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DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

MAJOR RESULTS OF GEOPHYSICAL INVESTIGATIONS AT YUCCA MOUNTAIN AND VICINITY, SOUTHERN NEVADA

H.W. Oliver, D.A. Ponce, and W. Clay Hunter
Editors

1995

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Menlo Park, California

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U.S. Geological Survey Open-File Report 95-74

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Menlo Park, California
1995

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MAJOR RESULTS OF GEOPHYSICAL INVESTIGATIONS AT YUCCA MOUNTAIN AND VICINITY, SOUTHERN NEVADA

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ABSTRACT

On December 17, 1987, Congress named Yucca Mountain in southern Nevada as the only site in the United States to be characterized for long-term underground storage of high-level nuclear waste from nuclear power plants. Yucca Mountain is located about 110 km north of Las Vegas and is near the southwest corner of the Nevada Test Site. The potential storage area itself is located under the east-central part of Yucca Mountain. The so-called site area is a large area (12 by 18 km) which includes hydrologic, geologic, and environmental study areas. In the consideration of Yucca Mountain as a possible site for storing high-level nuclear waste, a number of geologic concerns have been suggested for study by the National Academy of Sciences which include (1) natural geologic and geochemical barriers, (2) possible future fluctuations in the water table that might flood a mined underground repository, (3) tectonic stability, and (4) considerations of shaking such as might be caused by nearby earthquakes or possible volcanic eruptions.

This volume represents the third part of an overall plan of geophysical investigation of Yucca Mountain, preceded by the Site Characterization Plan (SCP; dated 1988) and the report referred to as the "Geophysical White Paper, Phase I," entitled *Status of Data, Major Results, and Plans for Geophysical Activities, Yucca Mountain Project* (Oliver and others, 1990). The SCP necessarily contained uncertainty about applicability and accuracy of methods then untried in the Yucca Mountain volcano-tectonic setting, and the White Paper, Phase I, focused on summarization of survey coverage, data quality, and applicability of results. For the most part, it did not present data or interpretation. The important distinction of the current volume ("Geophysical White Paper, Phase II") lies in presentation of data, results, and interpretations of selected geophysical methods used in characterization activities at Yucca Mountain, largely through 1990. Constraints of funding, scheduling, and applicability or availability of methods resulted in unavoidable variability of time frame of individual investigations. Separate chapters combined here were completed at various times over several years.

Yucca Mountain consists of a series of north-trending, eastward-tilted structural blocks bounded by steeply westward-dipping Cenozoic faults. These blocks consist of terrigenous volcanic and sedimentary rocks of Miocene age. The configuration of the base of the Tertiary section is poorly known as only one drill hole in the site area has reached the pre-Tertiary basement rocks. That hole (UE-25 p#1) was intentionally drilled near a regional gravity high near the eastern edge of central Yucca Mountain and intersected Paleozoic dolomite at a depth of about 1.2 km. Several other drill

holes to the north and west within Yucca Mountain have penetrated up to 1.8 km of Tertiary rocks without reaching the Paleozoic basement rocks.

Some of the most important geologic questions that need to be answered are (1) the depth to, and nature of, the contact between the Cenozoic and Paleozoic rocks, (2) the origin and possible activity of the Quaternary faults, (3) the origin and stability of a rise of about 300 m in the potentiometric surface to the north of an approximate boundary of a potential repository, and (4) the possibility of future nearby volcanic activity. As the surface of Yucca Mountain is largely covered with Miocene volcanic flows assigned to the Tiva Canyon Tuff of the Paintbrush Group, geophysical methods and drilling are required to determine the subsurface structure and to answer these questions.

Gravity investigations began about 1979 at Yucca Mountain and immediately showed that Yucca Mountain does not have a basement core like so many ranges in Nevada. Rather, it is characterized by a gravity high at its east edge and a westward gravity decrease of about 20 mGal (milligals) across Yucca Mountain to about 7 km inside Crater Flat. This gravity decrease has been modeled, and the models show a rather linear westward increase in the depth to Paleozoic basement rocks from about one to three or four km depending on the assumed density contrast between the Cenozoic volcanic rocks and the Paleozoic basement rocks. This westward drop-off in the basement rocks was initially interpreted as the edge of a caldera but has more recently been envisioned as a low-angle fault surface with a dip of about 10° to the west. Farther west, gravity rises rapidly across Crater Flat by about 50 mGal to the west edge of Bare Mountain where it levels out and stays rather flat across Bare Mountain. The curious observation is that the maximum gravity gradient occurs well out into Crater Flat and thus can't be modeled by a simple frontal fault at the edge of Bare Mountain. These data suggest the possibility of a significant basement down-drop to the east about 3 km west of the Bare Mountain front, although a significant facies change within the Cenozoic section could also explain the data.

Gravity investigations support additional conclusions about the setting of Yucca Mountain. North of Yucca Mountain, several circular gravity lows of up to 50 mGal amplitude outline a series of calderas, the largest of which is the Timber Mountain Caldera. To the east, the gravity field drops only about 6 mGal over Jackass Flats and stays rather constant for a distance of 15 to 20 km. Thus, no significant structures apparently lie under Jackass Flats. More recently, the gravity method has become very helpful in locating and tracing north-striking concealed faults near the east side of Yucca Mountain and in Midway Valley where extensive surface facilities are planned.

Regional magnetic investigations of the Yucca Mountain area have been facilitated by the compilation of 39 aeromagnetic surveys in southern Nevada and 11 surveys in adjacent parts of California. The most important regional feature near Yucca Mountain is a magnetic high that extends from southeast to northwest over Wahmonie, the Calico Hills, and across the northern third of Yucca Mountain to the Prospector Pass caldera. This feature is associated with exposed Tertiary granitic rocks at Wahmonie and with altered magnetite-bearing Paleozoic argillites in the Calico Hills. Thus, where the magnetic high crosses

Yucca Mountain, it probably indicates a change in the basement rocks from the dolomite drilled under the east-central part of Yucca Mountain to some sort of granite, perhaps with some intervals enhanced by baked argillite. Depth analysis of the maximum gradient of the edge of the anomaly where it crosses Yucca Mountain indicates contact between magnetic and nonmagnetic basement at about 2.2 km, and this is presently the only estimate of basement depth under the northern part of Yucca Mountain. This finding has important implications on structural and mineral assessment models of the area.

Several local dipolar magnetic anomalies have been found within Crater Flat and the nearby Amargosa Desert, and these may be caused by buried volcanic centers. The largest of these anomalies occurs just south of Lathrop Wells was drilled in 1991. Basalt was penetrated at a depth of 104 m. Similarly, drilling near another nearby magnetic anomaly encountered basaltic cobbles at 183 m. Thus, the magnetic method is apparently able to locate buried basaltic centers, and this information is making an important contribution to estimates of the probability of future volcanic activity in the region.

Both aeromagnetic and ground magnetic methods have also proven useful for locating concealed faults, because there are several layers within the tuffs that form the Paintbrush Group which have large remanent magnetizations, both normal and reversed. In the Yucca Mountain area, the expected signal from north-striking faults is a magnetic low to the west followed by a rise to the east of the fault of about double the magnitude of the western low. This model has been tested with airborne data which show that a 70-m-offset vertical fault displacement is required to produce a significant aeromagnetic anomaly. However, smaller displacements can be detected with ground magnetic data, and initial studies in Midway Valley and of the Ghost Dance fault indicate that the method can be very helpful for tracing concealed faults.

Another application of aeromagnetic data is the determination of the depth and structure of the Curie isotherm (400° to 580° C depending on the amount of titanium in the magnetite). This temperature is reached at a depth of about 25 km under Yucca Mountain, but the isotherm structure is uncertain because of present limitations of data, particularly to the west in the Death Valley area. In southern Nevada, there is a good correlation between Curie isotherm depth greater than 25 km and low heat flow values north of Yucca Mountain.

Five magnetotelluric surveys were made from 1965 to 1986 in the region of Yucca Mountain. These surveys provide (1) comparative cross-sections across the Walker Lane (tectonic) belt southwest of Yucca Mountain (based on composited one-dimensional modeling), (2) a complementary cross section across the southern part of Yucca Mountain from Bare Mountain through part of Jackass Flats (based on 2-D modeling), and (3) tipper (vertical magnetic field) data that indicate a regional north-northwestern strike in electrically conductive faults, locally perturbed by conductive elements associated with caldera structures. Four main resistivity layers are found in the Yucca Mountain region, including (1) a ubiquitous, conductive, surface layer (10 to 30 ohm-m) composed of alluvium or weathered rock outcrops; (2) variably shallow (2 to 12 km), relatively conductive layers (30

Amargosa Desert and suggested that the top of this lower crustal sequence is shallower to the west, toward metamorphic core-complex exposures in the Funeral Mountains. Interpretations of the reflection data suggest that the crust is between 30 and 33 km thick under the Amargosa Desert. Reflection profiling in the vicinity of Yucca Mountain conducted in 1994 has helped to reveal the geometry of the pre-Tertiary/Tertiary contact under Crater Flat, Yucca Mountain and Jackass Flats, as well as the regional crustal structure in the Walker Lane belt.

Teleseismic tomography of compressional phases in the Yucca Mountain site area and region has been used to delineate any extant magma systems and to map tectonic structures that might affect a potential nuclear waste repository. An upper-mantle high-velocity anomaly has been interpreted beneath the Miocene Silent Canyon caldera. If this anomaly is related to volcanic activity in the Southwestern Nevada Volcanic Field, it may represent cooled residuum from the volume that once delivered heat to that system. Hence, the Southwestern Nevada Volcanic Field appears to be dead at its roots. A large volume of low-velocity upper mantle adjacent to this high may be any of several things, including partial melt. If it is the latter, it represents a large heat source for possible volcanism near the site area. The presence of large, mature, silicic magma chambers in the crust near Yucca Mountain can be ruled out, but a weak columnar low-velocity feature is present. This low-velocity object may be interpreted in various ways, one interpretation being local heating of the crust. Lastly, teleseismic tomography suggests that the eastern boundary of the Crater Flat depression falls very near or beneath the repository block and should be evaluated further.

Over most of the southwestern United States, heat flow is high, between 60 and 90 mW m^{-2} (milliwatt per square meter). There are significant areas of both higher and lower heat flow, however, and these heat-flow sources and sinks generally correspond to the tectonic history of the area under consideration. Yucca Mountain is located near the southern boundary of the "Eureka Low," a region of low heat flow (<63 mW m^{-2}), which occupies much of east-central Nevada. From both deep temperature profiles and hydrologic studies, the primary cause of the low heat flow is thought to be interbasin water flow with a downward component of seepage velocity of a few millimeters per year. Measurements of heat flow near Yucca Mountain do not provide unambiguous indications of tectonic processes. In fact, within the area of the potential repository, the thermal regime appears to be dominated by water flow in the Paleozoic carbonate rocks underlying the Tertiary section. For this reason, the interpretation of existing shallow thermal data is more relevant to hydrologic characterization than to identification of tectonic hazards. Proposed deep holes at Yucca Mountain and Crater Flat might provide thermal data that bear on both tectonic and hydrologic investigations.

Stress measurements indicate that the present-day stress regime at Yucca Mountain is coupled to the extensional tectonics of the Basin and Range province. The present-day state of stress is consistent with recurrent movement on normal faults dipping about 60° and striking about N25°E. The magnitude of shear stress on faults with this orientation is near the value required for faulting on preexisting faults. A modest increase in the shear stress or the fluid pressure therefore could cause movement on preexisting faults. The best set of stress data was obtained in drill hole USW G-1, where measurements between 646 meters and 1288 meters define a linear increase of the least horizontal stress with depth. This systematic linear increase of the magnitude of horizontal stress with depth suggests that this stress may reflect some failure mechanism. The dimensionless stress-parameters (vertical versus horizontal stress, shear versus normal stress, and orientation of the shear stress relation) associated with rock deformation and faulting are invariant with depth in drill hole USW G-1 and suggest that the stresses are limited by rock deformation in the present-day stress field. The ratio of shear to normal stress may be interpreted as a dimensionless coefficient of friction in a Mohr-Coulomb frictional faulting model. We explicitly avoid that association, however, to reach the more general conclusion that some failure mechanism is limiting the stresses observed on Yucca Mountain.

The ground water system at Yucca Mountain may be coupled to the tectonic stress field. In crystalline rocks, most of the permeability and connected porosity is contained in open fractures. When rocks in an extensional environment begin to fail, fractures open, the porosity and permeability increase, and the hydrologic system may be modified. A magnitude 5.6 earthquake occurred, however, at Little Skull Mountain, 23 km southeast of the potential repository, in June 1992. Temporary earthquake-induced fluctuations of water level were measured in instrumented boreholes. The maximum estimated short-term water-level fluctuation from the Little Skull Mountain earthquake was 40 cm.

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MAJOR RESULTS OF GEOPHYSICAL INVESTIGATIONS AT YUCCA MOUNTAIN AND VICINITY, SOUTHERN NEVADA

CHAPTER 1: INTRODUCTION AND GEOLOGIC SETTING

By H. W. Oliver and D.A. Ponce

INTRODUCTION

On December 17, 1987, Congress named Yucca Mountain in Nevada as the only site in the United States to be characterized for long-term underground storage of high-level nuclear waste. This decision preempted earlier plans for the evaluation of at least three western sites by the Department of Energy (Oliver, 1987; American Geophysical Union, 1987; Manastersky, 1988; U.S. Department of Energy, 1986, p. 1). The location of the Yucca Mountain site relative to major physiographic features is shown in fig. 1.1, and the site's relation to terrain and drainage in southern Nevada and southeastern California is shown in fig. 1.2. The Nevada Test Site and the Yucca Mountain site area located in the southwestern part of the Nevada Test Site are depicted in fig. 1.3. Other areas within the Nevada Test Site that have been considered for storage of radioactive waste are Syncline Ridge, Wahmonie and the Calico Hills. Nuclear tests were initially made in Frenchman Flat, followed by larger tests in Yucca Flat, Rainier Mesa, and Pahute Mesa. The potential storage area for radioactive waste is shown in comparison to the "Preliminary Boundary of the Accessible Environment" (fig. 1.4). This environmental, hydrologic and geologic study boundary extends 3 to 6 km outside the approximate potential repository boundary to the eastern edge of the site area. The Site Area itself is about 12 km wide by 20 km long and is an informal boundary marking the area of detailed study by participants in the characterization of the Yucca Mountain site.

This volume is intended as a companion, and successor, to preceding descriptions of selected past and planned geophysical investigations at Yucca Mountain embodied in two documents, the Site Characterization Plan for the Yucca Mountain site (U.S. Department of Energy, 1988), and the report referred to as the "Geophysical White Paper, Phase I," entitled *Status of Data, Major Results, and Plans for Geophysical Activities, Yucca Mountain Project*, produced in 1990 and authored by H.W. Oliver, E.L. Hardin, and P.H. Nelson (Oliver and others, 1990). The Site Characterization Plan necessarily contained uncertainty about applicability and anticipated accuracy of geophysical methods then untried in the Yucca Mountain volcano-tectonic setting. The initial White Paper (Phase I) provided an integrated summary of geophysical survey coverage, data quality, and applicability of results as a means to relate planned and completed activities. That report for the most part did not present data or interpretation, and therein is the important distinction of the current volume. This White Paper (Phase II) presents data, results, and interpretations developed from application of selected geophysical methods to the task of characterization of the Yucca Mountain site, largely through 1990. This volume joins the preceding two documents in an overall plan to provide a synthesis of geophysical investigations at Yucca Mountain. It should be carefully noted that constraints of scheduling, funding, and applicability or availability of method(s) resulted in variability of the time frame of separate

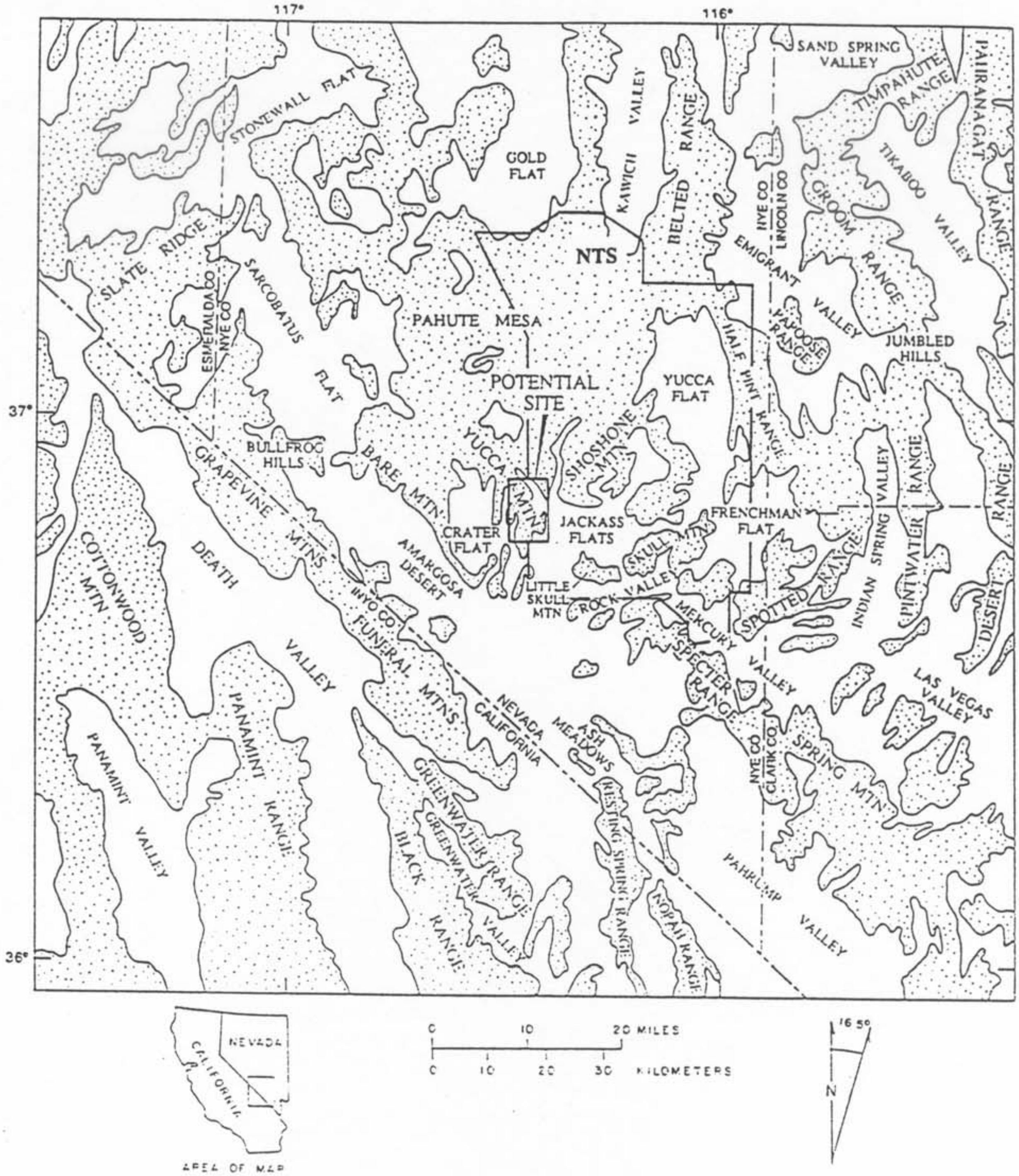


Figure 1.1 Location of Yucca Mountain site. Outline of the Nevada Test Site (NTS) is also shown. Elevated regions and major physiographic features are labeled. Modified from U.S. Geological Survey (1984, fig. 1).

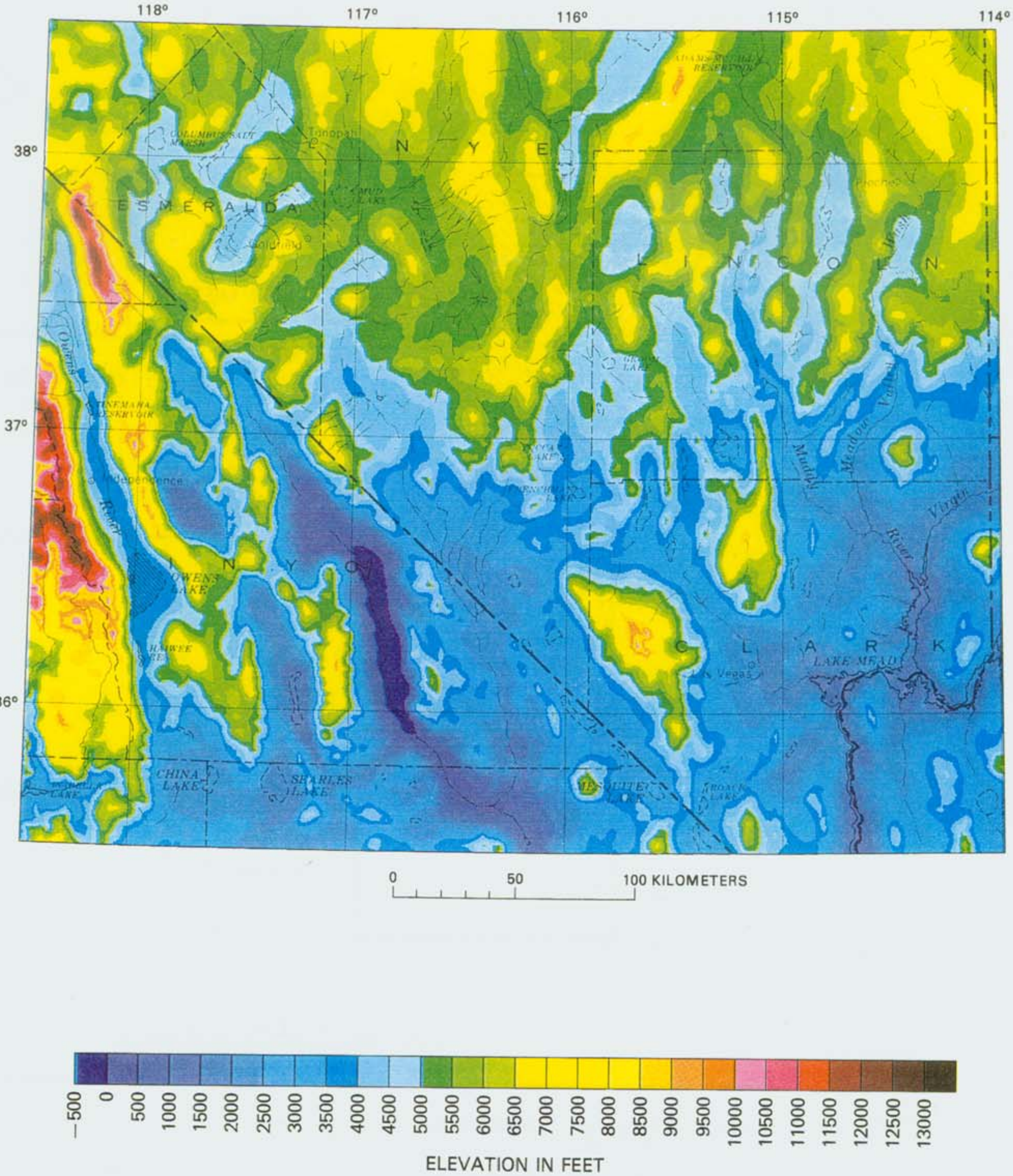


Figure 1.2. Terrain map of the southern Great Basin showing the potential site at Yucca Mountain. Modified from Hildenbrand and others (1988, fig. 2.5).

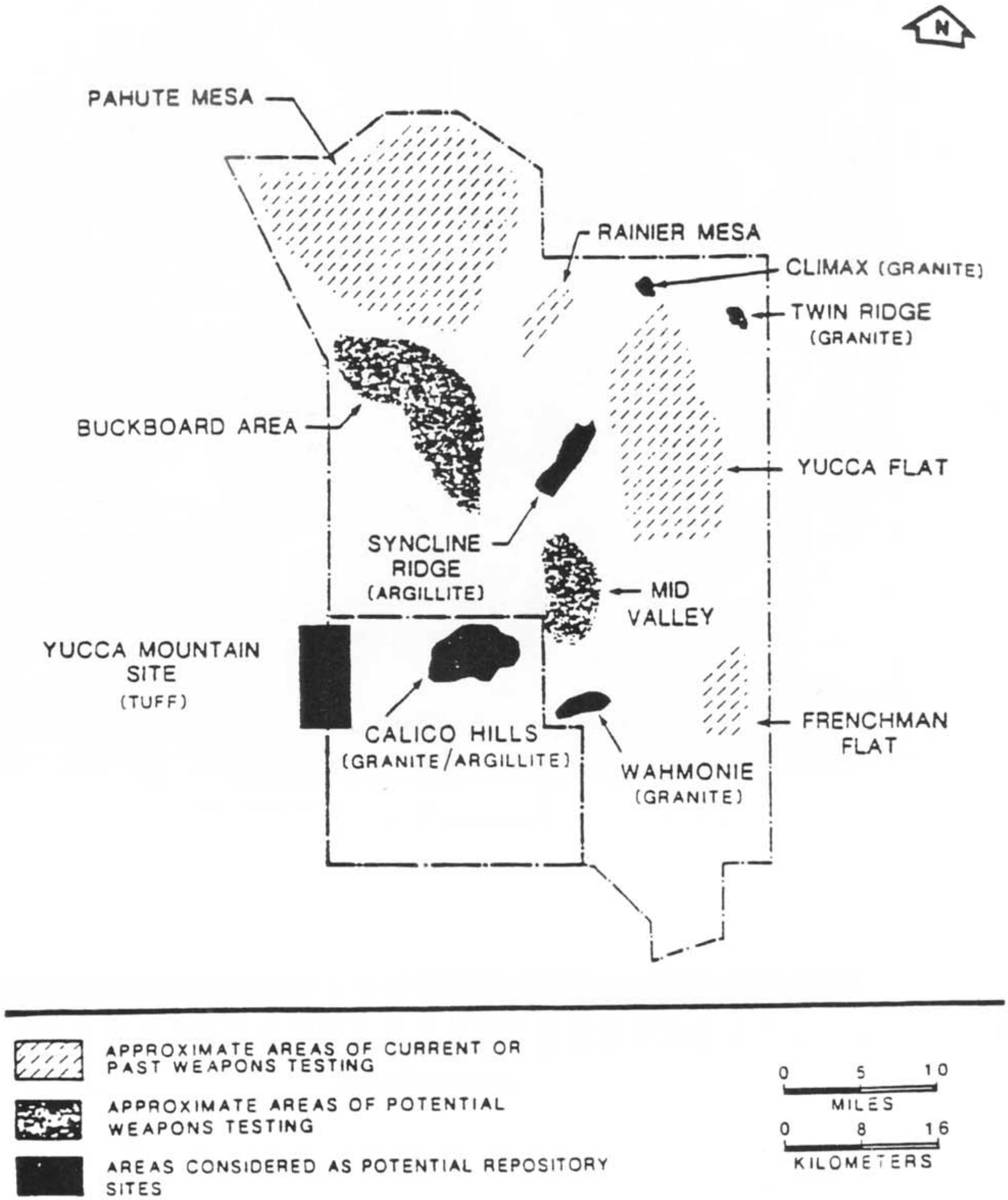


Figure 1.3. Past, current, or potential future weapons-testing areas on the Nevada Test Site and areas initially considered for high-level nuclear waste storage. See fig. 1.1 for location of Nevada Test Site. Modified from U.S. Department of Energy (1984, fig. 2-7).

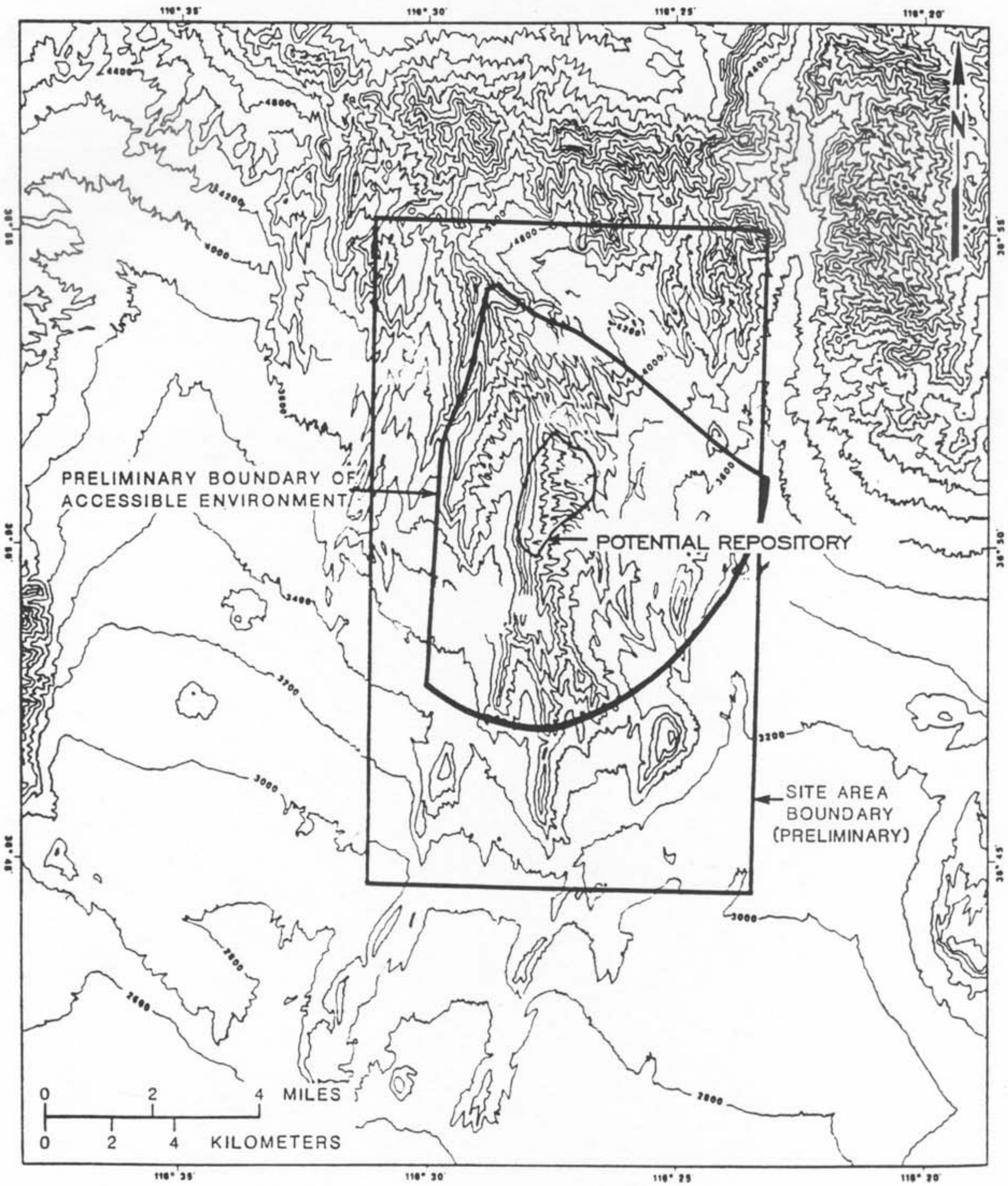


Figure 1.4. Locations of the potential repository and the preliminary boundary of accessible environment within the potential site area. Modified from U.S. Department of Energy (1988, fig. 8.3.1.4.-2).

investigations, and separate chapters combined here were completed at various times over several years. Limited updates of data sets or interpretation are incorporated into some chapters, but an inconsistency of time frame is an unavoidable part of this document.

In considering Yucca Mountain and other locations as possible sites for storing high-level radioactive waste, the National Academy of Sciences (1978) and the Nuclear Regulatory Commission (1983) recommended study of a number of geologic topics, supported in part by geophysical investigations. These topics include (1) natural geologic and geochemical barriers to help contain possible contaminated ground water and isolate it from the biosphere, (2) future fluctuations in the water table that might flood an underground repository, (3) tectonic stability of the storage area, that is, likelihood that the area will be free from possible surface or underground rupture, (4) effects of shaking that might be caused by nearby earthquakes or other sudden releases of energy, and (5) possible volcanic eruptions that might redistribute stored radionuclides.

The area northeast of Yucca Mountain has been fairly well mapped geologically because of previous need to understand and contain transmission of energy from nuclear tests in Yucca Flat and on Pahute Mesa (fig. 1.3). A compilation of the regional geology is shown in figure 1.5. An introduction to the types of geologic problems of possible significance to waste isolation is appropriate here as a guide to the geophysical methods needed to assess subsurface geologic structures.

REGIONAL GEOLOGIC PROBLEMS

The regional geologic map (fig. 1.5) together with a regional Quaternary fault and seismicity map at the same scale (fig. 1.6) provide basic information on surface geology. A larger-scale geologic map of Yucca Mountain and vicinity is given in Chapter 2 (fig. 2.4) and indexed in figure 1.5. The regional geologic map (fig. 1.5) shows that Yucca Mountain is made up of Tertiary volcanic deposits which extend about 100 km to the north forming a plateau nearly 2 km above sea level (fig. 1.2). The 1000-km^2 area within which the potential site is located includes 32 Quaternary faults (fig. 1.6; Swadley and others, 1984). Pre-Cenozoic basement rocks crop out about 20 km west of Yucca Mountain at Bare Mountain, about 10 km northeast in the Calico Hills, and about 20 km southeast at Striped Hills (figs. 1.3 and 1.5).

The nature of the contact between Paleozoic and Cenozoic rocks beneath Yucca Mountain is an important factor in understanding the origin of Quaternary faults there and the associated seismic hazard. Two possibilities are that these faults could either merge with a low-angle fault at this contact, or they could cut the contact and continue to depth as planar faults. In the Calico Hills, however, the Paleozoic/Tertiary contact is marked locally by an erosional contact, with paleotopography on the Paleozoic rocks overlain by Tertiary sedimentary and volcanic depositional facies (Simonds, 1995). This depositional contact is best exposed along the southern margin of the Calico Hills, and juxtaposition of Paleozoic and Tertiary sequences by normal faulting elsewhere in the Calico Hills appears to have occurred later than the depositional contact. The Paleozoic/Tertiary contact is a hydrologic barrier; the ground water in the pre-Cenozoic rocks below the contact has a head 20 m higher than in Cenozoic rocks above the contact (Craig and

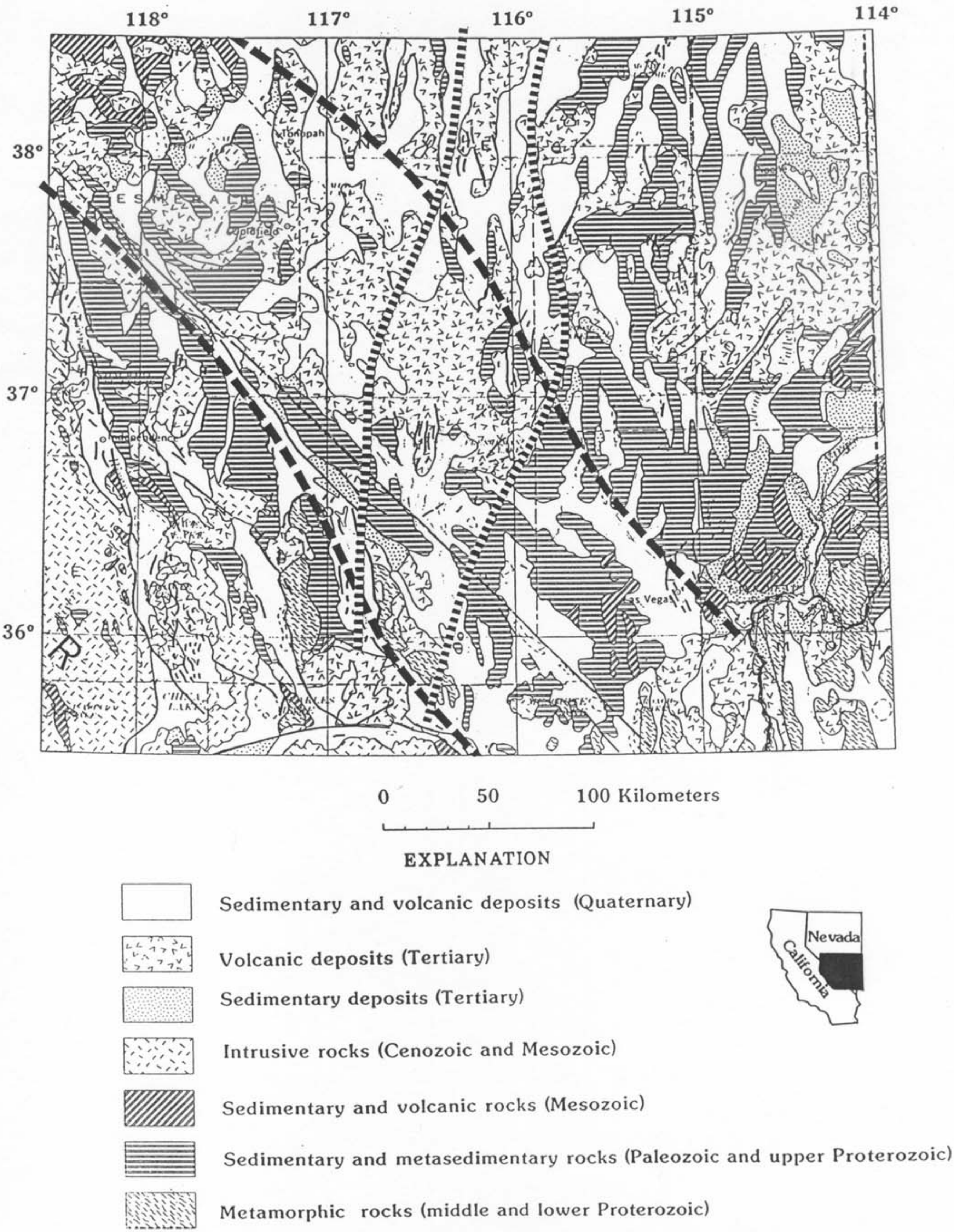
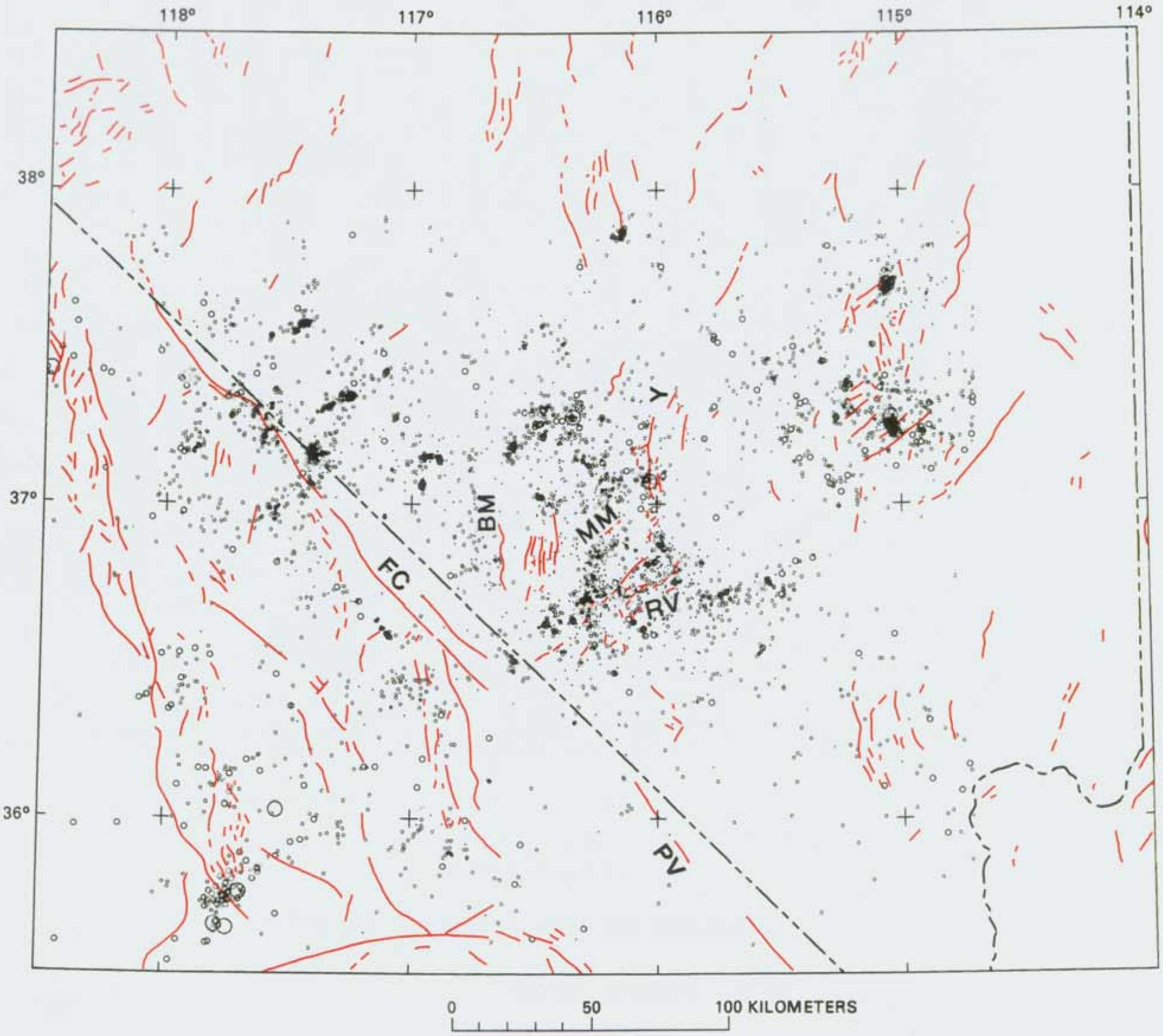


Figure 1.5. Generalized geologic map of the southern Great Basin. Long dashed lines are approximate boundaries of the Walker Lane structural belt; short dashed lines are boundaries of the Death Valley-Pancake Range volcanic zone. The Las Vegas shear zone (LVSZ) is shown within the Walker Lane. The rectangular area delineates a map area also shown in fig. 2.4. Modified from King and Beikman (1974).



EXPLANATION

Earthquake epicenters

Magnitude

○ $M>3$

∘ $2<M\leq3$

· $1<M\leq2$

· $M\leq1$

Quaternary fault

Figure 1.6. Location of potential site relative to Quaternary faults and earthquake epicenters which occurred from August 1978 through December 1986. Faults discussed in text are labeled as follows: BM, Bare Mountain fault; FC, Furnace Creek fault; MM, Mine Mountain fault zone; PV, Pahrump Valley fault; RV, Rock Valley fault zone; Y, Yucca fault. FC is right-lateral; RV and MM are left-lateral. BM is a normal fault, down to the east. Modified from Hildenbrand and others (1988).

Johnson, 1984). Regional geophysical studies indicate that this contact slopes west about 15° from a depth of 1.1 km below eastern Yucca Mountain to a depth of more than 3 km in Crater Flat (Oliver and Fox, 1993). Regional ground-water movement is controlled by aquatards, aquifers, and structural features within the pre-Cenozoic basement rocks (Winograd and Thordarson, 1975). Determination of the approximate areal and vertical distribution of these features through geophysical mapping is needed to help establish the ground water travel paths and travel times.

Evaluation of subsurface structures associated with the Walker Lane belt (fig. 1.5) and potential active faulting is also needed. The Walker Lane belt, which includes the Yucca Mountain area, has been interpreted as a diffuse intracontinental boundary zone along which right-lateral wrench faulting such as that along the Las Vegas Shear Zone predominates (Stewart, 1988). The Death Valley extensional area, about 20 km west of Yucca Mountain, is generally recognized as an area of active contemporary tectonism (Burchfiel and others, 1987). Geophysical studies may help determine the extent to which Yucca Mountain is linked to or decoupled from this region of active faulting.

The Walker Lane belt (fig. 1.5) has been seismically active recently, particularly between 36° 30'N and 37° 30'N. Within this broad zone, several local zones of diffuse seismicity are associated with known Quaternary faults such as the northeast-striking Rock Valley fault zone and the north-striking zones associated with the Yucca fault (fig.1.6). A second north-striking zone intersects the western parts of the Rock Valley and Mine Mountain faults obliquely. At about 37°N, the zone of seismicity expands both to the east and to the west forming an east-west trend across the Walker Lane belt from 115°W into California at 118°W. This trend is not continuous but consists of three concentrations of seismicity centered around 115°, 116° 30', and 117° 45' west longitude. No through-going east-west Quaternary faults break the surface within this seismic zone.

Basaltic lava, scoria, and ash erupted from vents west of Yucca Mountain at 3.7 Ma (intersected in drill hole USW VH-1; Carr, 1982), in central Crater Flat at 1.2 Ma (Crowe and others, 1983), an age modified to 1.0 to 1.1 Ma in later studies (Crowe and others, 1995), and at southern Yucca Mountain (southeastern Crater Flat) 10,000 to 150,000 years ago (Crowe and others, 1992; Crowe and others, 1995). These occurrences are part of the Death Valley-Pancake Range volcanic zone (Carr, 1984, 1990), a diffuse region of late Pliocene and Quaternary basaltic eruptive rocks (fig. 1.5) The distribution of late Pliocene and Quaternary basaltic cones within 10 km of the Potential Site is shown on the detailed geologic map (fig. 1.7). Estimation of the probability that magma might invade the repository site sometime over the next 10,000 years requires information on the distribution, volume, and ages of buried basalts (Crowe and others, 1983; Crowe and others, 1995). Several aeromagnetic anomalies found in Crater Flat and the northern Amargosa Desert could be caused by buried basalt cones (see chap. 3).

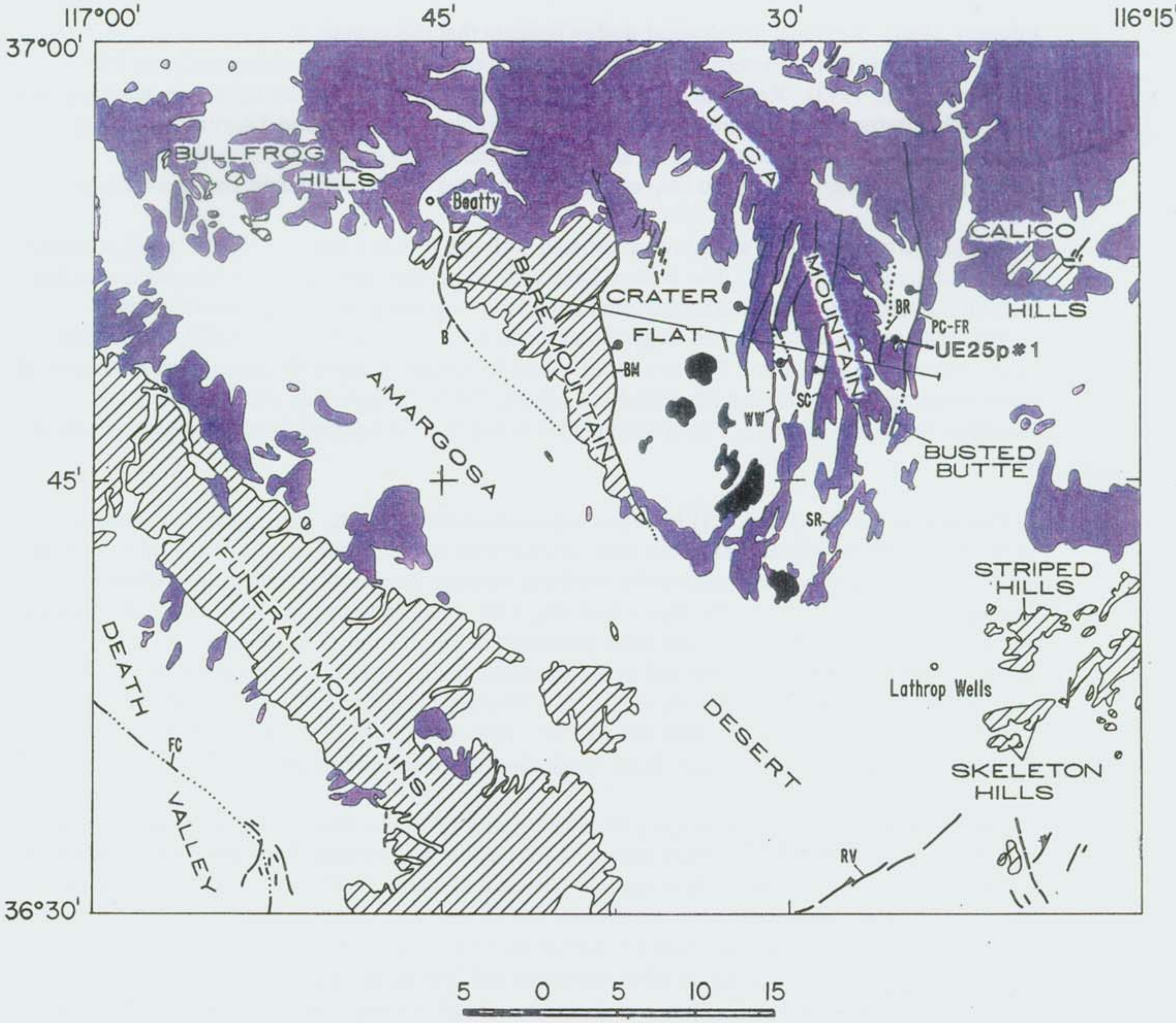


Figure 1.7. Generalized geologic map of the Crater Flat-Yucca Mountain area, emphasizing faults with known or suspected Quaternary displacement and Pliocene and Quaternary basaltic volcanoes. Explanation of patterns: diagonal lines, Precambrian and Paleozoic rocks; shaded, Tertiary volcanic and sedimentary rocks; black, late Pliocene and Quaternary basalt; unpatterned, Quaternary surficial deposits. Explanation of symbols: B, Beatty scarp (faulting suspect); BM, eastern range-front fault of Bare Mountain; BR, Bow Ridge fault; FC, Furnace Creek fault; PC-FR, Paintbrush Canyon-Fran Ridge fault zone; RV, Rock Valley fault; SC, Solitario Canyon fault; SR, Stage Coach Road fault; WW, Windy Wash fault; UE-25p#1, location of drill hole to pre-Cenozoic "basement" rocks. Generalized from Cornwall (1972) and Streitz and Stinson (1974). Modified from M.D. Carr (written commun., 1988).

GEOPHYSICAL METHODS

The gravity method, combined with limited seismic refraction and drilling methods, has been the most economically successful technique for determining the configuration of the pre-Cenozoic basement in southern Nevada (Healey, 1968; Snyder and Carr, 1984; chaps. 2 and 5, this volume). Lithologic, density, and sonic logs combined with surface measurements of gravity are essential to control two- and three-dimensional computer models of the upper crust (for example, Muller and Kibler, 1984, pl. 1). Electrical methods, particularly magnetotelluric methods, are also helpful in characterization of the upper and middle crust, and preliminary results (chap. 5, this report) indicate the desirability of more of this work.

Late Proterozoic and Paleozoic rocks composing the basement underlying the Cenozoic volcanic and surficial deposits at and near Yucca Mountain include (from oldest to youngest) 2 to 7 km of siliceous clastic rocks (quartzite, siltite), 4.5 km of carbonate rocks (limestone, dolomite), and 2 to 3 km of interlayered argillite, quartzite, and limestone (U.S. Geological Survey, 1984). These rocks have been invaded by granite at several localities. Basement rocks whose geophysical signature is sought thus include five rock types: (1) siliceous clastic rocks, (2) limestone, (3) dolomite, (4) argillite, and (5) granitic rocks. Stratified rocks were thrusted and folded in Mesozoic time and then partially dismembered by low-angle extensional faulting in late Cenozoic time. Thus, neither their vertical arrangement nor their lateral distribution can be predicted from surface mapping (K.F. Fox, written commun., 1988). Geophysical methods must be used instead. General physical properties of these chief rock types are summarized in table 1.

Densities range from about 2.5 to 2.85 g/cm^3 for the basement rocks, but densities of the chief lithologic types overlap significantly. The density contrast between basement rocks and Cenozoic cover ranges from 0.25 to 1.25 g/cm^3. This large contrast causes the gravity field to be very sensitive to the configuration of the basement surface and the distribution of Cenozoic rocks but at the same time masks the much smaller contrasts between basement rock types. Because the dolomites are the most dense, however, gravity highs generally occur over them within areas of exposed basement rocks. Seismic velocities are similar to densities in that there is considerable overlap in values from different rock types. Significant fracturing of these basement rocks, however, may be detected by reduced velocities (Ackermann and others, 1988).

Magnetic susceptibility of the basement rocks ranges over several orders of magnitude, from 10^{-6} to 10^{-2} emu/cm^3. Using magnetic susceptibility to distinguish basement rock types is complicated, however, because there are both nonmagnetic and magnetic argillic rocks in the southwestern part of the Nevada Test Site. Nonmagnetic argillite, such as that at Syncline Ridge (fig. 1.3; Ponce and Hanna, 1982), has a susceptibility of about 10^{-6} emu/cm^3, and magnetic argillite that has been altered, such as at Calico Hills (fig. 1.3; Snyder and Oliver, 1981), has a susceptibility of about 10^{-3} to 10^{-2} emu/cm^3. Where close to the surface, the magnetic argillite produces sharp magnetic highs, but where deeply buried, its magnetic signature cannot be distinguished from that of magnetic granitic rocks.

The resistivity of all three basement rock types is generally quite high (>100 ohm-m) Where the dolomites are fractured and carry even a few percent water, however, the resistivity may be

Table 1.1.—Physical properties of rocks based on several hundred sample measurements and several bore-hole logs (Snyder and Oliver, 1981; Ponce and Hanna, 1982; Healey and others, 1984; Muller and Healey, 1986; Hoover and others, 1982; Frischknecht and Raab, 1984; Snyder and Carr, 1984).

Rock Type	Density (gm/cm^3)	Velocity (km/s)	Magnetic susceptibility (emu/cm^3)	Resistivity (ohm-m)
		Pre-Cenozoic basement rocks		
Argillite	2.6-2.7	5.4-5.8	10^{-6}-10^{-2}	>100
Granite	2.62-2.75	5.6-6.1	10^{-4}-10^{-3}	>100
Dolomite	2.7-2.85	5.8-6.5	10^{-6}	20-200
Limestone	2.6-2.7	5.3-5.8	10^{-6}	20-200
Siliceous clastic rocks	2.50-2.65	5.0-5.6	10^{-6}	>100
		Cenozoic deposits		
Miocene volcanic rocks	1.8-2.5	3-5	0-10^{-2}	10-1000
Quaternary surficial deposits	1.4-2.3	2-4	0-10^{-4}	5-1000

significantly reduced (<50 ohm-m) with the contrast detectable by electrical surveys (Hoover and others, 1982).

Seismic reflection methods have been used sparingly at Yucca Mountain because of their considerable expense and problems of high absorptivity of elastic wave energy by the highly porous volcanic rocks at Yucca Mountain (H.D. Ackermann, written commun., 1984). Recent tests made in the Amargosa Valley to the southwest (fig. 1.1) are encouraging (chap. 6, this report), however, and indicate that the Las Vegas shear zone, the Walker Lane belt, and other regional tectonic features could be imaged using this method.

The teleseismic method (chap. 7, this report) uses travel-time data recorded on a 53-station seismic network established primarily to determine contemporary local seismicity (fig. 1.6; see Hildenbrand and others, 1988, p. 4-5 for specifications of the network). The seismic network also records distant earthquakes (>1,000 km distant), and relative arrival times can be converted to a three-dimensional velocity image of southern Nevada to a depth of about 300 km. This inexpensive method, combined with seismic refraction data to strip off near-surface seismic anomalies, is capable of defining the depth, extent, and overall nature of the Walker Lane structural belt, the Death Valley-Pancake Range volcanic belt, and the Timber Mountain caldera complex.

Regional heat flow studies (chap. 8, this volume) are essential to an understanding of the regional ground-water and isothermal flow paths and possible radionuclide pathways to the biosphere. For a review of selected geophysical methods, procedures, and measurements at Yucca Mountain and vicinity, see Oliver and others (1990), Oliver and others (1982), and Oliver (1984). For a more general discussion of the role of geophysics for characterizing high-level radioactive waste repositories, see Wynn and Roseboom (1987).

Stress measurements at Yucca Mountain (chap. 9, this report) indicate that rocks at Yucca Mountain are close to their limiting strength. The state of stress by itself, however, does not pose a threat to a potential repository. Stress measurements are important because they relate to other mechanisms that may threaten a potential repository, including earthquakes, volcanism, and faulting. A concern associated with the state of stress is the possibility of some interaction between the stress field and the hydrologic regime that might result in change of the level of the water table.

GEOLOGIC SETTING

Yucca Mountain comprises a series of north-striking, eastward-tilted structural blocks bounded by steeply westward-dipping Cenozoic faults (figs. 1.7 and 1.8; Christiansen and Lipman, 1965; Lipman and McKay, 1965; Scott and Bonk, 1984). These blocks consist of terrigenous volcanic and sedimentary rocks, mostly of Miocene age. The Tertiary rocks rest on a pre-Cenozoic basement consisting, at least in part, of Paleozoic marine sedimentary strata. A summary of the geology of Yucca Mountain has been published by the U.S. Geological Survey (1984). The present discussion summarizes some of the geologic problems yet to be resolved in evaluating Yucca Mountain as a potential disposal site for high-level nuclear waste, concentrating on those problems to be addressed substantially on the basis of geophysical techniques. The reader should note the position of this report, as mentioned above, in a sequence of efforts describing geophysical investigations at Yucca Mountain. The Site Characterization Plan (U.S. Department of Energy, 1988) and the Geophysical White Paper, Phase I (Oliver and others, 1990) , are important precursors to the present volume.

Depths to the base of the Tertiary section in the vicinity of Yucca Mountain (fig. 1.7) were estimated by Snyder and Carr (1984) on the basis of gravity data to range from about 1 km near Busted Butte to more than 4 km in Crater Flat. Uncertainty in the density contrasts used for gravity modeling made these estimates reliable only to within about ±30 percent of the estimated depth. Seismic-refraction profiles suggest that the base of the Tertiary section is approximately 3.2 km below the surface of Crater Flat (Ackermann and others, 1988). These depth estimates were, in part, confirmed by a drill hole [UE-25 p#1] that intersected pre-Tertiary rocks about 1.25 km

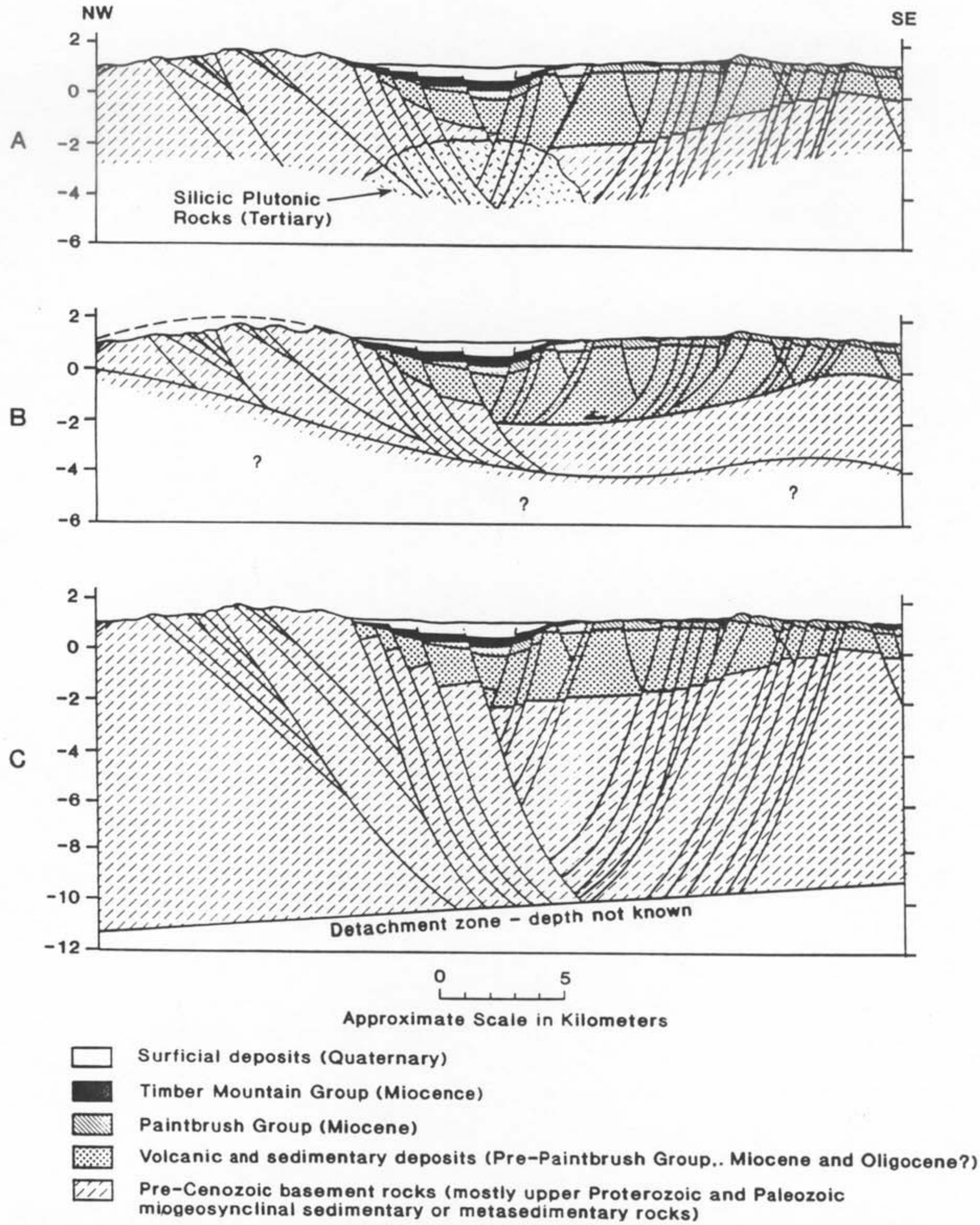


Figure 1.8. Schematic east-west geologic cross sections across central Crater Flat showing some alternative interpretations of the subsurface structural geometry. Symbols: A, Crater Flat interpreted as a middle Miocene caldera (modified from Snyder and Carr, 1984); B, listric fault model accommodated by a detachment fault at the base of the Tertiary section (modified from Scott, 1990); C, planar near-surface faulting model accommodated by ductile flattening and (or) low-angle normal faulting in middle crust. The approximate line of this section shown in figure 1.7. Modified after U.S. Geological Survey (1984, fig. 4, west half of section A-A'). After M.D. Carr, written commun., 1988).

below eastern Yucca Mountain, 5 km north of Busted Butte (fig. 1.7; Carr, Waddell, and others, 1986). Paleozoic marine carbonate rocks, part of a regional aquifer in the deep ground-water flow system of the southern Great Basin, represent the pre-Cenozoic basement in the drill hole. The composition of the pre-Cenozoic basement under the northern part of Yucca Mountain remains unknown. Interpretations based on gravity and magnetic data predict either intrusive rocks (Snyder and Carr, 1984) or Mississippian clastic rocks (Bath and Jahren, 1984) beneath northern Yucca Mountain.

The westward-dipping faults that cut Yucca Mountain are part of a system of normal and (or) oblique-slip faults in the eastern wall of a westward-deepening asymmetric graben that extends in east-west profile from Bare Mountain at least as far east as eastern Yucca Mountain (fig. 1.8). The subsurface geometry, kinematics, and mechanics of this fault system, as well as the extent, origin, and history of the Crater Flat-Yucca Mountain graben remain unresolved. A persisting question concerns whether the faults at Yucca Mountain are predominantly listric, flattening to a detachment surface at the base of the Tertiary strata (fig. 1.8B), or whether they are mostly planar-rotational faults that penetrate deeper into the crust before they are accommodated by some sort of low-angle extensional surface, possibly a low-angle normal fault within pre-Cenozoic strata or in the ductile-brittle transition zone (fig. 1.8C). Available geophysical data are insufficient to determine the fault geometry, which is important in assessing the seismic source and displacement potential of the faults, as well as their possible influence on hydrology. There is no doubt that, as a whole, the fault system at Yucca Mountain remains active, but the rate of contemporary tectonic activity for the system and for individual faults remains a subject of intensive investigations being conducted as part of the Site Characterization program. The state of stress within Yucca Mountain is consistent with active normal faulting in the principal system of westward-dipping faults (Stock and Healey, 1988). A critical element in the prediction of future activity on this fault system is a more concrete understanding of the interactive role of the Yucca Mountain fault system within the tectonic framework of the southern Great Basin.

The Crater Flat-Yucca Mountain graben was interpreted as a Miocene caldera (fig. 1.8A) by Snyder and Carr (1984) and Carr (1988). The gravity low that coincides with the graben continues south of Crater Flat into the Amargosa Desert (Healey and Miller, 1972; Snyder and Carr, 1984), however, and an east-west seismic-refraction profile crossing the Amargosa Desert about 10 km south of Lathrop Wells (Mooney and Schapper, chap. 5, this volume) shows a structural depression in the inferred surface of pre-Cenozoic basement rocks that has dimensions similar to and generally on trend with the Crater Flat-Yucca Mountain graben.

The set of east-dipping faults that control the western wall of the Crater Flat-Yucca Mountain graben at Bare Mountain formed before intrusion of 13.9-Ma quartz latite dikes, which cut some of these faults (Carr and Monsen, 1988). Therefore, the inception of faulting along the western wall of the graben system predated the inferred caldera in Crater Flat, which was postulated as the source of the 13.4- to 13.6-Ma Crater Flat Group (Carr, Byers, and Orkild, 1986; Sawyer and others, 1994). Faults in both walls of the Crater Flat-Yucca Mountain graben exhibit evidence for episodes of movement younger than 13.9 Ma, and some of these faults, including the Bare Mountain range front, and the Windy Wash, Solitario Canyon, and Paintbrush Canyon-Fran Ridge faults, remain active. Thus, the faults at Yucca Mountain appear to be part of a long-lived system of faulting in the Crater Flat-Yucca Mountain graben, which appears to extend southward and may also extend northward of its area of active surface rupture in Crater Flat and at Yucca Mountain. If a Miocene caldera existed in the Crater Flat area, then volcanism probably was localized by faulting within an areally more extensive and longer-lived structure, rather than volcanism and caldera formation being the cause of the faulting. The waning of silicic volcanism in the late Miocene does not necessarily imply a concomitant cessation of significant tectonic activity as suggested by Carr (1984), but rather, it may signal fundamental changes in the tectonic framework and different rates of continuing tectonic activity. The long and episodic history of tectonic and volcanic activity in the Crater Flat-Yucca Mountain graben makes it especially important to distinguish those structural and volcanic features that remain active and to evaluate independently the causes and consequences of the contemporary tectonic regime.

The coincidence of a Quaternary basalt field with the Crater Flat-Yucca Mountain graben (fig. 1.7) suggests that the graben is a deep-seated structure and that a genetic relationship exists between patterns of faulting and the site of volcanism. Seismic-reflection data from nearby Death Valley were interpreted as indicating that a moderately steep fault serves as a magma conduit between a Quaternary cinder cone and a zone of high-amplitude, relatively broad-bank reflections at 6 s (15 km), interpreted as a partially molten intrusion (deVoogd and others, 1986). A similar relationship between faulting and volcanism might be hypothesized for the Crater Flat basalt field, but geophysical data are as yet insufficient to evaluate this hypothesis. Neither are there sufficient data pertinent to crustal structure to suggest why Quaternary volcanism in the Great Basin (other than that coincident with the margins of the province) is confined to a 50- to 100-km-wide zone roughly medial to the southern Great Basin between Death Valley and the Pancake Range (fig. 1.5; Crowe and others, 1986). Identifying the source of the basaltic magmas and structural controls on the locations of eruptive centers within the Death Valley-Pancake Range volcanic zone is certainly germane to the estimation of future volcanic activity in the vicinity of Yucca Mountain.

The Crater Flat-Yucca Mountain graben lies within a region typified by a complex interplay of extensional and wrench-fault tectonics. Analyses of focal-mechanism data provide an impression that strike-slip faulting is the predominant generator of contemporary seismicity in the southern Great Basin (Rogers and others, 1983). The coincidence of recent seismic activity and (or) Quaternary surface rupture with important northeast- and northwest-striking zones of wrench faulting, such as the Rock Valley and Mine Mountain faults, the Pahranagat shear zone, and the Death Valley-Furnace Creek fault zone, emphasizes the continued importance of such fault systems as potential seismic sources within the regional setting. Yucca Mountain lies within the Walker Lane, a poorly understood belt of dextral oroclinal bending that generally parallels the Nevada-California border. The Walker Lane seems to have served as an important, albeit diffuse, intraplate boundary between tectonic subprovinces of the Great Basin during the Cenozoic, and wrench faulting apparently continues to play an important role in the evolution of this belt.

In contrast, areally extensive low-angle normal faults (detachment faults), such a those exposed in the northwestern Spring Mountains (Burchfiel, 1965), the Bullfrog Hills-Bare Mountain area (Ransome and others, 1910), and the mountain ranges around Death Valley (Noble, 1941; Hunt and Mabey, 1966) also have been integral in the tectonic development of the southern Great Basin. While some of these low-angle faults appear at the surface to be inactive remnants of major middle-and late-Miocene structures, others (especially those west of the Death Valley-Furnace Creek fault zone) show evidence for activity and in some cases initiation during Pliocene and Quaternary time (Burchfiel and others, 1987). Many current models of crustal extension (for example, Hamilton, 1987) predict that even the steepest range-front faults in the Great Basin must be accommodated at some depth along gently dipping zones of detachment, whether they be the base of the crust, the ductile-brittle transition zone, or some brittle low-angle normal fault within the upper crust. The depth at which steep faults are accommodated and the location within the crust of low-angle faults, which could themselves be seismic sources or could obscure other deeper seismic sources, seem fundamental parameters for evaluating the size and location of potential seismic sources in the southern Great Basin.

A complex interplay between detachment surfaces, low- and high-angle normal faults, and wrench faults exists in the southern Great Basin. The predominance of one structural style over another varies with location, scale, and time. The kinematic behavior of individual structures may vary as the mechanical framework varies with time. Adequate characterization, or even identification, of tectonic features that could affect future faulting, surface rupture, ground motion, volcanism, and (or) the hydrology at Yucca Mountain requires a better understanding of how the structural features in the vicinity of Yucca Mountain fit into the evolving regional geologic system. The geologic setting of Yucca Mountain cannot be understood out of regional context, nor can the future performance of an arbitrarily restricted part of the geologic system be meaningfully assessed out of context.

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MAJOR RESULTS OF GEOPHYSICAL INVESTIGATIONS AT YUCCA MOUNTAIN AND VICINITY, SOUTHERN NEVADA

CHAPTER 2: GRAVITY INVESTIGATIONS

By D.A. Ponce and H.W. Oliver

INTRODUCTION

As part of a geoscientific effort to evaluate the Nevada Test Site and vicinity for favorable areas for the storage of commercial spent nuclear fuel and high-level radioactive waste, gravity investigations were begun in about 1977 and have been used to characterize the general geologic and tectonic setting. Gravity studies are particularly useful for determining (1) the general subsurface configuration of pre-Tertiary bedrock or basement, (2) the location and extent of concealed or unrecognized faults, (3) the location and extent of calderas and plutons, and (4) tectonic stability. Gravity methods can reveal shallow as well as deep features wherever rocks of different densities are juxtaposed. Such shallow features include faults and edges of calderas. Gravity data can also reveal deep undulations in the base of the crust, such as those which occur at a depth of about 33 km beneath Yucca Mountain.

SUMMARY OF PREVIOUS WORK

Gravity studies at the Nevada Test Site and vicinity initially were made during 1957-1978 to help define the configuration of the pre-Cenozoic basement under Frenchman and Yucca Flats, Pahute Mesa (fig. 1.1, chapter 1, this volume; Healey, 1968), and the Nevada Test Site in general (Healey and Miller, 1979). Much of this work served as the basis for more detailed studies, begun in 1977, in a search for a possible site within the Nevada Test Site for the storage of radioactive waste.

A detailed geophysical investigation was begun in 1977 at Syncline Ridge (fig. 1.3) that utilized gravity as well as magnetic, seismic, and electrical methods (Hoover and others, 1982b; Ponce and Hanna, 1982). Although Syncline Ridge was believed to be a relatively undisturbed synclinal structure, geophysical data revealed that the area was structurally complex. These studies supported geological studies (Hoover and Morrison, 1980) and in addition indicated that faulting was more extensive, displacements were larger than previously known, and that the argillic host-rock lacked homogeneity.

Early gravity surveys in the Timber Mountain area, in particular, the Pahute Mesa and Buckboard Mesa areas (fig. 1.6), included about 765 stations that were used by Healey and Miller (1979) to investigate the configuration of buried pre-Cenozoic rocks. These studies revealed that the Timber Mountain area lies within a broad circular gravity high which correlates with an arcuate intrusive body and that adjacent gravity lows are associated with moat areas of the Timber Mountain caldera. A two-dimensional gravity model of Timber Mountain by Healey and Miller (1979) indicated that volcanic rocks were about 2,700 to 3,700 m thick. About 940 subsequent gravity measurements by D. L. Healey (written commun., 1979) were supplemented by over 300 additional measurements to search for concealed granitic plutons (Kane and others, 1981). According to Kane and others (1981), gravity data in the southern part of Timber Mountain suggest that this area may be underlain by intrusive rocks similar to those exposed along the southeast side of Timber Mountain, and further, that the northern part of the Timber Mountain caldera truncates the southern edge of the older Silent Canyon caldera. Also, Kane and others (1981) speculated that the deformation associated with volcanism in the region has taken place along a system of linear faults that combine to give a curvilinear appearance to the regional structure. If gravity gradients along the eastern and western sides of Timber Mountain are remnants of gradients associated with the original Silent Canyon caldera, then the caldera might extend substantially southward.

Because of proximity to weapons testing areas, earlier studies in these areas were discontinued and subsequent studies were focused in the southwest quadrant of the Nevada Test Site (U.S. Department of Energy, 1986). One of these sites was Wahmonie (fig. 1.3), where aeromagnetic data indicated the presence of granitic rocks (G.D. Bath, oral commun., 1980). Detailed gravity and magnetic data obtained in 1979-1981 (Ponce, 1981, 1984) revealed large, positive, and coincident gravity and magnetic anomalies near Wahmonie. Two smaller local magnetic anomalies, along a magnetic prominence extending from the main anomaly, directly correlated with two small exposures of granitic rocks. This suggested that the main anomaly was also associated with a granitic intrusion. Gravity modeling and other geophysical data suggested that Wahmonie was underlain by granitic rocks, that the upper parts of the intrusion were altered or fractured or both, and that there was a possibility that the causative body might represent a magnetic and altered argillic member of the Eleana Formation (Mississippian to Upper Devonian).

A study similar to that at Wahmonie was undertaken at Calico Hills in 1979 (Snyder and Oliver, 1981). The combination of hydrothermal alteration, structural doming of Calico Hills, and an aeromagnetic anomaly suggested that the area was underlain by a shallow Tertiary granitic intrusion (Maldonado and others, 1979; G.D. Bath, oral commun., 1980). Two-dimensional modeling of an elliptical gravity high, centered over exposed Paleozoic rocks, indicated that the anomaly could be attributed entirely to a density contrast between the Paleozoic rocks and the overlying Tertiary volcanic rocks, but the model did not preclude the existence of an intrusion. Moreover, a drill hole in the central part of Calico Hills revealed that the inferred intrusion, if present, must be deeper than 760 m, and that at least locally, the argillic facies of the Eleana Formation is strongly magnetic, containing 1 to 3% magnetite. Although much of the magnetic anomaly at Calico Hills could be attributed to magnetic rocks of the Eleana Formation, an intrusion may exist at a depth too great to be considered for a repository.

DENSITY DATA

Rock densities at the Nevada Test Site and vicinity can be separated into three broad groups: pre-Cenozoic sedimentary rocks and intrusive rocks with an average density of about 2.67 g/cm^3, Cenozoic volcanic rocks with a density of about 2.4 g/cm^3, and nonwelded and partially welded ash-flow tuffs and alluvium with a density of about 2.0 g/cm^3. There are three primary sources of rock density information at the Nevada Test Site and vicinity: rock samples (including core samples), borehole gravity-meter surveys, and borehole density logs. A brief summary of bulk density data of rock samples, unless otherwise specified, is given below for the three major rock groups.

Density data from pre-Cenozoic rocks are available from several areas of the Nevada Test Site and vicinity. Density measurements on undivided Paleozoic rocks from the Nevada Test Site and vicinity average 2.67 g/cm^3 (Healey, 1983). Density data on intrusive rocks include measurements on samples of quartz monzonite and granodiorite from the Climax Stock which have an average density of 2.68 g/cm^3 (Izett, 1960) and 2.64 g/cm^3 (F. N. Houser, written commun., 1962), respectively. An average density of 2.65 g/cm^3 (Ponce, 1984) was determined on 23 samples of granodiorite from Wahmonie.

Volcanic rocks vary widely in density partly due to their degree of welding. Keller (1959) reported an average density of 2.18 for 31 tuff samples from the Rainier Mesa Tuff (Sawyer and others, 1994) of the Timber Mountain Group. Data from 91 Cenozoic volcanic samples from the Timber Mountain area have an average saturated bulk density of 2.08 g/cm^3 (Heinrichs, 1963). Johnson and Ege (1964) reported numerous density measurements made on drill core samples obtained in the vicinity of Wahmonie. These samples were predominantly dacite porphyry yielding an average density of 2.27 g/cm^3. Healey (1968) reported that the average density of alluvium and nonwelded tuff averages 1.94 g/cm^3 and that partially welded to welded tuff averages 2.36 g/cm^3. Seventy-seven undivided volcanic rocks at the Nevada Test Site had an average density of 2.22 g/cm^3 (Ponce, 1984). Ponce (1984) listed average densities for volcanic rocks at Wahmonie where 17 samples of rhyolite averaged 2.31 g/cm^3, nine samples of intrusive rhyolite averaged 2.57 g/cm^3, 27 samples of rhyodacite averaged 2.58 g/cm^3, and eight samples of andesite averaged 2.66 g/cm^3.

Samples of Quaternary alluvium have a wide range in density that is partly dependent on the lithology of the source rocks. In the Yucca Flat area, the average density of 2,225 m of alluvium was 2.01 g/cm^3 as measured in several drill holes by density logs and borehole gravity meter (Healey, 1970). Ponce (1981) summarized density data from four sets of alluvial samples that yielded an average density of 1.46, 1.58, 1.66, and 1.92 g/cm^3. Healey and Kibler (written commun., 1987) compiled densities of alluvium from 12 drill holes on the Nevada Test Site that yielded an average of 1.89 g/cm^3.

Although borehole gravity meters are essentially logging tools, their results are included here because of their application to gravity interpretation. Borehole gravity-meter surveys provide an independent measurement of bulk density, and because they measure a larger volume of rocks than do conventional logging tools, they reflect the density of rocks surrounding the drill hole. Structure adjacent to the borehole and the density of the overburden can also be determined using borehole gravity surveys along with gamma-gamma density logs. Robbins (1980) compiled an extensive bibliography, which included abridged abstracts, of subsurface gravimetry collected prior to 1980. Robbins and others (1982) reported on the results from drill-hole USW H-1, on Yucca Mountain. The data show an increase in density of volcanic rocks from 2.23 g/cm^3 near the surface to about 2.50 g/cm^3 at a depth of 1,792 m. Healey and others (1984, 1986) reported on the results of four drill holes on Yucca Mountain. Borehole gravity data from the deepest of the four drill-holes (UE-25 p#1), on the east side of Yucca Mountain, show an increase in density of volcanic rocks from about 1.92 g/cm^3 to a value of about 2.67 g/cm^3 at a depth of 1,244 m, and that Paleozoic rocks at a depth of 1,792 m have a density of 2.80 g/cm^3. According to Healey (1968), the increase in density with depth is a function of the lithology of the volcanic rocks and does not imply compaction from loading. However, we suspect that rocks of similar lithology show an increase in density with depth that is a function of compaction.

REGIONAL GRAVITY DATA COMPILATIONS

Concurrent with the specific site studies, existing gravity data within the Nevada Test Site and to a radius of 100 km were compiled as required by early drafts of the guidelines for the disposal of nuclear waste in geologic repositories by the U.S. Nuclear Regulatory Commission (1983). These data were released as Bouguer gravity maps of the four 1- by 2-degree quadrangles at a scale of 1:250,000 that describe the Nevada Test Site and vicinity as follows: Las Vegas (Kane and others, 1979), Death Valley (Healey and others, 1980), Goldfield (Healey and others, 1980), and Caliente (Healey and others, 198l). Gravity data for the southwestern part of the NTS and vicinity were released by Jansma and others (1982) and included gravity and magnetic data along three profiles across Yucca Mountain. The data from the four 1:250,000-scale maps have since been recompiled and extended south to 35° 30'N, north to 38° 30'N, and west to 118° 30'W using subsets of the gravity data releases for California (Snyder and others, 198l) and Nevada (Saltus, 1988). A Bouguer gravity map of the southern Great Basin is shown (fig. 2.1) with the site area plotted for perspective. A detailed complete Bouguer gravity anomaly map of the Nevada Test Site and vicinity at a scale of 1:100,000, based on about 16,000 gravity stations (Healey and others, 1988), and documentation for these gravity stations (Harris and others, 1989) are available.

Although regional Bouguer gravity maps are useful for interpreting or modeling small- and large-scale features, the longer-wavelength components of Bouguer gravity anomalies correlate inversely to topography. This correlation to topography produces a regional gravity gradient that may influence local anomalies. At the Nevada Test Site and vicinity, this effect is a function of the general increase in average topographic elevation to the northeast (Oliver and others, 1982). Thus, it is desirable to remove this effect by making a correction for topography by using an isostatic model which assumes that topographic loads are supported at depth by compensating masses. Isostatic corrections were made using a procedure by Simpson and others (1983), based on a model of Airy-Heiskanen local compensation with the following parameters: an assumed upper crustal density of 2.67 g/cm^3, a crustal thickness of 25 km, and a density contrast between the upper crust and lower mantle of 0.4 g/cm^3. Although other isostatic model parameters or other isostatic models could be used, differences in the resulting isostatic corrections are small compared to the total correction (Jachens and Griscom, 1985). Because the main features on isostatic gravity maps produced by various models appear similar, the application of some type of isostatic correction is more important than the character of the actual model (Simpson and others, 1986). Isostatic residual gravity anomalies enhance short- to moderate-wavelength anomalies caused by bodies in the upper parts of the crust.

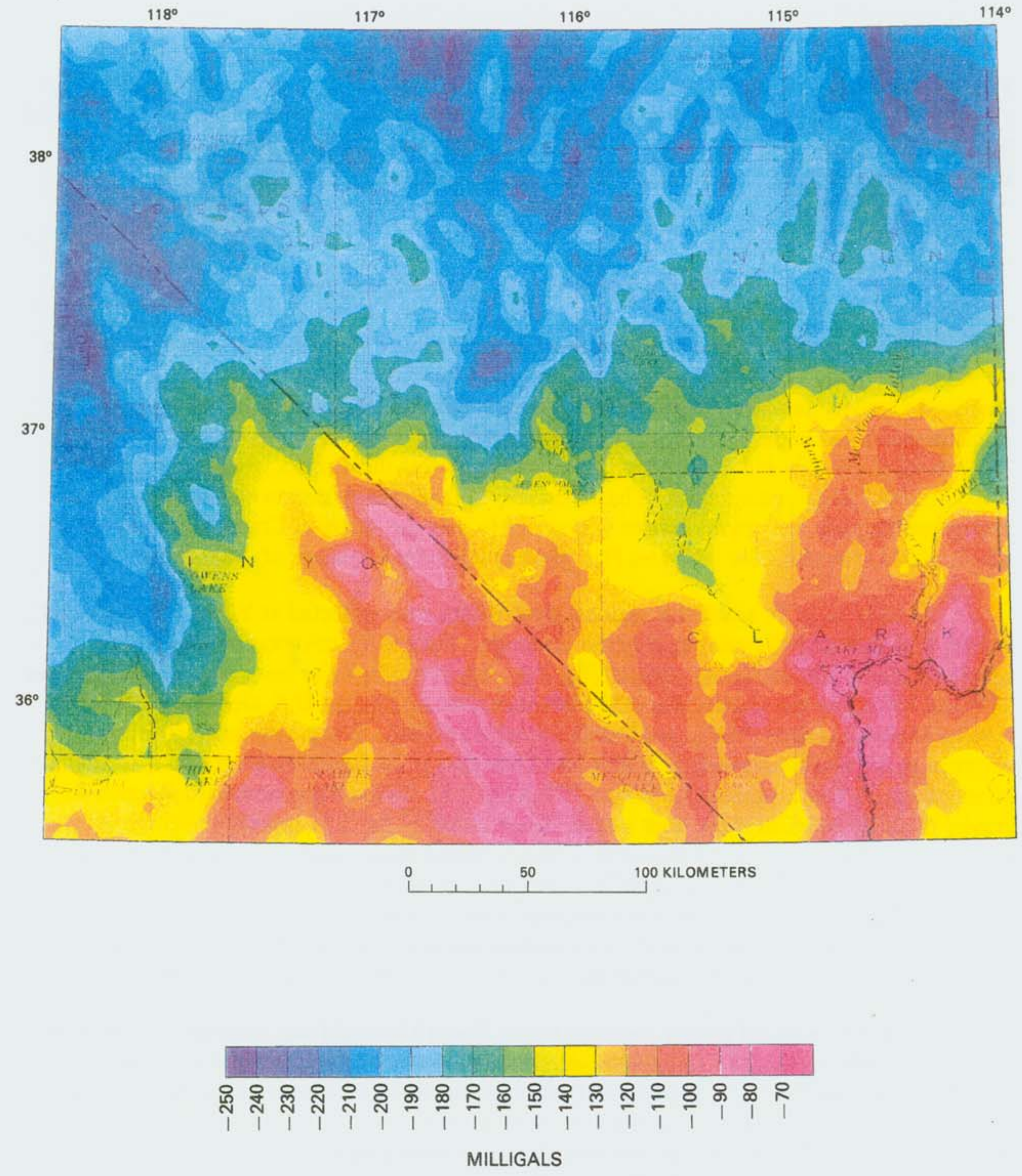

Figure 2.1.—Complete Bouguer gravity map of the southern Great Basin using a Bouguer reduction density of 2.67 g/cm^3. Modified from Hildenbrand and others (1988).

A preliminary isostatic residual gravity map of the area within a radius of 100 km from Yucca Mountain was released by the U.S. Geological Survey at a scale of 1:500,000 (1984, fig. 2). An isostatic residual gravity map of the southern Great Basin is shown in figure 2.2 (modified from Hildenbrand and others, 1988). A detailed isostatic gravity map of the Nevada Test Site and vicinity at a scale of 1:100,000 is available (Ponce and Harris, 1988).

YUCCA MOUNTAIN AND VICINITY

Regional gravity studies of Yucca Mountain and Crater Flat were included in reports on the Amargosa Desert and Timber Mountain areas by Healey and Miller (1971, 1979). They described a gravity anomaly associated with Yucca Mountain, attributed it to low-density volcanic rocks, and initially suggested that volcanic rocks in Crater Flat were about 1,700 to 2,400 m thick. Healey and Miller later (1979) estimated that these rocks were about 2,000 to 2,400 m thick. These estimates were based on very limited gravity station control. Along the gravity profile, only one gravity station was available over the center of Crater Flat and only one was available at each border of Crater Flat, yielding a gravity amplitude of -40 mGal.

As early as 1979, additional regional gravity data were collected at Yucca Mountain and vicinity to supplement the existing regional coverage. The gravity coverage in the Yucca Mountain area is still somewhat regional (fig. 2.3). Many of the major isostatic gravity anomalies of Yucca Mountain and vicinity (fig. 2.2) have been discussed by the U.S. Geological Survey (1984), Snyder and Carr (1984), and Harris and others (1986). The gravity anomalies most pertinent to the characterization of Yucca Mountain are (1) the northwestward decrease of about 20 mGal across Yucca Mountain (marked "Y" in fig. 2.2), (2) the sharp westward increase in gravity of about 30 mGal at the west side of Crater Flat (CF, fig. 2.2), and (3) the configuration and extent of the gravity low to the north of Yucca Mountain centered over the Silent Canyon caldera (SC, fig. 2.2), reaching a negative value of about -60 mGal. This major gravity feature over the Silent Canyon caldera is clearly associated with Cenozoic rocks and is similar in extent and amplitude to gravity lows over the Yellowstone caldera (Evans and Oliver, 1987, Oliver and Carle, 1988) and Long Valley caldera (Oliver and Robbins, 1982; Jachens and Roberts, 1985).

The northwestward gravity decrease across Yucca Mountain was modeled by Snyder and Carr (1982; 1984) as a 3,000- to 4,000-m-deep caldera extending from the repository area to Bare Mountain (see fig. 1.2). Snyder and Carr's models included both two and three-dimensional analyses and differ from Healey and Miller's (1979) models by the following: detailed gravity data that included at least 13 gravity stations over Crater Flat along each of three two-dimensional models, a gravity low of about 44 mGal, a multi-layered geologic model, and (for the three-dimensional model) a linear density function based on borehole log measurements. Because density information is lacking below a depth of about 2 km, an accurate tuff thickness is difficult to determine. Seismic refraction studies by Hoffman and Mooney (1983) indicated a depth to basement of about 3,200 m, supporting the gravity results. Gravity modeling also predicted a rise in basement under the eastern part of Yucca Mountain to a depth of 1,100 m that was verified by

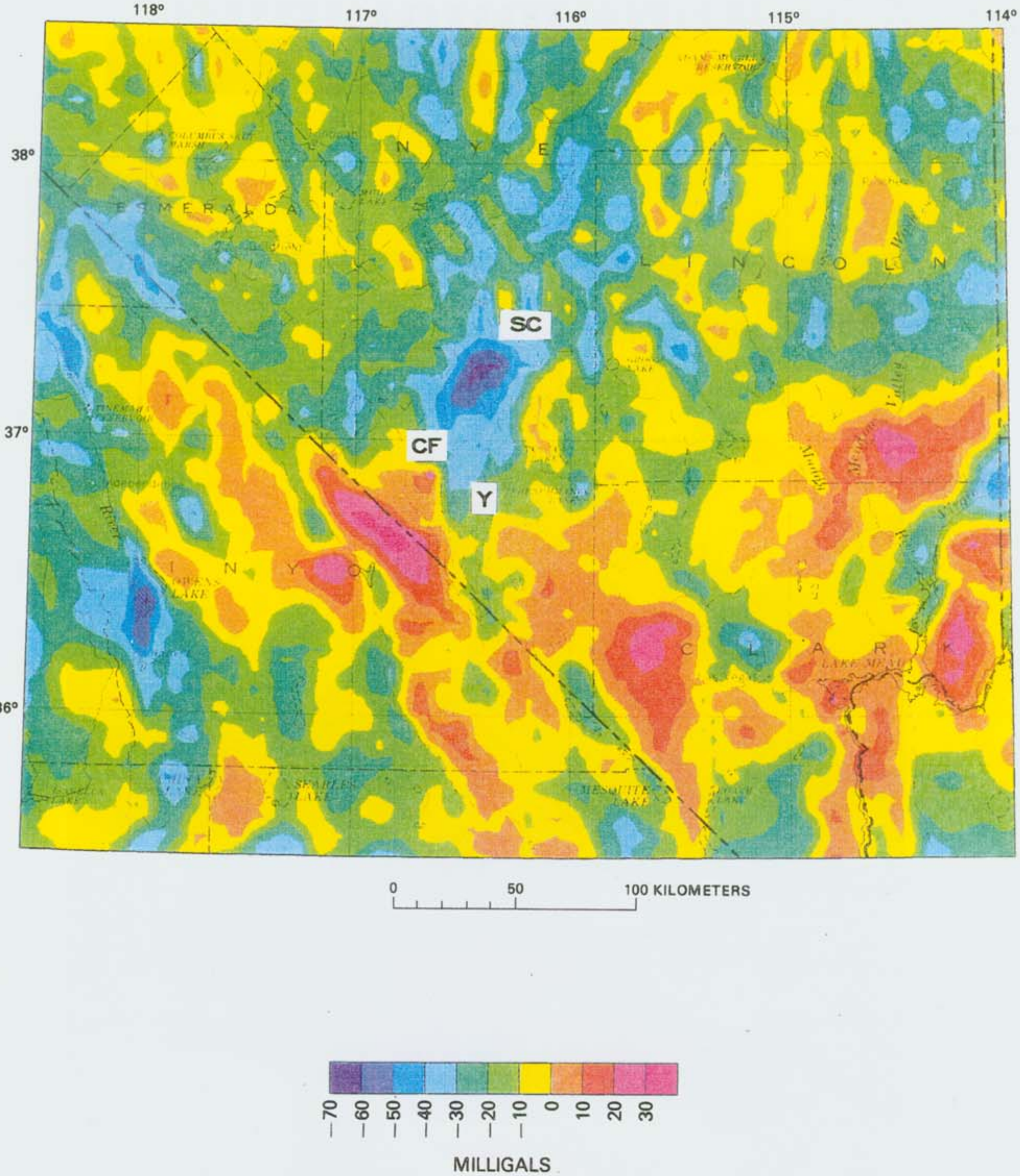

Figure 2.2.—Isostatic residual gravity map of the southern Great Basin reduced with an assumed upper crust density of 2.67 g/cm^3, a crustal thickness of 25 km, and a density contrast between the upper crust and lower mantle of 0.4 g/cm^3. Modified from Hildenbrand and others (1988). Symbols: CF, Crater Flat; SC, Silent Canyon caldera; Y, Yucca Mountain.

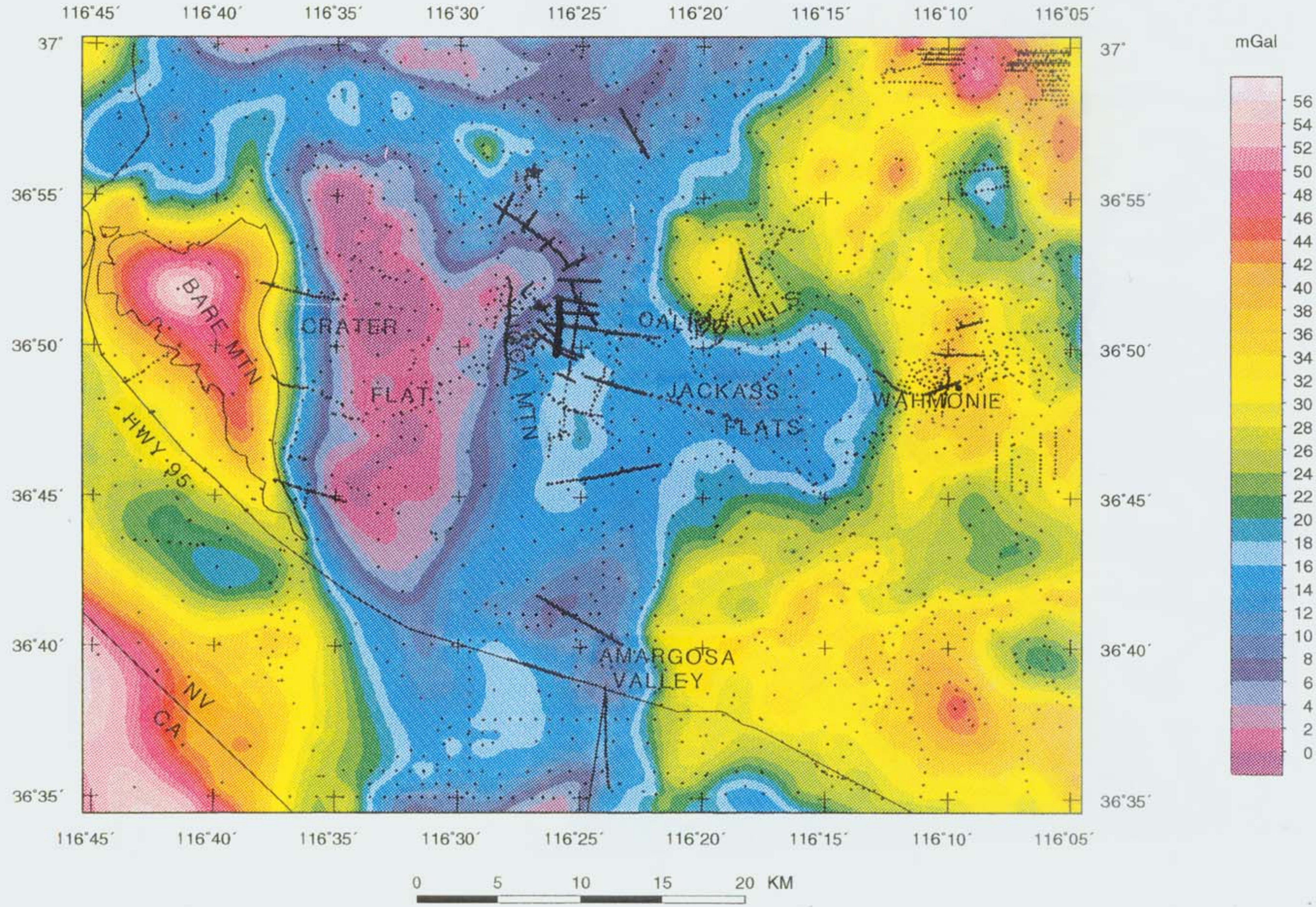

Figure 2.3. Location of Yucca Mountain site area and surrounding region, southwestern Nevada, showing gravity stations and gravity contours. See figure 3.7 for explanation of traverses.

drill-hole UE-25 p#1 which encountered Paleozoic rocks at about 1,244 m below the surface (Carr and others, 1986).

A conceptually different model for the Yucca Mountain—Crater Flat region, suggested by K. F. Fox (written commun., 1986), is illustrated in figures 2.4 and 2.5 which show a relatively smooth base of the volcanic pile below Yucca Mountain. In this model, there is an east-dipping "master" detachment fault near the west edge of Bare Mountain, a listric normal fault forming the east face of Bare Mountain and merging with the master detachment fault at depth, and a west-dipping Yucca Mountain detachment terminating below Crater Flat at its intersection with the master detachment. At present, the inherent ambiguity in the gravity method does not allow differentiation between the caldera or the detachment model.

GRAVITY AND SEISMIC DATA

Gravity data have been interpreted along three of the five seismic refraction profiles in the vicinity of Yucca Mountain: Yucca Mountain, Beatty, and Amargosa profiles (see Mooney and Schapper, this volume, fig. 6.1). Snyder and Carr's (1984) gravity model from Bare Mountain, across Yucca Mountain, and extending to Jackass Flats is nearly coincident with the Yucca Mountain seismic refraction profile. The gravity model correlates well with the seismic-refraction model and is constrained by geologic and drill-hole data. In particular, the gravity model is in better agreement with the depth to pre-Cenozoic rocks in drill hole UE-25 p#1 than is the seismic interpretation (Mooney and Schapper, this volume). Snyder and Carr (1984) interpreted a deep volcanic depression extending from Crater Flat to central Yucca Mountain and a rise of pre-Cenozoic rocks in the eastern part of Yucca Mountain.

The Beatty profile extends from the Bullfrog Hills, along the northernmost part of Bare Mountain, and into Crater Flat (Mooney and Schapper, this volume, fig. 6.1). A preliminary seismic and gravity interpretation made by Ackermann and others (1988) suggested that a low-angle fault or detachment surface, exposed in the Grapevine Mountains, may correspond to a modeled layer with a velocity of 6.3 km/s and a density of 2.74 g/cm^3. This layer possibly continues east to Crater Flat.

Detailed gravity data were collected along a seismic-reflection traverse (Brocher and others, 1990) that was coincident with a part of the Amargosa seismic-refraction traverse described and interpreted by Mooney and Schapper (this volume). A gravity model by Brocher and others (1990) was based on the refraction model and primarily differs in the shape of the basin fill-basement interface. The gravity model also indicated narrow basement highs that were not detected in the refraction data but were later detected in the reflection data. Near the western end of the reflection traverse, about 6.4 km south of Lathrop Wells, gravity data indicate the presence of a major west-dipping normal fault, bounding the basin, that extends to a depth of several kilometers. About 3.2 km to the east of this fault, gravity data indicate another high in the basement rocks that correlates with seismic data. Electrical data also detected the presence of a major fault that was inferred to represent the eastern boundary of the Ash Meadows ground-water system (Hoover and others, 1982a).

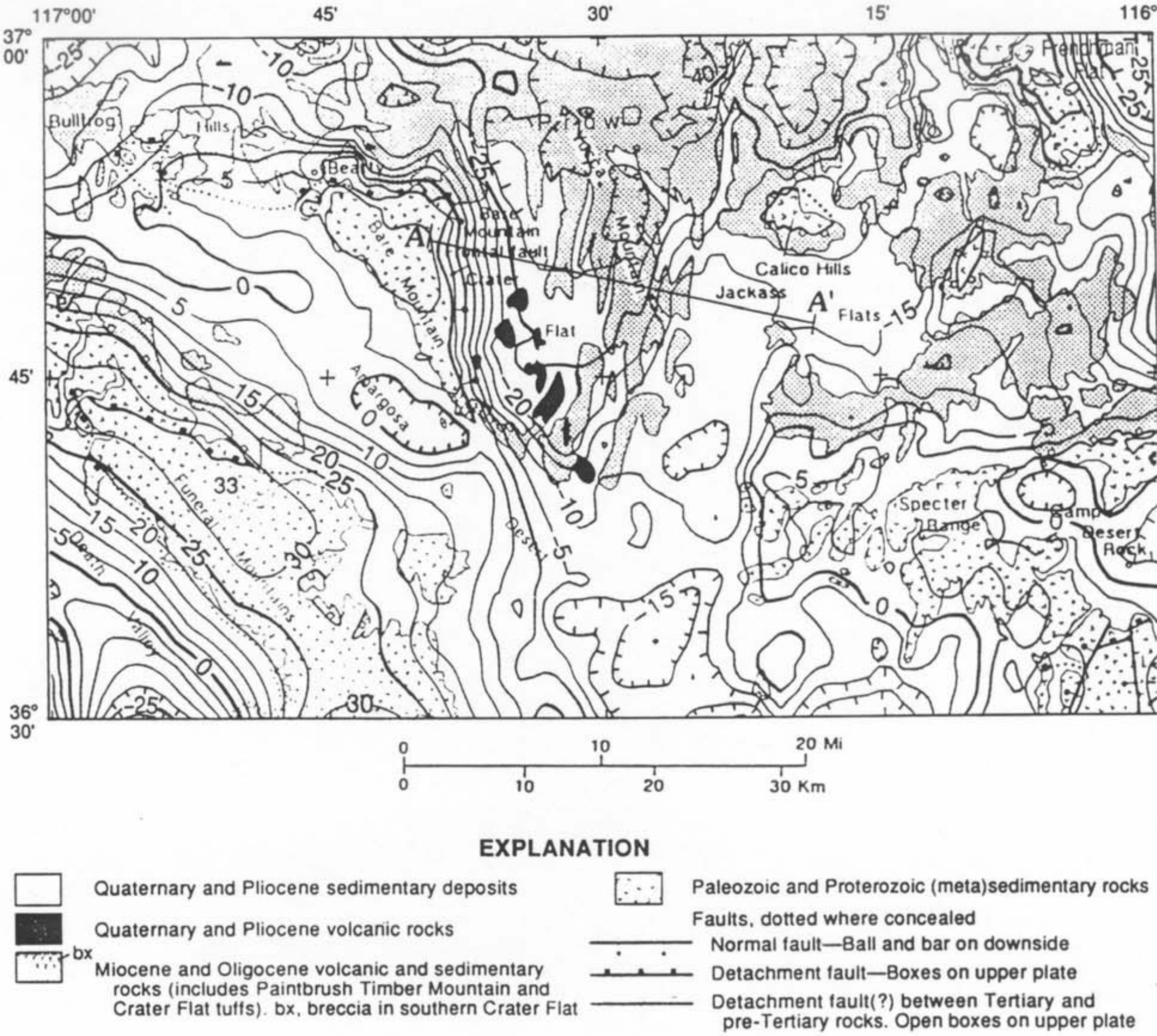

Figure 2.4. Isostatic gravity map of the Beatty ½° by 1° quadrangle, Nevada, showing the location of the gravity model along profile A-A', overprinted on a simplified geologic base. Gravity contour is 5 mGal, and the reduction density is 2.67 gm/cm^3. The gravity map is controlled by over 2000 gravity stations. Hachured contours indicate gravity lows.

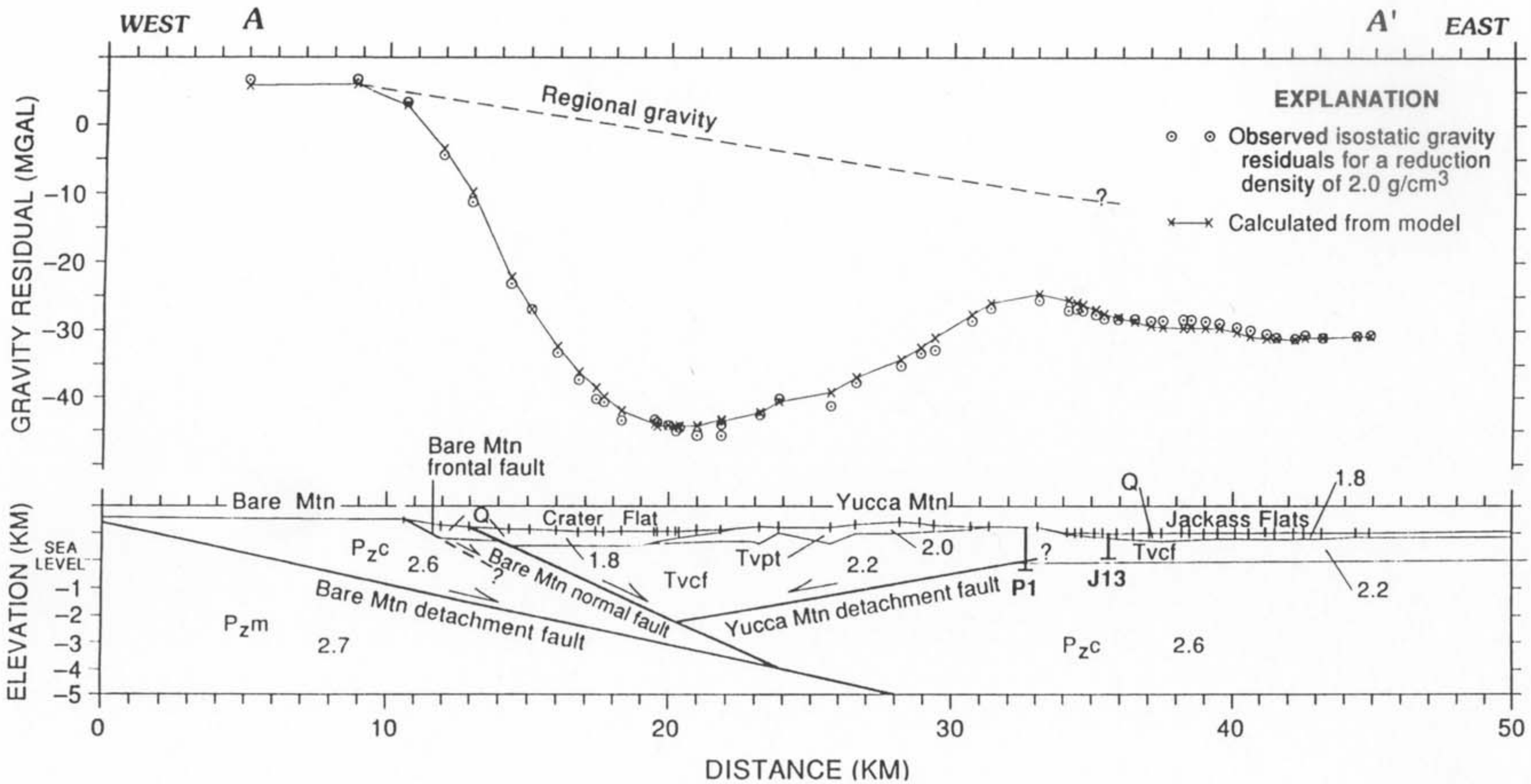

Figure 2.5.—Detachment model of subsurface structure under Yucca Mountain area. Numbers within units are the densities in g/cm^3 assumed in the model. Vertical exaggeration is 2. The observed gravity values are isostatic gravity residuals based on the same isostatic model as in figure 2.2 but using a local reduction density of 2.0 g/cm^3 (see text). Symbols used in this figure: P_Zc, Paleozoic carbonate rocks; P_Zm, Paleozoic metamorphic rocks, Tvcf, Tertiary volcanic rocks, Crater Flat Group; Tvpt, Tertiary volcanic rocks, Paintbrush Group; and Qs, Quaternary deposits. Modified from K.F. Fox (written commun., 1986).

FORTYMILE WASH

Another current regional gravity study is that of Fortymile Wash, a linear feature that extends for about 65 km, partly along the east side of Yucca Mountain (fig 2.4). Because Fortymile Wash was believed to be fault-controlled (Lipman and McKay, 1965), there was concern that if a fault extended to repository depths of about 400 m, it might provide a highly permeable zone through which water-borne radionuclides might travel rapidly. For these reasons, electrical data were collected along four profiles (Hoover and others, 1982a) and subsequently, detailed gravity and ground magnetic data were collected along six profiles (Ponce and others, 1992) across Fortymile Wash (fig. 2.6). Profiles for two of the gravity traverses are shown (fig. 2.7), reduced for a density of 2.0 g/cm^3. This reduction density was determined using density profiling (Nettleton, 1976), an interpretive technique to determine the average density of small topographic features by selecting the density profile that exhibits the least correlation to topography. Combined results from all six profiles suggest that a density between 1.8 to 2.0 g/cm^3 produces the least correlation to topography and probably represents the average density of the near-surface layer of Fortymile Wash.

The largest gravity (and magnetic) anomaly in the vicinity of Fortymile Wash is the Paintbrush fault, on the west side of Fran Ridge (figs. 2.6 and 2.7). Because the gravity stations are closely spaced, they provide a very accurate location of the fault, which is about 300 m east of the location shown on the geologic map of Lipman and McKay (1965). A later detailed geologic map utilizing geophysical evidence shows the fault in the correct location (Scott and Bonk, 1984). The amplitude of the gravity anomaly associated with the Paintbrush fault is about 2 mGal. Using as a model the maximum effect of a vertical fault (Nettleton, 1976, p. 193-195), the anomaly implies an offset of about 180 to 240 m.

Gravity data suggest that Fortymile Wash does not itself lie over a fault unless movement has occurred between rock types of similar density. In the vicinity of Fran Ridge, essentially coincident with gravity lines 2 and 3 (figs. 2.6 and 2.7), electrical data by Hoover and others (1982a) revealed four north-south zones of low resistivity, two on either side of Fortymile Wash, that were interpreted to be fault zones. Gravity anomalies along line 2 (fig 2.7) correlate well with faults inferred from electrical data, especially at the Paintbrush fault, and suggest that vertical offsets along faults, if present, on the east side of Fortymile Wash are small compared to the offset at the Paintbrush fault. In contrast, gravity anomalies along line 3 (fig 2.7) do not correlate very well to faults inferred from electrical data, especially on the east side of the wash. In addition, gravity anomalies along profiles south of line 3 and Busted Butte (fig. 2.6, lines 4, 5, and 6) are of lower amplitude than those near Fran Ridge and are probably not related to large vertical offsets. Because of their short wavelength, gravity anomalies south of Busted Butte, but near Fortymile Wash, could be related to variations in density within the underlying alluvium or volcanic rocks.

Because these gravity studies were intended to determine whether or not Fortymile Wash lies over a fault, detailed gravity data were not collected more than about 3.2 km beyond the edge of the wash. Thus, the southernmost detailed profiles did not cross major regional anomalous gravity features that probably indicate major faults on either side of Fortymile Wash. Healey and Miller (1971) also recognized these gravity features, and electrical data (Hoover and others,

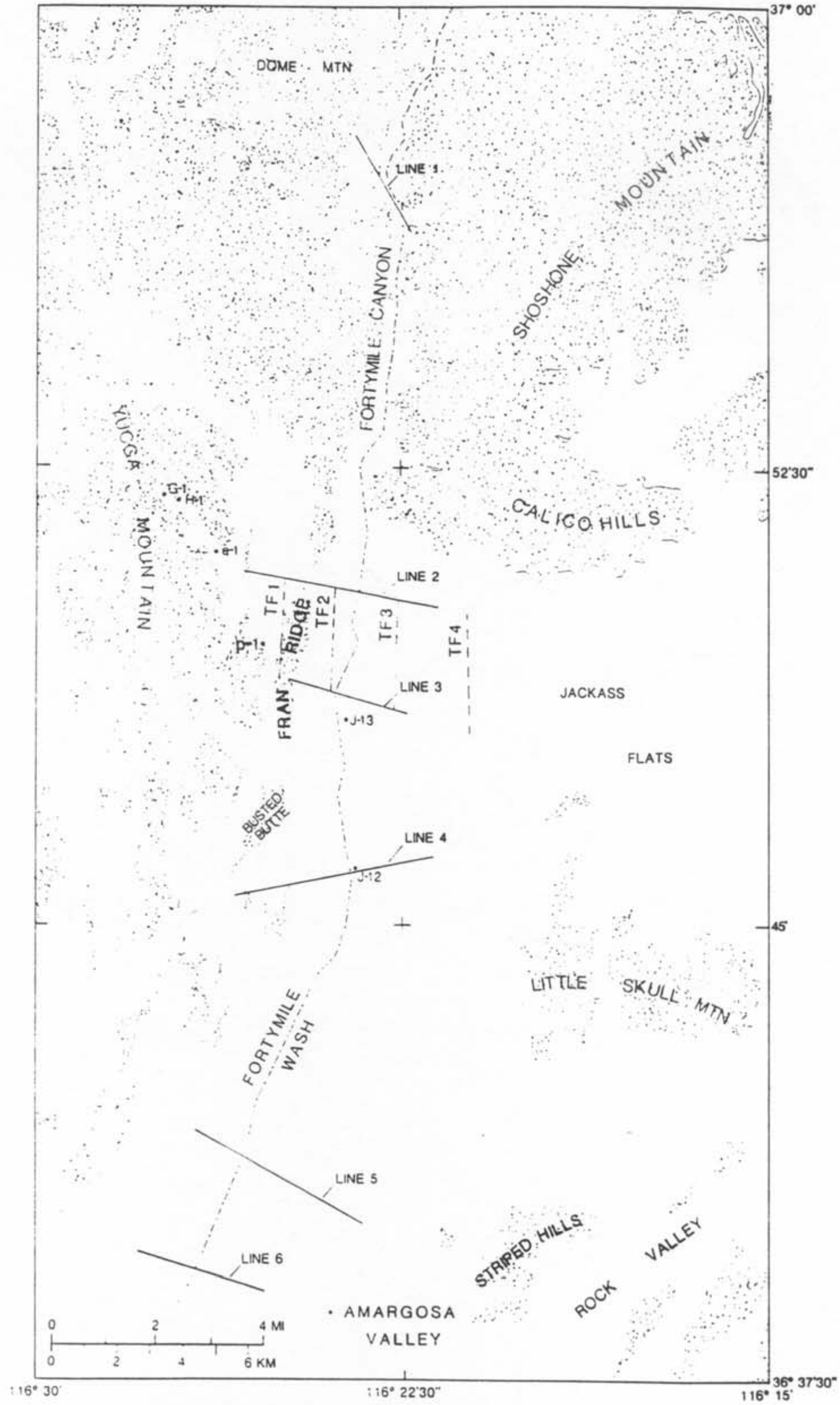

Figure 2.6.—Index map showing gravity profiles across Fortymile Wash and vicinity. TF1 to TF4 are faults inferred from electrical data. Stippled area denotes exposed rocks. Modified from Ponce and others (1988).

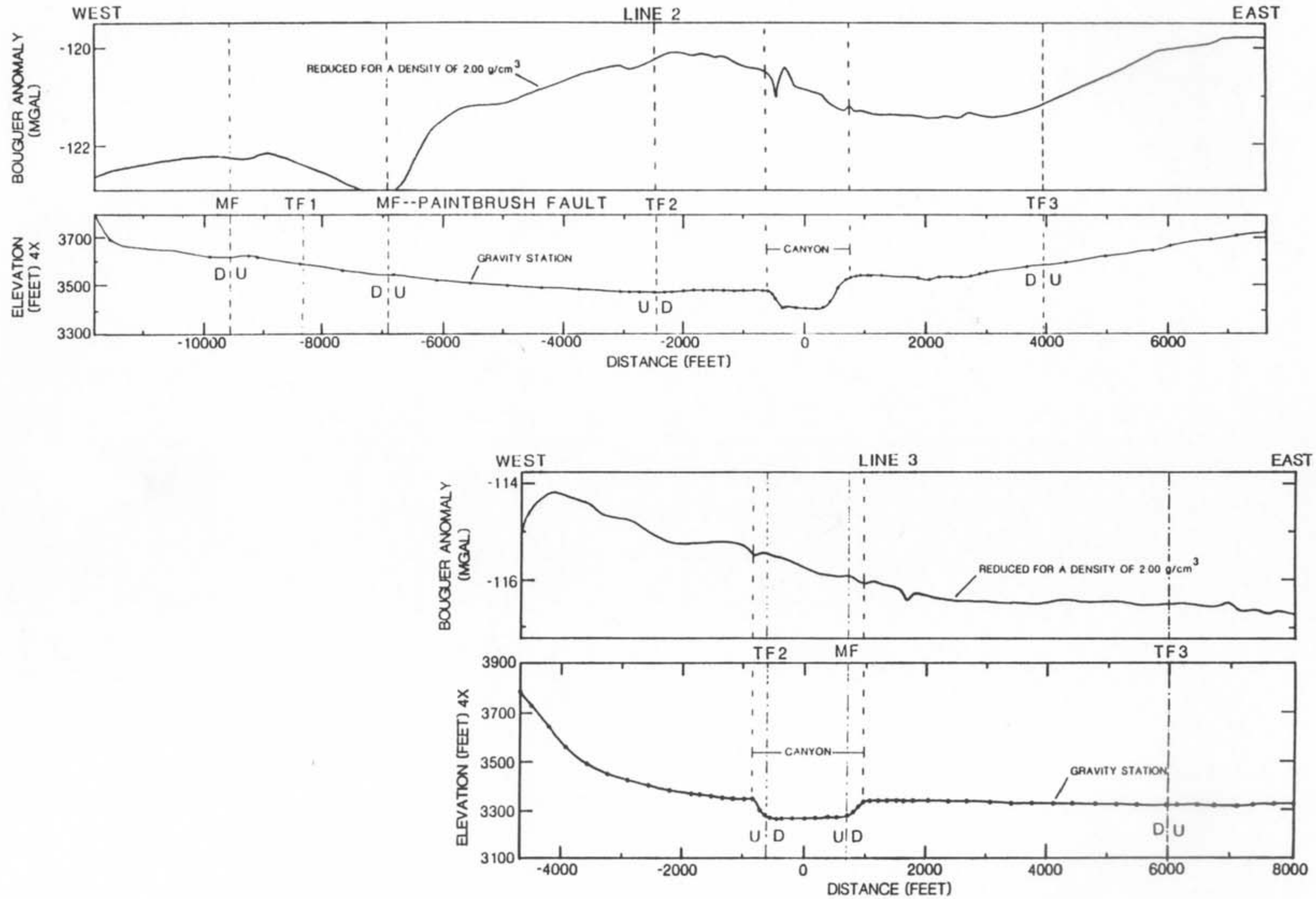

Figure 2.7.—Gravity and topographic profiles of line 2 and line 3 across Fortymile Wash, both near Fran Ridge. Refer to fig. 2.6 for locations. Symbols: MF, mapped geologic fault (Lipman and McKay, 1965); TF1 to TF3, inferred faults from electrical data (Hoover and others, 1982a) with electrode spacing of 500 m, where TF1 is the Paintbrush fault; U, upthrown side of fault; D, downthrown side. Modified from Ponce and others (1992).

1982a) and seismic refraction data (Mooney and Schapper, this volume) support the location of a major fault along the eastern edge of northern Amargosa Valley. In order to determine the exact nature of faulting, if present, in the immediate vicinity of Fortymile Wash, several profiles need to be extended, and additional detailed gravity, magnetic, and especially electrical data must be collected between the present profiles. These data would help determine whether or not faults inferred from geologic and electrical data in the immediate vicinity of Fortymile Wash (fig. 2.3; Ponce and others, 1992) and the major faults on either side of the wash in the northern part of the Amargosa Valley are related.

Detailed gravity data along line 2, at about -2,740 m, show the presence of a gravity anomaly. This gravity anomaly is located near a mapped, although concealed, fault of Lipman and McKay (1965). This anomaly is continuous to the south for at least 2,000 m and probably represents a fault. Subsequently, a seismic refraction profile (H. D. Ackermann, written commun., 1984) indicated a low-velocity zone at depth, and electromagnetic soundings by Frischknecht and Raab (1984) indicated a major lateral discontinuity at this location. However, according to G. D. Bath (oral commun., 1984), the absence of an associated magnetic anomaly probably precludes the existence of large vertical offsets in the underlying magnetic units. Additional data, especially ground magnetic data, are required to determine the exact nature of this anomaly.

OTHER INVESTIGATIONS

Ponce and Oliver (1981) established a gravity calibration loop over Charleston Peak to test meter performance and check calibration factors of the meters, the first such calibration loop in Nevada. Based on repeated occupations of the loop they found the loop to be sufficiently stable for calibrating the meters to about 1 part in 10,000. This calibration loop is well suited for studies at the Nevada Test Site due to its proximity and because it encompasses the range of observed gravity values at the Nevada Test Site.

Subsequently, Zumberge and others (1988) established four absolute gravity stations in southern Nevada. Three of them are on the Nevada Test Site, at Mercury, at Test Cell C, and at Check Point 2. The fourth station is at the Kyle Canyon Ranger Station along the Charleston Peak calibration loop. The purpose of these measurements is to provide absolute gravity control for the calibration loop and to provide an absolute datum for high-precision gravity measurements over Yucca Mountain. Comparisons between absolute and relative gravity measurements between Mercury and Kyle Canyon Ranger Station indicate that the calibration factors are good to not quite 1 part in 10,000. The Kyle Canyon absolute-measurement site is apparently of poor quality which adversely affects the comparison. Preliminary work at the Mt. Hamilton calibration loop in California indicates that the calibration factors there are better than 0.1 part in 10,000 (R.N. Harris and C.W. Roberts, oral commun., 1987). To resolve this discrepancy between the Charleston Peak and Mt. Hamilton calibration loops, the Kyle Canyon site should be reoccupied or another absolute site on Mt. Charleston should be selected.

A high-precision gravity loop was established across Yucca Mountain providing a rapid and inexpensive method of monitoring temporal changes in gravity (Harris and Ponce, 1988). The gravity loop has been tied to absolute gravity measurements (Zumberge and others, 1988), establishing a datum for monitoring absolute changes in gravity. Moreover, the high-precision gravity loop has been established along a first-order geodetic level line to study the relationship between possible variations in gravity and elevation. Fluctuations in the gravity field may result from vertical movements along the free-air gradient or variations in the subsurface density field. Determining the relationship between changes in gravity and elevation helps to discriminate between these two processes. Additional reoccupations of the high-precision gravity loop will be made as opportunity and necessity permit.

LIMITATIONS OF EXISTING DATA

Interpretation of gravity data does not produce a unique solution. This arises from the fact that a given gravity distribution can be produced or modeled by an infinite number of mass or density distributions. Thus, it is important that all available geologic and geophysical information be used as independent constraints to discriminate between possible solutions. Conversely, it is important that gravity data be collected along other geophysical traverses such as seismic, magnetic, and electric, so that the interpretations from these various methods can help constrain one another.

Because current investigations are being concentrated in the southwestern part of the Nevada Test Site and vicinity, detailed gravity data are needed to supplement the existing, in general, regional coverage (fig. 2.3). In areas of special interest, closely spaced gravity data are needed to help define concealed or unknown faults or structures. Repeatable high-precision gravity surveys are necessary to monitor temporal variations in the gravity field, which may be related to tectonism or water-table changes. Absolute gravity measurements are necessary to provide a datum for the relative gravity measurements and can be used to monitor broad-scale changes in the gravity field.

Physical property measurements are critical to the interpretation of gravity, as well as magnetic, data. Although there are numerous reports on density data, a considerable effort is needed to synthesize the data. Density data should be summarized by lithology and method used, and sufficient information on density variations within layers is needed so that a detailed density model can be formulated. In addition, borehole gravity-meter data should be collected to provide an independent measure of in situ density and information on surrounding structures.

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MAJOR RESULTS OF GEOPHYSICAL INVESTIGATIONS AT YUCCA MOUNTAIN AND VICINITY, SOUTHERN NEVADA

CHAPTER 3: MAGNETIC INVESTIGATIONS

By H.W. Oliver, D.A. Ponce, and H.R. Blank

INTRODUCTION

Magnetic methods are useful for locating and delimiting plutons, calderas, and faults; for determining depth to basement; and for tracing magnetic horizons concealed below the surface. Because most rock units contain a small percentage of magnetite or other magnetic minerals, they can be detected by a magnetometer provided their magnetic susceptibility and thickness are sufficient to produce observable anomalies. Thus, it is important to establish a relation between magnetic anomalies and the causative rock units and their magnetic properties. Bath (1968) began these studies at the Nevada Test Site using rock samples collected from surface outcrops and drill holes and used these data to determine subsurface geologic structure. Bath showed that remanent magnetization was responsible for almost all of the prominent aeromagnetic anomalies associated with Tertiary volcanic rocks at the Nevada Test Site and vicinity. Of the more than 50 volcanic units that were investigated, only 13 had the remanent intensity and thickness required to produce aeromagnetic anomalies. Of these 13, seven are normally magnetized and six are reversely magnetized.

MAGNETIC FEATURES OF SOUTHERN NEVADA AND PART OF EASTERN CALIFORNIA

Some 39 aeromagnetic surveys in southern Nevada and 11 surveys in adjacent parts of California have been conducted within a radius of 140 km from the potential site area being evaluated for storage of radioactive waste at Yucca Mountain. These surveys have been compiled here (fig. 3.1). All of the 50 surveys have been downward-continued or, in a few cases, upward-continued to a common level of 300 m above terrain. The details of the locations, spacing, and flight elevations of the 50 sources are too numerous to show here but are contained in a separate report by Sikora and others (1993). Limitations in existing data are primarily a function of flight line spacing and draping (fig. 3.2). For example, there are now draped surveys with both 0.4 and 0.8 km spacing available within about 30 km of the potential site area (fig. 1.1), but control is weak in the Death Valley region beginning about 30 km west of the site area. A more detailed compilation at 120 m above terrain in the immediate vicinity of Yucca Mountain has also been compiled (fig. 3.3).

In southern Nevada, the regional aeromagnetic map (fig. 3.1) shows broad magnetic highs (1) adjacent to the site area, (2) over the Spring Mountains about 40 km west of Las Vegas, and (3) near the Las Vegas and Mormon Mountains northeast of Las Vegas. In adjacent parts of California, there is a northwest-trending magnetic lineament over the Greenwater Range as

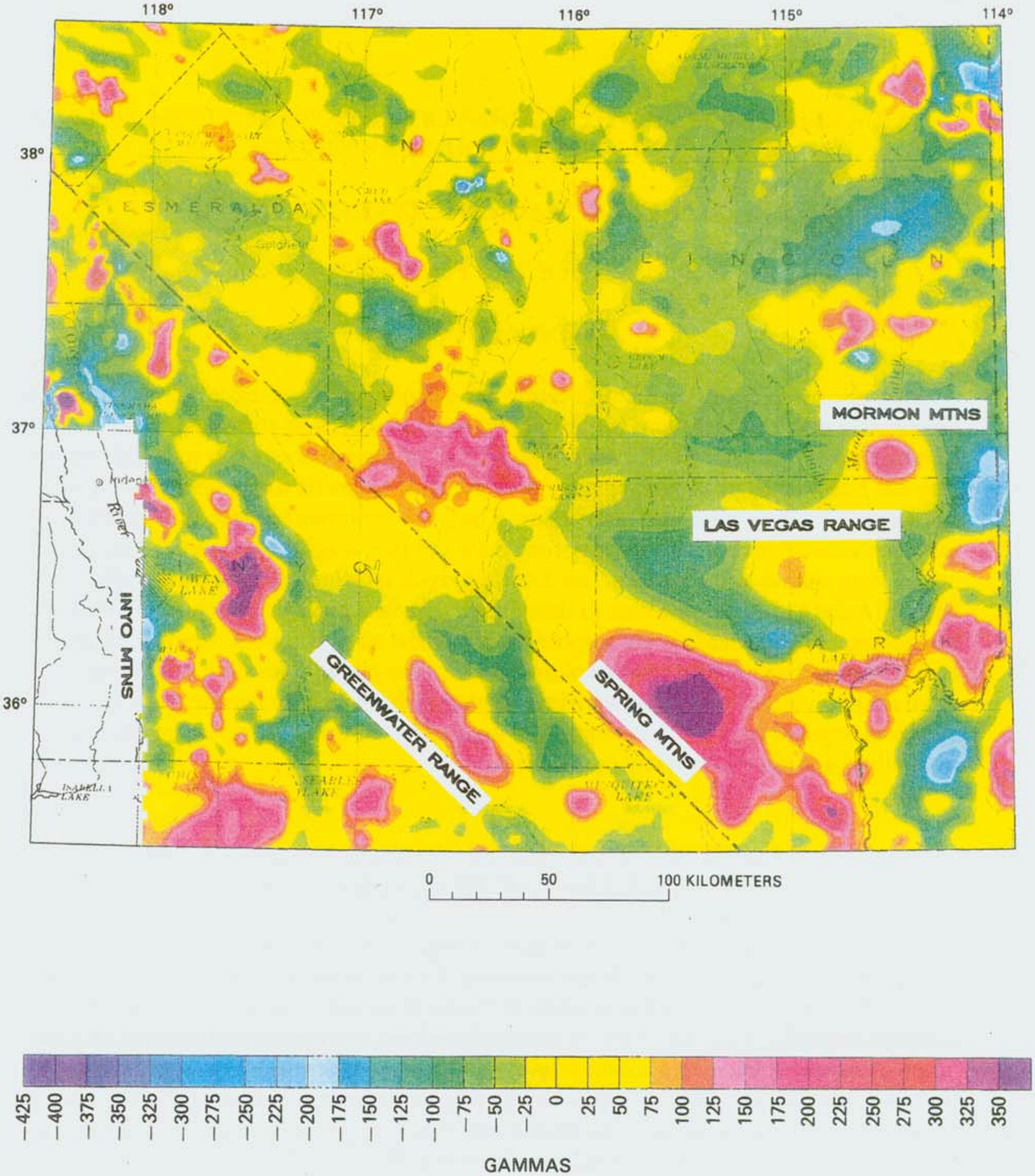

Figure 3.1—Residual total magnetic anomaly map of the southern Great Basin at 300 m above terrain. Modified from Hildenbrand and others (1988, fig. 2.12). Contour interval 25 nT.

well as a series of magnetic highs over the Inyo Mountains. A north-trending zone in the eastern part of Nevada with magnetic values of -100 to 0 nT (fig. 3.1) is characterized by a general lack of short-wavelength anomalies and is known as the "quiet zone".

The northwest-trending magnetic high near the site area has been enlarged about seven times to a scale of 1:357,000, recompiled, and continued downward to a level of 120 m above terrain (fig. 3.3). This format shows that the regional magnetic high is made up of a series of separated highs from southeast to northwest over Wahmonie, Calico Hills, the northern third of Yucca Mountain, and the Prospector Pass caldera. At Wahmonie, the magnetic high occurs over Miocene granitic intrusive rocks (Ponce, 1984). At Calico Hills, the center of the high is caused by local alteration of magnetite (known from drilling) within the Eleana Formation. There is also a broader component of the anomaly, and a depth analysis of that component suggests that the top of that source is about 3 km below the surface and that it has a magnetic susceptibility comparable to the granitic rocks exposed at Wahmonie.

Farther west, the magnetic high with values of 100 to 250 nT extends across the northern third of Yucca Mountain. Depth analysis at the eastern edge of Yucca Mountain indicates that the contact between these magnetic basement rocks and the nonmagnetic basement rocks to the south, known from drilling to be dolomite, is at a depth of about 2.2 km. The deepest well in the northern third of Yucca Mountain (USW G-2) reached depths of about 1.8 km and bottomed in 14 Ma tuff, and thus it may have come within about 0.4 km of basement. West of Yucca Mountain, the magnetic high turns north for about 5 km before returning to its westerly trend and finally ends inside the Prospector Pass caldera, a distance of about 50 km west of Wahmonie. The most likely candidates for these east-west anomalies are the granitic rocks (exposed at Wahmonie) or some older granite with some intervals enhanced by baked argillite of the Eleana Formation. This finding has possible implications on structural and mineral assessment models of Yucca Mountain.

Other major regional magnetic anomalies in the vicinity of the potential site occur over the Spring Mountains about 30 km west of Las Vegas and the Mormon Mountains about 100 km northeast of Las Vegas (fig. 1.2). Integrated qualitative/quantitative interpretation of the total magnetic and derivative maps suggests the following relations:

1) The northern Spring Mountains, the Las Vegas Range and the Mormon Mountains are underlain by three broad swells on the surface of the Precambrian crystalline basement. These three swells and their associated aeromagnetic anomalies (see fig. 3.1) are aligned to the northeast, roughly collinear with the "iron axis" of southwestern Utah, an alignment of 2-Ma, iron-rich monzonite intrusions.
2) The Spring Mountains swell, at the southwest end of the triad and the source of the largest (most intense and broadest) aeromagnetic anomaly, contains at its core near its crest (depth 4 to 5 km) an extremely magnetic body, elongated to the north, of somewhat lower density than that of the rocks comprising the bulk of the uplift. The northern and western margins of this body, if projected to the surface, closely follow the surface trace of the Keystone thrust. Thus, the anomalous body may be an iron-rich Tertiary (or at least post-Keystone) intrusion whose emplacement produced the basement swell.

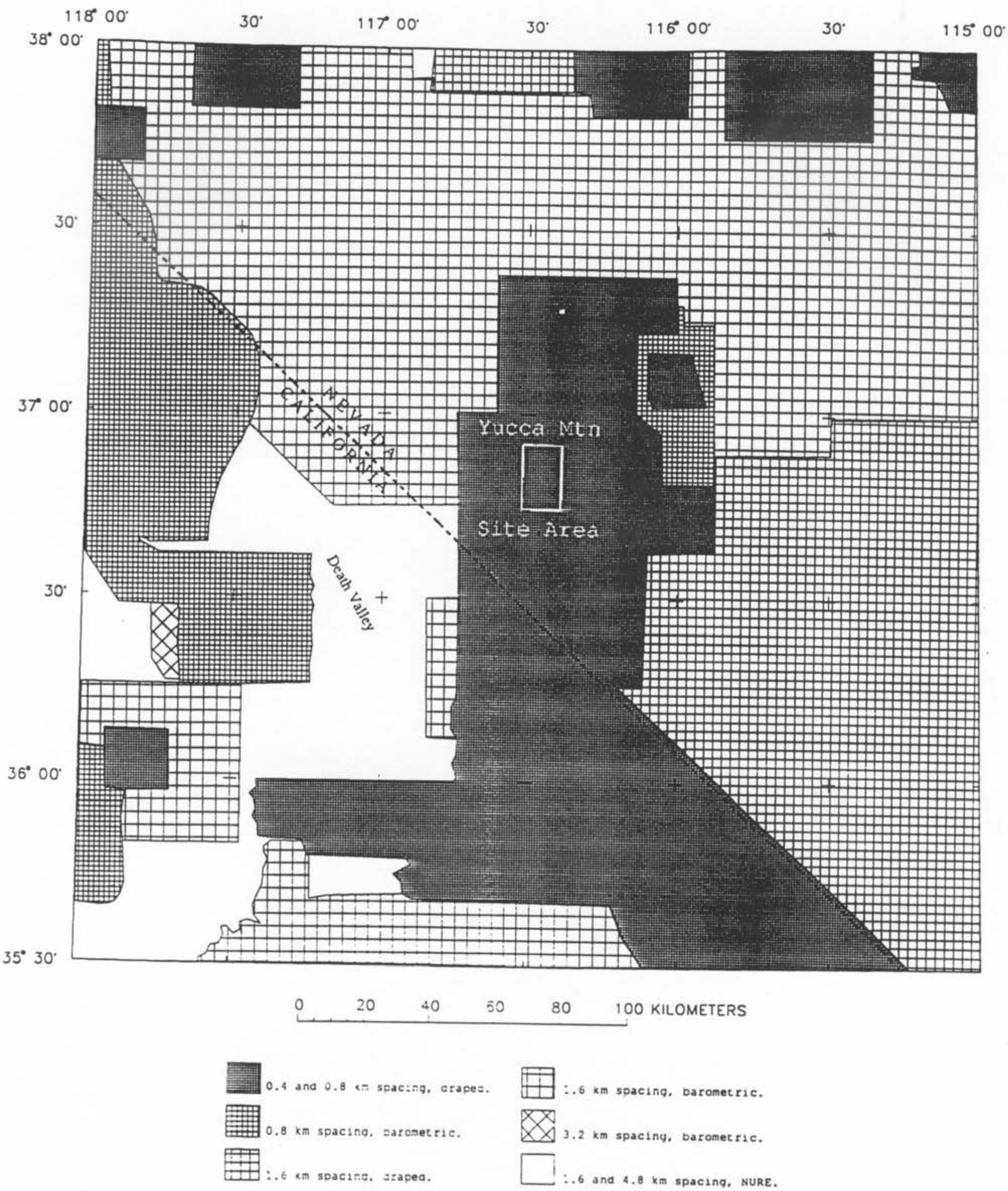

Figure 3.2—Aeromagnetic index map of the Regional Study Area showing flight line spacing of available data. These data consist of 39 separate surveys in Nevada and 11 in California. Symbols: NURE, National Uranium Resource Evaluation program. Modified from Oliver and others (1990).

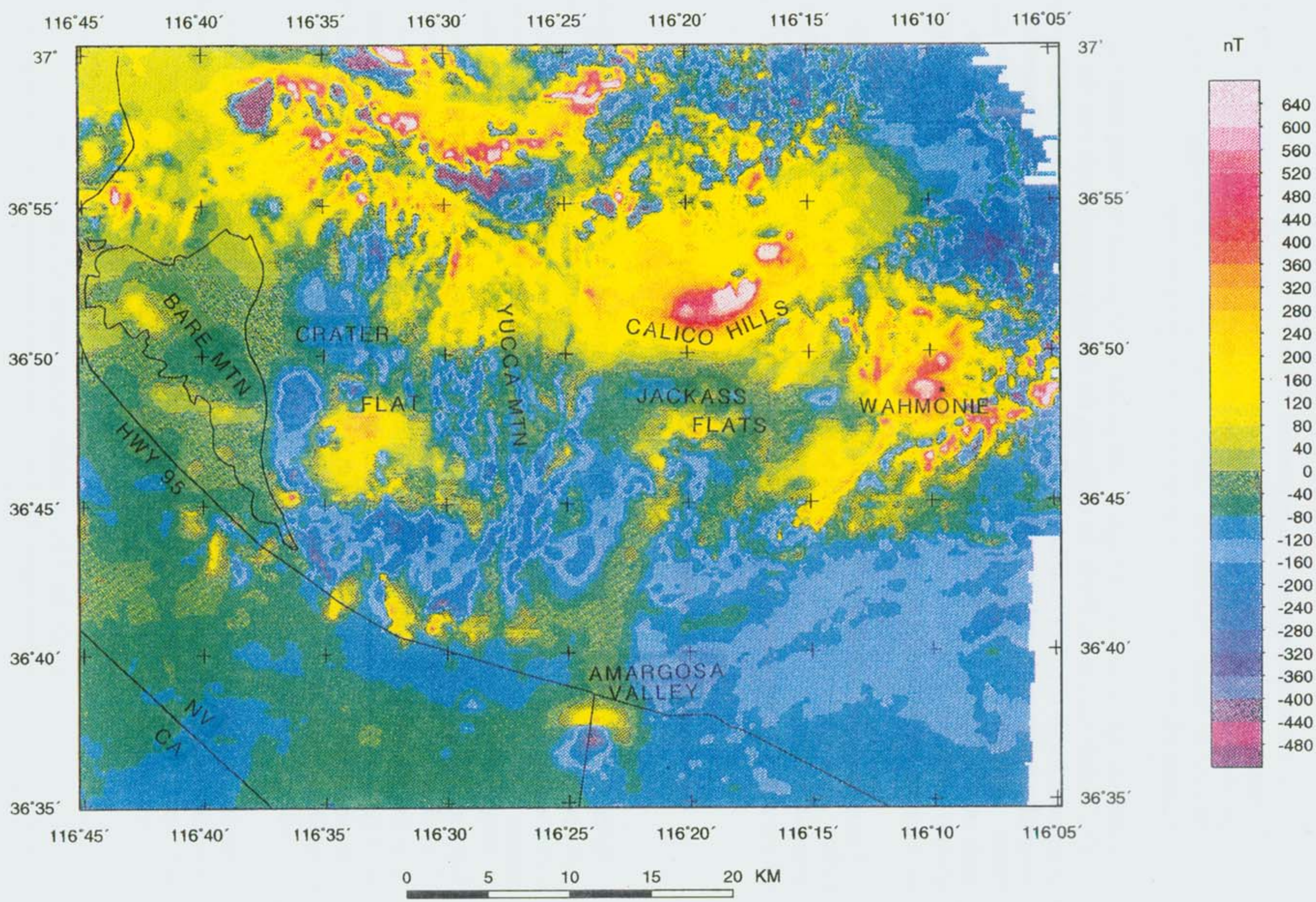

Figure 3.3—Total intensity aeromagnetic map of Yucca Mountain and vicinity at 120 m above terrain. Contour interval 25 nT. Flight line spacing about 0.4 km. Modified from McCafferty (pers. commun.).

3) The Mormon Mountains swell can be modeled as a symmetric dome of strongly magnetic basement rocks superimposed on a much broader basement uplift. The basement dome also involves Paleozoic cover rocks and the Miocene Mormon detachment fault, and it is the locus of Tertiary hydrothermal mineral systems. These relations suggest that the Mormon Mountains are also underlain by a Tertiary intrusive body.

Additional regional aspects of magnetic and gravity investigations have been described in the work of Blakely and others (1994). In California, the elongate magnetic high over the Greenwater Range overlies Precambrian to Tertiary rocks and extends to the northwest within remarkably continuous boundaries across Death Valley to Telescope Peak in the Panamint Range. Although recent geologic mapping indicates that this area has been grossly extended, depth analysis of these data by Blakely and others (1994) and the straight extension of the anomaly across currently active faulting suggest that the Greenwater Range has behaved as a coherent block at midcrustal depths.

The quiet magnetic zone in eastern Nevada described above has been studied by Blakely (1988). He concluded that the zone cannot be explained by a simple rise of the Curie temperature isotherm to shallower depth but rather by a lack of volcanic activity since 17 Ma and the preponderance of S-type, ilmenite-bearing granites.

VOLCANIC HAZARD STUDIES NEAR LATHROP WELLS AND IN CRATER FLAT

Volcanic hazard studies are being carried out to evaluate the probability of future volcanism and to predict the effect of such volcanism on a potential repository at Yucca Mountain. These studies are of primary importance for site characterization efforts at the Nevada Test Site because geologic mapping has identified, at the potential high-level nuclear waste site, two of the three structures most often associated with basaltic volcanism, specifically Basin-and-Range faults, and ring fractures of inactive calderas (Crowe and others, 1983; Crowe and others, 1992). Based on studies of the timing and volume of known volcanic centers in the southern Great Basin, Crowe calculated an annual probability of basaltic volcanism of between 4.7×10^{-8} and 3.3×10^{-10}. They felt that the actual probability is likely much less, based on an observed decrease in erupted volume over the past 4 m.y. If other volcanic centers were discovered and included in the calculations, the probability estimates could increase significantly (B. Crowe, personal commun., 1993) but remain similarly small.

Aeromagnetic surveys in the Lathrop Wells and Crater Flat areas (fig. 3.3) revealed several anomalies similar to those of subaerial basaltic volcanic centers, but those were not associated with exposed basaltic rocks (figs. 3.4 and 3.5). These anomalies may indicate shallow intrusions or buried volcanic centers (Kane and Bracken, 1983).

Reversed magnetic lows also occur over the exposed volcanic centers named Black Cone and Red Cone in Crater Flat (fig. 3.4). A similar, but normally polarized, anomaly (marked "A" in the lower left corner of that figure, fig. 3.4) occurs over a flat desert surface and suggests the presence of a shallow, buried cone similar to the exposed cones but of an age when the earth magnetic field was normally polarized.

In the Lathrop Wells area, there are five magnetic doublets located over flat desert terrain that were discovered from the air (fig. 3.5). The largest of these, anomaly B, is reversely polarized and has been checked by both ground magnetic and gravity measurements and modeled by Langenheim and others (1993). Their results showed that the top of the causative body may be buried less than 250 m below the surface and probably less than 150 m. The west edge of the body was drilled in 1991 in the oil-and-gas wildcat Felderhoff Federal 25-1 well (Carr and others, 1995), and basalt was penetrated at 104 m (Harris and others, 1992). Similarly, drilling much earlier near Anomaly D (fig. 3.5) encountered basalt cobbles at 183 m (Walker and Eakin, 1963). If all five of the dipolar anomalies (A-E, fig. 3.5) are caused by basaltic volcanic centers, this information could make an important contribution to estimates of the probability of future volcanism in the region.

TRACING CONCEALED FAULTS IN YUCCA MOUNTAIN

Because the fundamental structure of Yucca Mountain is a series of north-striking blocks each of which has been tilted down to the east along a series of faults, the detection of these faults, particularly where concealed by alluvium, is a vital part of the geologic-geophysical study. The easiest way to study these potential concealed structures is with aeromagnetic data supplemented with ground magnetic, gravity, and/or seismic refraction or reflection data as needed or affordable. Kane and Bracken (1983) were the first to call attention to the potential importance of fault-associated aeromagnetic anomalies but were soon followed by Bath and Jahren (1984), who summarized the magnetic properties and thicknesses of major near-surface ash flows in the potential repository area based on logs in drill holes USW G-1, G-2, and G-3. They also developed an understanding of expected aeromagnetic signatures associated with north-striking faults by computing the magnetic effect of offsetting these ash flows by vertical distances of 100, 250, 400, and 700 m, and at infinite distance (fig. 3.6). In all cases, the expected signal is a low to the west accompanied by a rise to the east of the fault of about double the magnitude of the western low. For example, a vertical fault displacement of 250 m down to the west should produce a magnetic low of about 20 nT west of the fault and an approximate 40 nT high to the east at an elevation of 152 m above ground.

This magnetic model has been tested with aeromagnetic data which show that the Topopah Spring Tuff of the Paintbrush Group (Sawyer and others, 1994) produces the main anomalies in the Yucca Mountain area. A vertical displacement of 70 m is required to produce a significant aeromagnetic anomaly (Bath and Jahren, 1984). For faults with smaller displacements, recent ground magnetic measurements have been successful in tracing concealed faults in Fortymile Wash (Ponce, and others, 1992), in Midway Valley (Ponce and others, 1993; Ponce, 1993), and in Yucca Wash (Langenheim, Ponce, and others, 1993). The profiles in Midway Valley are shown on the index map (fig. 3.7) as are lines FM-2 and -3 in Fortymile Wash and the several Yucca Wash profiles. The Solitario Canyon fault produces a magnetic signature similar to Bath's model (fig. 3.6) with a magnetic low to the west of about -150 nT and a high to the east

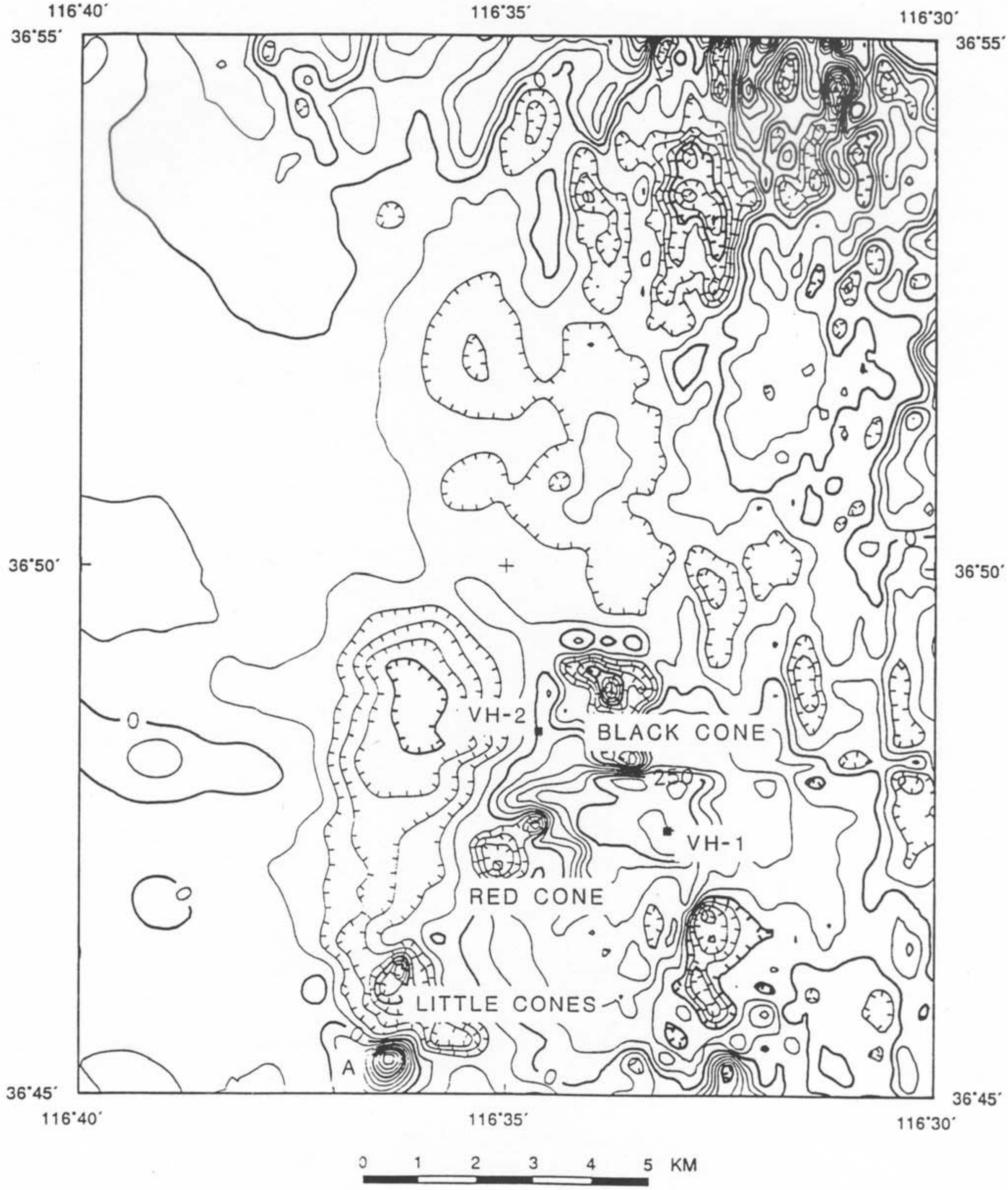

Figure 3.4—Aeromagnetic map of the Crater Flat area comparing the aeromagnetic signature over subaerial cinder cones (anomalies at Black Cone and at Red Cone) with an anomaly not associated with exposed lava (anomaly A). Also marked is the Little Cone anomaly which extends down the western and southwestern side of Crater Flat.

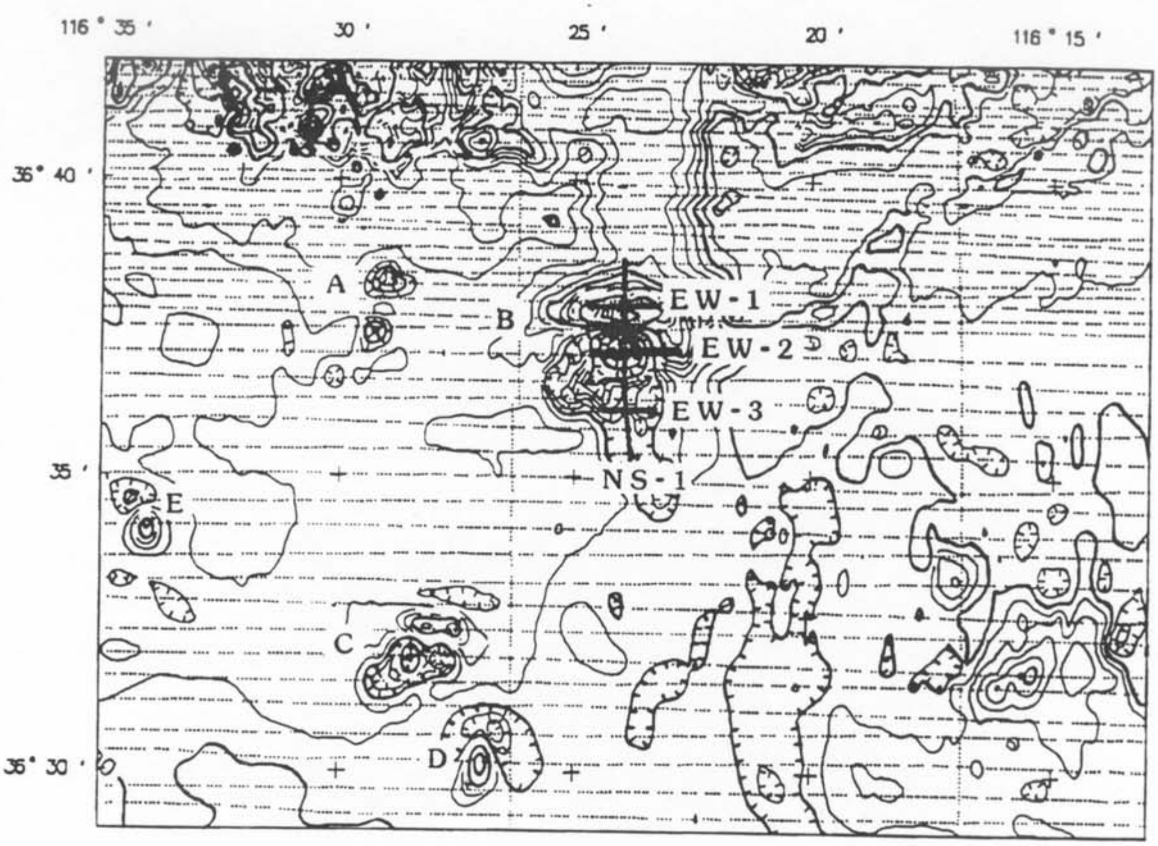

Figure 3.5—Aeromagnetic map of the Lathrop Wells area showing anomalies A to E. Thick lines indicate locations of ground magnetic measurements over anomaly B. Dotted lines denote flight-line locations. Contour interval 20 nT. Modified from Langenheim and others (1993).

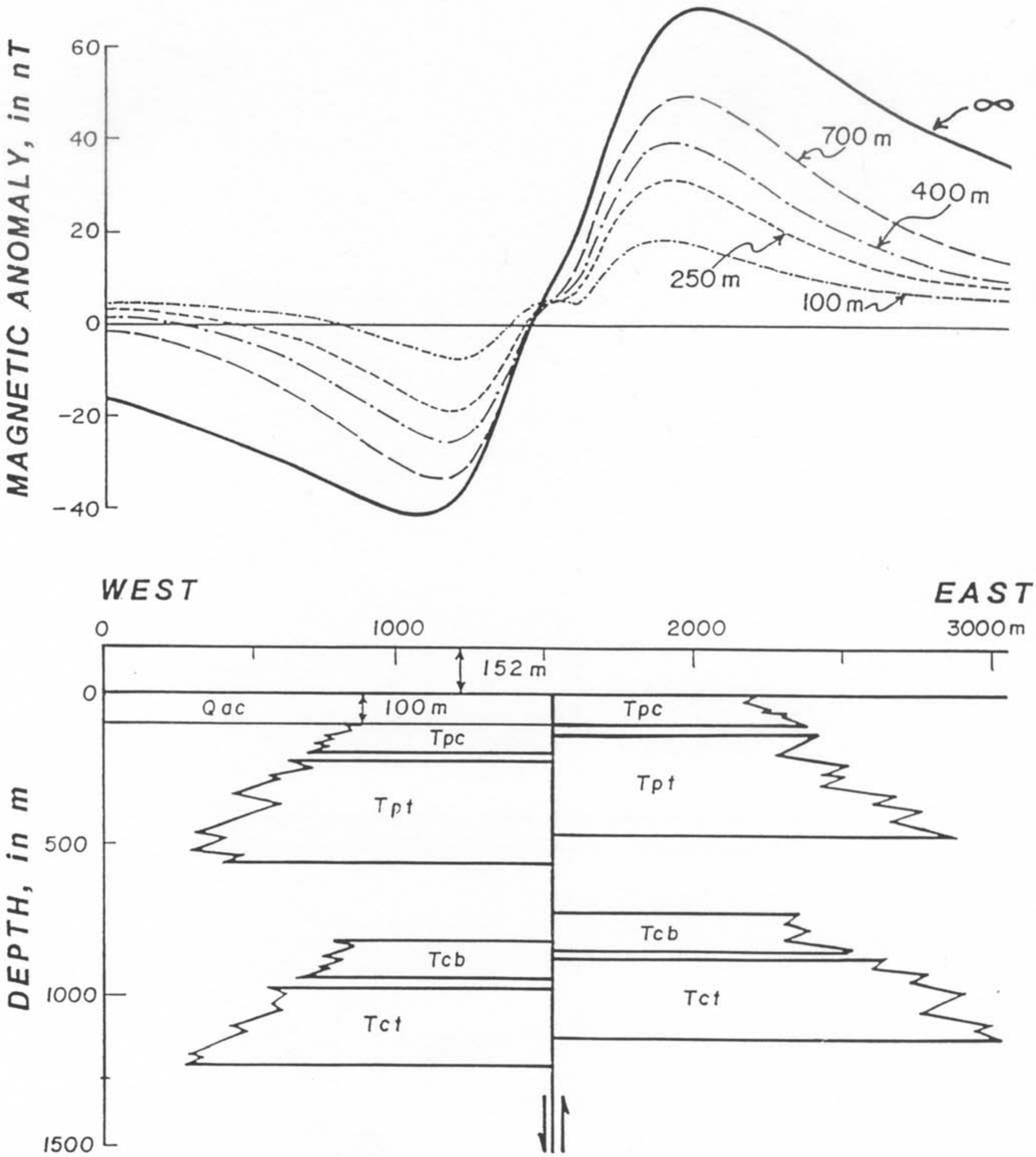

Figure 3.6—Cross section showing theoretical anomalies for total effect of flows of the Tram (Tct) and Bullfrog (Tcb) Tuffs of the Miocene Crater Flat Group and the Topopah Spring (Tpt) and Tiva Canyon (Tpc) Tuffs of the Miocene Paintbrush Group at a fault that strikes north-south. Theoretical anomalies are depicted with increasing vertical displacements down to the west. Modified from Bath and Jahren (1984, fig. 14).

of +133 nT. Similarly, both the Bow Ridge and Paintbrush Canyon faults in Midway Valley can be identified where concealed by magnetic steps up to the east of about 200 nT and 300 nT at ground level, respectively (Ponce, 1993, fig. 3).

The preliminary results of interpretation of profiles YA to YE in Yucca Wash (fig. 3.7) indicate that the inferred position of the Bow Ridge fault in the vicinity of line YB needs to be moved about 100 m to the west. Also, the three ground magnetic profiles of YF show a large (900 to 1250 nT) anomaly just north of drill hole UE-25 WT#6. From gradient analysis, the maximum depth to the top of the source is approximately 100 m. Further southeast, there is a broad magnetic high extending to profile YB which coincides with the rise in the water table of about 300 m between drill holes UE-25 WT#16 and UE-25 WT#6 (Langenheim, Ponce, and others, 1993).

Ground magnetic techniques were tested recently for tracing the Ghost Dance fault which runs north-south through the potential repository between the Solitario Canyon fault on the west and the Bow Ridge fault on the east (fig. 3.7). Detailed structural mapping by Spengler and others (1993) indicates that the fault is nearly vertical and offsets strata down to the west by about 30 m. There is no magnetic signature of the fault on aeromagnetic maps of data from lines flown at 150 m above ground, but new ground measurements have found a distinctive magnetic low of about 400 nT centered only 15 m east of the fault and flanked by lower amplitude highs stepping up to the east (Oliver and others, 1994), consistent with that found by Bath and Jahren (1984) across the fault in the next canyon to the north. The most promising result of preliminary modeling (Oliver and Sikora, 1994) is a tabular loss of magnetic remanence penetrating the normally polarized Topopah Spring Tuff, perhaps as a result of alteration or brecciation within the fault zone. Modeling further suggests that this signature could also be consistent with some shallow reversely polarized body within the fault plane such as a dike or mineralized zone with a greater reversed polarization than the Tiva Canyon Tuff (Oliver and Sikora, 1994). Such a body could be analogous to the tabular basaltic dike in the Solitario Canyon fault (U.S. Geological Survey, 1984, p. 29), but no geologic evidence for such a body has been found across the Ghost Dance fault trace. Investigations specifically targeting possible basalt in the fault zone have failed to preclude such intrusion(s), but the work suggests low likelihood of basalt: drill holes USW UZN-35 and USW UZ-7A were drilled into the Ghost Dance fault plane (Geslin and others, 1995; Geslin and Moyer, 1995) in drainages just north of the magnetic traverse (Oliver and Sikora, 1994) and found no basalt at the shallow depths suggested by the magnetic modeling. In addition, the tunnel-boring machine has excavated the Bow Ridge and Drill Hole Wash faults (R.W. Spengler, personal communication, 1995) and has encountered no basalt in 3300 m of drift.

OTHER MAGNETIC STUDIES

Other magnetic studies mentioned in connection with gravity work (chap. 2, this report) are investigations of Syncline Ridge (Ponce and Hanna 1982), and of the Timber Mountain area (Kane and Webring, 1981). The Wahmonie study (Ponce, 1984) is particularly important because

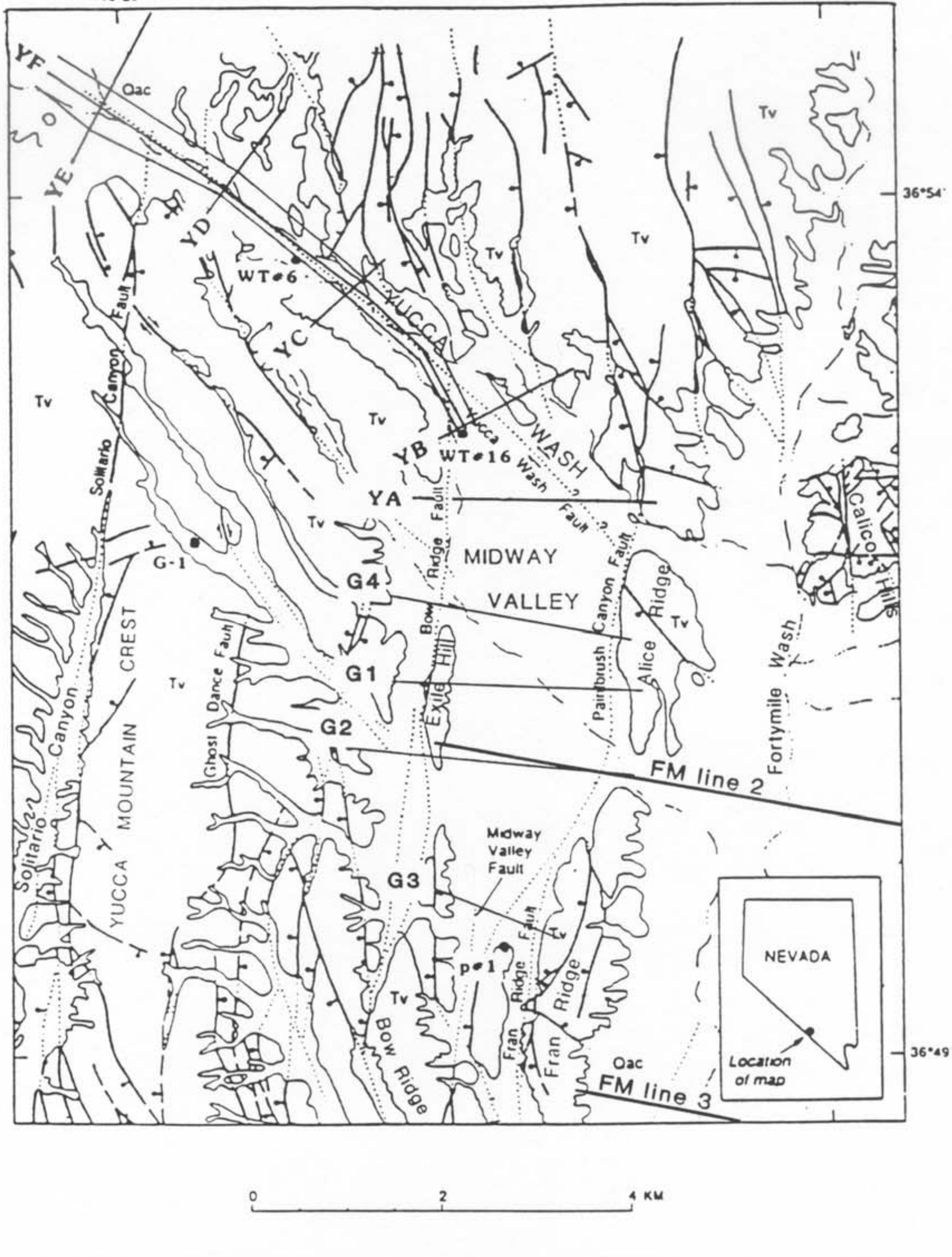

Figure 3.7. Index map of the study area showing locations of gravity and magnetic profiles along and across Yucca Wash (profiles YA through YF), Midway Valley (profiles G1 through G4), and Fortymile Wash (FM profiles), and pertinent drill holes (filled circles). Symbols, Tv, Tertiary volcanic rocks; Qac, Quaternary alluvium and colluvium; bold lines, faults, dotted where concealed, ball and bar on downthrown side, arrows to indicate relative movement. Geology taken from Lipman and McKay (1965). Profile YF consists of three profiles.

it describes magnetic evidence for a possible intrusive body at shallow depth just east of Yucca Mountain.

A recent analysis of regional magnetic data in the southern Great Basin in terms of depths to the bottom of magnetic sources shows these depths to vary from about 10 km to about 30 km (Blakely, 1988). Under Yucca Mountain, the computed depth is about 25 km, although the computation is approaches the southwestern edge of the magnetic data set. There is some rationale to consider these depths as depths to the Curie isotherm (400°C to 580°C depending on the amount of titanium in the magnetite), and therefore, indicative of major thermal structures. In southern Nevada, there is good correlation between the greater depth (>25 km) to the base of magnetic rocks and low heat flow values centered about 100 km north of the Yucca Mountain site (see chap. 9, this report).

LIMITATIONS OF EXISTING AEROMAGNETIC DATA

Limitations of existing data arise from spacing and focus of previous investigations, as well as from limits of coordination with geologic setting. Aeromagnetic data from traverses spaced at 5 km were flown in the California part of the southern Great Basin under the National Uranium Resource Evaluation (NURE) Program, and these data are being compiled to enable extension of the Curie isotherm study and analysis of the tectonic problems in this area (see chap. 1). Also, using existing data from traverses flown at 0.5-km spacing over Yucca Mountain, we are attempting to use computer-based redraping methods to isolate the effects of east-west-trending contacts within Paleozoic rocks from the predominately north-south grain of the overlying Cenozoic volcanic units. A merged aeromagnetic map of the Nevada Test Site has been compiled by Kirchoff-Stein and others (1989) at the same scale (1:100,000) as the recent geologic map (Frizzell and Shulters, 1990), and the results summarized by Oliver and others (1991).

In addition, mosaic aeromagnetic compilations have been made recently of the Las Vegas 1° by 2° quadrangle (Saltus and Ponce, 1988), and the Beatty 1/2° by 1° quadrangle (Glen and Ponce, 1991). Sikora and others (1993) recently compiled all the sources of existing aeromagnetic data within about 140 km of Yucca Mountain and concluded that the area to the west has the poorest quality as its primary source is the low-level NURE data flown at about 120 m above ground but with a flight line spacing of about 1.6 km, which is inadequate for locating buried faults and cinder cones (Oliver and others, 1990, p. 17).

CONCLUSIONS

Existing magnetic data have been very helpful for studying the nature of buried rocks under Yucca Mountain (Oliver and others, 1991; Oliver and Mooney, 1992), for finding buried basaltic cinder cones in Crater Flat and the Amargosa Desert (Langenheim and others, 1993), and for locating concealed faults within Yucca Mountain (Ponce, 1993; Langenheim, Ponce, and others, 1993). Resolution of the aeromagnetic data could be improved by closer flight line spacing and more accurate draping. Additional, detailed ground magnetic measurements should be made to help geologists trace concealed faults, and Curie isotherm analysis of the Yucca Mountain region should continue to compare areas of shallow isotherms with areas of high heat flow and recent volcanism.

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