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U.S. DEPARTMENT OF THE INTERIOR

U.S. GEOLOGICAL SURVEY

GRAVITY AND MAGNETIC ANOMALIES IN THE VICINITY OF YUCCA MOUNTAIN AND THEIR GEOLOGIC IMPLICATIONS

By

D.A. Ponce and H.W. Oliver

Open-File Report 96-662

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D.A. Ponce and H.W. Oliver[1]

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[1] U.S. Geological Survey, Menlo Park, CA

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ILLUSTRATIONS

ABSTRACT

Gravity and magnetic maps compiled for southwest Nevada reveal important geologic features of an area that includes a potential nuclear waste disposal site at Yucca Mountain. High-amplitude gravity lows characterize major valleys and nonresurgent calderas in the study area, whereas gravity highs reflect Paleozoic rocks at or near the surface. Short-wavelength magnetic anomalies reflect volcanic rocks in the study area, and high-amplitude magnetic highs are associated with known or inferred plutonic rocks. Magnetic anomalies also correlate with cinder cones in Crater Flat and northwest of the town of Amargosa Valley. Isolated magnetic anomalies south of the town of Amargosa Valley may reveal the presence of buried volcanic centers.

INTRODUCTION

The study area, about 110 km northwest of Las Vegas, includes a potential nuclear waste disposal site at Yucca Mountain (fig. 1). Surface outcrops consist predominantly of Tertiary silicic volcanic and intrusive rocks (fig. 2). Precambrian rocks, consisting of the Johnnie Formation and Stirling Quartzite primarily crop out in the easternmost part of the study area in the Halfpint Range. Paleozoic rocks crop out near the central part of the study area in an arcuate band in the Eleana Range, at Syncline Ridge, and at Mine Mountain. Paleozoic rocks also occur in the Striped Hills, Specter Range, and northeast of Mercury. At the southwest edge of the map, Paleozoic rocks crop out at Bare Mountain. Rocks of Mesozoic age are represented by scattered granitic plutons that include quartz monzonite stocks in the northern end of Yucca Flat. Rocks of Tertiary age mostly consist of voluminous ash-flow tuffs that range in age from about 26 to 7 Ma (Ekren, 1968). Two small exposures of Tertiary granitic rocks occur northwest of Wahmonie.

GRAVITY AND MAGNETIC MAPS

Isostatic gravity (Ponce and others, 1988) and aeromagnetic maps (Kirchoff-Stein and others, 1989) of the study area (fig. 1) have been compiled at a scale of 1:100,000. The isostatic gravity map (fig 3) is controlled by about 16,000 gravity stations reduced using a Bouguer reduction density of 2.67 g/cm^3. A regional isostatic gravity field was removed from the gravity anomalies by assuming an Airy-Heiskanen model for isostatic compensation of topographic loads (Simpson and others, 1983). On the basis of seismic refraction data, this model assumed a crustal density of 2.67 g/cm^3, a normal crustal thickness at sea-level of 25 km, and a density contrast across the base of the model crust of 0.4 g/cm^3. In addition, an isostatic gravity map reduced using a Bouguer reduction density of 2.20 g/cm^3 (fig 4) was compiled to aid in the interpretation of areas covered by relatively lower-density volcanic rocks. An aeromagnetic map of the study area was compiled by merging eight separate aeromagnetic surveys (fig 5). Each survey was compiled and merged by Kucks and Hildenbrand (1987), as part of a statewide aeromagnetic data compilation of Nevada (Hildenbrand and Kucks, 1988). Each data set was gridded at a 1-km interval, and either upward or downward continued to 305 m above the ground. Because of the large grid interval and the merging and continuation processes, caution was exercised in interpreting local anomalies and anomalies that cross survey boundaries.

GRAVITY ANOMALIES

The isostatic gravity map (fig 3) shows a range of values from -65 mGal over Silent Canyon caldera, the lowest value in Nevada, to +14 mGal over Bare Mountain in the southwest corner of the study area. Major negative gravity values occur over the Timber Mountain caldera moat (-42 mGal), Yucca Mountain (-38 mGal), and Emigrant Valley (-40 mGal). Significant gravity highs with amplitudes of +6 to +10 mGal are associated with Paleozoic argillites and carbonate rocks.

Major valleys in the study area, which include Emigrant Valley, Yucca Flat, and Frenchman Flat, are characterized by high-amplitude gravity lows that reflect thick alluvial basins. These gravity lows are caused by large density contrasts between basement rocks and lower-density basin fill. In addition, calderas are characterized by moderate- to large-amplitude gravity lows that reflect lower-density volcanic rocks, or superimposed local gravity highs that reflect higher-density resurgent domes.

The gravity low associated with the Silent Canyon caldera is one of the most conspicuous gravity features in Nevada. A large-amplitude elliptical gravity low trending N. 35° E. is associated with the caldera. The gravity low over Silent Canyon caldera extends southward into the northern part of the younger Timber Mountain caldera, suggesting that the Timber Mountain caldera overlies the southern part of the Silent Canyon caldera. In contrast to the major low over the Silent Canyon caldera, a nonresurgent caldera, a local gravity high of about 8 mGal in amplitude occurs over a resurgent dome in the central part of the Timber Mountain caldera (fig. 4) (Kane and others, 1981). A gravity high dominates the Black Mountain caldera in the northwest corner of the study area (fig. 3) and has an amplitude of about 6 mGal. The Oasis Valley and Sleeping Butte caldera segments are characterized by gravity gradients with lows to the east, and the Claim Canyon caldron segment (fig. 1) is overlain by a local gravity high.

South of Timber Mountain, a local gravity low with an amplitude of about 30 mGal occurs over Crater Flat. Gravity data indicate that Tertiary volcanic rocks thicken toward Crater Flat, to a depth of about 3,000 to 4,000 m. A part of the gravity low extends east to Yucca Mountain in a narrow east-west zone near Drill Hole Wash indicating the presence of a structural basement low. This structural low may influence ground-water movement within the Yucca Mountain area. Along the east edge of Yucca Mountain, a gravity high reflects pre-Cenozoic rocks near the surface at a depth of about 1,100 to 1,400 m. Drilling confirmed the presence of Paleozoic rocks at a depth of 1,244 m (Carr and others, 1986).

MAGNETIC ANOMALIES

Aeromagnetic data are useful for estimating depth to magnetic basement and locating and delimiting plutons, calderas, and faults. One of the most conspicuous aeromagnetic anomalies is a large amplitude magnetic high over Climax stock in the northeastern part of the area (fig. 5). This magnetic high is part of a regional magnetic trend in the northern part of the study area that includes magnetic highs over intrusive rocks at Gold Meadows and Twinridge stocks, Pahute Mesa, and Black Mountain (Bath and others, 1983).

In the northern part of Timber Mountain, aeromagnetic highs are associated with upper parts of the Ammonia Tanks Member of the Timber Mountain Tuff. In the southern part of Timber Mountain, magnetic anomalies are of lower amplitude, and negative or no anomalies occur over the lower parts of the Ammonia Tanks Member. In the central part of the Timber Mountain caldera and along the southeastern part of Timber Mountain, the magnetic relationship of the upper and lower parts of the Ammonia Tanks Member appears to be reversed, indicating that the magnetic properties of these rocks have been altered by heating (see Kane and others, 1981).

Another conspicuous feature of the aeromagnetic map is a large amplitude high at Calico Hills, in the south-central part of the study area (fig. 5). Although a part of the anomaly probably reflects a pluton at depth, strongly magnetized argillite of the Eleana Formation is the principal cause of the anomaly (Snyder and Oliver, 1981). Farther east, at Wahmonie, a relatively large amplitude magnetic high occurs south of two exposures of granitic rocks, each of which are locally associated with magnetic anomalies. This indicates that the larger anomaly is also related to a granitic intrusion (Ponce, 1984). An aeromagnetic survey flown at a barometric elevation of 2,450 m (Boynton and Vargo, 1963a,b) shows that magnetic anomalies at Calico Hills and Wahmonie occur along the distal eastern parts of a southeast-trending magnetic high across the study area.

Circular magnetic anomalies in Crater Flat and northwest of the town of Amargosa Valley (formerly Lathrop Wells) correlate to known cinder cones. In addition, similarly shaped anomalies occur over alluvium in the Amargosa Valley, including an anomaly just south of the town of Amargosa Valley. These anomalies may be related to buried basaltic volcanic centers.

In summary, gravity and magnetic studies in southwest Nevada reveal important geologic features of an area that includes a potential nuclear waste disposal site at Yucca Mountian. These studies are particularly useful for delineating calderas, volcanic centers, granitic intrusions, and basement rocks. In addition, these studies show that the eastern part of Yucca Mountain is located at the east edge of a large depression in the pre-Tertiary basement rocks.

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Controlled Area added by [illegible]

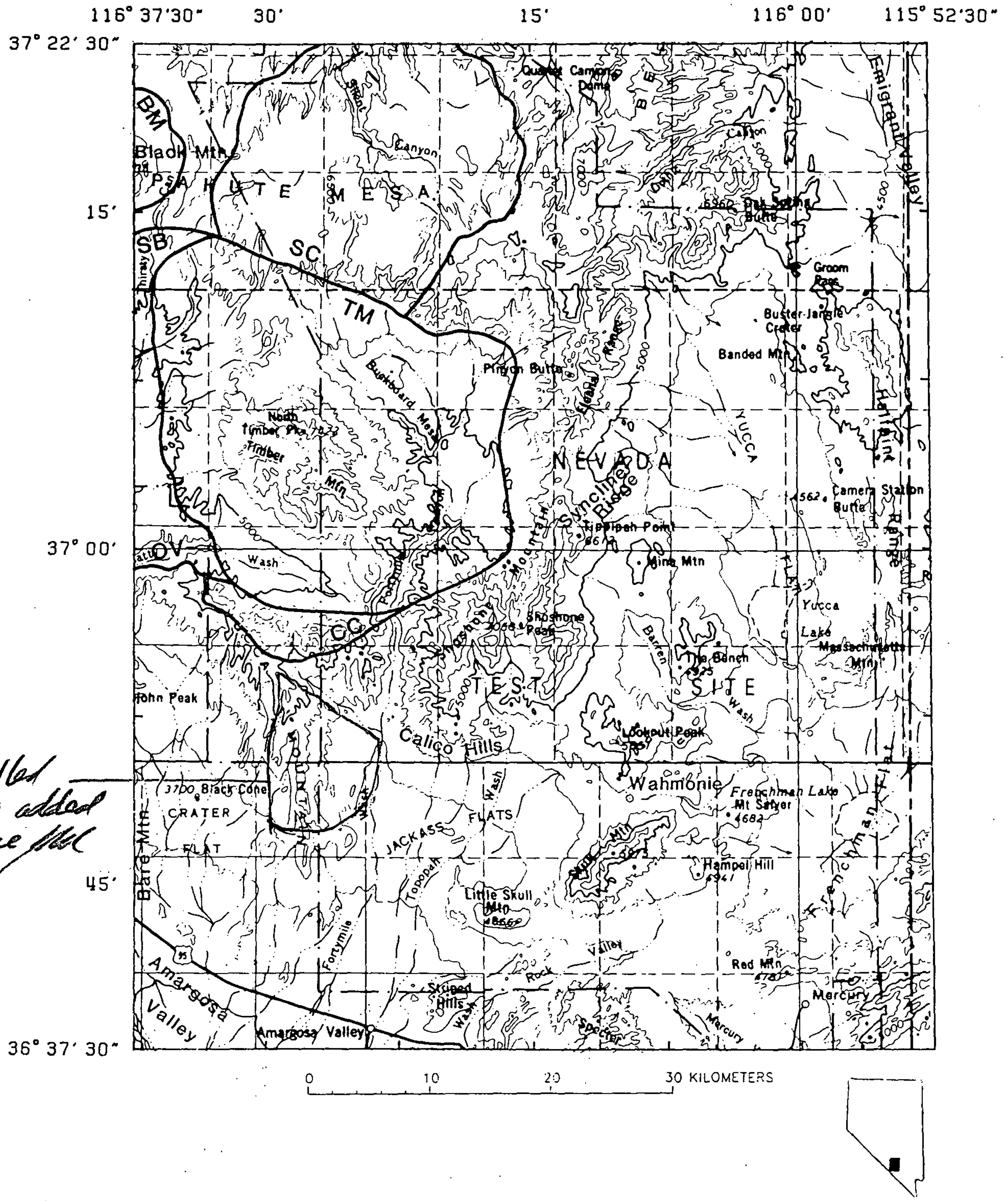
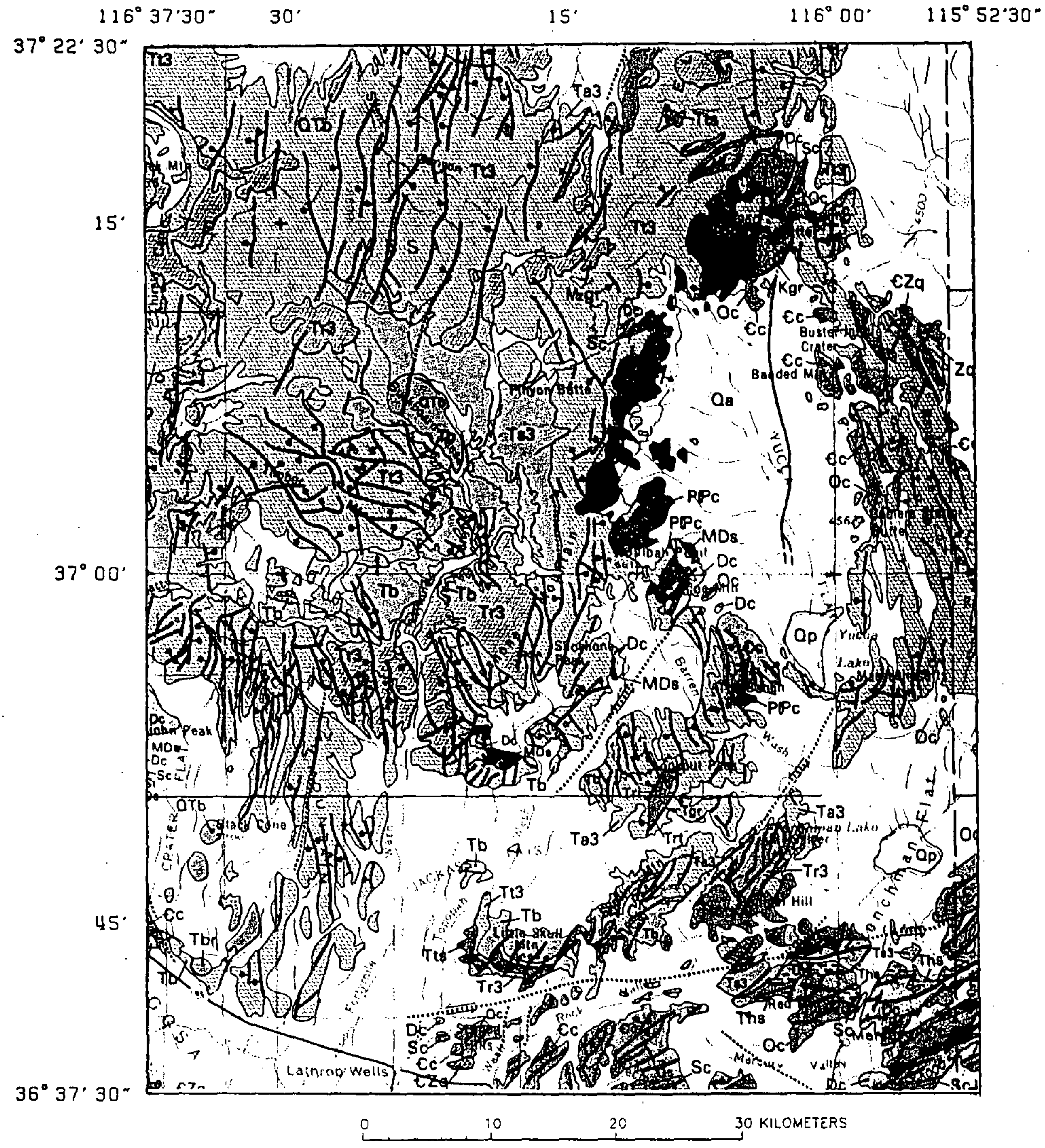


Figure 1. Index map of study area showing approximate boundaries of calderas (after Byers and others, 1976, fig. 1). BM, Black Mountain caldera; CC, Claim Canyon caldron segment; OV, Oasis Valley caldera segment; SB, Sleeping Butte caldera segment; SC, Silent Canyon caldera; TM, Timber Mountain caldera.



Colored map

Figure 2. Geologic map of study area. Modified from Stewart and Carlson (1978).

DESCRIPTION OF MAP UNITS

Qa — ALLUVIAL DEPOSITS—Locally includes beach and sand dune deposits

Qp — PLAYA, MARSH, AND ALLUVIAL-FLAT DEPOSITS, LOCALLY ERODED

BASALT FLOWS—Locally includes maar deposits

RHYOLITIC INTRUSIVE ROCKS

RHYOLITIC FLOWS AND SHALLOW INTRUSIVE ROCKS

ANDESITE AND RELATED ROCKS OF INTERMEDIATE COMPOSITION—Flows and breccias

ANDESITE AND BASALT FLOWS—Mostly in ~17 to ~6 m.y. age range. In Humboldt County, locally includes rocks as old as 21 m.y. May include rocks younger than 6 m.y. in places

BASALT FLOWS

BRECCIA—Volcanic, thrust, and jasperoid breccia and landslide megabreccia

WELDED AND NONWELDED SILICIC ASH-FLOW TUFFS—Locally includes thin units of air-fall tuff and sedimentary rock

ASH-FLOW TUFFS, RHYOLITIC FLOWS, AND SHALLOW INTRUSIVE ROCKS

RHYOLITIC FLOWS AND SHALLOW INTRUSIVE ROCKS

ANDESITE AND RELATED ROCKS OF INTERMEDIATE COMPOSITION—Flows and breccias

ASH-FLOW TUFFS AND TUFFACEOUS SEDIMENTARY ROCKS

TUFFACEOUS SEDIMENTARY ROCKS—Locally includes minor amounts of tuff

HORSE SPRING FORMATION—Tuffaceous sedimentary rocks, southern Nevada

PLUTONIC ROCKS

GRANITIC ROCKS—Mostly quartz monzonite and granodiorite

GRANITIC ROCKS, WESTERN NEVADA (Mesozoic)—Mostly quartz monzonite and granodiorite. Inconclusively dated or not dated radiometrically.

GRANITIC ROCKS—Mostly quartz monzonite and granodiorite

LIMESTONE AND SPARSE DOLOMITE, SILTSTONE, AND SANDSTONE (Lower Pennsylvanian to Lower Permian)—Includes units such as undivided Riepe Spring Limestone of Steele (1960) and Ely Limestone or their equivalent in Elko, White Pine, and northern Lincoln Counties and most of the Bird Spring Formation and Callville Limestone in Clark and southern Lincoln Counties. Includes some stratigraphically higher Permian rocks in Leppy Peak, easternmost Elko County

SHALE, SILTSTONE, SANDSTONE, CHERT-PEBBLE CONGLOMERATE, AND LIMESTONE—Includes units such as Pilot Shale, Joana Limestone, Chainman Shale, and Diamond Peak Formation in northern and eastern Nevada and Narrow Canyon Limestone, Mercury Limestone, and Eleana Formation in southern Nevada

Dc — DOLOMITE, LIMESTONE, AND MINOR AMOUNTS OF SANDSTONE AND QUARTZITE—Includes units such as Sevy and Simonson Dolomites, Guilmette and Nevada Formations, and Devils Gate Limestone

DOLOMITE—Includes units such as Laketown and Lone Mountain Dolomites. Locally includes rocks of Early Devonian age at top

LIMESTONE, DOLOMITE, SHALE, AND QUARTZITE—Includes units such as Pogonip Group, Eureka Quartzite, and Ely Springs Dolomite. Where Ely Springs Dolomite or equivalent rocks are included in SOc unit, this unit includes only the Pogonip Group and Eureka Quartzite or their equivalents

LIMESTONE AND DOLOMITE, LOCALLY THICK SEQUENCES OF SHALE AND SILTSTONE—Includes units such as Pioche Shale, Eldorado Dolomite, Geddes Limestone, Secret Canyon Shale, Hamburg Dolomite, Dunderberg Shale, and Windfall Formation of northern Nevada and Carrara, Bonanza King, and Nopah Formations of southern Nevada

QUARTZITE AND MINOR AMOUNTS OF CONGLOMERATE, PHYLLITIC SILTSTONE, LIMESTONE, AND DOLOMITE—Includes Prospect Mountain Quartzite, Osgood Mountain Quartzite, and Gold Hill Formation in northern Nevada and Stirling Quartzite, Wood Canyon Formation, and Zabriskie Quartzite in southern Nevada

QUARTZITE, PHYLLITIC SILTSTONE, CONGLOMERATE, LIMESTONE, AND DOLOMITE—Includes McCoy Creek Group (excluding Stella Lake Quartzite) of Misch and Hazzard (1962) in east-central Nevada and Johnnie Formation in southern Nevada

Contact

High-angle fault—Dashed where inferred or uncertain; dotted where concealed. Bar and ball on downthrown side

Low-angle fault—Dashed where inferred or uncertain; dotted where concealed. Sawteeth on upper plate

Strike-slip fault—Dashed where inferred or uncertain; dotted where concealed. Arrows indicate relative movement

Colored

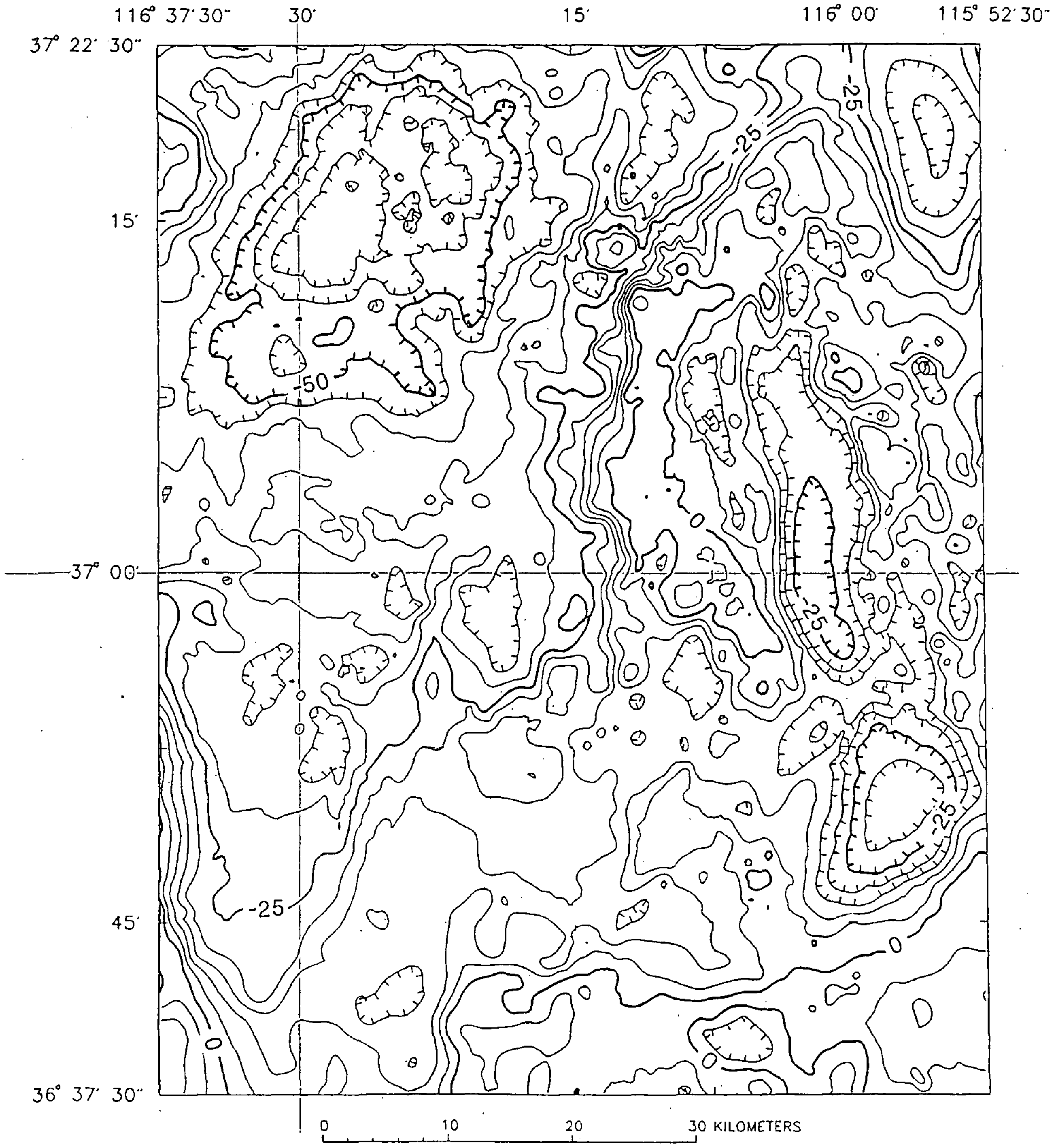


Figure 3. Isostatic gravity map. Isostatic corrections are based on an Airy-Heiskanen model of isostatic compensation, with an assumed crustal density of 2.67 g/cm^3, a crustal thickness at sea level of 25 km, and a density contrast across the base of the model crust of 0.4 g/cm^3. Contour interval 5 mGal.

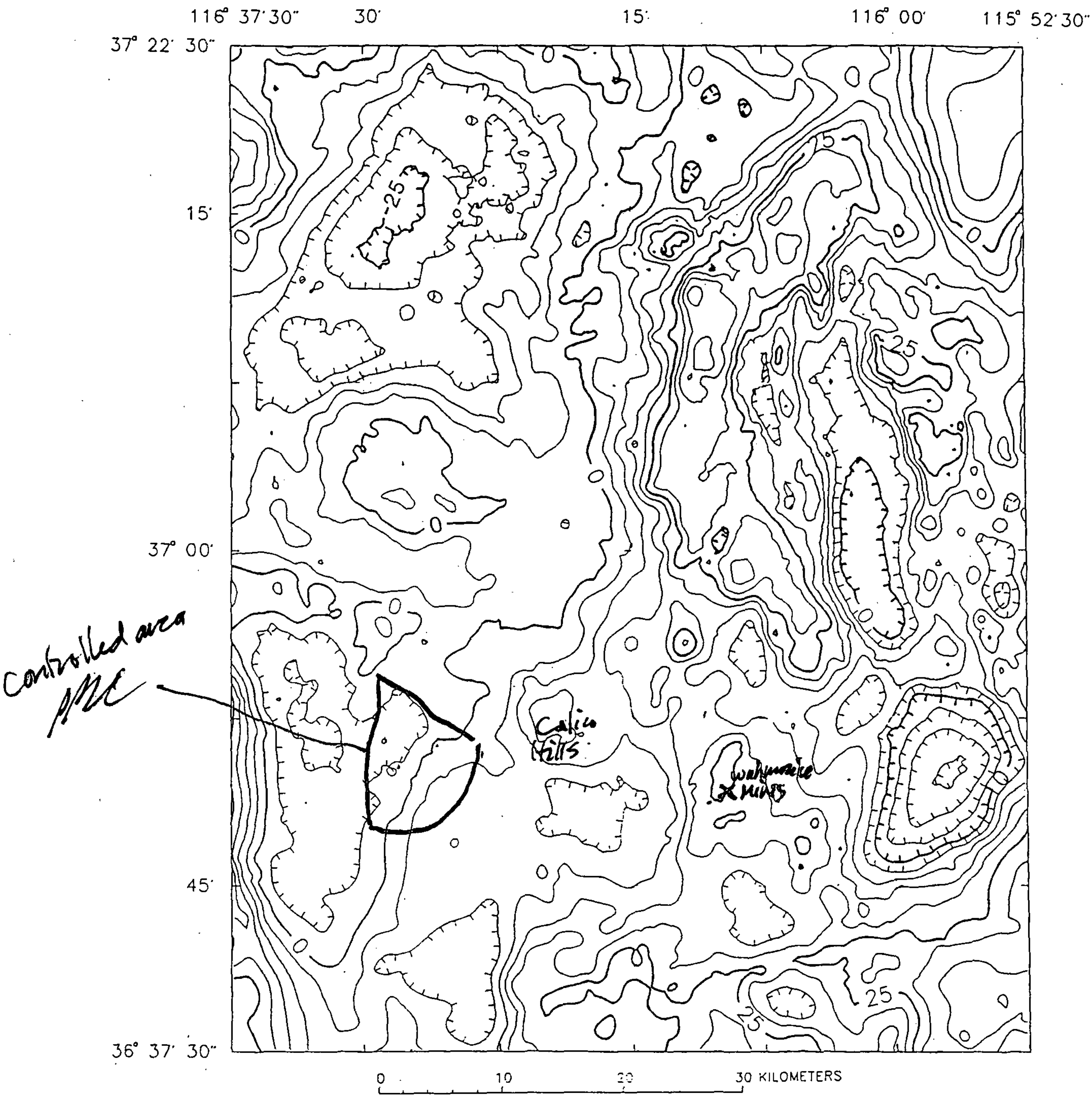


Figure 4. Isostatic gravity map reduced for a density of 2.20 g/cm^3. Contour interval 5 mGal.

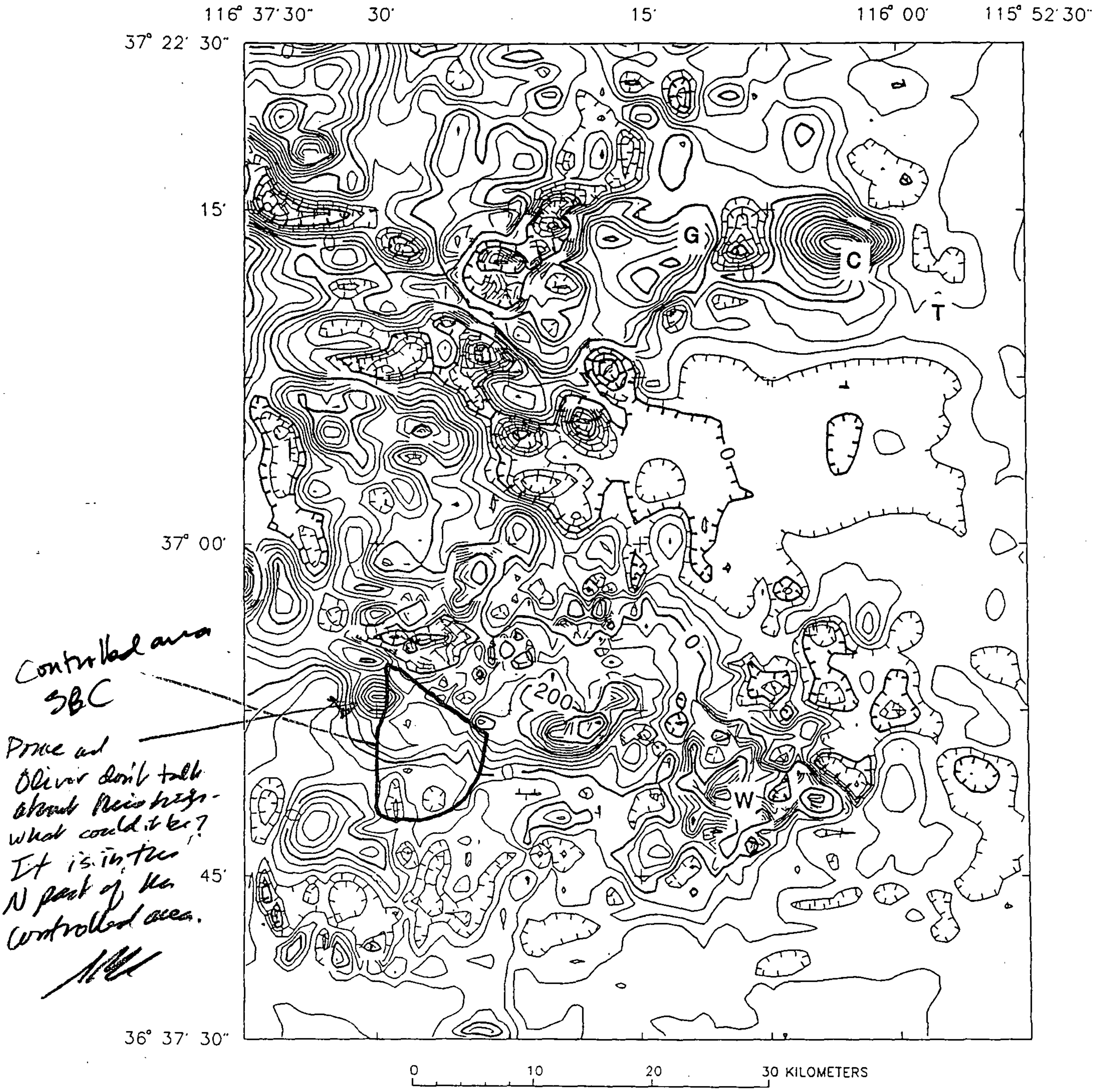


Figure 5. Aeromagnetic map. Contour interval 40 nT (1 nT = 1 gamma). C, Climax stock; G, Gold Meadows stock; T, Twinridge stock; W, Wahmonie.

Cpy

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SUMMARY AND CONCLUSIONS OF THE GEOPHYSICS-GEOLOGY INTEGRATION WORKSHOP
Held March 11-13 1996 at Lawrence Berkeley National Laboratory Earth Sciences Division

This document may be placed in scientific notebooks.

Note: Attendees, please reply with any additions, subtractions, or revisions of this summary so that I can pass them on.

Session I: Data Coverage, Availability, and Limitations

* The magnetic basement map and interpretation done by Earthfield Technologies during FY1995 is controversial (E. Majer). Because the flight lines over Yucca Mountain were north-south, the data are not useful for interpreting the north-south trending structures there. Additionally, the USGS has not had time or workscope to evaluate these data and the interpretation method, and so can not make an evaluation at this time (D. Ponce).
* The Paleozoic maps done by Earthfield have resolution of about 500 to 1000 meters (E. Majer). Majer (510) 486-6709 @LBL
* For gravity data, vertical resolution is highly dependant on vertical density control. Because only one control point to the Paleozoic exists near Yucca Mountain (p#1), depth resolution is poor (E. Majer, V. Langenheim).
* Gravity and magnetic surface traverses show fault locations quite readily, but do not usually reveal information about fault dips. No unmapped faults have been found on the main part of Yucca Mountain that have offsets greater than a few tens of meters (D. Ponce).
* Estimates of fault dips in seismic profiles are only as good as the velocity control and estimates. As with density data, this information is sparse. Velocities from refraction experiments have been used to help constrain stacking and migration velocities (T. Brocher). USGS-OFR-96-28, 97pp 96 Seismic
* Magnetic data are dominated by the highly magnetic Topopah Spring Tuff, and so most of the observed signal comes from shallow depths (D. Ponce).
* There is a one-to-one correspondence of known faults to anomalies in magnetic profiles at Yucca Mountain. Deep structures are not always expressed in the Tertiary rocks (D. Ponce).
* USGS Menlo Park has a new program that will improve their calculation of depth to Paleozoic (V. Langenheim). ? Assumed magnetic? Multi-body modeling?
* In the Earthfield Paleozoic maps, the surfaces are 1500 to 3000 feet

higher or lower than Paleozoic outcrops, with no systematic error, even though Earthfield was given extensive geologic maps (R. Spengler).
* Across Nevada, a density contrast of 0.4 g/cm3 is used at the Tertiary-Paleozoic contact, reflecting densities of 2.3 versus 2.7 (D. Ponce). Qal vs Pz ?
* The question was asked to the group: What does the magnetic basement map tell us? The answer from the group was: Not much.
* In a seismic refraction experiment, Walter Mooney found a body at 4 to possibly 10 km depth below Crater Flat with a (relatively high) velocity of 6.7 km/sec. This could perhaps be a stack of basaltic sills (J. Brune). This anomaly corresponds approximately to a magnetic anomaly of unidentified origin (B. Crowe).

Session II: Configuration of the Top of Paleozoic

* The favored model for the development of Crater Flat is that of a pull-apart basin in a combined strike slip--extensional regime (B. Crowe).
* The Bare Mountain fault appears to dip approximately 45 degrees east. Major Crater Flat and Yucca Mountain faults dip moderately (50-60 degrees) west, and extend from near borehole VH-1 to the west side of Jackass Flat (T. Brocher).
* The Paleozoic surface appears to have a relatively low-relief (but still faulted) section beneath eastern Yucca Mountain. Greatest fault offsets on the Pz are under western Yucca Mountain, the Windy Wash fault, and an unmapped fault just west of borehole VH-1 (T. Brocher).
* The Solitario Canyon and/or Ghost Dance faults may represent a shallower and younger expression of a fault which has greater offset at depth (T. Brocher).
* A model for fault evolution, based on the deep seismic profiles: During Miocene volcanism and extension, thermal gradients may have been higher, resulting in a shallower brittle-ductile transition in the crust. The Crater Flat pull-apart basin began to form in this high-heat environment, with the shallow Bare Mountain and steeper Crater Flat basin faults converging at the brittle-ductile transition. With time, the crust cooled and the brittle-ductile transition deepened. As a result, Crater Flat basin faulting migrated eastward as the juction of the faults deepened (T. Brocher).
* The deep seismic profiles imply that earthquake hazards on the western-central Crater Flat basin faults is reduced because these faults do not extend beyond 5-8 km depth where they intersect the Bare Mountain fault (J. Whitney).
* The shallow, conformal reflections across Crater Flat match concepts for Paintbrush Group deposition and (B. Crowe).
* Water chemistry suggests a boundary between boreholes VH-1 and VH-2 which would match the fault seen in seismic profiles (J. Stuckless).
* There is a 100's meter-wide block of west dips on the east side of Solitario Canyon, which may help explain anomalous west-dipping reflectors in the deep seismic profiles (W. Day, R. Spengler, T. Brocher).
* Some lower volcanic units (Bullfrog?) may have had initial westward dips in Crater Flat that have since been tilted east (W. Day, B. Crowe, T. Brocher).
* 3D geologic framework modelers should build a Paleozoic surface incorporating the Paleozoic elevation map of D. Ponce and the faulting concepts illustrated in the deep seismic profiles. This is the best solution (attendees).

Session III: Configuration of the Crater Flat Basin Eastern Margin

* Several structural models exist, each with different boundaries. The Miocene edge of the basin appears to have migrated with time.
* From aeromagnetic and gravity data, the CF basin structural edge would be drawn under western Jackass Flat (D. Ponce).
* The prominent aeromagnetic anomaly in Crater Flat appears to be a deep structure greater than 5 km depth (V. Langenheim), and is masking the north-south structural fabric of the basin (T. Brocher).

Session IV: Geometries of Faults At Depth

* The map geometries of faults may be reflective of their geometries in the third dimension (J. Whitney).
* The relatively short Fatigue Wash fault probably merges at depth with the longer Windy Wash fault based on the principle that a fault's depth does not greatly exceed its length (J. Whitney).
* The apparent density of faulting in Crater Flat and Yucca Mountain is similar to that north of the Timber Mountain Caldera at Pahute Mesa (J. Whitney).
* From the deep seismic profile, it would appear that the Bare Mountain fault is the major seismogenic structure, with the shallower faults responding passively on top (C. Potter).
* Quaternary displacement on the Bare Mountain fault is much less than the cumulative displacement on the Crater Flat-Yucca Mountain faults-- this is perplexing.
* The Ghost Dance fault could be a splay of the Solitario Canyon fault just as the Fatigue Wash could be a splay of the Windy Wash fault (J. Whitney).
* Below 3 km, there is not much constraint on CF-YM fault geometries (T. Brocher).
* The gravity location for the Bow Ridge fault at Exile Hill is east of the magnetic location. This results from the dip of the fault and consequent shift of the Topopah offset west of the surface trace (D. Ponce).
* Fault-related tilting of the Tertiary units dies out under Jackass Flat, where the rocks are thought to be more horizontal (W. Day, C. Potter).
* The favored mechanism for tilting of Tertiary units is a mild shallowing of fault dips with depth. This is shown in a recent cross section along the ESF South Ramp (W. Day, C. Potter).
* There are three related models of fault geometries in the Yucca Mountain region: Sub-parallel dominoes, upward horsetailing (or downward merging) of proximal faults, and partially listric curviplanar surfaces. Faulting in the region probably involves combinations of these (attendees).
* Dune Wash is a graben with Rainier Mesa Tuff fill (W. Day).
* A left-slip component on the north-south faults would permit opening of the northwest-trending grabens which are seen in a few places (W. Day).
* There is a thrust fault with dip of 35 degrees east in the South Portal area, which probably formed as fault blocks jostled (W. Day, C. Potter).
* The north-south and northwest-trending fault groups formed contemporaneously, based on mutually cross-cutting and truncating relations (W. Day, C. Potter).
* The evidence for faults merging at depth is their fault traces-- they must merge when projected to depth (W. Day, C. Potter).

* Rock properties appear to vary greatly from north to south, based on seismic reflections. Velocities vary by as much as 20% (E. Majer).
* Visual examination of core does not support widely varying properties (R. Spengler).
* There is a seismic anisotropy under Yucca Mountain, with variable slow direction (E. Majer).
* Much of the high-resolution seismic data looks like "stratigraphic vomit." (M. Tynan).
* Fault offsets of the Topopah Spring Tuff estimated from gravity and magnetic profiles agree with geologic estimates (D. Ponce).
* The Topopah Spring Tuff is not appreciably offset across Yucca Wash. Gravity and magnetic data do not allow more than a few meters offset. Any fault would have to be far under the northern side of the wash (D. Ponce, V. Langenheim).
* The Little Skull Mountain earthquake occurred on a 65 degree SE dipping plane (another seismologist calculated 56 degree dip). Main shock was at 12 km depth, aftershocks as shallow as 5 km. All aftershocks on high angle planes (greater than 45 degrees), including some strike slip. T axis (extension direction) was northwest (K. Smith).
* Very few quakes in the Crater Flat structural basin, with one at Alice Ridge and one in southern Crater Flat (K. Smith).
* The geology-geophysics group needs to develop a list of reasons and rationale why we do not interpret low angle detachment faults in the Yucca Mountain area (T. Sullivan).
* None of the faults interpreted in the deep seismic profiles are unrelated to mapped faults EXCEPT the fault just west of borehole VH-1 (T. Brocher).

Session V: Intrusions and Dikes

* Basaltic volumes in Crater Flat are quite small and feeder dikes are 1-5 meters thick, so they probably would not be seen by seismic profiling (B. Crowe).
* Aeromagnetic data detects basalts well in alluvium, but it is difficult under the bedrock at Yucca Mountain (V. Langenheim).
* Aeromagnetic and ground magnetic data are sufficient to address the intrusion and dike issue; however, the proposed aeromagnetic flights over Paiute Ridge would allow modeling of hidden intrusions and dikes at Yucca Mountain by providing a test case on known intrusions and dikes (B. Crowe).
* In teleseismic data, Crater Flat is fast compared to surrounding areas. There is nothing in the teleseismic data to indicate melts or partial melts at depth in Crater Flat (G. Biasi).
* Teleseismic data resolution is quite low-- it would not see a 400 meter cube (G. Biasi).

Session VI: Fractures

* UZ models do not have good enough information on how to characterize fractures. They use SZ information and air-K testing to help calibrate their models, but they need spatial distributions and densities, orientations, and anisotropies. Are hoping to receive some input from Larry Anna (M. Bandurraga).
* Fractures vary by lithologic unit, but the patterns are not always predictable. For example, the Topopah middle nonlithophysal zone is more fractured than the upper nonlithophysal, but the opposite is true in the Tiva middle nonlith and upper lith (C. Potter).

* VSP data from UZ#16 is being processed at the Colorado School of Mines. Subsets of that data could be evaluated in short order to assess the applicability to fractures (E. Majer).

Session VII: Natural Resources

* Metallic Resources evaluation mostly involves geochemistry, with the emphasis being on gold and silver. Samples taken across Yucca Mountain and in boreholes have ruled out shallow potential for metallic resources (S. Castor).
* The highest concentration found so far is a spike of 26 ppb gold in calcrete veins. 8 ppm would be the economic cutoff for mining (S. Castor).
* Typically, geophysical tools are not help in assessing metallic resources in this region (S. Castor).
* Calico Hills would probably be explored by a mining company because of the obvious hydrothermal alteration (S. Castor).
* Basaltic dikes are generally unimportant in economic mineralization (S. Castor).
* The interpreter of the shallow magnetic faults and intrusions map worked in relative isolation from the Project and under the model of Walker Lane-Las Vegas Valley shear zone for structure (M. Tynan).
* Magnetotellurics would show any melt present under Crater Flat (G. Biasi).
* A continuous MT profile across Yucca Mountain showed apparent conductivity at the Ghost Dance and Bow Ridge faults, with other patterns that could be interpreted in terms of geologic features (E. Majer).

Session VIII: Aluvium Thickness
* A lack of density contrast between alluvium and Rainier Mesa-Tiva Canyon Tuff makes this contact undetectable by most geophysical tools (E. Majer).
* No further information was offered.
<end of workshop>

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To: stuckles@qconhp.cr.usgs.gov, ken@seismo.unr.edu, cpotter@sedproc.cr.usgs.gov, ponce@mojave.wr.usgs.gov, elmajer@lbl.gov, zulanger@mojave.wr.usgs.gov, karag@ccs.lbl.gov, lrj@ccs.lbl.gov, mafeighner@lbl.gov, chornack@ympbgate1.cr.usgs.gov, wday@ympb.cr.usgs.gov, scastor@comstock.nbmg.unr.edu, brune@seismo.unr.edu, brocher@andreas.wr.usgs.gov, glenn@seismo.unr.edu, tmbandurraga@lbl.gov, "jwhitney @ ympbgate1.cr.usgs.gov%YMPGATE"@ccmail.ymppo.ymp.gov, John_Savino@NOTES.YMP.GOV, Tim_Sullivan@NOTES.YMP.GOV, Mark_Tynan@NOTES.YMP.GOV, Daniel_Soeder@NOTES.YMP.GOV, Richard_Quittmeyer@NOTES.YMP.GOV
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Please add the following to the Workshop Summary you received previously, and send any further corrections as soon as you can.
-- Robert Clayton, M&O/WCFS, 3D Modeling Coordinator

Previous Summary statement:
* The prominent aeromagnetic anomaly in Crater Flat appears to be a deep structure greater than 5 km depth (V. Langenheim), and appears to be masking the pattern produced by north-south faulting (T. Brocher).

Correction:
The source of the large positive aeromagnetic anomaly in Crater Flat is deeper than the linear anomalies produced by faulting. The maximum depth to the top of the source is about 5 km...the upper surface of the source may be shallower (but not shallower than the depth reached by VH-1 obviously; V. Langenheim).

Previous statement:
* The Topopah Spring Tuff is not appreciably offset across Yucca Wash. Gravity and magnetic data do not allow more than a few meters offset. Any fault would have to be far under the northern side of the wash (D. Ponce, V. Langenheim).

Correction:
"A few meters" should be "tens to hundreds of meters."...in other words, the potential field data rule out a significant northwest-trending fault under Yucca Wash proper. Also, it's the aeromagnetic anomaly that we believe is caused by the Topopah Spring Tuff that is not appreciably offset across the wash (V. Langenheim).

Previous statement:
* Aeromagnetic data detects basalts well in alluvium, but it is difficult under the bedrock at Yucca Mountain (V. Langenheim).

Correction:
"Bedrock" should be changed to "Tertiary volcanic rocks." (V. Langenheim).

Addition:
Seismic profiles on the repository block are early in the interpretation process. Recent migrations show good, measurable offset at the Ghost

Dance fault of 100 feet in agreement with previous geologic interpretation, and also decreased offset on the GD farther north. Other lines are expected to provide similarly useful information as the interpretation process progresses (M. Freighner).

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Please add this to your Geophysics-Geology Workshop Summary:

Original Statement:
* Fault-related tilting of the Tertiary units dies out under Jackass Flat, where the rocks are thought to be more horizontal (W. Day, C. Potter).

Revision:

We have no information on tilts beneath Jackass Flat. There is no observed flattening of the east tilts on Yucca Mountain bedrock at the west edge of Jackass Flat. (Potter)

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MIME-version: 1.0

Please add this to your Workshop Summary. Thanks for all the feedback--please keep it up!

Original Statement:
* Shallow metallic resources have been ruled out.

Correction:
The metallic resource study of Yucca Mountain is incomplete. On the basis of work on the Yucca Mountain Addition, no evidence for metallic resources was found on the surface; this has been backed up by analyses of samples from hole GU-3. There are some indications of mineralization in the Paleozoic rocks encountered by hole p#1. All results from analysis of the most recent round of surface and drill hole samples are not yet available, but based on what has been seen so far there is little evidence for shallow metallic mineral deposits (S. Castor).

Original Statement:
* The highest concentration was 26 ppb Au.

Correction/Revision:
Although an analysis of 26 ppb Au was found on two samples (one surface and one drill sample), neither were verified by reanalysis of the same pulp or by analysis of resampled rock from the same locality. The highest verified analyses were at 9 ppb Au in calcrete sampled on the surface and in Paleozoic rock cuttings from hole p#1 (S. Castor).

Original Statement:
* Geophysical tools have not been important in metallic resources exploration in this region.

Correction:
While geophysical tools have generally not been very important in gold and silver exploration in the Basin and Range province, they have been found useful in the search for other types of metallic deposits such as porphyry copper deposits. Attempts to constrain subsurface geology (location of faults, etc.) using geophysical techniques could be used to find gold and silver ore in areas that are known to be mineralized, but geophysical exploration per se is generally not helpful in gold and silver exploration. (S. Castor)

Langenheim, V.E., and Ponce, D.A., 1995, Depth to pre-Tertiary basement in southwest Nevada: American Nuclear Society Proceedings of the Sixth Annual International Conference on High-level Waste Management, Las Vegas, Nev., 3 p.

DEPTH TO PRE-CENOZOIC BASEMENT IN SOUTHWEST NEVADA

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ABSTRACT

An iterative procedure based on gravity data, surface geology, and an estimated density-depth function was used to estimate the depth to pre-Cenozoic basement at Yucca Mountain and vicinity.

I. INTRODUCTION

The composition of and depth to pre-Cenozoic basement are poorly known at Yucca Mountain and vicinity because of the thick sequence of tuff that was erupted between 15 and 7 Ma. Only one well (UE-25 p#1) of many deep wells drilled to characterize the Yucca Mountain site penetrated basement. Gravity data can be used to estimate the thickness of Cenozoic deposits because of the large density contrast between low-density volcanic and alluvial deposits and high-density pre-Cenozoic basement rock. We use an iterative procedure based on the gravity data, the surface geology, and an estimated density-depth function for the Cenozoic deposits to separate the gravity field into a "basement" gravity component and a "basin" gravity component[1]. We present a preliminary isopach map of Cenozoic deposits at Yucca Mountain and vicinity based on the "basin" gravity field.

II. METHOD

The method[1] separates gravity observations into two sets, one consisting of observations on basement outcrops and the other consisting of observations taken on Cenozoic outcrops. The second set of observations is inverted for thickness of Cenozoic deposits based on an estimate of the density-depth curve (from Jachens and Moring[1]) between these deposits and pre-Cenozoic basement. This inversion is complicated by two factors: (1) basement gravity stations are influenced by the gravity anomaly caused by low-density deposits in nearby basins, and (2) the basement gravity field varies because of density variations within the basement. The inversion does not take into account lateral variations in the density distribution of the Cenozoic deposits.

To overcome these difficulties, a first approximation of the basement gravity field is determined by interpolating a smooth surface through all gravity values measured on basement outcrops (curve labeled "iteration 1" in lower panel of Fig. 1b). The basin gravity is then the difference between the observed gravity field on the original map and the first approximation of the basement gravity field and is used to calculate the first approximation of the thickness of Cenozoic deposits. The thickness is forced to zero where basement rock is exposed. This first approximation of the basement gravity field is too low near basins because of the proximity of low-density deposits to the basement gravity stations. The basement gravity station values are "corrected" for the effects of the low-density deposits (the effects are calculated directly from the first approximation of the thickness of the Cenozoic deposits) and a second approximation of the basement gravity field is made by interpolating a smooth surface through the corrected basement gravity observations. This leads to an improved estimate of the basin gravity field, an improved depth to basement, and a new correction to the basement

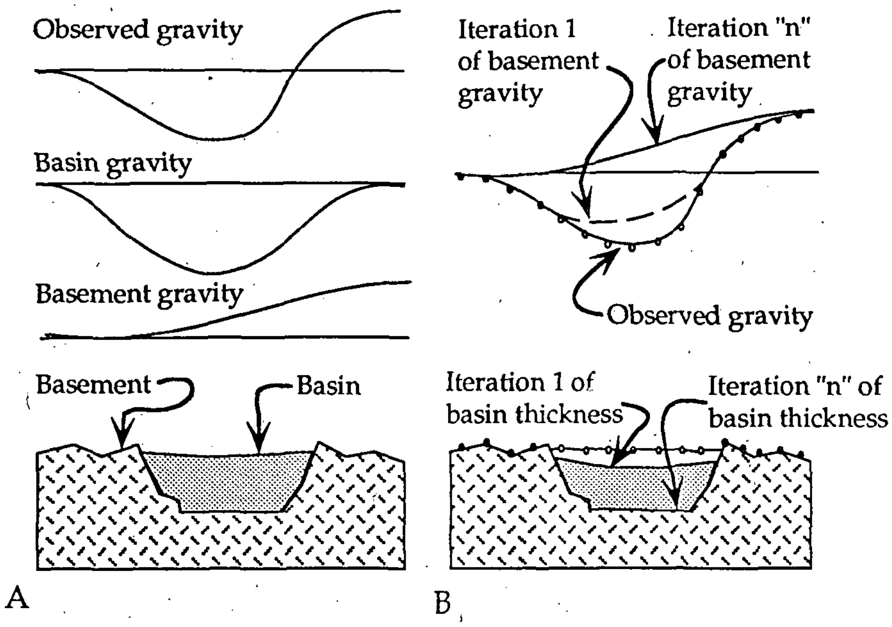

Figure 1. Schematic representation of the gravity separation procedure. "n" represents final iteration of basin-fitting procedure.

gravity values. This procedure is repeated until successive iterations produce no significant changes in the basement gravity field.

III. RESULTS

Using an updated gravity data set and more detailed surface geology we have produced a preliminary isopach map of Cenozoic deposits at Yucca Mountain and vicinity (fig. 2). Cenozoic deposits reach thicknesses greater than 2.5 km in Crater Flat, consistent with previous modeling results[2,3,4]. The isopach map indicates thicker deposits in western and southern Crater Flat and under northern Yucca Mountain. These local lows within Crater Flat and Yucca Mountain may indicate grabens that formed before the advent of voluminous silicic volcanism about 17 Ma[5]. This model predicts about 600 m of Cenozoic deposits at drillhole UE-25 p#1, which penetrated basement at a depth of 1244 m. Cenozoic deposits in Amargosa Desert and Jackass Flats are generally less than 1.5 km thick, in agreement with interpretations of electrical resistivity data[6] and with limited drill-hole data.

IV. CONCLUSIONS

Although the results of the iterative modeling procedure agree fairly well with other data, the preliminary isopach map has several inherent limitations arising from the procedure and data used to create the map. Better gravity coverage on basement outcrops would better constrain the known basement gravity field. However, uncertainties in the density-depth function, lateral variations in density within the volcanic sequence, and the presence of concealed basement sources (e.g., a hypothetical pluton underlying the Cenozoic sequence in Crater Flat) could all effect the predicted cover thicknesses. Nonetheless, the isopach map does provide target basement depths for deep drilling in Crater Flat and Yucca Mountain. Differences between the predicted thicknesses and thicknesses determined by other methods can be used to refine the model.

ACKNOWLEGMENTS

Prepared in cooperation with the U.S. Department of Energy (Interagency Agreement DE-AI08-92NV10874). The processed data are preliminary.

REFERENCES

1. R.C. Jachens and B.C. Moring, "Maps of the thickness of Cenozoic deposits and the isostatic residual gravity over basement for Nevada", U.S. Geological Survey Open-File Report 90-404, 15 p. (1990)

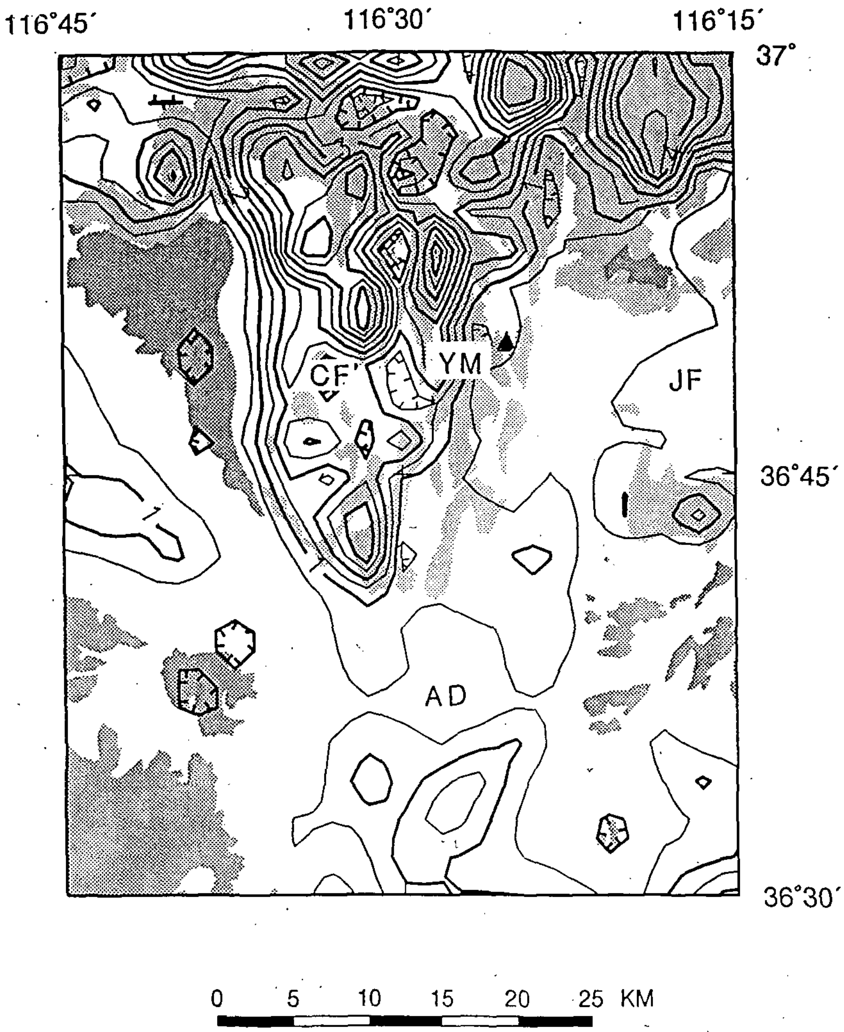

Fig. 2 Preliminary isopach map of Cenozoic sedimentary and volcanic rocks. Contour interval 0.5 km. Dark areas indicate outcrops of pre-Cenozoic rock; lightly shaded areas, Tertiary volcanic rock; unshaded areas, Quaternary and Cenozoic alluvial deposits. YM, Yucca Mountain; AD, Amargosa Desert; CF, Crater Flat; JF, Jackass Flats. Triangle shows location of well UE25 p#1.

2. D.B. Snyder and W.J. Carr, "Interpretation of gravity data in a complex volcano-tectonic setting, southwestern Nevada", Journal of Geophysical Research, v. 89, no. B12, p. 10193-10206 (1984).

3. H.W. Oliver and K.F. Fox, "Structure of Crater Flat and Yucca Mountain, southeastern *(sic)* Nevada, as inferred from gravity data", American Nuclear Society Proceedings of the Fourth Annual International Conference on High Level Nuclear Waste Management, April 26-30, 1993, Las Vegas, NV, v. 2, p. 1812-17 (1993).

4. V.E. Langenheim, "Constraints on the structure of Crater Flat, southwest Nevada, derived from gravity and magnetic data", U.S. Geological Survey Circular, 16 p., in press (1995).

5. F.M. Byers, Jr., W.J. Carr, P.P. Orkild, W.D. Quinlivan, and K.A. Sargent, "Volcanic suites and related cauldrons of the Timber Mountain-Oasis Valley caldera complex, southern Nevada", U.S. Geological Survey Professional Paper 919, 70 p. (1976).

6. M.R. Greenhaus and C.J. Zablocki, "A Schlumberger resistivity survey of the Amargosa Desert, southern Nevada", U.S. Geological Survey Open-File Report 82-897, 150 p. (1982).

1988, US Geol Survey Bull 1790, p. 23-34.

3. Preliminary Interpretation of Seismic-Refraction and Gravity Studies West of Yucca Mountain, Nevada and California

By Hans D. Ackermann, Walter D. Mooney, David B. Snyder, *and* Vickie D. Sutton

CONTENTS

Abstract

Crustal velocity sections based on two seismic-refraction profiles are presented for the area west of Yucca Mountain, Nye County, Nevada. The north-south Crater Flat profile nearly parallels the west side of Yucca Mountain and extends northward from the Amargosa Desert valley to the northeast corner of Crater Flat. The Beatty profile extends westward from northern Crater Flat past Beatty and the Bullfrog Hills to Death Valley.

The Crater Flat profile is interpreted in terms of six velocity layers ranging from 1.5 to 6.1 km/s. The interpreted prevolcanic surface has a relief of over 2,000 m, ranging from approximately 2.2 km below sea level (total depth below surface of 3.2 km) in the center of Crater Flat to approximately sea level (total depth of 1.3 km) beneath southern Yucca Mountain.

Interpretation of the Beatty profile reveals an escarpment near the northeast edge of Bare Mountain, where Paleozoic rocks are probably down-faulted 2,600 m into a volcano-tectonic depression in Crater Flat.

The seismic profiles and inferred density-velocity relations have been incorporated into an east-west gravity model from Death Valley to Crater Flat, corresponding to the Beatty seismic profile. An important feature of this model is the inferred continuity of a layer with a model density of 2.74 g/cm^3 (corresponding to a seismic velocity of 6.3 km/s) from the Grapevine Mountains to Bare Mountain. This layer is interpreted as the lower plate of a regional decollement or detachment fault.

INTRODUCTION

This report presents the velocity structure derived from two crustal seismic-refraction profiles recorded west of Yucca Mountain in 1983. These profiles, which we have named the Beatty and Crater Flat profiles (fig. 3.1), represent part of a continuing program of seismic investigations in the region of Yucca Mountain.

Previous seismic investigations in the region consisted of three reconnaissance refraction spreads east of Yucca Mountain (Pankratz, 1982), which had a maximum penetration depth of about 600 m; a reconnaissance "high-resolution" reflection survey by the Colorado School of Mines (Barry, 1980); two industry reflection surveys along the east flank of Yucca Mountain (McGovern, 1983); an engineering refraction survey (unpublished) by H.D. Ackermann along the east edge of Yucca Mountain; and an unreversed reconnaissance crustal refraction profile (Hoffman and Mooney, 1983), which crossed Yucca Mountain at the proposed repository site. With the exception of the Hoffman and Mooney (1983) profile, none of the surveys produced results that could be interpreted in terms of stratigraphic relations at Yucca Mountain. The three reflection surveys failed to record a single coherent reflection event, attesting to the high degree of variability and poor sound transmission properties of the shallower rocks in the area. These negative results were further complicated by the shallow refraction studies, which demonstrated not only the inherent difficulty of producing and recording coherent sound signals in the volcanic rocks, but also their high degree of lateral variablity.

On the other hand, good upper-crustal refraction returns were obtained from the reconnaissance survey by Hoffman and Mooney (1983) and from the work leading to this report. These results formed the basis for additional deep refraction studies in the Yucca Mountain region conducted in 1985, which are not reported here.

In their interpretation of the unreversed profile, Hoffman and Mooney (1983) relied upon inferred relations between seismic velocities and rock densities derived from the gravity modeling (Snyder and Carr, 1982) to compute depths to the prevolcanic surface beneath Crater Flat. The detailed gravity models have also provided an excellent framework for the interpretation and discussion of the present refraction results.

An objective of the present survey was to improve on the earlier depth estimates by using reversed refraction profiles. The results also suggest some revisions of the gravity models.

Acknowledgments

We wish to thank our U.S.G.S. colleagues for their valuable critical comments on this paper. The data analyzed in this paper were collected by the authors and G. Bloomberg, M. Burns, B. Colburn, T. Conway, E. Criley, B. Echols, L. Greene, R. Kaderabek, P. Meador, J. Murphy, and L. Pace. We thank all of them for their diligent field efforts.

GEOLOGIC SETTING

A brief discussion of the geologic framework pertinent to this report follows. A more thorough review is provided by Snyder and Carr (1984) and Carr (1984).

The study area lies within the southern part of the Great Basin, a large structural and physiographic section of the Basin and Range province. Whereas much of the Great Basin is characterized by linear, fault-bounded ranges separated by elongate deep structural basins of late Cenozoic age, most of the area considered here, between Death Valley and Yucca Mountain, does not contain well-developed typical basin-range structure. Instead the area is one of diverse structural style, trends, and topography, called the Walker Lane belt or Walker belt by some authors (Stewart, 1980; Carr, 1984).

The oldest rocks exposed in the region are partially metamorphosed sedimentary rocks of Proterozoic age, mainly on Bare Mountain and in the Funeral Mountains (fig. 3.1). These rocks, which are mostly quartzite and other mildly metamorphosed clastic rocks, are overlain by a very

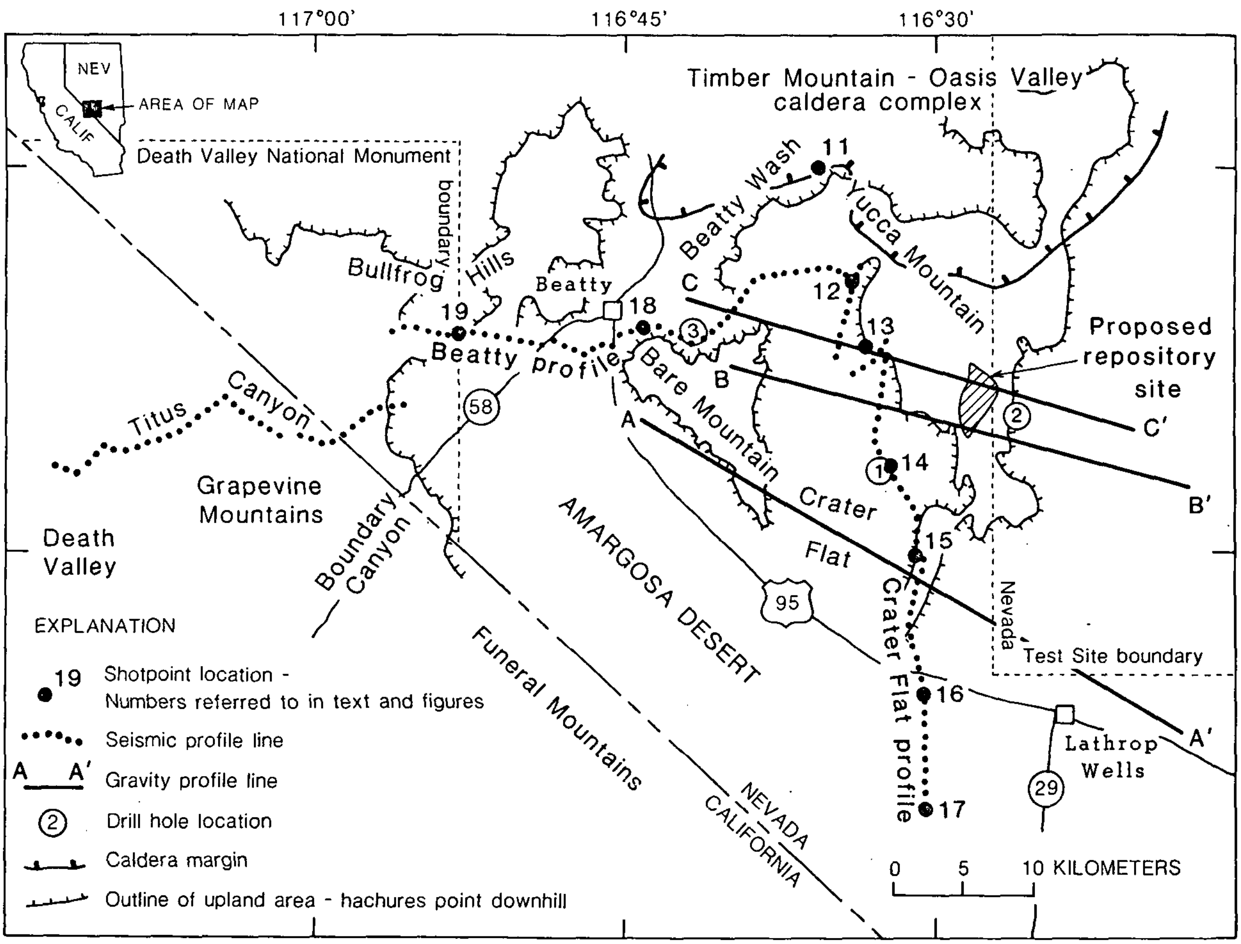

Figure 3.1. Map of study area showing locations of seismic and gravity profiles (Snyder and Carr, 1982) and shotpoint and drill hole locations. Drill hole 1, USW VH–1; 2, UE–25P1; and 3, US Borax.

thick section of Paleozoic, largely carbonate sedimentary rocks. In some areas, as in the northern part of Bare Mountain, these carbonate rocks are thrust over middle Paleozoic clastic rocks (Eleana Formation). Granite of Mesozoic age crops out at the northwest corner of Bare Mountain, and similar granites may be present in the subsurface in an east-west belt from the Grapevine Mountains to east of Yucca Mountain (Carr, 1984, fig. 13).

Locally thick Tertiary rocks lie unconformably above the Paleozoic rocks in most of the area. Oligocene rocks in the Grapevine Mountains consist mainly of conglomerate and other sedimentary rocks, as well as minor tuff. Most of the volcanic rocks of the Bullfrog Hills and north and east of Bare Mountain are tuff and subordinate lava flows of Miocene age. Yucca Mountain and Crater Flat contain thick (greater than 2,000 m) sections of welded tuff. The youngest volcanic rocks are scattered rhyolite and basalt lavas of late Miocene age and small basalt flows of Pliocene and Quaternary age in and near Crater Flat. Alluvium of Pliocene and Quaternary age is relatively thin (less than 500 m) in most of the area.

Several Miocene calderas are present. Shotpoint 11 (fig. 3.1) is at the south edge of the large Timber Mountain-Oasis Valley caldera complex (Byers and others, 1976). Another slightly older group of calderas, or a volcano-tectonic depression, may be present beneath Crater Flat and possibly the northern part of Yucca Mountain (Carr and others, 1986; Carr, 1982).

The pre-Tertiary and Tertiary rocks are moderately faulted in most areas. North of Bare Mountain and to the west in the Bullfrog Hills, the structure in the volcanic rocks is dominated by complex northeast- and northwest-striking faults, many of which have had some strike-slip displacement and may be listric, that is, level off at depth. The middle and southern parts of Yucca Mountain are cut by west-dipping, north-south-striking basin-range faults. The structure within Crater Flat may be controlled by largely buried caldera ring faults; the major fault on the east side of Bare Mountain is probably part of this system (Carr, 1982).

Of particular interest with respect to this report is the presence at Boundary Canyon in the Funeral Mountains (fig. 3.1) of a low-angle detachment fault (Giarmita and others, 1983). This structure separates metamorphosed lower plate, mostly Proterozoic rocks, from overlying relatively unmetamorphosed Paleozoic rocks. This structure probably continues northeastward into the Bullfrog Hills and possibly farther to the east.

DATA COLLECTION

Both profiles reported here were collected in April 1983. The Crater Flat profile (fig. 3.1) extends northward from the Amargosa Desert valley, obliquely across the southern tip of Yucca Mountain, along the east side of Crater Flat, and to a point near the northeast corner of Crater Flat. Seven shotpoints, numbered 11 through 17, were located at approximately 8-km intervals along this profile. Shotpoint 11 lay beyond the array of seismographs about 9 km north of shotpoint 12. Each shot consisted of approximately 900 kg of ammonium nitrate emplaced in 50-m drill holes. The 46-km-long profile length was designed to provide details of the crustal structure to a maximum depth at least as great as the prevolcanic rocks, estimated to be as much as 4 ± 1 km from gravity data.

The Beatty profile (fig. 3.1) extends west from shotpoint 12 of the Crater Flat profile, past the north edge of Bare Mountain to the Bullfrog Hills. Three shots with an average spacing of 14 km were fired along the profile. They are numbered 12, 18, and 19, and had the same drill-hole depths and charge size as those on the Crater Flat profile. In addition, reconnaissance measurements were made by placing seismographs as far west as Death Valley along the Titus Canyon road. Thus, the portion of the seismic profile between the Bullfrog Hills and northern Crater Flat is reversed, but the part between the Bullfrog Hills and Death Valley is unreversed.

Data for each profile were recorded by 120 portable seismographs of recent design (Healy and others, 1982). These instruments are equipped with vertical-component seismometers having a natural frequency of 2 Hz, and the data were recorded in frequency modulated format on cassette tapes. Analog tapes were digitized in the U.S. Geological Survey laboratory at Menlo Park, Calif., at a sampling rate of 200 samples per second.

The principal facts for these profiles (shotpoint and recorder locations, timing, instrumentation, and so forth) were reported by Sutton (1984).

DATA ANALYSIS

Many methods are available for processing seismic-refraction data; their theoretical bases are well described in a number of texts (see Grant and West, 1965; Telford and others, 1976). Some of these techniques involve essentially trial-and-error fitting of the observations by successive model calculations, a process that can be as tedious for the interpreter as it is arbitrary in the final result obtained. To avoid the inherent uncertainties of trial-and-error model fitting, these refraction profiles were recorded with field parameters satisfying the requirements of a method for the direct computer inversion of the data (Ackermann and others, 1982, 1983). The primary requirements are that there be close spatial sampling of the data and multiple shotpoints along the profile.

The complete seismic record sections obtained in this study were presented without analysis by Sutton (1984). For the present analysis, arrival times were picked from expanded record sections to improve timing accuracy. Samples of the data at this scale are shown in figure 3.2. Arrival times, complete traveltime curves, smoothed elevations, and surface velocities for all shots and recorders were entered into computer data files for use in final processing.

RESULTS

Complete analysis of refraction data consists of two stages, data processing and geologic interpretation. Processing is a problem of geometrical ray tracing, done with minimum regard to geology and resulting in velocity sections indicating layers having velocities that may vary laterally. The processed velocity sections for the Crater Flat and Beatty profiles, at 6.2 times vertical exaggeration and with no vertical exaggeration, are shown in figures 3.3 and 3.4. The upper boundary (or horizon) of each layer represents the calculated path (or portion of the path) of a critically refracted ray, and the varying layer velocities represent lateral changes in velocity along a particular ray path. Seismic horizons need not conform with geologic horizons. Instead, they represent minimum time paths, which can pass from one geologic regime into another, and hence can be represented on a processed velocity section only as a change in the velocity within a layer. A case in point is shown in figure 3.3 at the boundary between southern Yucca Mountain and Crater Flat. Here the velocity of the fifth layer changes from 4.8 to 5.4 km/s, which, from geologic interpretation, probably represents a lateral change from volcanic into prevolcanic rocks.

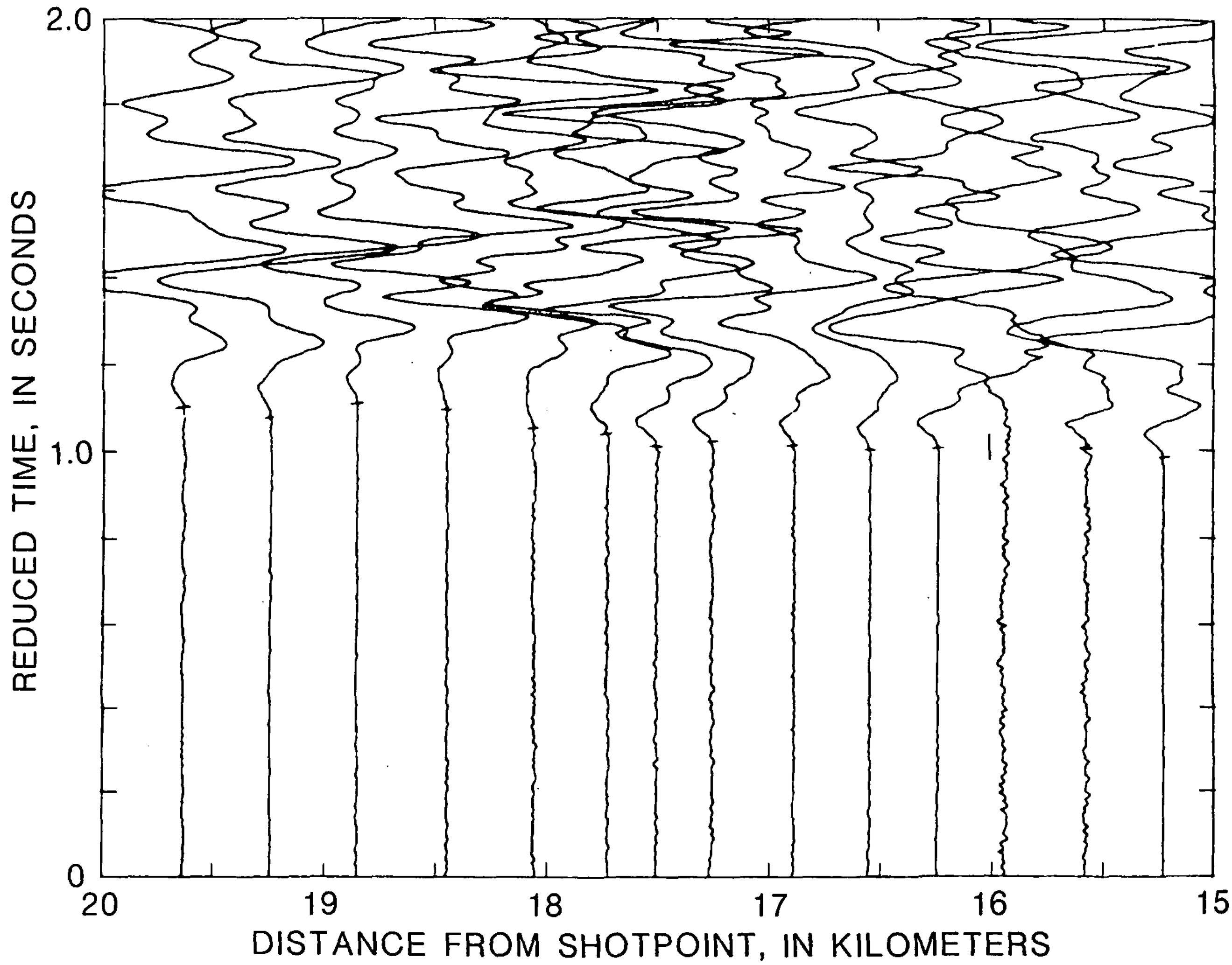

Figure 3.2. Seismic traces from shotpoint 17 on Crater Flat profile, plotted with reduced traveltime of 6.0 km/s. Small dashes on traces indicate first arrival picks. See figure 3.1 for location.

INTERPRETATION OF THE CRATER FLAT AND BEATTY VELOCITY SECTIONS

The velocity sections (figs. 3.3 and 3.4) show horizons as discrete boundaries at which an abrupt increase in layer velocity occurs. However, analysis of velocity surveys in boreholes in the Yucca Mountain area show that, although abrupt changes in velocity do occur in the subsurface, the velocity functions are best described by smooth curves rather than discrete breaks. Furthermore, analysis of borehole densities in the Tertiary tuff sequence (Snyder and Carr, 1982, 1984) show a downward increase in density mainly related to closing of pore spaces rather than to primary density variations in the tuff. Hence, we interpret, with reasonable confidence, that the discrete layers shown in the velocity sections do not necessarily represent true layering in a physical or geologic sense, but instead are our best representation of a velocity function gradually increasing with depth due to closing of fractures and pore spaces related to the depth of burial.

Two holes have been drilled near the line of sections, USW VH-1 (762 m total depth), 2 km west of the Crater Flat profile (figs. 3.1 and 3.3), and the US Borax hole (323 m total depth) along the Beatty profile (figs. 3.1 and 3.4). Both holes are relatively shallow compared to depths obtained from the present survey, and neither penetrated the prevolcanic surface.

Drill hole USW VH-1 (fig. 3.3) penetrated principally welded tuff below 155 m (Carr, 1982) and bottomed in the densely welded Bullfrog Member of the Crater Flat Tuff. A downhole velocity survey depicts a ragged curve, which we have approximated by three layers. The upper two have average velocities of 1.9 and 3.0 km/s, which are somewhat higher than the 1.5 and 2.5 km/s velocities of layers 1 and 2 (fig. 3.3). Layer 3 of the velocity survey, which begins 70 m deeper than layer 3 of figure 3.3, has an average velocity of 3.6 km/s, which is the same as that shown in the velocity section. Clearly, a closer match between velocities would be preferred in the very shallow section. Part of the discrepancy may be attributed to the assumed eastward dip of the Tertiary rocks at the location of shotpoint 14 (W.J. Carr, USGS, written commun., 1985), and the local presence of 20 m of dense basalt in drillhole USW VH-1. Furthermore, analysis of shallow seismic-refraction data and velocity logs at Yucca Mountain shows extreme variability in the velocity of the shallow volcanic rocks, and values obtained at a single drill hole may not be representative of an area. Hence, average values obtained over a broad area by refraction methods may be more representative than values obtained at a specific point location.

On the Beatty profile (fig. 3.4), Paleozoic rocks occur near the surface west of shotpoint 18. The 4.8 km/s velocity in the surface layer, therefore, indicates that these rocks are fractured, but that fractures are essentially closed or much less abundant at depths ranging between 400 and 700 m, where velocities reach 5.7 km/s. East of shotpoint 18, the seismic line runs along the north foot of Bare Mountain, entirely within tuff, but generally parallel to a major fault that dips northward and drops the tuff down along the north edge of Bare Mountain. The US Borax hole east of shotpoint 18 (fig. 3.4) bottomed at 323 m in rhyodacite lava under the thick, welded Tram Member of the Crater Flat Tuff (W.J. Carr, USGS, written commun., 1985), within the seismic layer of 4.7 km/s velocity. However, projection of the northward dip of the fault at the north edge of Bare Mountain suggests that the prevolcanic surface may also lie within this velocity layer. Our interpretation, indicated by the queried stippled region in figure 3.4, assumes that fractured prevolcanic rocks of approximately 4.7 km/s lie beneath the welded tuffs, and that fractures are closed at depths below approximately 300 to 1,300 m, where velocities are between 5.7 and 5.9 km/s.

The intrinsic seismic velocity of crystalline and other dense rocks devoid of cracks is approximately 6 km/s; joints, fractures, and weathering tend to lower this value. Beneath Crater Flat (fig. 3.3) the approximately horizontal layers 1 through 4 show the increase in velocity with depth in the thick sequence of volcanic rocks. Layer 5, of 4.7 to 4.8 km/s velocity, begins at a depth of approximately 1,600 m, and continues to a maximum depth of approximately 3,200 m beneath shotpoint 14. The prevolcanic surface may lie within this layer; however, we believe that confining pressures at these depths should be sufficient to close most cracks and pores and raise velocities of a hypothetical prevolcanic surface in this layer to well above 5 km/s. Thus, we interpret the 4.7 to 4.8 km/s layer beneath Crater Flat as comprising the deeper portion of the volcanic section filling the Crater Flat depression and the pre-volcanic rock surface (shown by solid squares) as being represented by the basal 5.7 to 6.1 km/s layer.

At the south boundary of Crater Flat (fig. 3.3), the velocity of layer 5 changes from 4.8 km/s beneath Crater Flat to 5.4 km/s beneath southern Yucca Mountain, accompanied by a rise in elevation of approximately 600 m. This velocity change implies a corresponding lateral change in rock properties, which we suggest represents a transition from the volcanic rocks beneath Crater Flat to shallower, prevolcanic rocks beneath southern Yucca Mountain. Thus, the prevolcanic surface appears to transect layer 5 and emerge as the top of layer 5 beneath southern Yucca Mountain. Here its velocity (4.9 to 5.4 km/s) is less than beneath Crater Flat (5.7 to 6.1 km/s), perhaps because of less lithostatic load on the pre-Tertiary rocks at southern Yucca Mountain. This interpretation, of relatively high-standing prevolcanic rocks below southern Yucca Mountain, agrees remarkably well with the gravity model of Snyder and Carr (1982) along their section A–A′ (see fig. 3.1), which is perpendicular to the structural trend. Their gravity model shows an abrupt rise of the prevolcanic surface at the intersection with the seismic profile, rising from 2,000 m below sea level to 400 m below sea level, as compared to our interpretation (at approximately 20° to the structural trend) of a more gradual apparent rise

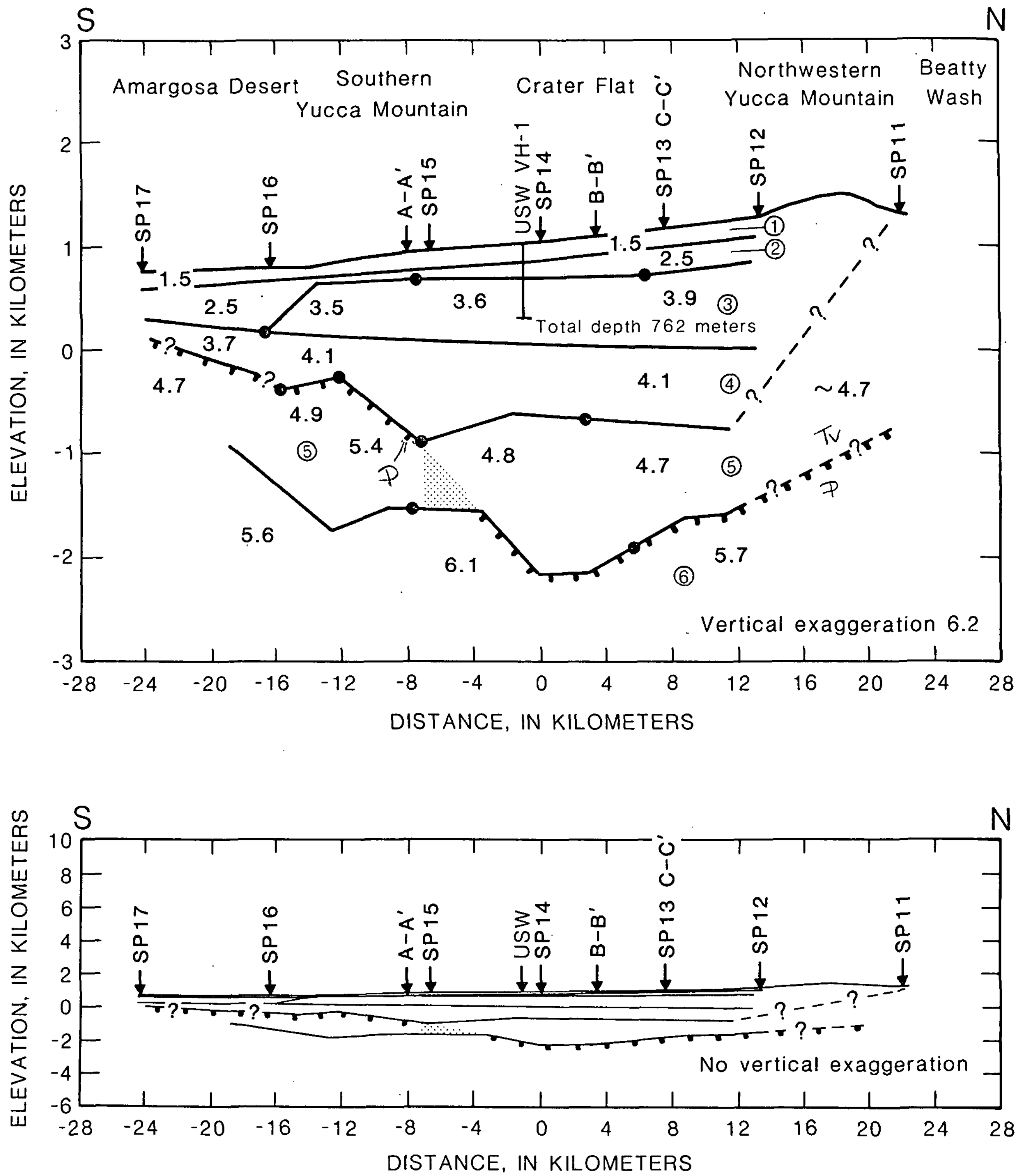

Figure 3.3. Crustal velocity section along Crater Flat profile at 6.2 times vertical exaggeration (top) and at true scale (bottom). Velocities (decimal numbers) are in kilometers per second. Inferred prevolcanic surface is shown by solid squares and zones of uncertainty by stipple pattern, queries, and dashed lines. Also shown are shotpoints (SP), layer numbers (circled), intersections with gravity profiles A–A′, B–B′, and C–C′ (fig. 3.1), and projection of drill hole USW VH–1. Dots show approximate location of lateral changes in velocity.

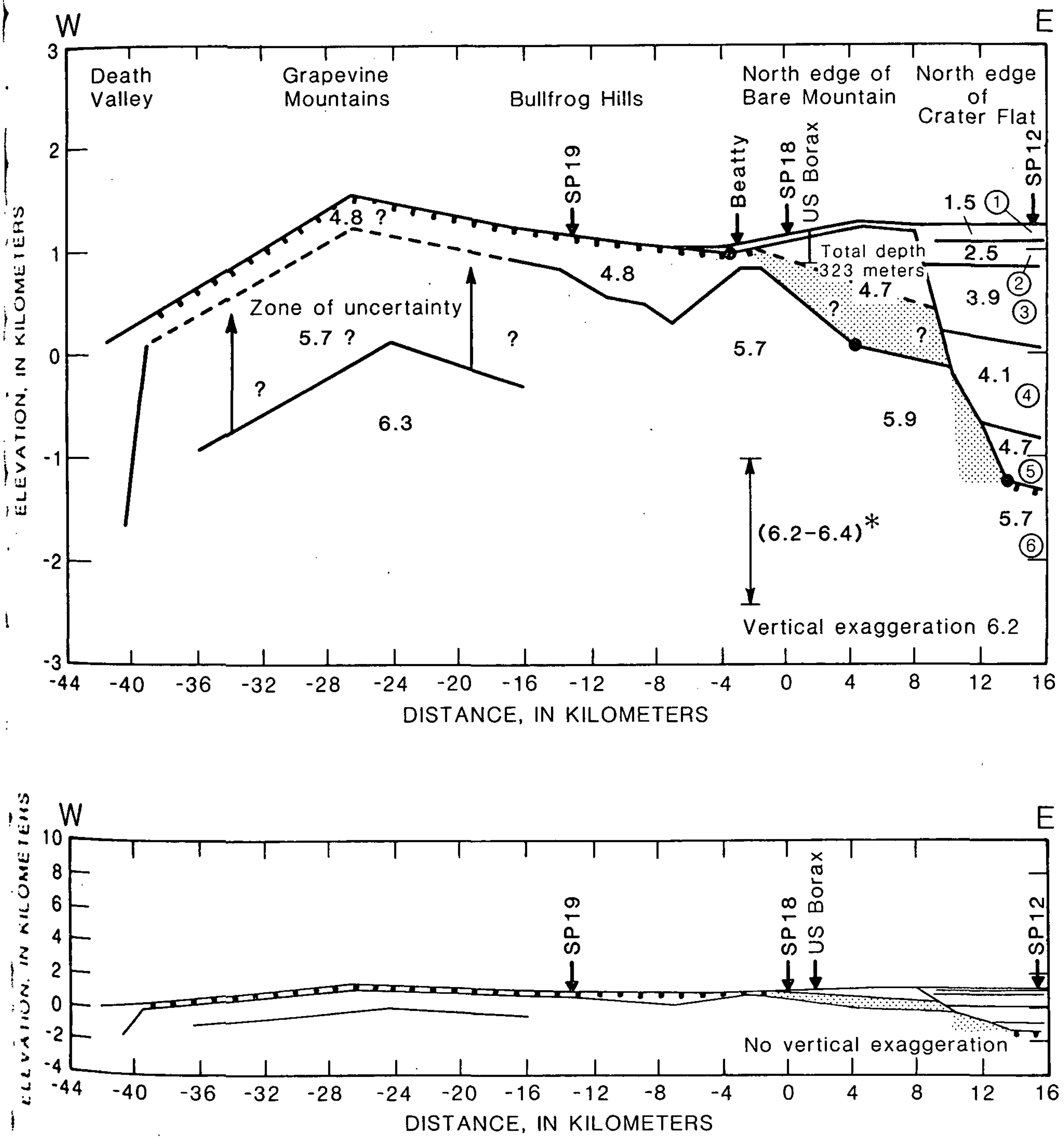

Figure 3.4. Crustal velocity section along Beatty profile at 6.2 times vertical exaggeration (top) and at true scale (bottom). Velocities (decimal numbers) are in kilometers per second. Inferred prevolcanic surface shown by solid squares and zones of uncertainty by stipple pattern, queries, and dashed lines. Also shown are shotpoints (SP), layer numbers (circled), and projection of drill hole US Borax. Dots show approximate location of lateral changes in velocity. Portion of profile from Crater Flat to Bullfrog Hills has reversed seismic coverage; that from Bullfrog Hills to Death Valley is unreversed. Shotpoint 12 (fig. 3.1) is common with Crater Flat profile. Star and double arrow indicate possible range in depth to a 6.2 to 6.4 km/s layer (Hoffman and Mooney, 1983).

from 1,600 m to 300 m below sea level. Furthermore, stratigraphic and structural data (Robert B. Scott, III, USGS, written commun., 1984) from the surface in southern Yucca Mountain also suggest a topographic high predating the deposition of the Paintbrush Tuff, which may reflect a high on the prevolcanic rock surface.

Southward on the Crater Flat profile, from southern Yucca Mountain into the Amargosa Desert valley, layer 5 decreases in velocity to 4.7 km/s and in depth to about 700 m at shotpoint 17. Although a 4.7 km/s velocity appears possible for Paleozoic or crystalline rocks at such a shallow depth, the actual rock type represented is uncertain. Nevertheless, it has been labeled with queried solid squares, suggesting a southward rise of the prevolcanic surface beneath the Amargosa Desert valley.

Geophones were not emplaced across northwestern Yucca Mountain beyond shotpoint 12. Therefore the shallow velocity structure beneath this part of the profile could not be determined. However, analysis of the traveltimes from horizons 5 and 6 for shotpoint 11 in Beatty Wash, recorded in Crater Flat, shows that velocities both beneath shotpoint 11 and the deeper part of the section beneath northwestern Yucca Mountain are significantly higher than within Crater Flat. The corresponding decreased delay times may be accounted for by projecting horizon 5 from below shotpoint 12 to near the surface at shotpoint 11 with a velocity of approximately 4.7 km/s, and projecting a corresponding rise of the prevolcanic surface beneath northwestern Yucca Mountain, shown by queried dashed lines in figure 3.3. Shotpoint 11 lies just inside the Timber Mountain-Oasis Valley caldera complex (fig. 3.1). The results from this single shotpoint suggest a marked velocity increase from Crater Flat northward into the Timber Mountain area.

Gravity modeling (Snyder and Carr, 1982) along section C–C′ (fig. 3.1) indicates that volcanic rocks could extend as deep as 5,000 m beneath the surface within Crater Flat. Snyder and Carr also discussed a three-dimensional gravity model with a prevolcanic rock surface at approximately 3,500 m depth (2,500 m below sea level). We suggest that the latter model is the more accurate given the present seismic interpretations (fig. 3.3), which indicate that volcanic rocks do not extend beyond 3,200 m depth.

The unreversed seismic-refraction profile by Hoffman and Mooney (1983) is approximately coincident with the gravity traverse B–B′ (fig. 3.1) of Snyder and Carr (1982), and was interpreted with reference to their two dimensional gravity model. Hoffman and Mooney concluded that a layer with a velocity of 5.7 km/s occurs at a depth of 2,200 m below sea level in central Crater Flat and interpreted it to represent prevolcanic rocks on the basis of its high velocity. The present Crater Flat profile crosses their earlier profile between shotpoints 13 and 14, where we have independently interpreted the same depth to a prevolcanic rock surface with a velocity between 5.7 and 6.1 km/s.

d = 2.2km

The salient feature of the Beatty profile (fig. 3.4) is the large displacement of the interpreted prevolcanic surface, marked by stipple, at the boundary between the north edge of Bare Mountain and the Crater Flat depression. Approximately 6 km to the east, near shotpoint 12, interpretation of the seismic profiles places the prevolcanic rock surface at a depth of about 2,600 m. The total fault displacement at this location is indeterminate due to complicating factors introduced by the intersecting east-west-trending fault discussed earlier, at the north foot of Bare Mountain. Approximately 3 km to the south, however, Paleozoic rocks at Bare Mountain are exposed at the surface, and the depth to the interpreted prevolcanic surface remains approximately the same. Therefore, we infer approximately 2,600 m of Tertiary (?) fault displacement near the northeast edge of Bare Mountain.

The portion of the Beatty profile between Death Valley and the Bullfrog Hills (fig. 3.4) is unreversed. Therefore, layer velocities and depths are poorly constrained and numerous solutions are possible. For example, data from the indicated 4.8 and 5.7 km/s layers were recorded only within 6 km west of shotpoint 19, due in part to the large offset (fig. 3.1) of the seismic line there. The boundary (dashed line, fig. 3.4) between these two layers has simply been extrapolated from shotpoint 19 west to Death Valley.

Although velocities and depths in the Grapevine Mountains area remain highly speculative, two conclusions can be drawn with certainty. The first is the existence of a large thickness of low-velocity material at the boundary between the Grapevine Mountains and Death Valley, shown in figure 3.4 by the abrupt termination of the 5.7 km/s horizon. The second is a layer shown beneath the Grapevine Mountains, whose approximate velocity is 6.3 km/s. The possible continuation of this layer northeastward beneath the Bullfrog Hills could not be determined without additional shotpoints. Choosing alternate ray paths permits this 6.3 km/s layer to be moved up beneath the Grapevine Mountains by as much as 500 to 1,000 m, indicated in figure 3.4 by the two queried arrows pointing upward. A shallower depth, however, would require a significant downward displacement or disappearance of the 6.3 km/s layer beneath the Bullfrog Hills, but Hoffman and Mooney (1983) did identify a seismic layer of 6.2–6.4 km/s at a depth 1.0–2.4 km below sea level beneath Beatty, as shown in figure 3.4. Several additional shotpoints would have helped to resolve the problem of depth to the 6.3 km/s layer beneath the entire Beatty profile.

VELOCITY, DENSITY, AND DEPTH RELATIONS

The relations of density and velocity vs depth, shown in figure 3.5, were obtained from borehole gravity measurements and gamma-gamma logs in drill hole USW H1, located at the proposed repository site on Yucca Mountain (Snyder and Carr, 1982, 1984). It shows a linear increase in density with depth of 0.26 g/cm^3 per kilometer. A similar gradient and lithologic sequence is assumed in Crater Flat. The layered velocity distribution at shotpoint 14 of the Crater Flat profile, shown by the step functions, has been roughly approximated on the assumption of a more uniform increase in velocity with depth by three linear segments labeled A, B, and C with respective gradients of 6, 0.9, and 0.4 km/s per kilometer. The gradient of segment C is constrained on the assumption of a possible maximum velocity of 5.2 km/s in the volcanic section, suggested by a 4,170-m-deep borehole (UE20f, not shown) in the Silent Canyon caldera (Pahute Mesa) that penetrated 468 m of lava and welded rhyolitic tuff in the deepest part of the hole having a maximum velocity of 5.1 km/s and bulk density of 2.56 g/cm^3 (Carroll, 1966). The decrease in gradient of the velocity curve at 1,750 m depth, which also marks the greatest depth of measured borehole densities, suggests a similar decrease in the gradient of the density curve.

In a plot of velocity against density (fig. 3.6), which may be representative of the Yucca Mountain region, segments A and B, obtained from the parametric plots in figure 3.5, represent the welded tuff. The point P1 (velocity 6.4 km/s, density 2.75 g/cm^3) was obtained from logs in drill hole UE-25P1 (fig. 3.1) (Muller and Kibler, 1984) and is representative of 661 m of Paleozoic dolomite penetrated at depths below about 1,200 m. We have connected point P1 with segment B in figure 3.6, and suggest that this part of the density-velocity plot roughly approximates both the prevolcanic and the volcanic rocks having velocities greater than 4.7 km/s. The point PM (velocity 5.1 km/s, density 2.56 g/cm^3) from the deep drillhole UE20f at Pahute Mesa, plots slightly above this line.

No previous density determinations have been made for the prevolcanic rocks beneath Crater Flat here interpreted to have velocities between 5.7 and 6.1 km/s. Densities between 2.64 and 2.70 g/cm^3 can be extracted from the density-velocity plot (fig. 3.6). These values may represent approximate typical density values for deeply buried

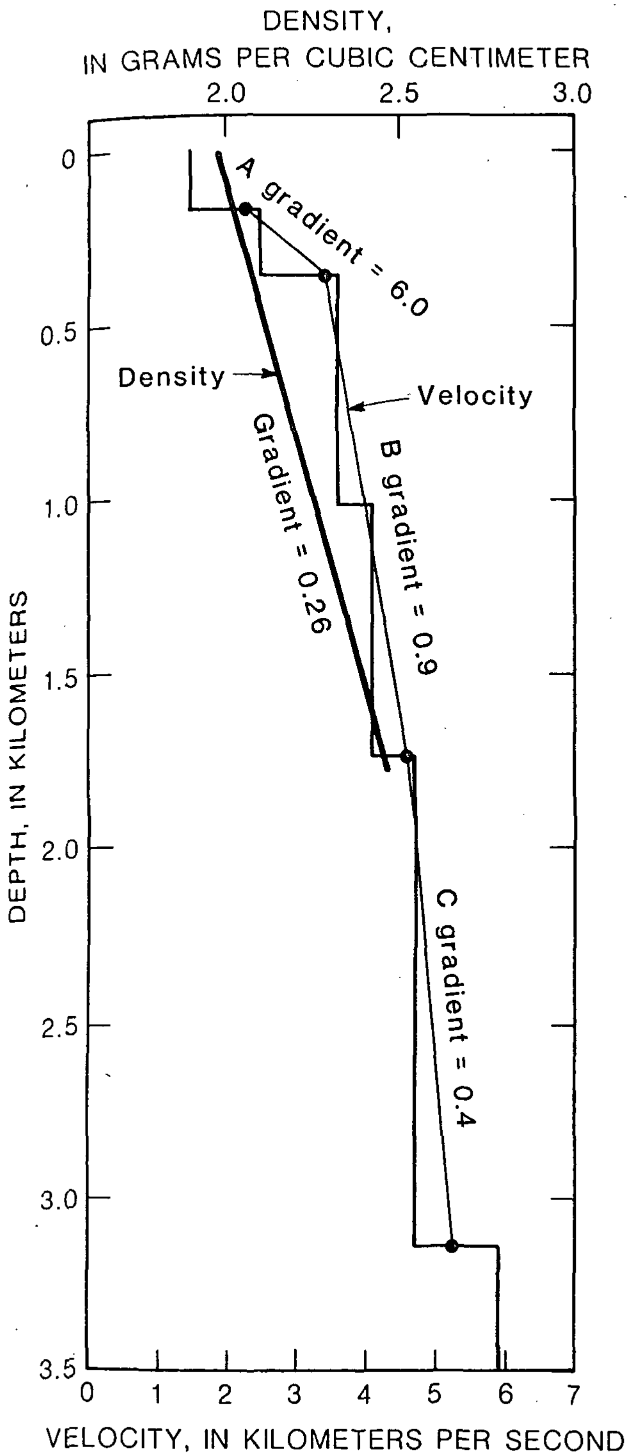

Figure 3.5. Plots of velocity and density against depth. Density plot is from Snyder and Carr (1982, 1984). Velocity step functions are from Crater Flat portion of figure 3.3. Line segments A, B, and C are smoothed representations of step functions.

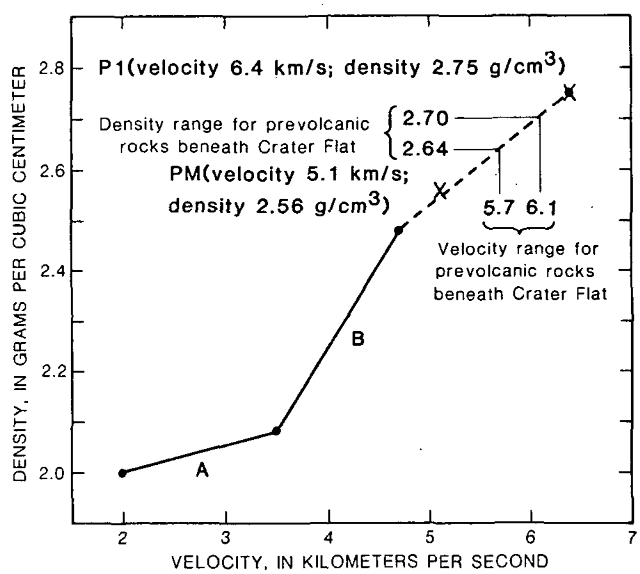

Figure 3.6. Plot of velocity against density. Segments A and B derived from figure 3.5. Point P1 obtained from prevolcanic rocks in drill hole UE-25P1 (fig. 3.1) on east side of Yucca Mountain, and point PM from volcanic rocks in drill hole UE20f (not shown) on Pahute Mesa.

prevolcanic rocks in this region. On the other hand, densities between 2.7 and 2.8 g/cm^3 were required for the rocks in Bare Mountain (Snyder and Carr, 1982) to satisfy gravity data, which implies that the Paleozoic rocks composing the core of Bare Mountain are different from the prevolcanic rocks beneath Crater Flat. However, differences may be due to a disordered state of the prevolcanic rocks under Crater Flat rather than to any lithostratigraphic difference.

On the basis of the conclusions discussed above, a new gravity model (fig. 3.7) has been constructed from Death Valley to Crater Flat that approximates the Beatty seismic profile (fig. 3.4). Densities were selected to match the velocity values suggested by figure 3.6. This gravity model indicates that the 6.3 km/s (2.74 g/cm^3) layer dips eastward from the Grapevine Mountains to Bare Mountain at depths from 1,000 m above to 1,500 m below sea level. Thus, the gravity model suggests continuity between the 6.2–6.4 km/s layer beneath Beatty (Hoffman and Mooney, 1983) and the 6.3 km/s layer beneath the Grapevine Mountains described in this study.

POSSIBLE RELATION OF GEOPHYSICAL DATA TO DETACHMENT FAULTS

A low-angle fault or detachment surface is exposed about 10 km south of the Beatty profile in the Grapevine Mountains at an elevation of about 1,000 m above sea level (Monsen, 1983; Giarmita and others, 1983). This structure, called the Boundary Canyon fault, juxtaposes a highly fractured Paleozoic section upon a metamorphosed Precambrian and lower Paleozoic section. The seismic and gravity interpretations presented here suggest the possibility that this fault surface may correspond to the 6.3 km/s, 2.74 g/cm^3 horizon and continue east of the Grapevine Mountains beyond the Bullfrog Hills area as far as the fault separating Bare Mountain and Crater Flat.

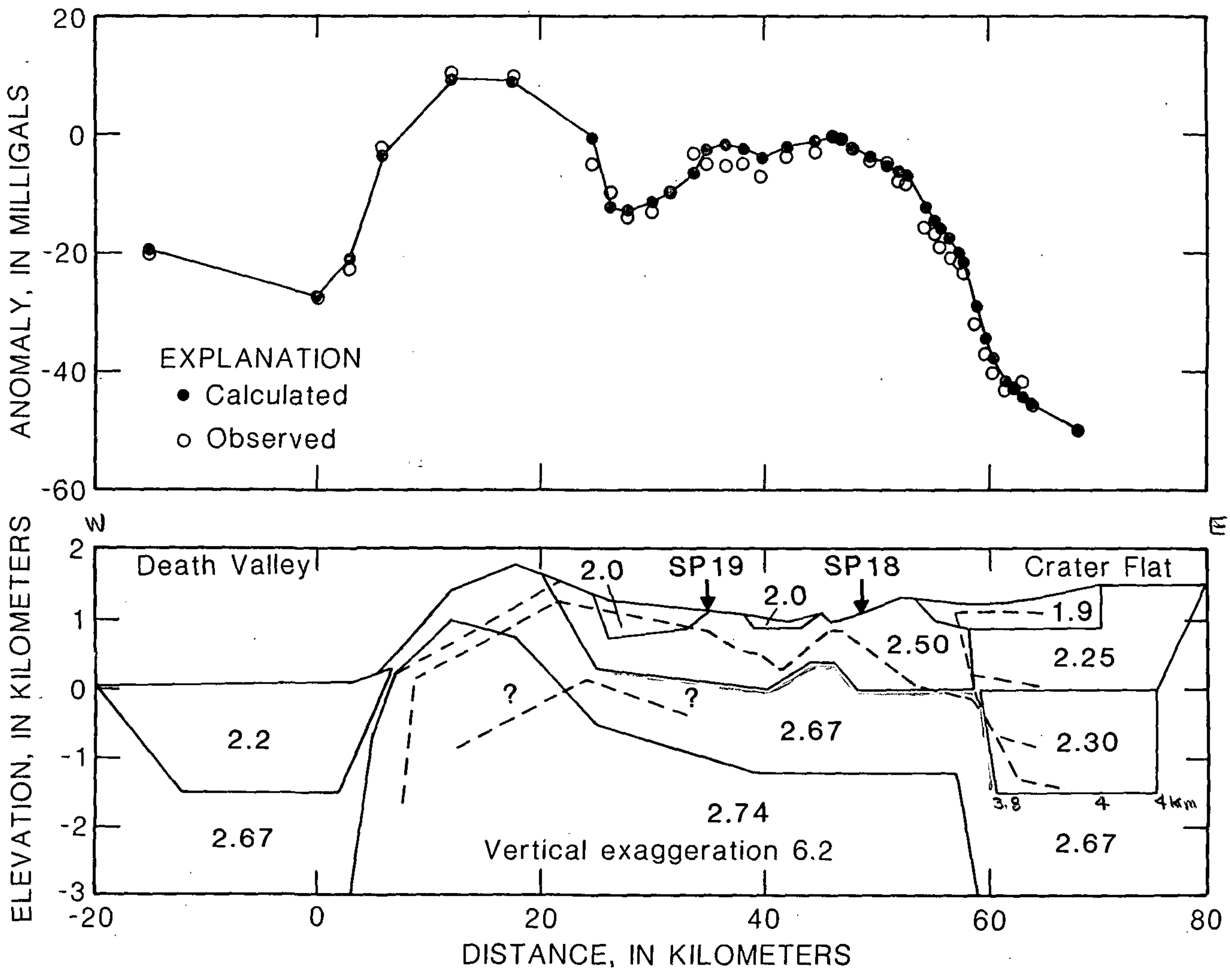

Figure 3.7. Two-dimensional gravity model approximately coincident with seismic-refraction section in figure 3.4. Values are in grams per cubic centimeter and indicated bodies are assumed homogeneous. Densities from figure 3.6. Observed gravity values from Healey and others (1980). Dashed lines show velocity section of figure 3.4; shotpoint, SP.

d @ YM (57) ≈ 1200 m

CONCLUSIONS

The interpretation of seismic-refraction velocity sections indicates that volcanic rocks have a maximum thickness of about 3,200 m in Crater Flat (fig. 3.3), filling a depression interpreted by Snyder and Carr (1982, 1984) and Carr and others (1986) as a caldera complex. The depression is 25–30 km long in a north-south direction and about 20 km wide east-west. The prevolcanic rock surface exhibits some 2,000 m of vertical relief between the south end of Yucca Mountain and the center of Crater Flat. A fault on the east side of Bare Mountain (fig. 3.4) downdrops exposed Paleozoic rocks about 2,600 m into Crater Flat.

The seismic velocities of the prevolcanic rocks are between 5.7 and 6.1 km/s within the deeper parts of the Crater Flat depression, where lithostatic loading has closed fractures. At shallower depth, velocities of the prevolcanic rocks may be less, possibly as low as 4.7 km/s within approximately 1,000 m of the surface.

The velocities in the volcanic section beneath Crater Flat reach 4.7 to 4.8 km/s at a depth of approximately 1,600 m. However, data from a single offset shotpoint (shotpoint 11) in Beatty Wash, just within the Timber Mountain-Oasis Valley caldera, suggest that volcanic rocks beneath the northwestern part of Yucca Mountain reach a 4.7 km/s velocity at considerably shallower depth and are near the surface beneath shotpoint 11.

A graph of density against velocity, which may be representative of the volcanic and prevolcanic rocks in the Yucca Mountain region, has been determined (fig. 3.6). Based on this graph, a gravity model approximately coincident with the Beatty profile suggests that the Boundary Canyon detachment fault, exposed in the Grapevine Mountains, may be continuous as far east as Bare Mountain.

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