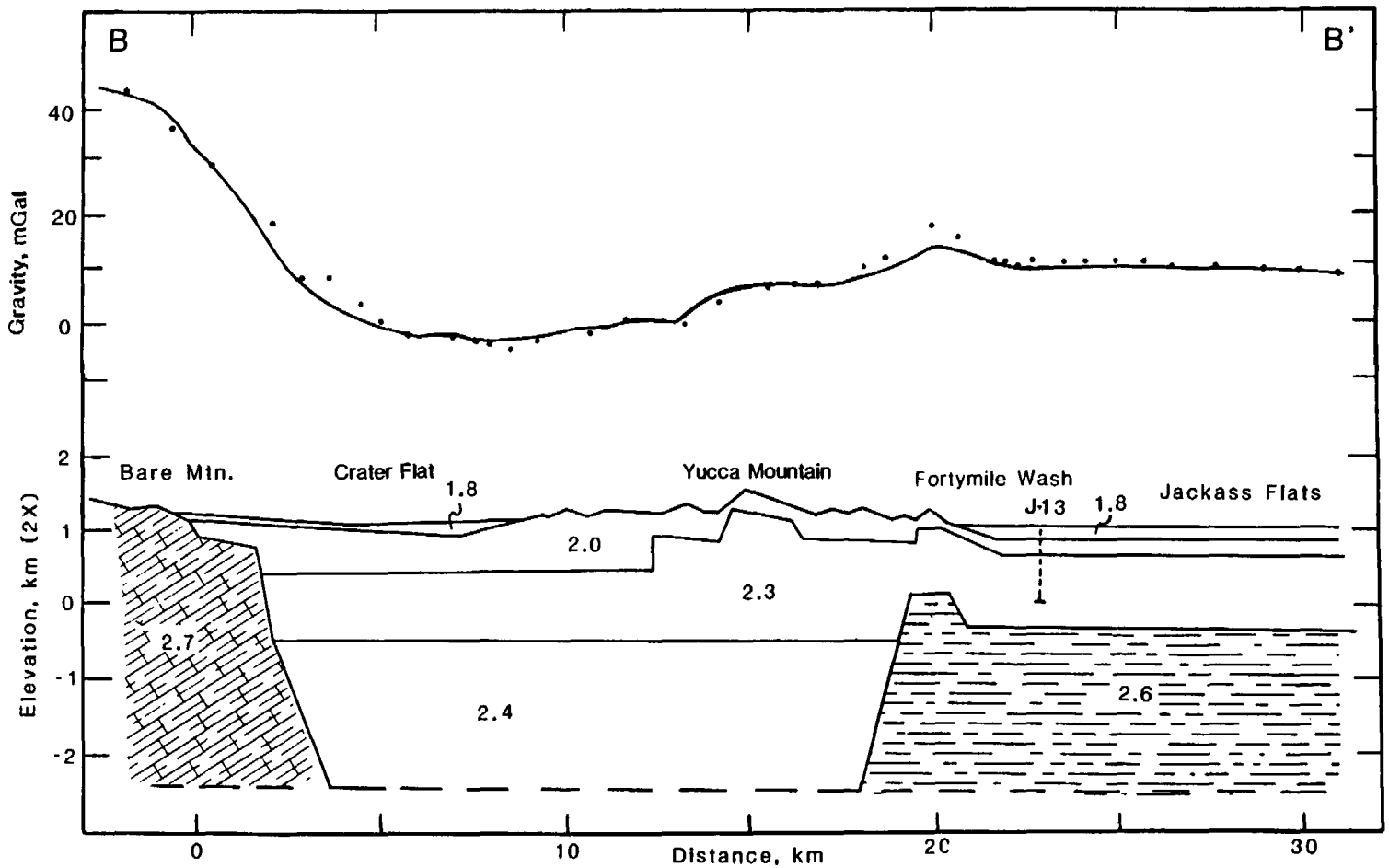


Figure 9 Gravity-modeling profile B-B'. Symbols same as in figure 8. Paleozoic rocks beneath Jackass Flats are assigned a density of 2.6 g/cm^3 because they are thought to be argillite of this density.

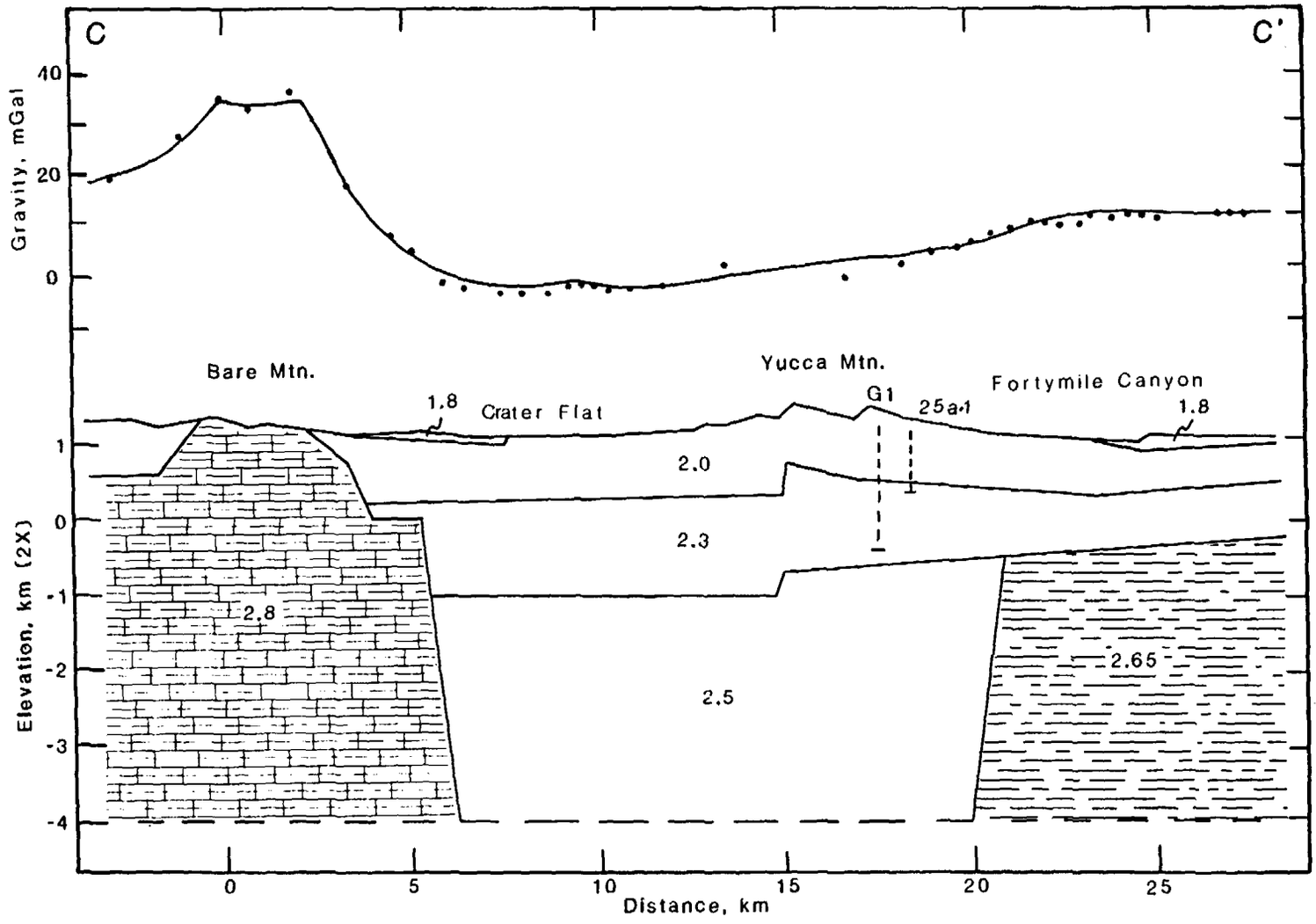


Figure 10 Gravity-modeling profile C-C'. Symbols same as in figure 8. Drill-hole G1 is projected onto the profile from 1 km to north. Paleozoic rock densities higher than those in profiles A-A' and B-B' and a deeper central depression were required for good gravity curve fit. Unlabeled body west of Bare Mountain is a 2.0-g/cm^3 body that exists only in northern half-space.

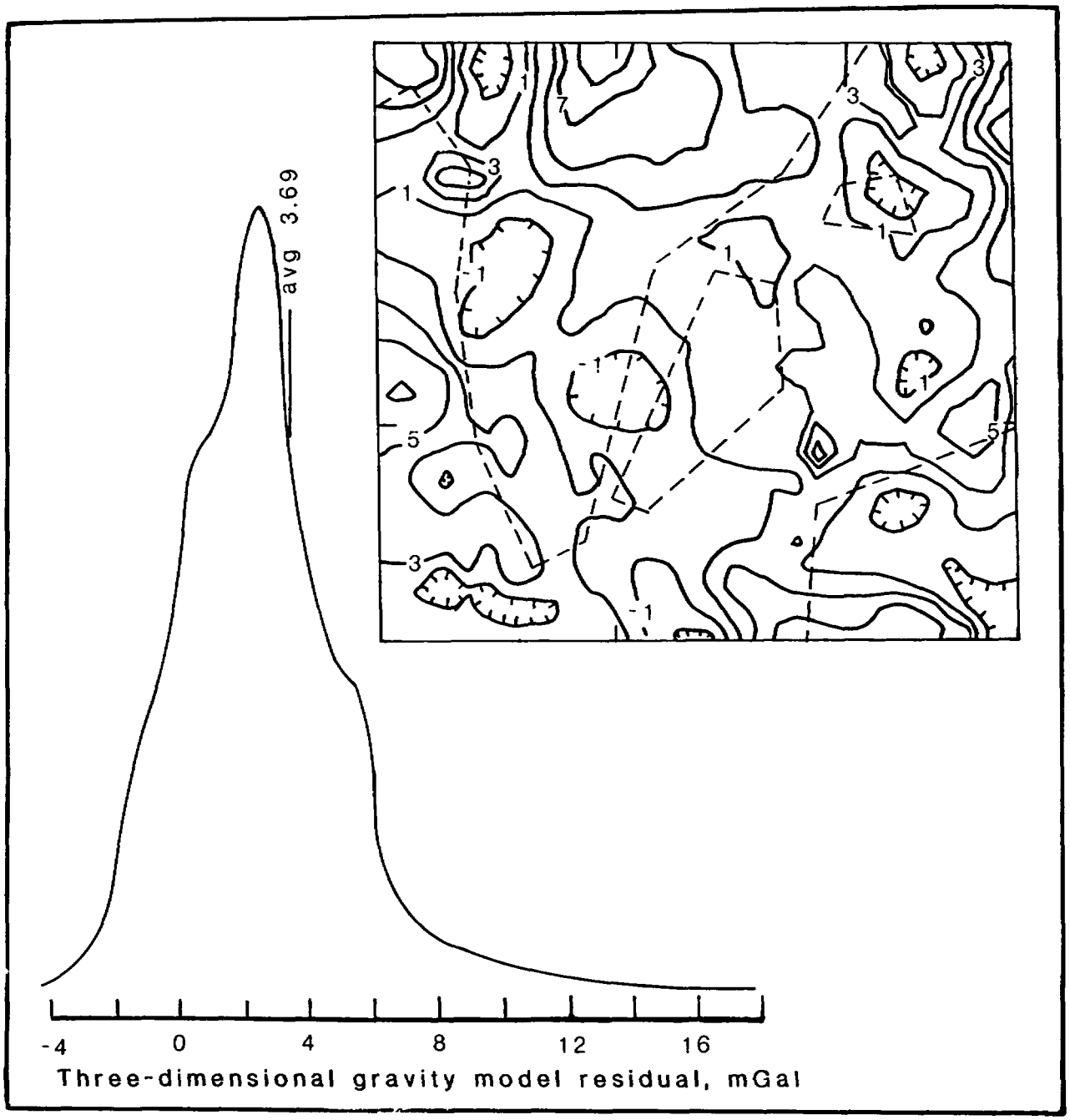


Figure 11 Countour plot of residual or mismatch of 3-dimensional gravity model. Contour interval, 2mGal: several 3-dimensional model bodies are outlined for reference. Graph shows relative distribution of residuals in contour plot.

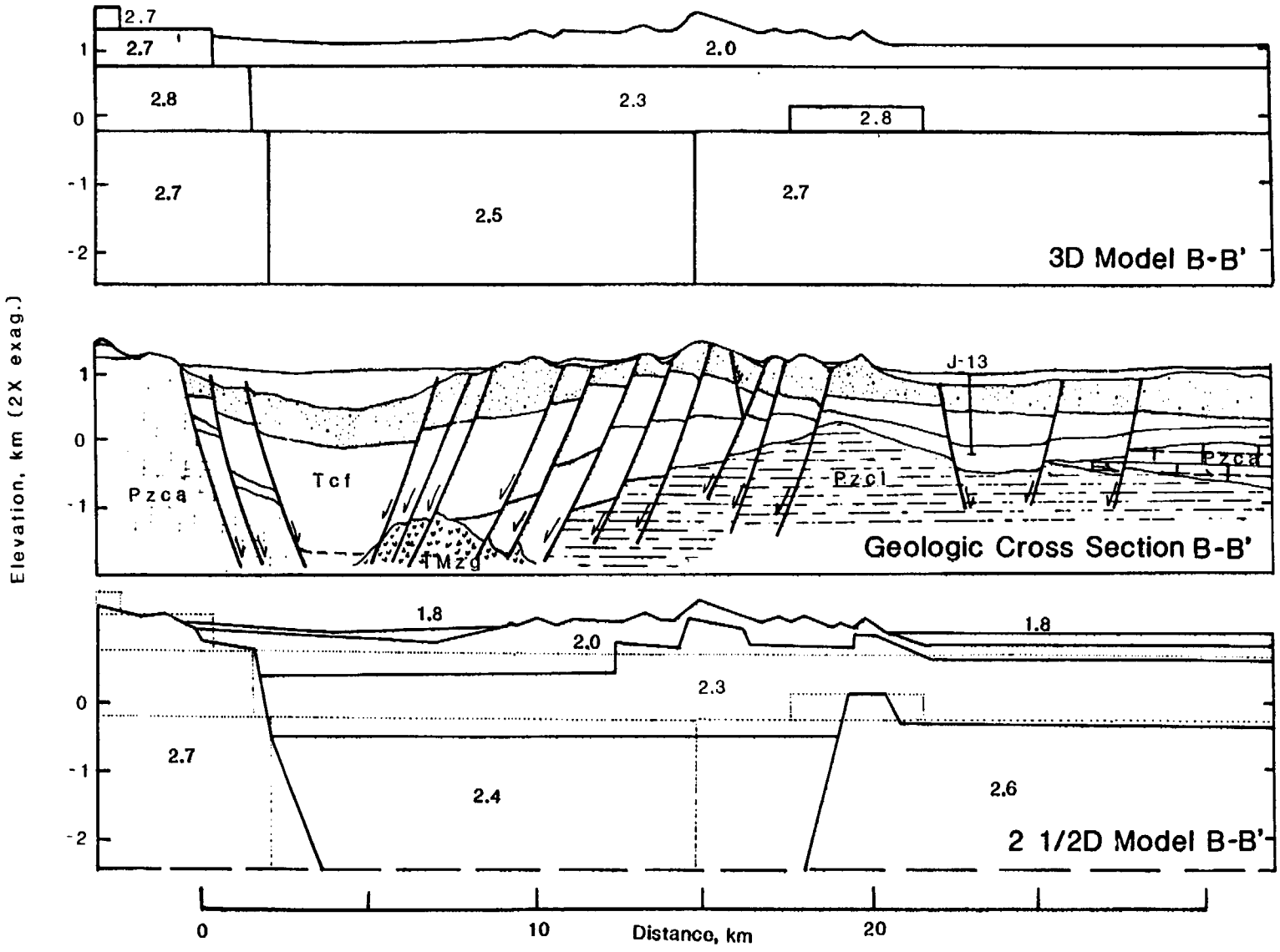


Figure 12 Gravity-modeling profile B-B', comparing 3-dimensional gravity model, 2 1/2-dimensional gravity model, and geologic cross section. Numbers are modeled bulk densities(in g/cm^3). Lower and middle Paleozoic carbonate rocks, Pzca; upper Paleozoic clastic rocks, Pzcl; Mesozoic or Tertiary granite, TMzg; and Crater Flat Tuff, Tcf.

The anomaly culminates in a maximum of about 48 mGal over Bare Mountain but has a southern part approaching 50 mGal at the edge of the map area (pl. 1). The two highs are separated by a gravity saddle of 18 mGal, that approximately coincides with that part of the Amargosa Valley occupied by the Amargosa River. The gradient to the southwest rises precipitously as it approaches the Funeral Mountains just across the Nevada-California border, where one of the highest isostatic gravity residuals in California occurs (Roberts and others, 1981). This gravity feature strongly suggests 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 an accumulation of Tertiary volcanic and sedimentary rocks underlying the alluvium of the Amargosa Valley and from faulting related to the Walker Lane in the Amargosa Valley west of Bare Mountain. Such faults may have created structural downwarps or basins that collected sufficient alluvium from Bare Mountain to account for the lower gravity values.

Study of the detailed shape of the gravity curve over the east flank of Bare Mountain in the 2 1/2-dimensional models (figs. 8-10) suggests that the Paleozoic rocks extend several kilometers farther eastward beneath Crater Flat than the surface contacts indicate. This shelf or downstepping of Paleozoic rocks is most evident in profile A-A' (fig. 8), where the step may occur 5 km into Crater Flat at a depth of less than 1 km.

The unusual isostatic character of the Funeral Mountains and Bare Mountain complicates the use of Bare Mountain as a reference point against which to compare the gravity over the rest of the map. After all surface geologic considerations are made in the 3-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 deficiency in the 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 mildly metamorphosed, and Bare Mountain may contain a low angle fault underlain by strongly metamorphosed rocks (M. D. Carr, oral commun., 1982).

Calico Hills-Busted Butte gravity high

The Calico Hills gravity high (B, pl. 1), which has been studied and modeled previously (Snyder and Oliver, 1981), is fairly well understood. The distribution of the Eleana Formation, which consists largely of fine-grained quartzite and argillite, becomes much more evident on the isostatic residual map reduced at 2.00 g/cm^3 than at the previous 2.67-g/cm^3 reduction. The relatively simple 3-dimensional approximation (pl. 1; fig. 13) gives excellent agreement between the calculated and observed values and provides a good reference between the contour map, the 3-dimensional model, and the known geologic structure. If defined locally by the 21-mGal contour (pl. 1; fig. 7), the anomaly interpretation supports the structural-dome hypothesis of the geologic studies (Maldonado and others, 1979). If extended to include the 14-mGal contour, the anomaly is no longer closed and extends much more to the northeast. The gravity high enclosed by the 14-mGal contour to the southwest of the Calico Hills near Busted Butte appears to extend this trend in that direction. Remanant topographic highs of the Paleozoic surface along the

eastern borders of the Timber Mountain and Crater Flat caldera complexes could explain the local gravity highs along this trend. A long narrow structural block of dense rock, upraised relative to its surroundings at depth by sills or diapirs, would also cause such a gravity anomaly.

The 10-mGal gravity saddle between the Calico Hills high and the Busted Butte high (pl. 1, fig. 7) is on the trend of Yucca Wash, a conspicuous northwest-trending valley bounding part of Yucca Mountain. A fault zone as old as Mesozoic is suspected along Yucca Wash on the basis of rock-unit distributions; this structure may interrupt or offset the buried pre-volcanic surface discussed above.

The 2 1/2- and 3-dimensional models estimate depths between 1,300 and 1,500 m (4,500 and 5,000 ft) to Paleozoic rocks at the gravity saddle between Calico Hills and Busted Butte, and between 1,000 and 1,200 m (3,000 and 4,000 ft) near the 14-mGal closure near Busted Butte. Geologic maps (Lipman and McKay, 1965) indicate a north-northeast-trending horst in the tuff at Busted Butte. If the mapped surface offsets continue at depth, the higher density tuff is slightly elevated below Busted Butte and contributes to the gravity high. Calculations from the 2 1/2-dimensional model of profile B-B' (fig. 9) indicate that the tuff horst and Paleozoic high contribute equally to the anomaly. This is an extreme case because no such major 0.3-g/cm^3-density-contrast contact exists within the tuff sequence; the model is a necessary simplification of a much more gradually varying density-depth relation. Thus, much of the gravity anomaly would be attributable to anomalously denser tuff masses deeper than indicated in the profile, where they would contribute somewhat less. The 3-dimensional model assumes no lateral variations in the tuff and requires a topographic high approximately twice as wide as in the 2 1/2-dimensional model (fig. 12). The alternative assumption of doubling the height would be geologically unlikely. Profile B-B' is probably nearly correct for 2 1/2-dimensional modeling, a reasonable variation of this model would widen rather than raise the pre-Tertiary topographic high.

The thinner tuff cover in the Busted Butte area suggested by this gravity interpretation may have resulted in propagation to the surface of faults of a different trend than common in the Yucca Mountain site area. These faults have an arcuate tendency and strike north-northwest; a few are downthrown on the northeast side, contrary to the general style in this part of Yucca Mountain. Also, slightly but consistently higher dips in the tuff in this same area than elsewhere on Yucca Mountain indicate more rotation and structural disturbance of the units.

Striped Hills-Little Skull Mountain gravity high

The gravity high in the southeast corner of the study area, delineated by the 14-mGal contour, encompasses both Little Skull Mountain and the Striped Hills (C, pl. 1; fig. 7); this gravity feature arises mainly from buried and exposed Paleozoic rocks. The 3-dimensional model approximates the Striped Hills rocks to within a few milligals and thus provides another reference point for comparing the gravity-contour map, the 3-dimensional model, and the geologic structure. Using the Striped Hills and Calico Hills areas as controls, we estimate the general elevation of the Paleozoic rocks beneath Jackass Flats with some confidence (fig. 12) to lie just a few hundred meters below sea level, or about 1,300 m (4,200 ft) below the ground surface.

Profile A-A' (fig. 8) indicates that west of the Striped Hills the Paleozoic rock surface slopes gently downward to the west, then steepens abruptly near Topopah Wash. The steepness and linearity of the gravity gradient at this point strongly suggest a north-northwest-trending buried fault, with rocks downthrown to the west. The 3-dimensional model (fig. 13) suggests as much as 1,000 m (3,600 ft) of western downdrop. The near-vertical and slightly overturned beds of the Striped Hills indicate additional geologic structures within the Paleozoic rocks, structures that may also influence the gravity signature within the Striped Hills-Little Skull Mountain high.

Crater Flat-Yucca Mountain gravity low

A large triangular gravity low, defined by the 8-mGal-residual-gravity contour, dominates the gravity field in the study area (D, pl. 1). 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. Reduction at the 2.00 g/cm^3 average density of the tuff at Yucca Mountain better defines this feature. The anomaly extends northeastward from Bare Mountain nearly to the Calico Hills and southeastward over a low saddle toward the Striped Hills, and encloses an area containing no outcrops of pre-Tertiary rock. Figure 6 shows that choices of reduction density as low as 1.8 g/cm^3 and as high as 2.4 g/cm^3 reveal the same general characteristics of this feature.

The 3-dimensional model indicates that the volcanic rocks extend at least to 2.5 km (8,200 ft) below sea level beneath Crater Flat. These relatively low density rocks, which lie south of the south wall of Timber Mountain caldera (Byers and others, 1976), and may derive from material filling a combination of sector grabens and old calderas, possibly the source areas for the Crater Flat Tuff. This gravity low extends to the south of the study area, into the Amargosa Desert. 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 minimums. Tuff density below 2,000 m (6,000 ft), 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 drillhole. 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, although 3 km of overburden may increase the density of these Paleozoic sedimentary rocks. 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 2.5 km below sea level, the estimated floor of the caldera fill. Floor-elevation uncertainties of $\pm$1.0 km or greater could be possible from this range of density contrast.

The 2 1/2-dimensional cross sections (figs. 8-10) indicate steep-sided walls on the Paleozoic rocks bordering the gravity low. A crude sense of downstepping along normal faults in the upper tuff units is also suggested by the models (beneath Yucca Mountain, figs. 8-10). This downstepping may have resulted from subsidence beneath Crater Flat along north-south-trending normal

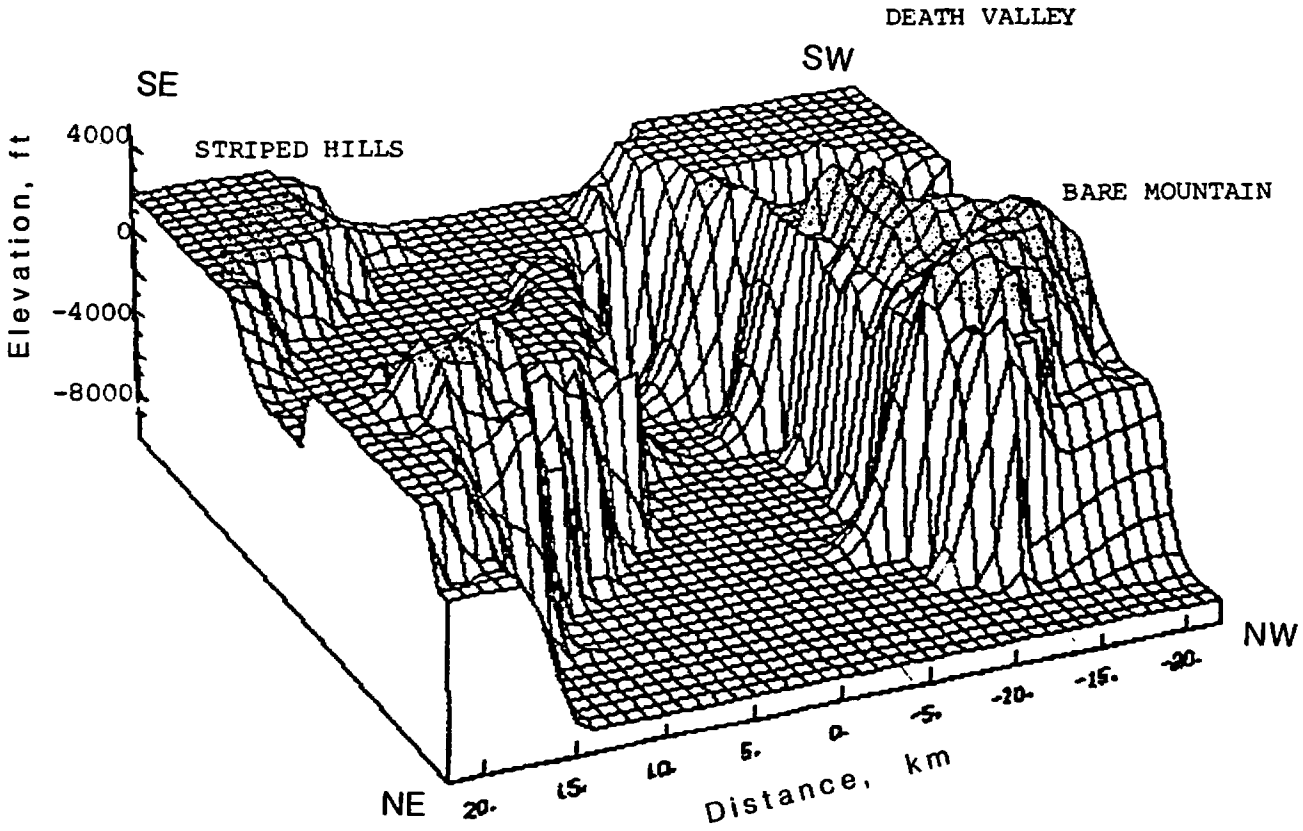


Figure 13 Mesh perspective of prevolcanic bodies in 3-dimensional gravity model of Yucca Mountain and vicinity, as viewed from northeast. Surface represents prevolcanic surface beneath topographic surface. Stippling indicates where these surfaces coincide at Bare Mountain, Striped Hills, and Calico Hills (in foreground).

faults at the west edge of Yucca Mountain. Most of this displacement took place before the Timber Mountain Tuff was deposited and after emplacement of the Paintbrush Tuff, although minor faulting of the same strike that cuts Quaternary alluvium indicates that small tectonic adjustments have continued.

The -2-mGal closures in the northern and southern parts of the Crater Flat anomaly are separated by a narrow band anchored by protruding positive anomalies. This configuration of the gravity field suggests a septum or ridge of higher density rock cutting across the depression at this point. Relations in the volcanic rocks coeval with the Crater Flat Tuff suggest that Crater Flat may contain the source areas for this tuff and lavas. 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 the "older tuff" caldera or sag feature shown on the tectonic-structural map (fig. 4).

Chocolate Mountain-Northern Yucca Mountain gravity high

A narrow band of gravity highs (E, pl. 1; fig. 7), peaking at 14-, 12-, and 16-mGal, separates the large negative anomalies associated with Crater Flat and Timber Mountain caldera to the north. The most prominent gravity high along this band coincides with Chocolate Mountain and the Claim Canyon caldron segment (Byers and others, 1976). The 3-dimensional model indicates that more than 4,000 m (14,000 ft) 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 caldron segment is an eccentric resurged block of the very thick densely welded intracaldera Tiva Canyon Member and other members of the Paintbrush Tuff. Field samples collected at Chocolate Mountain yielded specific gravities of 2.32 ± 0.12 g/cm^3. The absence of a commonly present depression or moat filled with relatively low density materials associated with the densely welded intracaldera tuff causes the 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 unnamed member of the Crater Flat Tuff exposed here and there outside the Timber Mountain-Oasis Valley caldera complex. The unnamed member exposed in this area may also be part of a fragmented resurgent dome (fig. 4).

Timber Mountain caldera gravity low

At the north edge of the study area, a large gravity low projects southward from the area of Timber Mountain (F, pl. 1, fig. 7). The part of the gravity low shown on the map (pl. 1) is associated with the southern moat area of Timber Mountain caldera. The gravity signatures of Timber Mountain and Silent Canyon calderas have been analyzed previously (Kane and Webring, 1981) and here we note only that together they form the most conspicuous gravity low in southern Nevada.

SUMMARY AND SIGNIFICANCE OF GRAVITY ANOMALIES

The 2.0-g/cm^3 reduction density used to generate the 2-mGal-contour map (pl. 1, fig. 7) provides a significant new perspective from which to understand the gravity field and subsurface geology of Yucca Mountain and vicinity. Previous maps reduced at 2.67 g/cm^3 showed an extended gravity low over all of Crater Flat and much of Yucca Mountain (Healey and others, 1980). Much greater resolution of small features is achieved in the new plot. Surface-terrain effects are removed in the area of primary interest, Yucca Mountain, although consequential terrain-related gravity anomalies over the denser rocks of Bare Mountain are exaggerated by the lower reduction density. More importantly, however, the gravity field can now be approximately correlated more directly with the pre-Tertiary surface, assuming relative lateral homogeneity of the overlying tuff. Although gravity maps should never be considered directly representative of topography, this study allows just such an approximate interpretation of the topography of the Paleozoic surface.

The dominating central gravity low on the residual-gravity map (fig. 7) represents a large tuff-filled hole or depression in the Paleozoic rocks beneath both Crater Flat and parts of Yucca Mountain (fig. 13). A minimum thickness of 1,830 m (6,000 ft) of tuff beneath Yucca Mountain is confirmed by the drill holes. The reference gravity values at the Paleozoic outcrops of the Calico and Striped Hills, give a modeling estimate of at least 3,000 m (10,000 ft) of tuffaceous fill in the Crater Flat-Yucca Mountain depression. The absences of data on density and lithology below -1-km elevation makes precise determination of the tuff thickness impossible. With the existing data, it is also impossible to determine whether the pretuff lithology in this area is Paleozoic sedimentary rocks or intrusive rocks. The 3-dimensional model, using a linear vertical density gradient at Yucca Mountain (fig. 5), suggests 3,400$\pm$400 m (11,150 $\pm$ 1,300 ft) of tuff beneath Crater Flat. Great variations in the density of the tuff either laterally or vertically would affect this estimate, as would a significant mass anomaly directly below the study area. The present uncertainty in density contrast between caldera-flooring material and neighboring precaldera rocks makes the depth estimates of the gravity interpretation uncertain by 30 percent or about $\pm$1,000 m (3,000 ft) for the deeper estimates.

In addition to the gravity evidence, surface geologic relation and information from drill holes VH-1 and G1 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 minimum closures in Crater Flat may indicate two gravity structures--the caldera associaated with the unnamed member (= Tram unit) in generally the northern part of Crater Flat, and the caldera assoicated with the Bullfrog and Prow Pass Members in the southern part of Crater Flat. These two collapse areas may be separated by a narrow septum of Paleozoic rocks or lava flows beneath central Crater Flat. It is unlikely, however, that the northeastern lobe of the gravity low extending beneath Yucca Mountain is part of the collapse area related to the Crater Flat Tuff. The three members of the Crater Flat Tuff are nearly as thick in well J-13 as in drill-hole G1 within the gravity-low lobe. Therefore, the northeastern lobe of the gravity low at Yucca Mountain is presumably unrelated to the Crater Flat Tuff but is probably a sag or older caldera within which thick units predating the Crater Flat Tuff accumulated.

The regional gravity high that extends southwestward from the northeast corner of the map area (pl. 1) is interpreted to arise from a structural high on the buried Paleozoic rock surface. Paleozoic rocks crop out at several places along this high, for example, in the Calico Hills and the Eleana Range (fig. 1). The Eleana Range, the Calico Hills, and the dense rocks beneath Busted Butte may all be related as a pre-Miocene mountain range, predominantly composed of 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.

The saddle in the gravity field between Busted Butte and the Calico Hills may indicate an intervening rock discontinuity and the presence of a buried northwest-trending shear zone along Yucca Wash. The eastern part of Yucca Mountain may be underlain by argillite of the Eleana Formation as suggested by the presence of siltstone lithic fragments in the Prow Pass and Bullfrog Members of the Crater Flat Tuff. Alternatively, if the Paleozoic rocks beneath Busted Butte correlate with the Cambriam through Devonian carbonate formations of the Striped Hills, this gravity saddle might also represent a structural contact between these rocks and argillite of the Eleana Formation in the Calico Hills. The contact could be a southeastward extension of a buried northwest-trending shear zone beneath Yucca Wash, or a buried fault in the general area of Jackass Flats (fig. 4) resulting in a structural contact between the carbonate rocks and argillite.

Whatever its lithology, the existence of a high on the Paleozoic surface in the Busted Butte area is fairly certain from the gravity modeling. We suggest that the somewhat anomalous near-surface structure here is the result of drag and shear of the tuff near the intersection of the north-south-trending fault system with the northwest edge of northeast-trending faults that lie to the southeast beneath Jackass Flats (fig. 4). The expression of this structure may be facilitated by the thinner tuff cover in this area. In addition, a buried northwest-trending shear zone similar to the one postulated in Yucca Wash may be present at depth beneath Busted Butte.

An important question is the possible existence of a large east-west-trending intrusive body beneath the northern part of Yucca Mountain and Crater Flat. The primary evidence for this intrusive body is a distinct east-west-trending lineament of several parallel contours on the 8,000-ft 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 (east of D, pl. 1). 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 G1, 25a-1, and J-13. The gravity modeling is somewhat ambiguous with regard to a deep intrusive body. All the gravity anomalies can be adequately accommodated by the anomalous masses at the Paleozoic-Tertiary unconformity, assuming that all the pre-Tertiary rocks are nonigneous. Large intrusive bodies however, generally act as structurally stabilizing masses for overlying units in parts of the Basin and Range province. This may also be the case beneath the northern part of Yucca Mountain.

The depth and extent of an intrusive body beneath the nearby Calico Hills remain unresolved. Extensive hydrothermal and contact-metamorphic alteration within the rocks drill-hole UE25a-3 (Maldonado and others, 1979), the high heat flow of 3.2 HFU (Sass and others, 1980), and topographic uplift (D. L. Hoover, oral commun., 1980) all suggest an intrusive body beneath at least the structural high of the Eleana Formation in the Calico Hills.

Estimates based on the aeromagnetic contours between the Calico Hills and Yucca Mountain (Boynton and Vargo, 1963) indicate that the source anomaly, probably a magnetite-replacement-halo, lies at depths of 2,200 m (7,200 ft) or deeper (G. D. Bath, written commun., 1981). These depths which are near the bottom of the gravity models, 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 geometric and density control of the overlying rocks. Other geophysical techniques or drill holes are required to resolve this problem.

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Open-File Report 82-701

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UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

PRELIMINARY RESULTS OF GRAVITY INVESTIGATIONS AT YUCCA MOUNTAIN AND VICINITY, SOUTHERN NYE COUNTY, NEVADA

Open-File Report 82-701
1982

Prepared by the U.S. Geological Survey
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UNITED STATES
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PRELIMINARY RESULTS OF GRAVITY INVESTIGATIONS AT YUCCA MOUNTAIN AND VICINITY, SOUTHERN NYE COUNTY, NEVADA

BY

D. B. SNYDER AND W. J. CARR

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ABSTRACT

Exploration for a high-level-nuclear-waste-repository site in the Yucca Mountain area, Nev., resulted in the addition of 423 new gravity stations during the past 2 years to the 934 existing stations to form the data base of this study. About 100 surface-rock samples, three borehole gamma-gamma logs, and one borehole gravity study provide excellent density control. A linear increase in density of 0.26 g/cm^3 per km is indicated in the thick tuff sequences. This steady increase of density within the tuff sequences makes the density contrast across the basal contact of the tuff the only strong source of gravity fluctuations. Isostatic and 2.0-g/cm^3 Bouguer corrections were applied to the observed gravity values to remove deep-crust-related regional gradients and topographic effects, respectively. The resulting residual-gravity plot shows significant gravity anomalies that correlate closely with the structures inferred from drill-hole and surface geologic studies.

Gravity highs over the three Paleozoic rock outcrops within the study area--Bare Mountain, the Calico Hills, and the Striped Hills--served as reference points for the gravity models. The Bare Mountain gravity high, which peaks at 48 mGal, connects with a larger gravity high over the Funeral Mountains to the south; together, these highs may result from a continuous block of mildly metamorphosed Precambrian and Paleozoic rocks stretching from the east edge of Death Valley to Bare Mountain. The Calico Hills gravity high appears more likely to originate from a northeast-trending remanent topographic high of buried Paleozoic rocks rather than from an isolated structural dome. This buried ridge may extend southwestward beneath Busted Butte, 5 km southeast of the proposed repository, where 2 1/2- and 3-dimensional modeling indicates that the pre-Cenozoic rocks may be less than 1,000 m deep.

At least 3,000 m of tuff fills a large steep-sided depression in the prevolcanic rocks beneath Yucca Mountain and Crater Flat. The gravity low and thick tuff section probably lie within a large collapse area comprising the Crater Flat-Timber Mountain-Silent Canyon caldera complexes. Gravity lows in Crater Flat itself are thought to coincide with the source areas of the Prow Pass Member, the Bullfrog Member, and the unnamed member of the Crater Flat Tuff. 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 Timber Mountain caldera and superimposed on the other structures within Crater Flat.

INTRODUCTION

Location

Yucca Mountain is in southern Nye County, Nevada, near the southwest corner of the Nevada Test Site (NTS) (fig. 1). The valleys of Crater Flat and Jackass Flats lie to the west and east, respectively. The study area, here called Yucca Mountain and vicinity, is roughly defined by and includes the edges of Jackass Flats on the east, Timber Mountain on the north, Bare Mountain on the west, and the Amargosa Valley on the south.

Lathrop Wells, 132 km (85 mi) northwest of Las Vegas on U.S. Highway 95, is in the southeast corner of the study area. The climate is arid, and the vegetation sparse. The land is nearly totally devoted to mining and projects of the Nevada Test Site. A well-maintained dirt road leads north from U.S. Highway 95 in the western part of the study area; the eastern portion is accessible from Mercury via Jackass Flats but only by authorized entry on the Nevada Test Site. U.S. 95 is the only paved public thoroughfare within the study area, and land travel is difficult after leaving these established routes. Gold, silver, and tungsten mines are found on Bare Mountain; a cinder quarry operates just west of Lathrop Wells.

Purpose of the gravity study

Gravity investigations play an important role in characterizing Yucca Mountain as a possible nuclear-waste repository. Obtaining subsurface information is critical because thick Cenozoic sedimentary rocks and tuff obscure the complex pre-Tertiary geology in most areas. The candidate site lies within the tuff composing the northern end of Yucca Mountain, a relatively coherent block of rock within a stratigraphically and structurally complex region. This study explores the 3-dimensional structure and geometry of the rocks surrounding the candidate site.

Several other geophysical methods have been employed to explore the Yucca Mountain area. Electrical soundings and magnetic traverses are best suited to characterize the upper few thousand feet of the mountain. The gravity method which commonly is best suited to characterize the relatively deep features of an area, at times surpasses other geophysical techniques in continuity and subsurface definition. Such is the case at Yucca Mountain, where the surface rocks appear to be seismically opaque and magnetically complex. The gravity method also serves as a pioneering exploration tool by proposing structures and geologic concepts to be better defined and established by later work.

Other geophysical investigations at Yucca Mountain

The characterization of Yucca Mountain as a radioactive-waste-disposal site involves a multidisciplinary Earth-science approach. This report is one of the first to integrate geologic and geophysical results but does not necessarily contain final interpretations of the area. The following paragraphs attempt to summarize work done to date; ongoing drilling, seismic, electrical, surface-mapping, and other studies continue to bring new data and facts to bear on the problems. Therefore, this report, though comprehensive as to the gravity studies, is preliminary in its interpretations; future reports will undoubtedly add much to the understanding of Yucca Mountain and vicinity.

Several drill-holes and a full suite of geophysical logs have recently been completed. All but two of these holes are located (fig. 1) in or near the candidate site area and include drill-holes UE25a-1 (Spengler and others, 1979), UE25a-4 through UE25a-b,, USW-G1 (Spengler and others, 1981), and USW-H1. Recently drilled holes outside the site area include drill-hole UE25a-3 in the Calico Hills (Maldonado and others, 1979) and drill-hole USW-VH-1 in Crater Flat. Many geologic, geophysical, and hydrologic data have been obtained from these and older holes (wells J-11 through J-13), and this information has been used both directly and indirectly in the preparation of this report. Only drill-hole 25a-3 reached pre-Tertiary rocks, even though two holes (G1 and H1) were drilled to a depth of 1,830 m (6,000 ft). In these deep holes, especially, alteration was notable in the lower part of the section penetrated, and metamorphic effects, including density change, increase downward nearly linearly.

Four aeromagnetic surveys are encompassed by the area of the gravity study. Constant-barometric-pressure surveys (Boynton and Vargo, 1963; U.S. Geological Survey, 1971), flown at 2,440 m (8,000 ft) and 2,740 m (9,000 ft), respectively, indicate a strong gradient across northern Yucca Mountain rising in total intensity to the north. The breadth of this feature suggests that it arises from deep sources, estimated to lie at a minimum depth of 2,200 m (7,200 ft) (G. D. Bath, written commun., 1980). Later, two 122-m (400 ft) draped surveys also covered the study area (U.S. Geological Survey, 1977, 1978). Zietz and others (1977) included the earlier surveys in a compilation of the aeromagnetic coverage for all of Nevada.

Seismic and electrical techniques thus far have been only partly successful; no clear characterization of the rocks below 500 m (1,640 ft) has been obtained as yet by these methods.

Acknowledgments

H. W. Oliver, U.S. Geological Survey, supervised all phases of the gravity study and provided advice and guidance throughout. P. P. Orkild, also of the U.S. Geological Survey, graciously permitted use of some unpublished geologic data. We are greatly indebted to the many other scientists investigating the suitability of Yucca Mountain as a waste-isolation site, for freely sharing their data and thoughts, particularly to: G. D. Bath, F. M. Byers, Jr., G. L. Dixon, D. L. Healey, D. B. Hoover, and R. W. Spengler, all of the U.S. Geological Survey. Many others assisted with the field operations at Yucca Mountain, including: I. Madin, D. A. Ponce, R. W. Saltus, and R. W. Tang of the U.S. Geological Survey and R. Lahoud, L. Parish, R. Orsak, and S. Waddell of Fenix & Sisson, Inc. W. McQuary drafted most of the illustrations; T. A. Sagara produced figure 13.

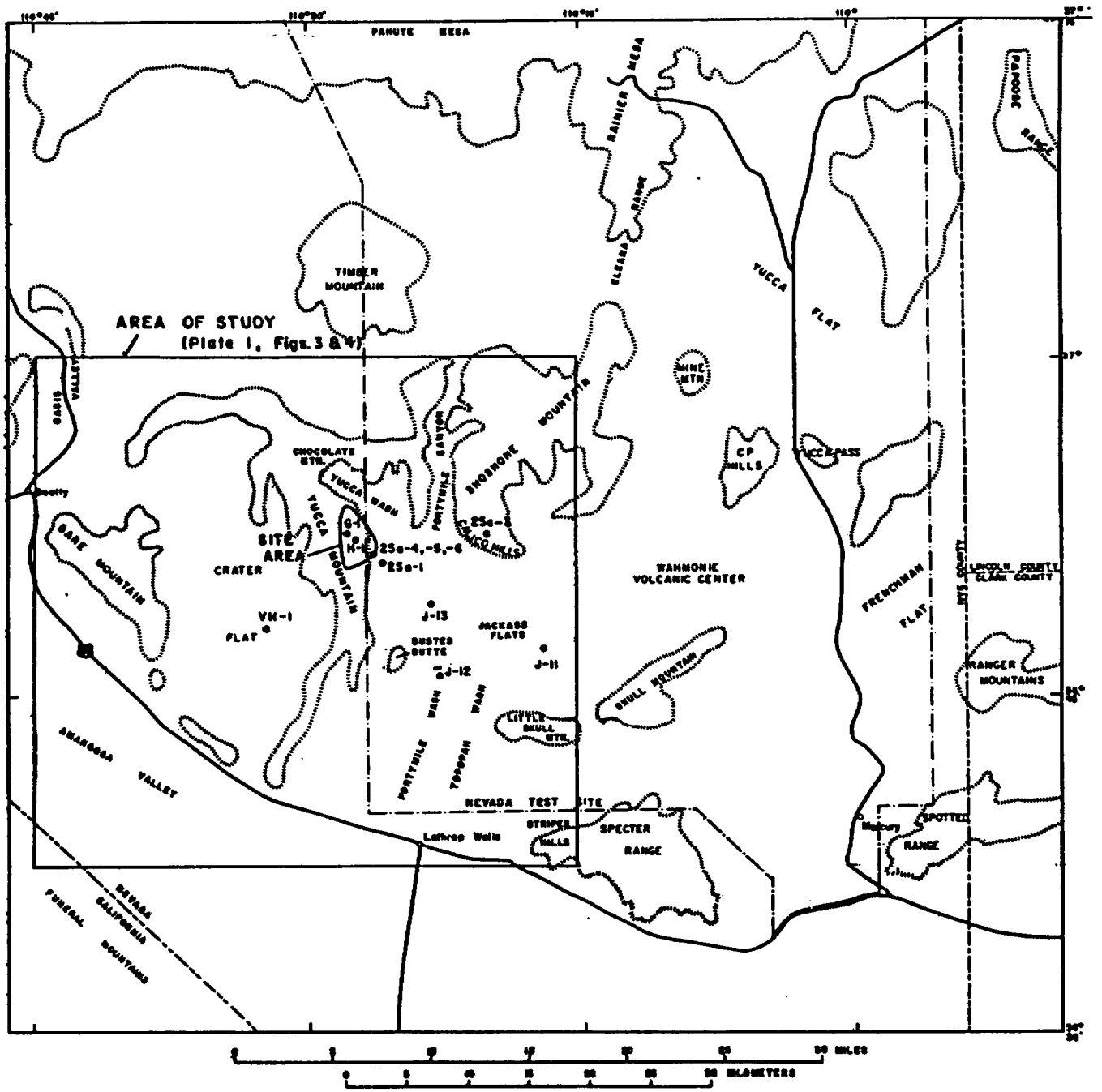


Figure 1. Index map of southern Nevada Test Site area.

GEOLOGY OF YUCCA MOUNTAIN AND VICINITY

Physiography

Yucca Mountain lies near the south edge of the Great Basin section of the Basin and Range physiographic province; further subdivision places the area within the Walker Lane belt (fig. 2) and the southern part of the Lahontan subsection of the Great Basin[1]. Much of the Great Basin is characterized by classic basin-and-range topography, with alternating ridges and valleys oriented nearly due north. The Walker Lane belt exhibits a more diverse topography of generally lower relief and, locally, chaotic or 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 Walker Lane belt; 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 to the north.

The lowest elevation in the study area, approximately 800 m (2600 ft), is along its south border, where the Amargosa Desert decreases in elevation to the south. Crater Flat and Jackass Flats lie between 850 m (2800 ft) and 1220 m (4000 ft), and Yucca Mountain ranges from 1770 m (5800 ft) in the north to 900 m (3000 ft) at its south end. The highest points within the study area are a 1925-m (6316 ft) peak on rugged Bare Mountain and 2043-m (6703 ft) Chocolate Mountain.

Stratigraphy

Table 1 is a simplified stratigraphic column of the geologic units in the Yucca Mountain area, pertinent to the gravity study. The distribution of pre-Tertiary rocks in the vicinity of Yucca Mountain is not well known at present, because in most areas, stratigraphy and structure combine in a very complex way deep beneath volcanic rocks and alluvium. These buried rocks consist of upper Precambrian and Cambrian clastic units, lower and middle Paleozoic carbonate rocks, and upper Paleozoic detrital rocks and local granitic intrusions. Several ancient structural features and depositional zones of Precambrian and Paleozoic age are thought to cross in this general area (Poole, 1974; Stewart, 1980, p. 40-52), but vast amounts of volcanic materials 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 unexposed, thermal-alteration zones, dikes and small plugs, and domical structures (Cornwall and Kleinhampl, 1961; Carr and Quinlivan, 1968; Maldonado and others, 1979) suggest the presence of buried intrusive rocks. Quartzite and other clastic rocks, which predominate within the upper Precambrian and lower Paleozoic assemblage, crop out mainly in the southwestern part of the study area, where they are mildly metamorphosed. A thick sequence of limestone and dolomite predominates in the middle part of the section, approximately Cambrian through Devonian in age; these rocks crop

[1]W. J. Carr (unpub. data, 1982) suggests that the Great Basin can be subdivided into two parts or subsections, the Lahontan on the west and the Bonneville on the east, based on physiography, Neogene tectonism and volcanism, and other characteristics.

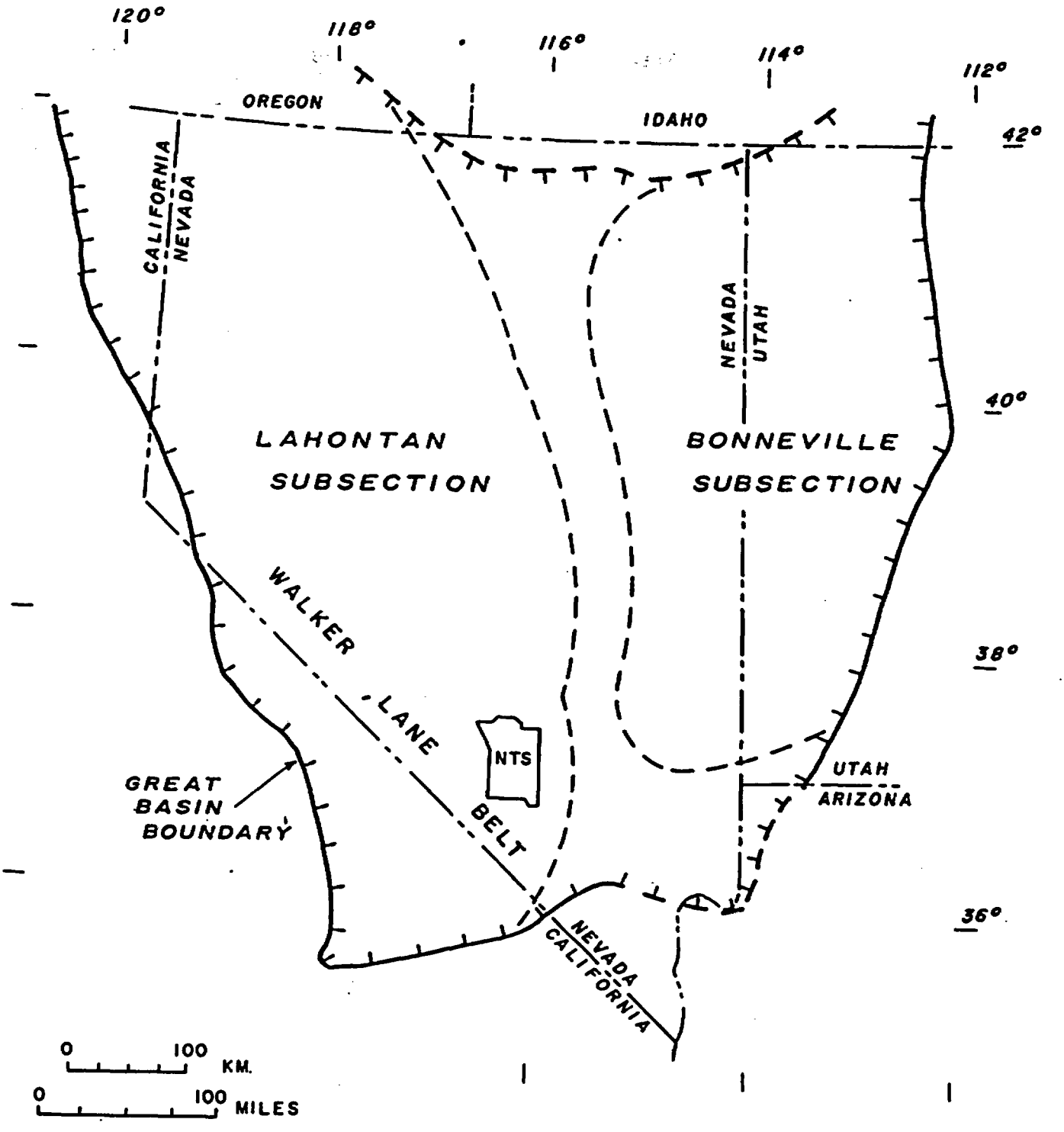


Figure 2. Great Basin, showing location of Nevada Test Site with respect to Walker Lane belt and Lahontan subsection.

Table 1.--Density and thickness of selected stratigraphic units in the Yucca Mountain area

Age	Stratigraphic unit	Approximate thickness (m)	Average density (g/cm^3)
Quaternary and Tertiary	Alluvium	0-300	1.6-2.0
	Basalt	0-50	2.9
Tertiary	Rhyolite lava flows of Shoshone Mountain	0-100	2.2
	Rhyolite lava flows of Fortymile Canyon	0-150	2.2
	Timber Mountain Tuff		
	Ammonia Tanks Member and Rainier Mesa Member	0-100	1.9
	Paintbrush Tuff		
	Tiva Canyon Member	120	2.1±0.4
	Yucca Mountain Member	0-60	1.9
	Pah Canyon Member	0-70	
	Topopah Spring Member	300	2.2±0.2
	Tuff and rhyolitic lavas of the Calico Hills	10-150	1.9±0.1
	Crater Flat Tuff		
	Prow Pass Member	100	2.1
	Bullfrog Member	120	2.1
	Unnamed Member	300	2.25
	Rhyodacitic lavas	0-60	2.35
	"tuff of Lithic Ridge"	300	2.35
	Ash-flow and bedded tuff	300+	2.45
Tertiary and Mesozoic	Granitic intrusive rocks	unknown	2.4?
Upper Paleozoic	Tippipah Limestone and Eleana Formation	1,000	2.6
Middle and Lower Paleozoic	Devils Gate Limestone, Ely Springs Dolomite, Eureka Quartzite, Pogonip Group, Nopah Formation, Bonanza King Formation	1,800	2.7
Lower Paleozoic and Precambrian	Carrara Formation, Zabriskie Quartzite, Wood Canyon Formation, Stirling Quartzite, Johnnie Formation	2,500+	2.65

out mostly on Bare Mountain and in the Striped Hills (figs. 1, 3). Thrust or slide masses of Devonian rocks are also present in the Calico Hills. Mississippian and Pennsylvanian rocks, principally argillite, quartzite, and limestone, form the lower plate of thrust faults from the Calico Hills northeastward through the Eleana Range (fig. 1).

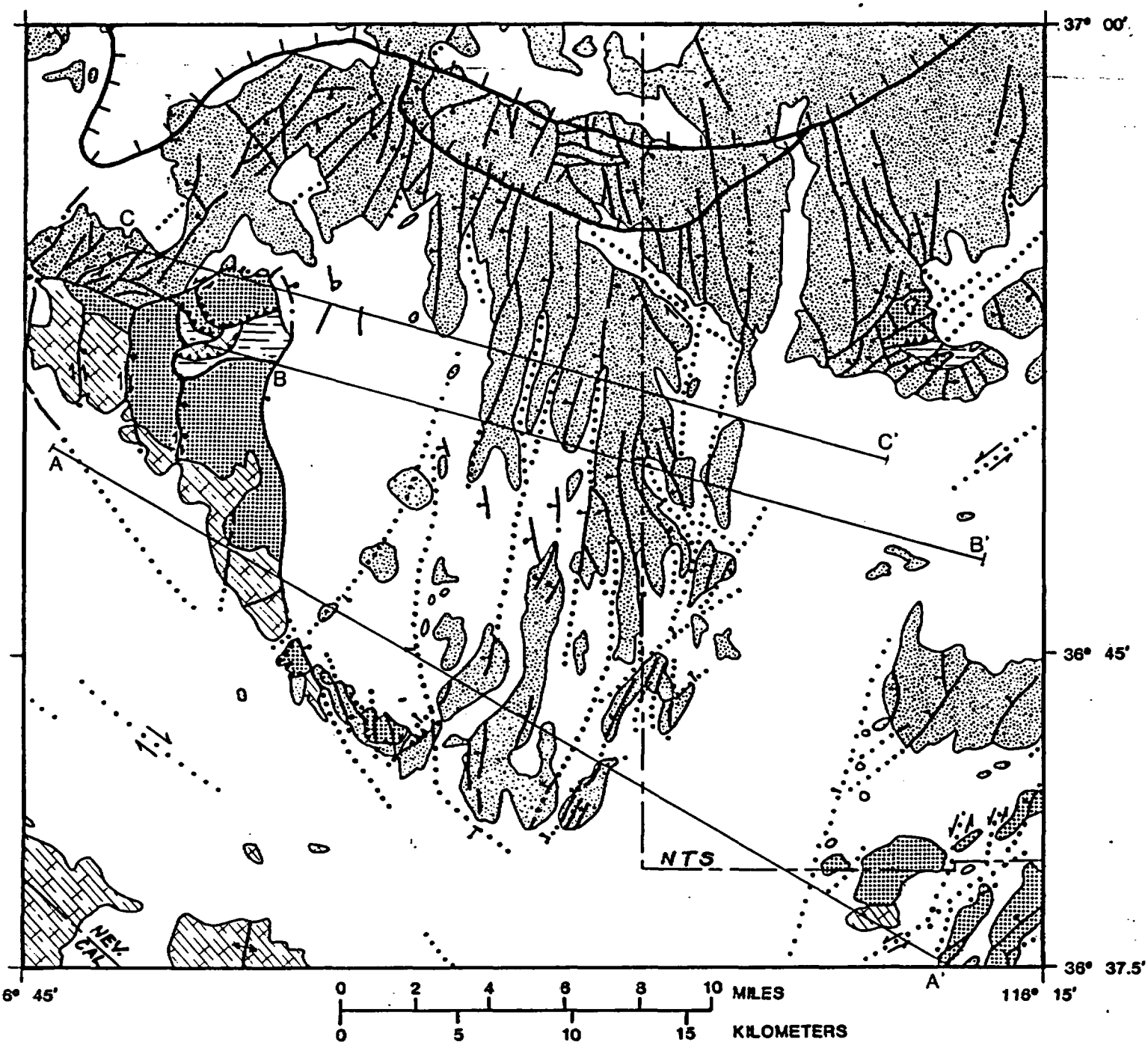
Granite crops out at only one locality within the study area. An altered east-west-trending granite dike occurs near Beatty at the northwest end of Bare Mountain (fig. 1); geologic relations suggest, but do not prove, that it is pre-Tertiary in age. Granite of Mesozoic age occurs at several localities in the northern part of the NTS, and granodiorite of Tertiary age crops out at the Wahmonie volcanic center, just east of the study area (Ponce, 1981).

The exposed Cenozoic stratigraphy of the area has been well studied. Several volcanic centers within and adjacent to the Timber Mountain-Oasis Valley caldera complex (Marvin and others, 1970; Byers and others, 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 m.y. ago, B.P., although the oldest units recently encountered in deep drill holes have not yet been dated. The great thickness of this buried tuff indicates the close proximity of its sources. The degree of welding and the density of the tuff vary greatly both laterally and vertically.

Quaternary alluvium is a significant unit 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 cementation is conspicuous in the alluvium. Basalt crops out and intertongues with the alluvium, principally in southern Crater Flat and around Jackass Flats. The basaltic activity spans most of the alluvial depositional history but has had pulses about 3.75, 1.1, and 0.3 m.y. ago (Vaniman and others, 1980), basalt forms several cinder cones in and near Crater Flat.

STRUCTURAL SETTING

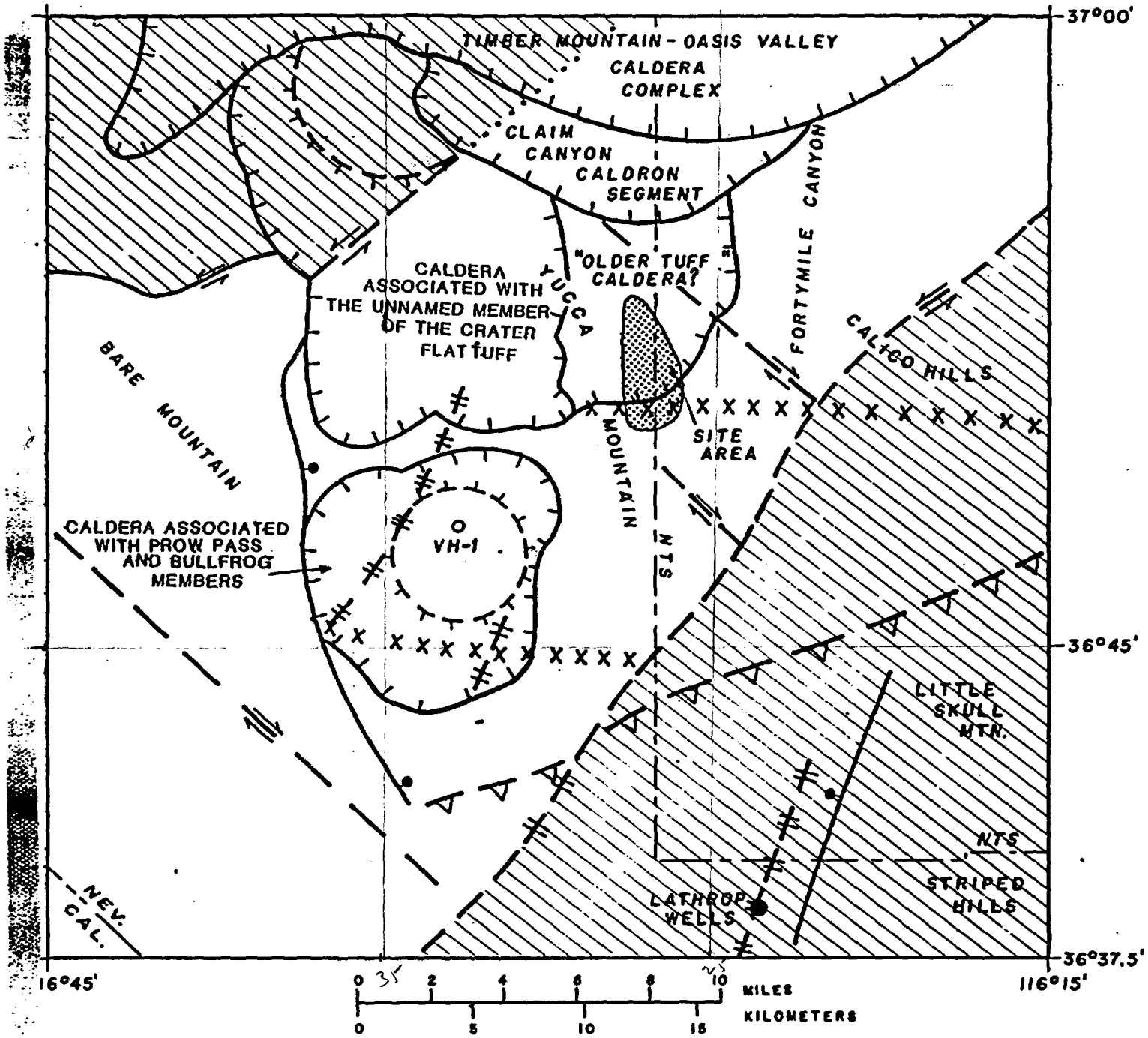
The Nevada Test Site and Yucca Mountain lie within the Walker Lane belt of the southern Great Basin (fig. 2). In most of the study area, however, the northwest-trending shear zones or arcuate mountain ranges commonly associated with this belt are not obvious. Nevertheless, three principal structural elements can be recognized in the area (figs. 3, 4): (1) northwest-trending valleys (Amargosa Valley, Yucca Wash, fig. 1) that probably represent the position of shear zones of that trend; (2) northeast-trending shear zones situated southeast of a line through Busted Butte, well J-13, and the western Calico Hills and northwest of a line from the northeast corner of Bare Mountain to the northwest end of Yucca Mountain; and (3) north-south- to north-northeast-trending basin-and-range faults and possible rifts in the Lathrop Wells area, on Yucca Mountain, and in Crater Flat (fig. 4). Superimposed on these elements and to some extent controlled by them are large volcanotectonic features, such as the Timber Mountain-Oasis Valley caldera complex, and postulated caldera or sector graben-type collapse segments in the Crater Flat area.



EXPLANATION

- Tertiary and Quaternary alluvium
- Tertiary and Quaternary volcanic rocks
- Upper Paleozoic clastic rocks
- Lower and middle Paleozoic carbonate rocks
- Precambrian and lower Paleozoic clastic rocks
- Contact
- Fault, dotted where concealed; bar and ball on downthrown side
- Caldera wall
- Low-angle fault or glide plane; teeth on upper plate

Figure 3 Simplified geologic map of Yucca Mountain and vicinity, showing location of gravity-model profiles (figs. 8-10).



Area dominated by northeast-trending faults

Major high-angle fault zone, bar and ball on downthrown side

Important strike-slip shear zone or boundary of zone, as shown by hatching; arrows indicate direction of lateral displacement in pre-Pliocene time

Possible "rift" zone with associated basaltic volcanism

Approximate buried trace of CP thrust system; teeth on upper plate of predominantly carbonate rocks; Eleana Formation (Devonian and Mississippian) predominant in lower plate to northwest

Caldera wall

Possible resurgent dome

XXXX Aeromagnetic lineament marking southern edge of possible east-west trending granitic bodies

Figure 4 Tectonic-structural map of study area. Caldera locations are based on gravity interpretaions as well as drill-hole and surface geologic evidence.

The tectonic history of the region, and structures mapped in the pre-Tertiary rocks, indicate that all the structural elements mentioned, except for the north-southerly trending faults and caldera structures, were at least partly present before the regional volcanism, and that the structures developed in the Tertiary rocks commonly either are reactivated old faults or are influenced by old fault trends. The north-south- to north-northeast-trending fault set occurs largely in the volcanic terrane of Yucca Mountain and Crater Flat, on the basis of aeromagnetic and gravity evidence, however, a relatively young structural trough of this set is thought to be buried in the valley near Lathrop Wells marked by Fortymile and Topopah Washes (fig. 1). The association of this north-southerly trend with thicker alluvium and Quaternary basaltic eruptive centers and faulting suggests that at times it has been the most active trend tectonically, although Yucca Mountain has persisted as a series of relatively high standing fault blocks between the volcanotectonic depression in Crater Flat and the trough north of Lathrop Wells. Scattered patches of the Rainier Mesa Member of the Timber Mountain Tuff on the flanks of Yucca Mountain indicate however, that most of the basin-and-range-fault displacement occurred there after the Paintbrush Tuff and before the Timber Mountain Tuff were deposited. At the candidate-site area at Yucca Mountain, most faults of the north-southerly trending set decrease markedly in displacement as they approach the site from both the north and south.

VOLCANOTECTONIC HISTORY

Because most of the study area contains thick sequences of tuff and lavas and the candidate-site area is underlain by more than 2,000 m (6,500 ft) of tuff, a summary of the volcanic history of the study area is warranted.

The stratigraphy and nomenclature of the lower part of the volcanic-rock sequence in this area is currently being studied in detail and revised. The oldest tuff units at Yucca Mountain, those statigraphically below the "tuff of Lithic Ridge" (table 1), are known only from drill hole USW G1 (Spengler and others, 1981). The general thickness (more than 600 m [2000 ft]), flat-lying attitudes, abundance of lava lithics, fragments, and absence of structural disturbance suggest accumulation of this older tuff in some sort of sag or collapse feature, possibly a caldera (fig. 4). If correlations are correct, tuffaceous sediment and thin layers of ash-flow tuff were deposited elsewhere in the area during this time. Scattered small exposures of the "tuff of Lithic Ridge" occur on the southeast side of Shoshone Mountain and across the southern NTS area. Local occurrences of rhyodacite lava flows above and below the "tuff of Lithic Ridge" further indicate the proximity of the source.

Next to be deposited in the site area were the three members of the Crater Flat Tuff: in ascending order, the unnamed member (= Tram unit), 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 all three members have a total thickness of more than 450 m (1,480 ft). The source areas or calderas, and greater thicknesses of the Crater Flat Tuff, are thought to lie to the southwest and northwest of Yucca Mountain, mostly beneath Crater Flat itself (fig. 4).

The tuff and lavas of the Calico Hills were emplaced atop the Crater Flat Tuff. The main source areas were in the western Calico Hills-Fortymile Canyon area, but a little lava reached as far southwest as the northeast edge of Yucca Mountain, where the section consists mostly of about 100 m (330 ft) of bedded air-fall and thin ash-flow tuff units. After deposition of the tuff and lavas of the Calico Hills, eruptions began from the Timber Mountain-Oasis Valley caldera complex and the Claim Canyon caldron segment just north of Yucca Mountain. These eruptions produced voluminous widespread ash-flow tuff sheets of the Paintbrush and Timber Mountain Tuffs. Regional tumescence or doming is thought to have immediately preceded formation of the complex (Christiansen and others, 1977), and the edge of that dome may have been near the north end of Yucca Mountain. Very thick layers of the Paintbrush and Timber Mountain Tuffs 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.

ROCK DENSITIES

The density of the rocks within the study area, together with their three-dimensional distribution, are the two characteristics most critical to a gravity study. Collection and laboratory measurement of surface-rock samples is the standard method of obtaining the density or specific gravity of the rocks. If this is the only source of density control available several assumptions become necessary; an excellent discussion addressing these assumptions was given by Mabey (1960). In the Yucca Mountain area, the surface-density data from samples is 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 specific gravities of six core samples from drill holes USW-G1 and USW-VH-1, and of 95 surface samples, were measured, using tapwater at standard temperature and pressure as the reference fluid and an electronic balance accurate to four significant figures. Table 2 summarizes these results.

Gamma-gamma density logs have been completed in drill holes USW-G1, H1, and VH-1. These logs have been borehole compensated; that is, any change in hole diameter caused by wall collapse or the drilling process has been accounted for in the density determinations. The compensated logs provided by the Birdwell logging team were then averaged by dividing the area measured under the density curve by the depth interval considered. This analysis further smoothed irregularities caused by fractures and localized effects in the drill-hole walls. Figure 5 plots these average densities; least-squares-fit line represents the density gradient as a function of depth for the entire length of drill hole USW-H1, extrapolated to about 500 m (1,650 ft) beneath the bottom of the drill hole. The downward increase in density appears to be related to the closing of pore space due to alteration and compaction rather than to primary density variations in the tuff. Four core samples are also shown for comparison, although they represent nonsaturated measurements on tuff obtained from within the saturated zone. Table 3 lists the average density values derived from the gamma-gamma log in drill-holes USW-H1, VH-1, and G1.

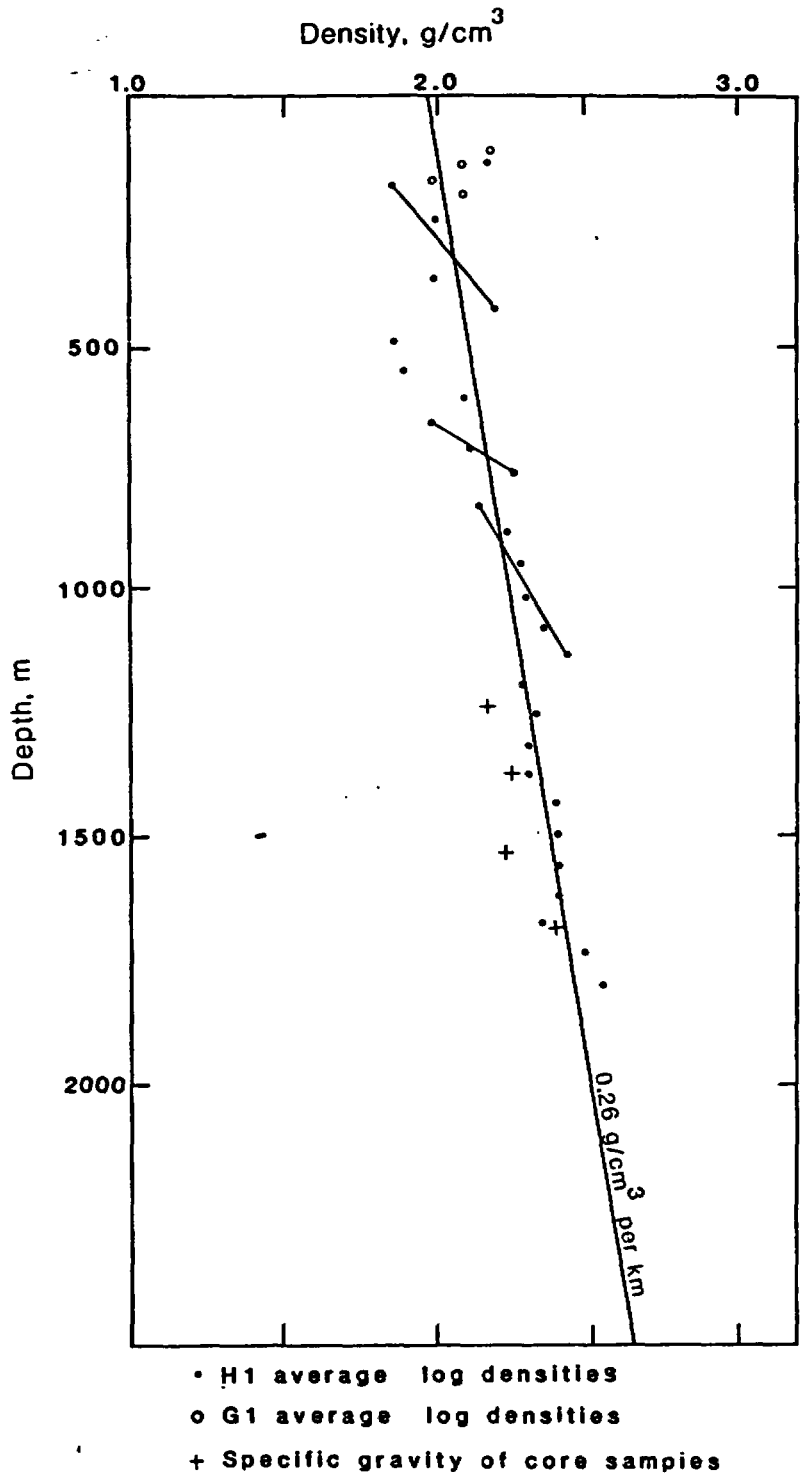


Figure 5 Drill-hole G1 specific-gravity measurements and gamma-gamma log density averages with respect to depth. Line is least-squares-fit of data points. Short segments indicate linear density increases within tuff members. Four core samples represent nonsaturated measurements of tuff obtained from saturated zone in Yucca Mountain.

A downhole gravity study was made at drill-hole USW-H1 (S. L. Robbins, written commun., 1981). Values agree with the gamma-gamma measurements in almost all cases. This agreement is significant, because borehole gravity samples a much greater lateral volume than do the density logs and includes fractures, cavities, and other large irregularities in the rock. The gamma-gamma method surveys the true atomic density of the rocks in the immediate vicinity of the drill hole and is much more sensitive to fractures and irregularities immediately next to the instrument.

The locations of 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 in figure 5, if it is, indeed, due to alteration, compaction, and lithostatic loading, is probably applicable to all the thick tuff sequences within the study area.

Surface samples provide the only real density control on the lower Paleozoic rocks modeled in this study. Other pre-Tertiary rocks beneath Crater Flat, Yucca Mountain, and Jackass Flats have never been sampled, and their composition and density remain unknown. The specific gravity for the pre-Tertiary rocks exposed at the surface ranges from 2.58 to 2.70 g/cm^3, with a mean of 2.64 ± 0.06 g/cm^3, on the basis of samples taken from Bare Mountain and the Striped Hills during this study.

Table 2. Specific gravity measurements of surface and drill-hole samples

Sample	Rock unit	Specific gravity	
		Unsaturated	Saturated
G1 5500	Older tuff	2.37	--
G1 5005	Older tuff	2.22	--
G1 4531	Older tuff	2.25	--
G1 4021	"Tuff of Lithic Ridge"	2.16	--
VH-1 762	Tiva Canyon Member[1]	2.40	--
VH-1 151	Basalt	2.88	--
CF 09	Rainier Mesa Member[2]	2.00	2.08
CF 11	Rainier Mesa Member[2]	1.86	2.26
CF 11	Basalt	2.76	--
CF 39	Basalt cinder	1.39	1.55
CF 39A	Basalt cinder	1.90	2.04
CF 46	Basalt	2.77	2.78
CF 48	Basalt	2.88	2.89
CF 49	Tiva Canyon Member[1]	2.27	2.30
CF 50	Tiva Canyon Member[1]	2.34	2.35
CF 52	Tuff, undifferentiated	2.84	2.85
CF 59	Tiva Canyon Member[1]	2.14	2.36
70 samples of rhyolite of Calico Hills		2.12±0.26	2.26±0.17
C-28	Argillite, Eleana Formation	2.59	2.63
CF 85	Carboniferous argillite	2.59	2.61
CF 86	Carboniferous argillite	2.58	2.61
CF 90	Devonian limestone	2.81	2.82
CF 91	Devonian limestone	2.64	2.67
CF 81	Devonian dolomite	2.68	2.69
CF 82	Limestone	2.68	2.70
CF 62	Limestone, Bonanza King Formation	2.66	2.67
CF 72	Limestone, Bonanza King Formation	2.59	2.62
CF 30	Zabriskie Quartzite	2.64	2.65
CF 31	Zabriskie Quartzite	2.59	2.60
CF 32	Zabriskie Quartzite	2.70	2.72
CF 33	Zabriskie Quartzite	2.61	2.63
CF 61	Zabriskie Quartzite	2.64	2.64

[1] member of the Paintbrush Tuff
[2] member of the Timber Mountain Tuff

Table 3. Average gamma-gamma well-log measurements

Depth interval (ft)[1]	Area under the curve / actual interval length (in.)	Average density (g/cm^3)	Geologic unit[2]
USW-H1			
350- 500	2.93	2.17	Topopah Spring Member[3]
500- 700	2.17	1.87	
700- 900	2.52	2.01	
900-1100	2.60	2.04	
1100-1300	2.50	2.00	
1300-1500	2.99	2.20	Tuff of Calico Hills
1500-1700	2.17	1.87	
1700-1900	2.26	1.90	
1900-2100	2.74	2.10	Prow Pass Member[4]
2100-2250	2.48	1.99	
2260-2400	2.70	2.08	Bullfrog Member[4]
2400-2600	3.12	2.25	
2600-2800	2.82	2.13	Unnamed member[4]
2800-3000	3.04	2.22	
3000-3200	3.19	2.28	
3200-3400	3.26	2.30	
3400-3600	3.39	2.36	
3600-3800	3.57	2.43	Flow breccia
3800-4000	3.92	2.28	
4000-4200	3.31	2.32	
4200-4400	3.29	2.32	"Tuff of Lithic Ridge"
4400-4600	3.25	2.30	
4600-4800	3.48	2.39	
4800-5000	3.46	2.38	
5000-5200	3.44	2.38	Older tuff
5200-5400	3.48	2.39	
5400-5600	3.39	2.36	
5600-5800	3.70	2.48	
5800-6000	3.84	2.54	
USW-VH-1			
50- 100	1.32	1.53	Alluvium
100- 200	3.01	2.20	Basalt and basalt cinders
200- 300	2.31	1.92	
300- 400	2.53	2.01	Alluvium
400- 500	3.07	2.23	Tiva Canyon Member[3]
500- 600	2.36	1.94	
USW-G1			
300- 400	2.98	2.19	Topopah Spring Member[3]
400- 500	2.76	2.10	
500- 600	2.50	2.00	
600- 700	2.76	2.10	

[1] To obtain approximate depth in meters, multiply by 0.305.
[2] Unit contacts are approximate only.
[3] member of the Paintbrush Tuff
[4] member of the Crater Flat Tuff

GRAVITY DATA COLLECTION AND REDUCTION

Field work

A substantial number of gravity measurements already existed in the area before this study as a result of many years of work, mostly by D. L. Healey of the U.S. Geological Survey (Healey and others, 1980). From his work, 934 stations have been incorporated into this study. Though not generally available for many of these stations, accuracy specifications are commensurable with those of later measurements.

Field work to supplement these existing data for the Yucca Mountain area began in autumn, 1979. A helicopter was used to occupy 55 gravity stations on many ridges and hilltops. A detailed profile along an access road in Jackass Flats, as well as a detailed grid in "drill-hole wash," also established at this time, added 28 and 64 stations, respectively. The complete data set of 1,357 stations was completed in autumn, 1980, with the surveying, both geodetic and gravity, of 70 stations along three profiles extending from Bare Mountain eastward to the center of Jackass Flats.

Accuracy of data

An observed gravity precision of ±0.1 mGal was the goal of the data collection in support of this study. LaCoste and Romberg gravity meters G17, G177, and G192 were used, commonly operated in tandem. In addition to the factory calibrations, each gravity meter was recalibrated on either the Mount Hamilton, Calif. (Barnes and others, 1969), or Charleston Peak, Nev. (Ponce and Oliver, 1981), gravity loops before and after each field session. Each day, work was closed on a reoccupied station to check the gravity meter drift during that day, and as many times during the day as was convenient.

Most stations were located on U.S. Geological Survey bench marks, spot elevations, and other previously established standard reference points. The remaining stations were surveyed in by the gravity field parties using Hewlett-Packard Total and Total Electric stations. Surveying precision was checked many times against standard reference marks; this surveying adds an additional uncertainty of ±0.5 m to the published uncertainty of the reference bench mark. Exhaustive accuracy information is available from the senior author upon request.

Standard reductions

All gravity stations have been reduced by a method used by the U.S. Geological Survey, Menlo Park, California utilizing the computer procedures of Plouff (1977) and D.F. Barnes (written commun., 1978), and the formulae of Oliver (1980, p. 50). The gravity datum is IGSN 71 (Morelli, 1974); free-air anomalies are referenced to the Geodetic Reference System of 1967 (International Association of Geodesy, 1971). Terrain corrections to a radial distance of 0.068 km from the station were made in the field; those from 0.068 km to 0.59 km were made by using cylindrical-ring templates (Swick, 1942). The remaining correction for terrain variations out to 167 km were computer generated with the U.S. Geological Survey modification of Defense Mapping Agency digital terrain data. The primary base station, Mercury, has an observed gravity value of 979,518.80 mGal (Ponce and Oliver, 1981, p. 13).

Additional reductions

The analysis of complete Bouguer gravity anomalies reduced at the average crustal density of 2.67 g/cm^3 was deemed inadequate for the Yucca Mountain area. Density measurements discussed previously indicate that rocks making up the topographic relief in 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 commun., 1980), at a density of 2.0 g/cm^3. Thus, gravity effects, difficult to quantify in an obvious way (fig. 6), attributable to the topographic distribution of the stations have been reduced or eliminated.

To remove large-scale effects arising from lateral density variations deeper than 5 km within the crust, an isostatic correction was also applied to the complete Bouguer anomalies (fig. 6). This correction assumes complete Airy-Heiskanen isostatic compensation at the Moho, primarily on the basis of the elevation of the land within a 166.7 km radius of the study area. The actual 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 (Roberts and others, 1981). The purpose of this final correction was not to estimate the deep crustal structure beneath Yucca Mountain but to filter out long-wavelength gravity effects related to the surface topography.

The final product of all these corrections and reductions is a model of 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 (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.

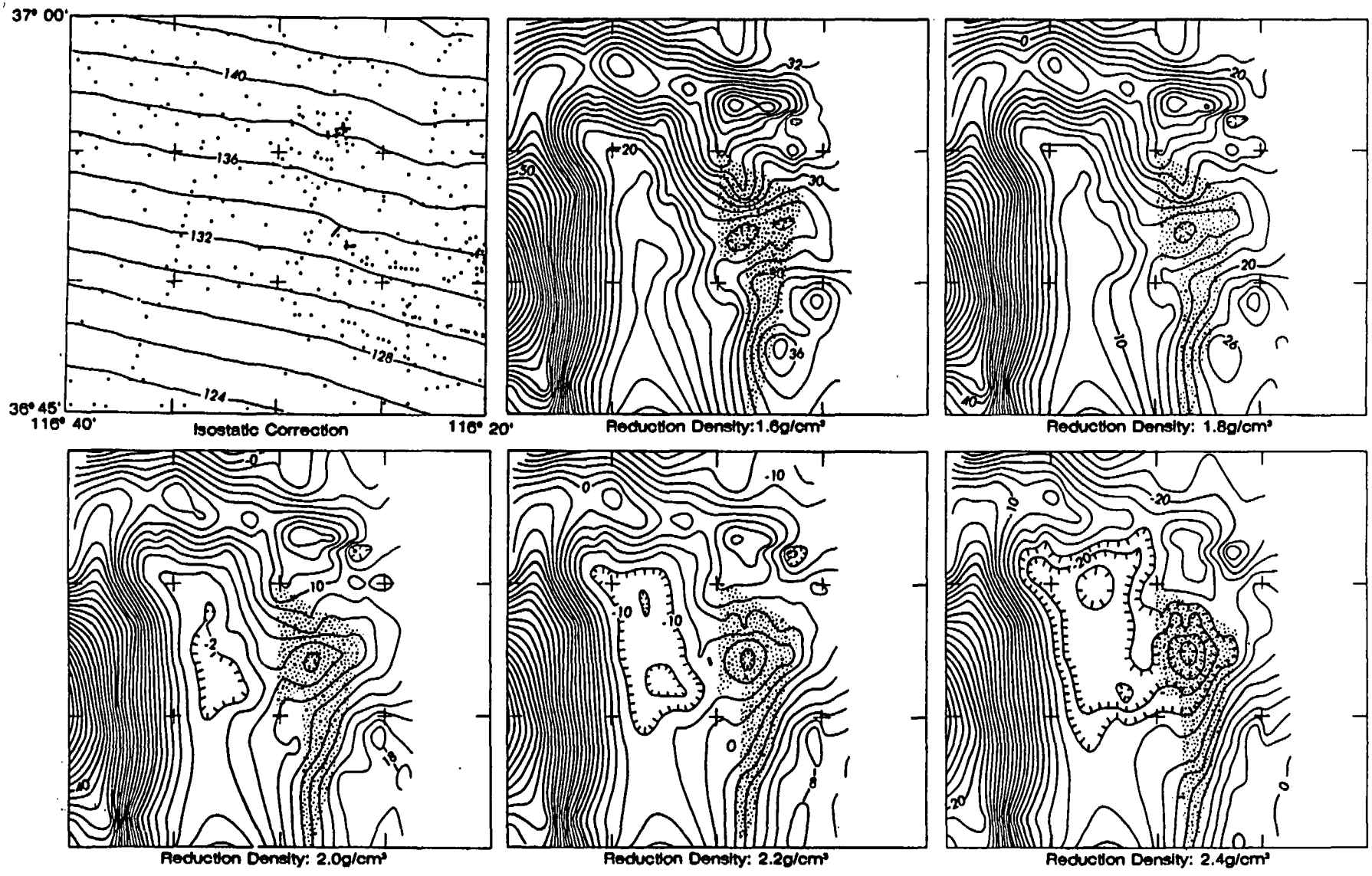


Figure 6 Gravity-contour maps of central part of study area, showing effects of choosing various Bouguer reduction densities. Stippling represents topographically highest part of Yucca Mountain. Upper left-hand map shows isostatic correction applied to data; the correction is nearly planar in character, tilted slightly to north-northeast.

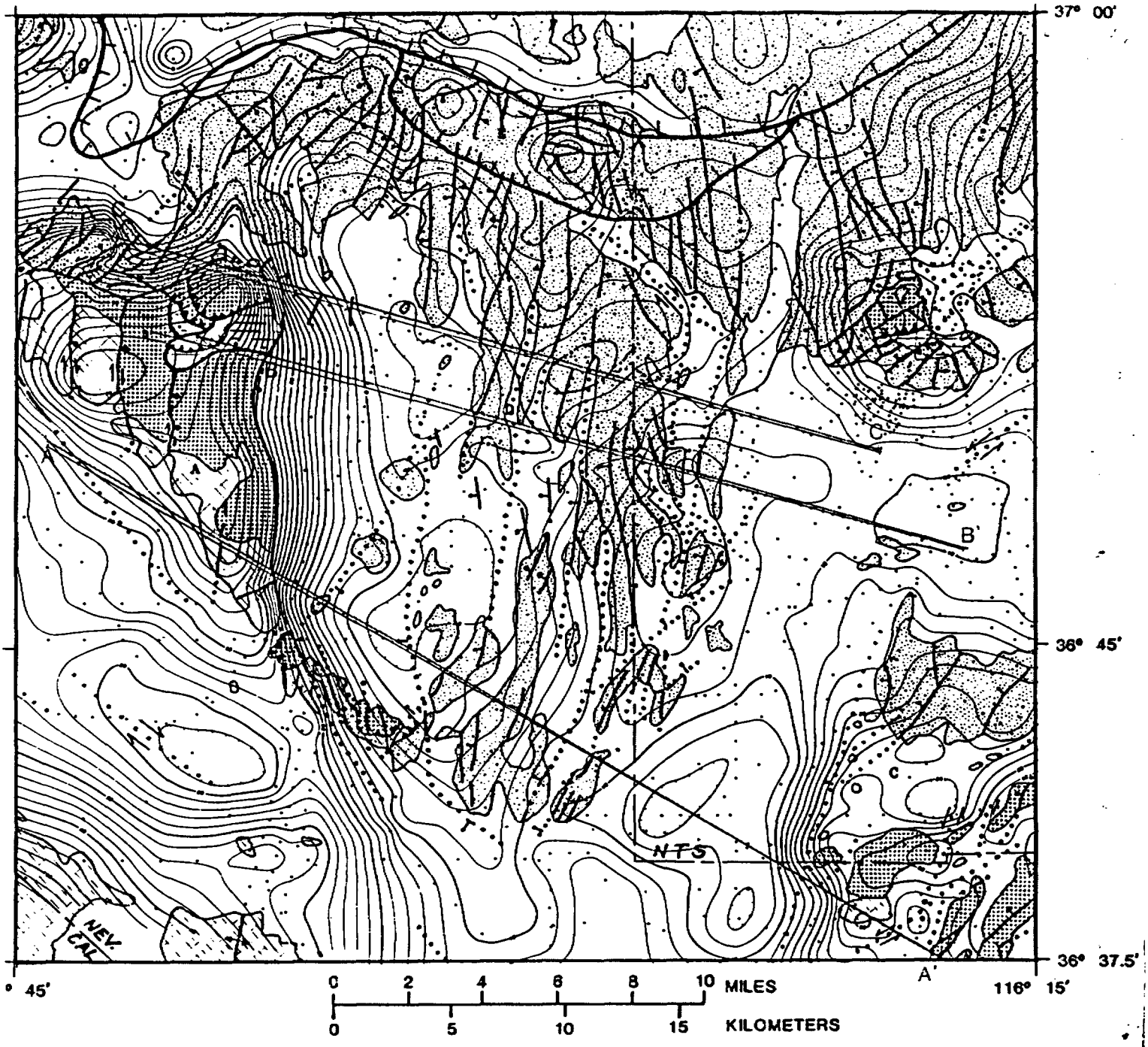
INTERPRETATION OF THE GRAVITY FIELD AT YUCCA MOUNTAIN AND VICINITY

The interpretation of the gravity field at Yucca Mountain uses three analytical tools: a 2-mGal contour map (pl. 1; fig. 7;) reduced at 2.00 g/cm^3 and corrected for perfect isostasy; three $2\frac{1}{2}$-dimensional modeled cross sections extending east-westward across the study area (figs. 8-10); and a 3-dimensional multiple-polygon gravity model (pl. 1). The contour map incorporates three significant refinements not included in previously published gravity maps of the area (for example, Healey and others, 1980). (1) reduction density of 2.00 g/cm^3 appropriate to most of the surface rocks in the area, which removes some gravity features resulting only from surface topography, (2) the 2-mGal-contour interval, which emphasizes many localized gravity features; and (3) the isostatic corrections, which remove broad gravity effects arising from masses near the base of the crust on the basis of their general correlation with broad surface elevation.

The $2\frac{1}{2}$-dimensional modeling utilizes the geophysical theory developed by Cady (1980), in which source bodies remain invariant within a given cross section but may terminate at a specifiable finite distance along strike in either direction. The use of varying extensions along strike and of nested bodies permits much of the generality of 3-dimensional modeling to be retained in this much simpler process. The three models of figures 8 through 10 all incorporate the third dimension by specification of varying extensions of the modeled bodies into the northern and southern half-spaces. The small 2.7-g/cm^3 body at 30 km in figure 8 and the near-surface 2.0-g/cm^3 body at the far left in figure 10 do not exist south of the respective profiles--a geometry critical to obtaining a satisfactory fit of the gravity curves. These models are useful in determining contact dips and small structures within the subsurface rocks. The more generalized three-dimensional model (Plouff, 1975), using flat polygonal source bodies, provides more accurate depth estimates, even though it is limited to eight prevolcanic bodies, three bodies of the dense tuff of Chocolate Mountain (see pl. 1), two bodies of the Crater Flat Tuff, and one alluvial body along Topopah Wash. Figure 11 shows that this simple model approximates the observed gravity field to within 3 mGal in all the central areas of primary interest. The average difference is 3.7 mGal, whereas the root-mean-square mismatches of the models in figures 8 through 10 were 2.8, 2.1, and 1.5 mGal, respectively. Given these modeling errors, the excellent correspondence of the $2\frac{1}{2}$- and 3-dimensional models, as suggested by figure 12, adds confidence to the subsurface geometries estimated by these models.

Bare Mountain-Funeral Mountains 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 (A, pl. 1) and the Funeral Mountains (fig. 1). Residual-gravity values of at least 14 mGal delimit the anomaly. The rocks of Bare Mountain and the Funeral Range--Precambrian and Paleozoic limestone, dolomite, argillite, and quartzite, some metamorphosed, especially in the Funeral Mountains--have some of the highest densities in the study area. As a result, the anomaly is accentuated 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.



EXPLANATION

- Tertiary and Quaternary alluvium
- Tertiary and Quaternary volcanic rocks
- Upper Paleozoic clastic rocks
- Lower and middle Paleozoic carbonate rocks
- Precambrian and lower Paleozoic clastic rocks
- Contact
- Fault, dotted where concealed; bar and ball on downthrown side
- Caldera wall
- Low-angle fault or glide plane; teeth on upper plate

Figure 7 Residual gravity map of Yucca Mountain and vicinity, superimposed on geologic map in figure 3. Contour interval, 2 mGal; reduction at 2.0 g/cm^3.

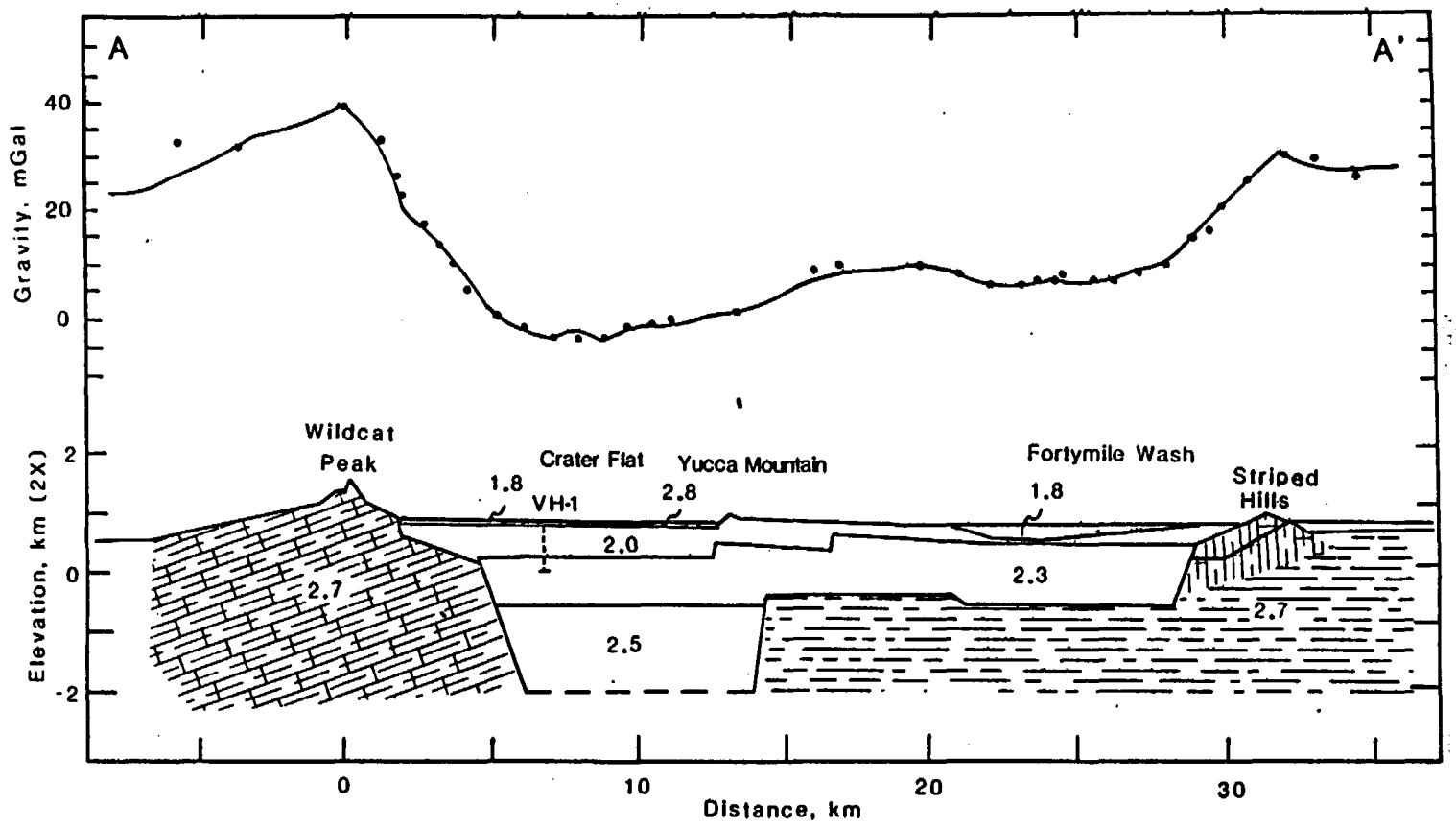


Figure 8 Gravity-modeling profile A-A'. Curve represents calculated gravity values; data points denote observed gravity values(fig. 7); numbers are bulk densities of modeled bodies(in g/cm^3). Drill-hole VH-1 is projected onto profile from 4.5 km. to north. Patterns represent Paleozoic rock at approximate observed attitude. Additional body in striped Hills is a 2.7-g/cm^3 body that exists only in northern half-space.

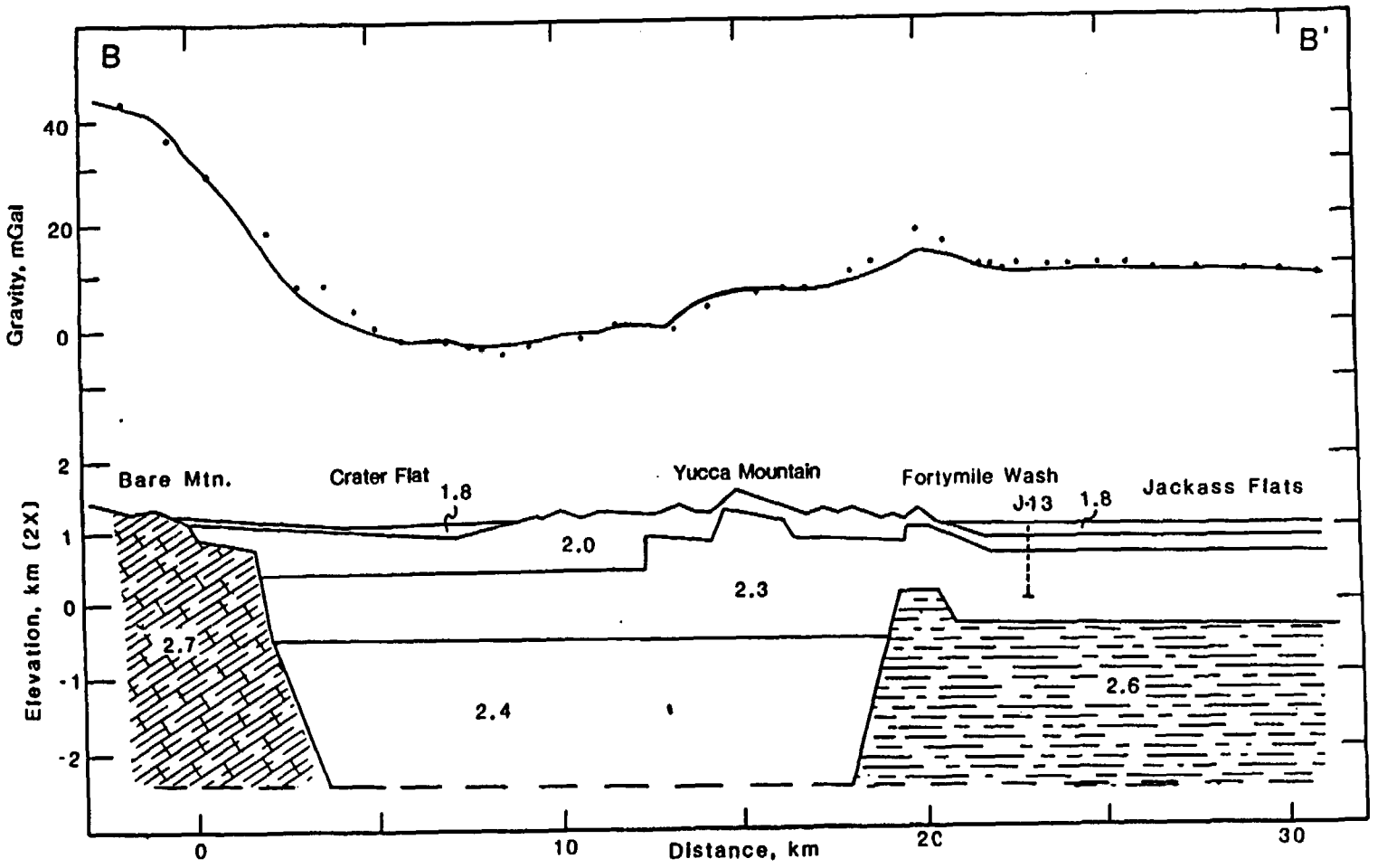


Figure 9 Gravity-modeling profile B-B'. Symbols same as in figure 8. Paleozoic rocks beneath Jackass Flats are assigned a density of 2.6 g/cm^3 because they are thought to be argillite of this density.

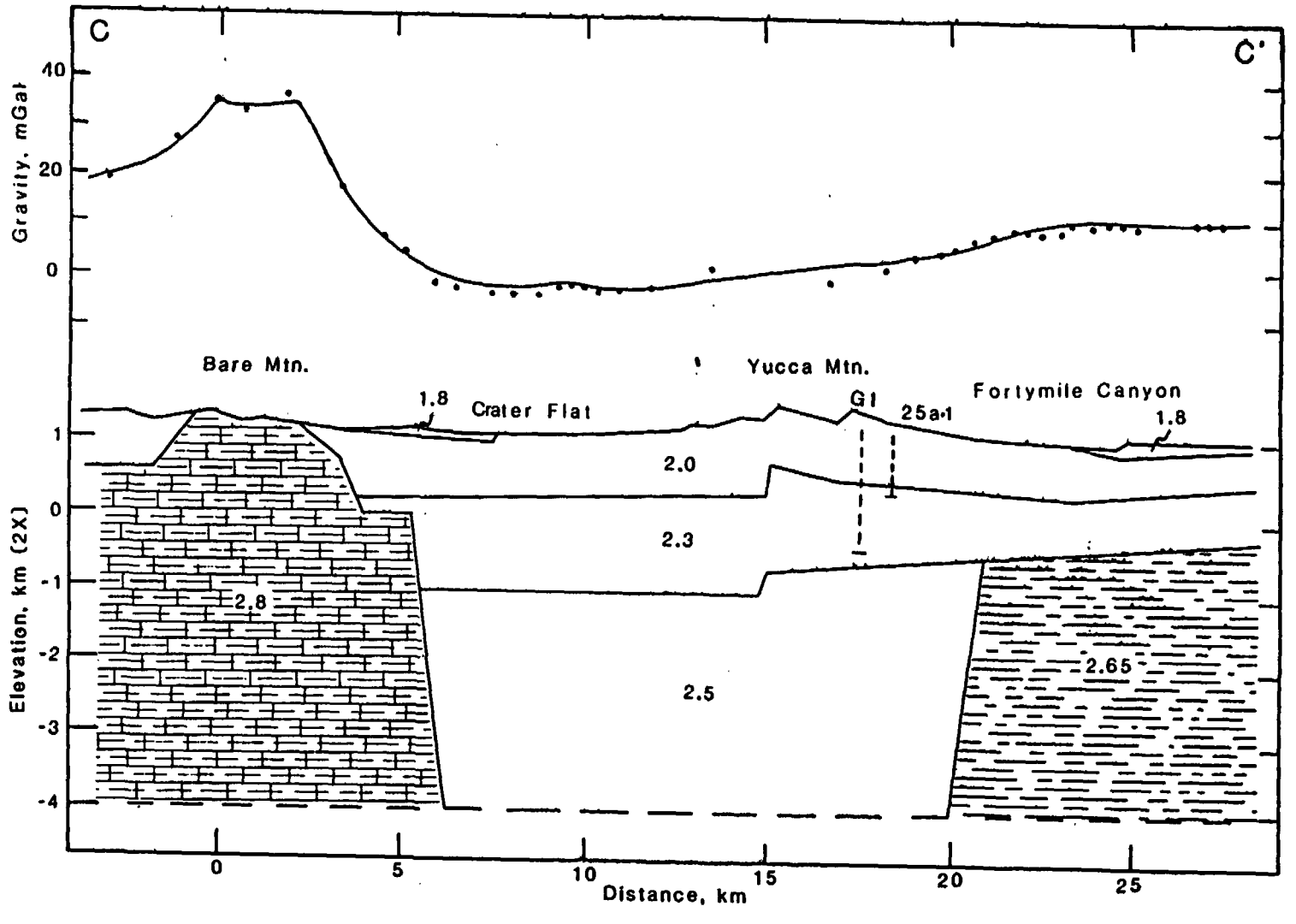


Figure 10 Gravity-modeling profile C-C'. Symbols same as in figure 8. Drill-hole G1 is projected onto the profile from 1 km to north. Paleozoic rock densities higher than those in profiles A-A' and B-B' and a deeper central depression were required for good gravity curve fit. Unlabeled body west of Bare Mountain is a 2.0-g/cm^3 body that exists only in northern half-space.

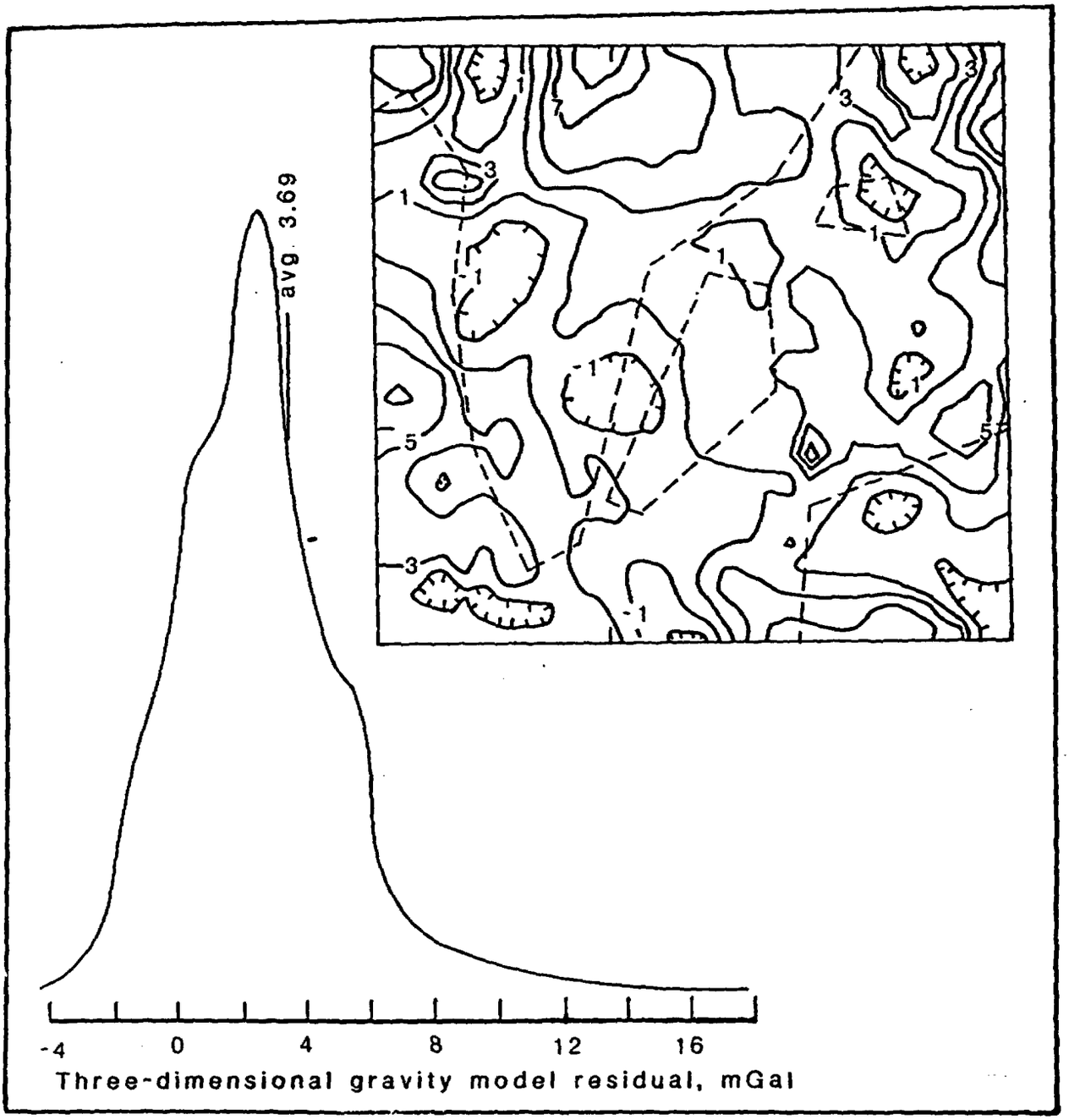


Figure 11 Countour plot of residual or mismatch of 3-dimensional gravity model. Contour interval, 2mGal: several 3-dimensional model bodies are outlined for reference. Graph shows relative distribution of residuals in contour plot.

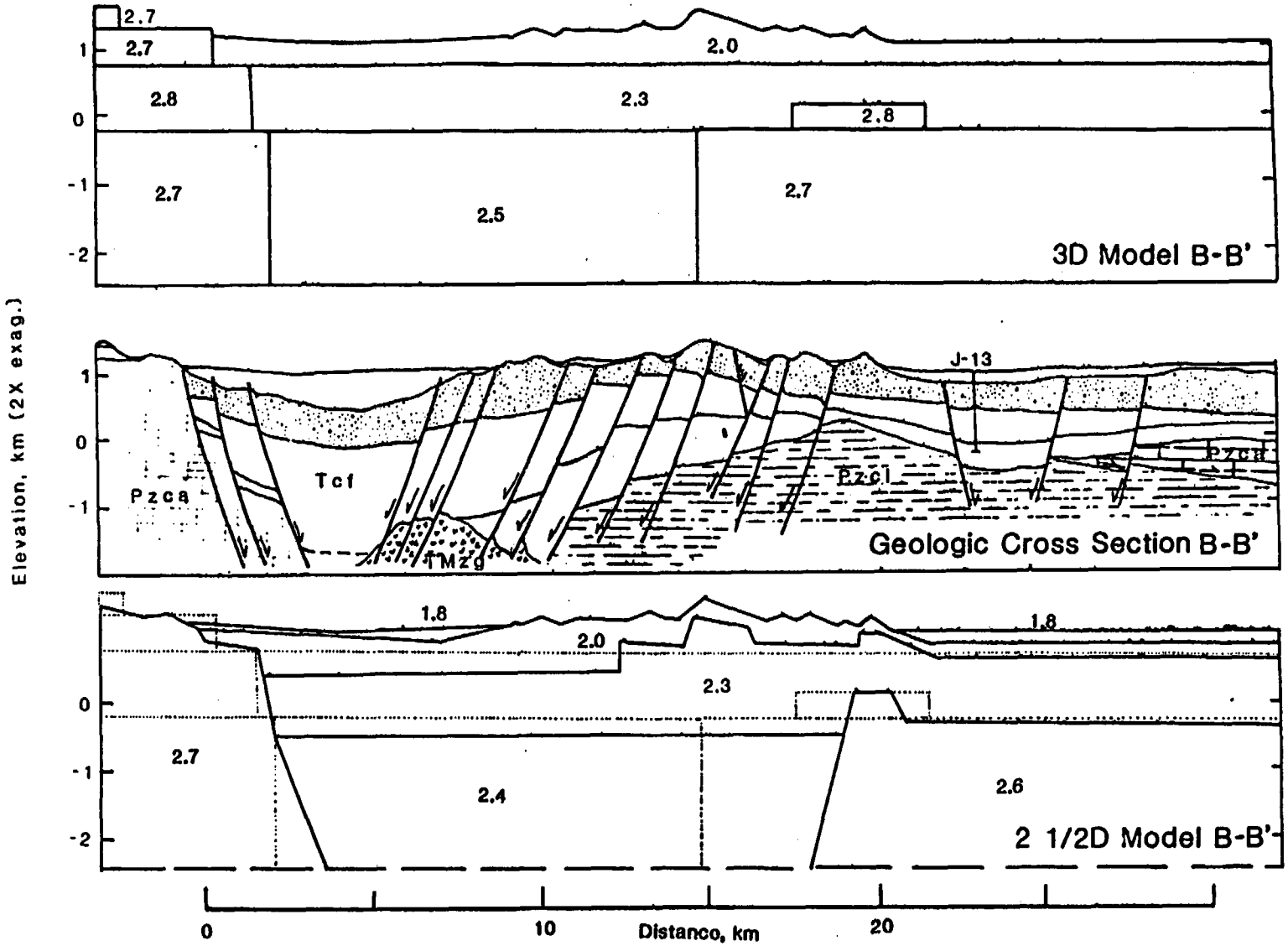


Figure 12 Gravity-modeling profile B-B', comparing 3-dimensional gravity model, 2 1/2-dimensional gravity model, and geologic cross section. Numbers are modeled bulk densities(in g/cm^3). Lower and middle Paleozoic carbonate rocks, Pzca; upper Paleozoic clastic rocks, Pzcl; Mesozoic or Tertiary granite, TMzg; and Crater Flat Tuff, Tcf.

The anomaly culminates in a maximum of about 48 mGal over Bare Mountain but has a southern part approaching 50 mGal at the edge of the map area (pl. 1). The two highs are separated by a gravity saddle of 18 mGal, that approximately coincides with that part of the Amargosa Valley occupied by the Amargosa River. The gradient to the southwest rises precipitously as it approaches the Funeral Mountains just across the Nevada-California border, where one of the highest isostatic gravity residuals in California occurs (Roberts and others, 1981). This gravity feature strongly suggests 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 an accumulation of Tertiary volcanic and sedimentary rocks underlying the alluvium of the Amargosa Valley and from faulting related to the Walker Lane in the Amargosa Valley west of Bare Mountain. Such faults may have created structural downwarps or basins that collected sufficient alluvium from Bare Mountain to account for the lower gravity values.

Study of the detailed shape of the gravity curve over the east flank of Bare Mountain in the 2 1/2-dimensional models (figs. 8-10) suggests that the Paleozoic rocks extend several kilometers farther eastward beneath Crater Flat than the surface contacts indicate. This shelf or downstepping of Paleozoic rocks is most evident in profile A-A' (fig. 8), where the step may occur 5 km into Crater Flat at a depth of less than 1 km.

The unusual isostatic character of the Funeral Mountains and Bare Mountain complicates the use of Bare Mountain as a reference point against which to compare the gravity over the rest of the map. After all surface geologic considerations are made in the 3-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 deficiency in the 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 mildly metamorphosed, and Bare Mountain may contain a low angle fault underlain by strongly metamorphosed rocks (M. D. Carr, oral commun., 1982).

Calico Hills-Busted Butte gravity high

The Calico Hills gravity high (B, pl. 1), which has been studied and modeled previously (Snyder and Oliver, 1981), is fairly well understood. The distribution of the Eleana Formation, which consists largely of fine-grained quartzite and argillite, becomes much more evident on the isostatic residual map reduced at 2.00 g/cm^3 than at the previous 2.67-g/cm^3 reduction. The relatively simple 3-dimensional approximation (pl. 1; fig. 13) gives excellent agreement between the calculated and observed values and provides a good reference between the contour map, the 3-dimensional model, and the known geologic structure. If defined locally by the 21-mGal contour (pl. 1; fig. 7), the anomaly interpretation supports the structural-dome hypothesis of the geologic studies (Maldonado and others, 1979). If extended to include the 14-mGal contour, the anomaly is no longer closed and extends much more to the northeast. The gravity high enclosed by the 14-mGal contour to the southwest of the Calico Hills near Busted Butte appears to extend this trend in that direction. Remanant topographic highs of the Paleozoic surface along the

eastern borders of the Timber Mountain and Crater Flat caldera complexes could explain the local gravity highs along this trend. A long narrow structural block of dense rock, upraised relative to its surroundings at depth by sills or diapirs, would also cause such a gravity anomaly.

The 10-mGal gravity saddle between the Calico Hills high and the Busted Butte high (pl. 1, fig. 7) is on the trend of Yucca Wash, a conspicuous northwest-trending valley bounding part of Yucca Mountain. A fault zone as old as Mesozoic is suspected along Yucca Wash on the basis of rock-unit distributions; this structure may interrupt or offset the buried pre-volcanic surface discussed above.

The 2 1/2- and 3-dimensional models estimate depths between 1,300 and 1,500 m (4,500 and 5,000 ft) to Paleozoic rocks at the gravity saddle between Calico Hills and Busted Butte, and between 1,000 and 1,200 m (3,000 and 4,000 ft) near the 14-mGal closure near Busted Butte. Geologic maps (Lipman and McKay, 1965) indicate a north-northeast-trending horst in the tuff at Busted Butte. If the mapped surface offsets continue at depth, the higher density tuff is slightly elevated below Busted Butte and contributes to the gravity high. Calculations from the 2 1/2-dimensional model of profile B-B' (fig. 9) indicate that the tuff horst and Paleozoic high contribute equally to the anomaly. This is an extreme case because no such major 0.3-g/cm^3-density-contrast contact exists within the tuff sequence; the model is a necessary simplification of a much more gradually varying density-depth relation. Thus, much of the gravity anomaly would be attributable to anomalously denser tuff masses deeper than indicated in the profile, where they would contribute somewhat less. The 3-dimensional model assumes no lateral variations in the tuff and requires a topographic high approximately twice as wide as in the 2 1/2-dimensional model (fig. 12). The alternative assumption of doubling the height would be geologically unlikely. Profile B-B' is probably nearly correct for 2 1/2-dimensional modeling, a reasonable variation of this model would widen rather than raise the pre-Tertiary topographic high.

The thinner tuff cover in the Busted Butte area suggested by this gravity interpretation may have resulted in propagation to the surface of faults of a different trend than common in the Yucca Mountain site area. These faults have an arcuate tendency and strike north-northwest; a few are downthrown on the northeast side, contrary to the general style in this part of Yucca Mountain. Also, slightly but consistently higher dips in the tuff in this same area than elsewhere on Yucca Mountain indicate more rotation and structural disturbance of the units.

Striped Hills-Little Skull Mountain gravity high

The gravity high in the southeast corner of the study area, delineated by the 14-mGal contour, encompasses both Little Skull Mountain and the Striped Hills (C, pl. 1; fig. 7); this gravity feature arises mainly from buried and exposed Paleozoic rocks. The 3-dimensional model approximates the Striped Hills rocks to within a few milligals and thus provides another reference point for comparing the gravity-contour map, the 3-dimensional model, and the geologic structure. Using the Striped Hills and Calico Hills areas as controls, we estimate the general elevation of the Paleozoic rocks beneath Jackass Flats with some confidence (fig. 12) to lie just a few hundred meters below sea level, or about 1,300 m (4,200 ft) below the ground surface.

Profile A-A' (fig. 8) indicates that west of the Striped Hills the Paleozoic rock surface slopes gently downward to the west, then steepens abruptly near Topopah Wash. The steepness and linearity of the gravity gradient at this point strongly suggest a north-northwest-trending buried fault, with rocks downthrown to the west. The 3-dimensional model (fig. 13) suggests as much as 1,000 m (3,600 ft) of western downdrop. The near-vertical and slightly overturned beds of the Striped Hills indicate additional geologic structures within the Paleozoic rocks, structures that may also influence the gravity signature within the Striped Hills-Little Skull Mountain high.

Crater Flat-Yucca Mountain gravity low

A large triangular gravity low, defined by the 8-mGal-residual-gravity contour, dominates the gravity field in the study area (D, pl. 1). 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. Reduction at the 2.00 g/cm^3 average density of the tuff at Yucca Mountain better defines this feature. The anomaly extends northeastward from Bare Mountain nearly to the Calico Hills and southeastward over a low saddle toward the Striped Hills, and encloses an area containing no outcrops of pre-Tertiary rock. Figure 6 shows that choices of reduction density as low as 1.8 g/cm^3 and as high as 2.4 g/cm^3 reveal the same general characteristics of this feature.

The 3-dimensional model indicates that the volcanic rocks extend at least to 2.5 km (8,200 ft) below sea level beneath Crater Flat. These relatively low density rocks, which lie south of the south wall of Timber Mountain caldera (Byers and others, 1976), and may derive from material filling a combination of sector grabens and old calderas, possibly the source areas for the Crater Flat Tuff. This gravity low extends to the south of the study area, into the Amargosa Desert. 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 minimums. Tuff density below 2,000 m (6,000 ft), 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 drillhole. 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, although 3 km of overburden may increase the density of these Paleozoic sedimentary rocks. 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 2.5 km below sea level, the estimated floor of the caldera fill. Floor-elevation uncertainties of $\pm$1.0 km or greater could be possible from this range of density contrast.

The 2 1/2-dimensional cross sections (figs. 8-10) indicate steep-sided walls on the Paleozoic rocks bordering the gravity low. A crude sense of downstepping along normal faults in the upper tuff units is also suggested by the models (beneath Yucca Mountain, figs. 8-10). This downstepping may have resulted from subsidence beneath Crater Flat along north-south-trending normal

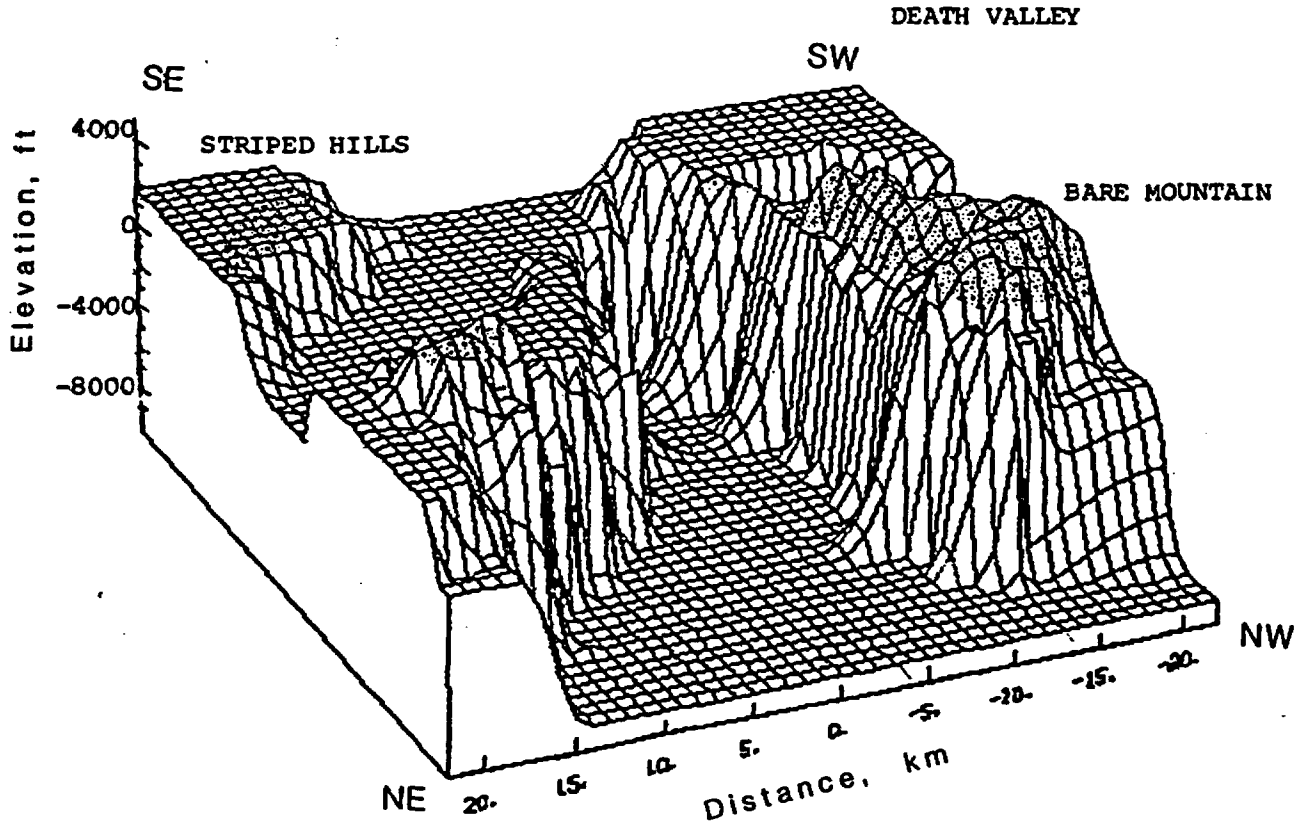


Figure 13 Mesh perspective of prevolcanic bodies in 3-dimensional gravity model of Yucca Mountain and vicinity, as viewed from northeast. Surface represents prevolcanic surface beneath topographic surface. Stippling indicates where these surfaces coincide at Bare Mountain, Striped Hills, and Calico Hills (in foreground).

faults at the west edge of Yucca Mountain. Most of this displacement took place before the Timber Mountain Tuff was deposited and after emplacement of the Paintbrush Tuff, although minor faulting of the same strike that cuts Quaternary alluvium indicates that small tectonic adjustments have continued.

The -2-mGal closures in the northern and southern parts of the Crater Flat anomaly are separated by a narrow band anchored by protruding positive anomalies. This configuration of the gravity field suggests a septum or ridge of higher density rock cutting across the depression at this point. Relations in the volcanic rocks coeval with the Crater Flat Tuff suggest that Crater Flat may contain the source areas for this tuff and lavas. 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 the "older tuff" caldera or sag feature shown on the tectonic-structural map (fig. 4).

Chocolate Mountain-Northern Yucca Mountain gravity high

A narrow band of gravity highs (E, pl. 1; fig. 7), peaking at 14-, 12-, and 16-mGal, separates the large negative anomalies associated with Crater Flat and Timber Mountain caldera to the north. The most prominent gravity high along this band coincides with Chocolate Mountain and the Claim Canyon caldron segment (Byers and others, 1976). The 3-dimensional model indicates that more than 4,000 m (14,000 ft) 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 caldron segment is an eccentric resurged block of the very thick densely welded intracaldera Tiva Canyon Member and other members of the Paintbrush Tuff. Field samples collected at Chocolate Mountain yielded specific gravities of 2.32 ± 0.12 g/cm^3. The absence of a commonly present depression or moat filled with relatively low density materials associated with the densely welded intracaldera tuff causes the 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 unnamed member of the Crater Flat Tuff exposed here and there outside the Timber Mountain-Oasis Valley caldera complex. The unnamed member exposed in this area may also be part of a fragmented resurgent dome (fig. 4).

Timber Mountain caldera gravity low

At the north edge of the study area, a large gravity low projects southward from the area of Timber Mountain (F, pl. 1, fig. 7). The part of the gravity low shown on the map (pl. 1) is associated with the southern moat area of Timber Mountain caldera. The gravity signatures of Timber Mountain and Silent Canyon calderas have been analyzed previously (Kane and Webring, 1981) and here we note only that together they form the most conspicuous gravity low in southern Nevada.

SUMMARY AND SIGNIFICANCE OF GRAVITY ANOMALIES

The 2.0-g/cm^3 reduction density used to generate the 2-mGal-contour map (pl. 1, fig. 7) provides a significant new perspective from which to understand the gravity field and subsurface geology of Yucca Mountain and vicinity. Previous maps reduced at 2.67 g/cm^3 showed an extended gravity low over all of Crater Flat and much of Yucca Mountain (Healey and others, 1980). Much greater resolution of small features is achieved in the new plot. Surface-terrain effects are removed in the area of primary interest, Yucca Mountain, although consequential terrain-related gravity anomalies over the denser rocks of Bare Mountain are exaggerated by the lower reduction density. More importantly, however, the gravity field can now be approximately correlated more directly with the pre-Tertiary surface, assuming relative lateral homogeneity of the overlying tuff. Although gravity maps should never be considered directly representative of topography, this study allows just such an approximate interpretation of the topography of the Paleozoic surface.

The dominating central gravity low on the residual-gravity map (fig. 7) represents a large tuff-filled hole or depression in the Paleozoic rocks beneath both Crater Flat and parts of Yucca Mountain (fig. 13). A minimum thickness of 1,830 m (6,000 ft) of tuff beneath Yucca Mountain is confirmed by the drill holes. The reference gravity values at the Paleozoic outcrops of the Calico and Striped Hills, give a modeling estimate of at least 3,000 m (10,000 ft) of tuffaceous fill in the Crater Flat-Yucca Mountain depression. The absences of data on density and lithology below -1-km elevation makes precise determination of the tuff thickness impossible. With the existing data, it is also impossible to determine whether the pretuff lithology in this area is Paleozoic sedimentary rocks or intrusive rocks. The 3-dimensional model, using a linear vertical density gradient at Yucca Mountain (fig. 5), suggests 3,400$\pm$400 m (11,150 $\pm$ 1,300 ft) of tuff beneath Crater Flat. Great variations in the density of the tuff either laterally or vertically would affect this estimate, as would a significant mass anomaly directly below the study area. The present uncertainty in density contrast between caldera-flooring material and neighboring precaldera rocks makes the depth estimates of the gravity interpretation uncertain by 30 percent or about $\pm$1,000 m (3,000 ft) for the deeper estimates.

In addition to the gravity evidence, surface geologic relation and information from drill holes VH-1 and G1 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 minimum closures in Crater Flat may indicate two gravity structures--the caldera associaated with the unnamed member (= Tram unit) in generally the northern part of Crater Flat, and the caldera assoicated with the Bullfrog and Prow Pass Members in the southern part of Crater Flat. These two collapse areas may be separated by a narrow septum of Paleozoic rocks or lava flows beneath central Crater Flat. It is unlikely, however, that the northeastern lobe of the gravity low extending beneath Yucca Mountain is part of the collapse area related to the Crater Flat Tuff. The three members of the Crater Flat Tuff are nearly as thick in well J-13 as in drill-hole G1 within the gravity-low lobe. Therefore, the northeastern lobe of the gravity low at Yucca Mountain is presumably unrelated to the Crater Flat Tuff but is probably a sag or older caldera within which thick units predating the Crater Flat Tuff accumulated.

The regional gravity high that extends southwestward from the northeast corner of the map area (pl. 1) is interpreted to arise from a structural high on the buried Paleozoic rock surface. Paleozoic rocks crop out at several places along this high, for example, in the Calico Hills and the Eleana Range (fig. 1). The Eleana Range, the Calico Hills, and the dense rocks beneath Busted Butte may all be related as a pre-Miocene mountain range, predominantly composed of 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.

The saddle in the gravity field between Busted Butte and the Calico Hills may indicate an intervening rock discontinuity and the presence of a buried northwest-trending shear zone along Yucca Wash. The eastern part of Yucca Mountain may be underlain by argillite of the Eleana Formation as suggested by the presence of siltstone lithic fragments in the Prow Pass and Bullfrog Members of the Crater Flat Tuff. Alternatively, if the Paleozoic rocks beneath Busted Butte correlate with the Cambriam through Devonian carbonate formations of the Striped Hills, this gravity saddle might also represent a structural contact between these rocks and argillite of the Eleana Formation in the Calico Hills. The contact could be a southeastward extension of a buried northwest-trending shear zone beneath Yucca Wash, or a buried fault in the general area of Jackass Flats (fig. 4) resulting in a structural contact between the carbonate rocks and argillite.

Whatever its lithology, the existence of a high on the Paleozoic surface in the Busted Butte area is fairly certain from the gravity modeling. We suggest that the somewhat anomalous near-surface structure here is the result of drag and shear of the tuff near the intersection of the north-south-trending fault system with the northwest edge of northeast-trending faults that lie to the southeast beneath Jackass Flats (fig. 4). The expression of this structure may be facilitated by the thinner tuff cover in this area. In addition, a buried northwest-trending shear zone similar to the one postulated in Yucca Wash may be present at depth beneath Busted Butte.

An important question is the possible existence of a large east-west-trending intrusive body beneath the northern part of Yucca Mountain and Crater Flat. The primary evidence for this intrusive body is a distinct east-west-trending lineament of several parallel contours on the 8,000-ft 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 (east of D, pl. 1). 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 G1, 25a-1, and J-13. The gravity modeling is somewhat ambiguous with regard to a deep intrusive body. All the gravity anomalies can be adequately accommodated by the anomalous masses at the Paleozoic-Tertiary unconformity, assuming that all the pre-Tertiary rocks are nonigneous. Large intrusive bodies however, generally act as structurally stabilizing masses for overlying units in parts of the Basin and Range province. This may also be the case beneath the northern part of Yucca Mountain.

The depth and extent of an intrusive body beneath the nearby Calico Hills remain unresolved. Extensive hydrothermal and contact-metamorphic alteration within the rocks drill-hole UE25a-3 (Maldonado and others, 1979), the high heat flow of 3.2 HFU (Sass and others, 1980), and topographic uplift (D. L. Hoover, oral commun., 1980) all suggest an intrusive body beneath at least the structural high of the Eleana Formation in the Calico Hills.

Estimates based on the aeromagnetic contours between the Calico Hills and Yucca Mountain (Boynton and Vargo, 1963) indicate that the source anomaly, probably a magnetite-replacement-halo, lies at depths of 2,200 m (7,200 ft) or deeper (G. D. Bath, written commun., 1981). These depths which are near the bottom of the gravity models, 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 geometric and density control of the overlying rocks. Other geophysical techniques or drill holes are required to resolve this problem.

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