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Geophysical Framework of the Southwestern Nevada Volcanic Field and Hydrogeologic Implications

By V.J.S. Grauch,[1] David A. Sawyer,[2] Chris J. Fridrich,[2] *and* Mark R. Hudson[2]

Abstract

Gravity and magnetic data, when integrated with other geophysical, geological, and rock-property data, provide a regional framework to view the subsurface geology in the southwestern Nevada volcanic field. We have loosely divided the region into six domains based on structural style and overall geophysical character. For each domain, we review the subsurface tectonic and magmatic features that have been inferred or interpreted from previous geophysical work. Where possible, we note abrupt changes in geophysical fields as evidence for potential structural or lithologic control on ground-water flow. We use inferred lithology to suggest associated hydrogeologic units in the subsurface. The resulting framework provides a basis for investigators to develop hypotheses for regional ground-water pathways where no drill-hole information exists.

We discuss subsurface features in the northwestern part of the Nevada Test Site and west of the Nevada Test Site in more detail to address potential controls on regional ground-water flow away from areas of underground nuclear-weapons testing at Pahute Mesa. Subsurface features of hydrogeologic importance in these areas are (1) the resurgent intrusion below Timber Mountain, (2) a NNE.-trending fault system coinciding with western margins of the Silent Canyon and Timber Mountain caldera complexes, (3) a north-striking, buried fault east of Oasis Mountain extending for 15 km, which we call the Hogback fault, and (4) an east-striking transverse fault or accommodation zone that, in part, bounds Oasis Valley basin on the south, which we call the Hot Springs fault. In addition, there is no geophysical nor geologic evidence for a substantial change in subsurface physical properties within a corridor extending from the northwestern corner of the Rainier Mesa caldera to Oasis Valley basin (east of Oasis Valley discharge area). This observation supports the hypothesis of other investigators that regional ground water from Pahute Mesa is likely to follow a flow path that extends southwestward to Oasis Valley discharge area.

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Introduction

The southwestern Nevada volcanic field has been the focus of extensive geologic, hydrologic, and geophysical investigations by the U.S. Geological Survey (USGS) and other agencies for more than 30 years. The studies were conducted in support of underground nuclear-weapons testing at the Nevada Test Site and nuclear waste storage activities at Yucca Mountain, funded by the U.S. Department of Energy (DOE) and its predecessor agencies. Laczniak and others (1996) summarized the state of knowledge about ground-water systems in the Nevada Test Site and Yucca Mountain region and placed constraints on radionuclide migration away from contaminated test sites.

Because ground water throughout the area occurs at depths typically greater than 500 m (Laczniak and others, 1996), studies must rely on subsurface information to understand structural or lithologic controls on ground-water flow. Although a vast data set of subsurface geologic information from hundreds of deep (> 600 m) drill holes is available (Ferguson and others, 1994), these data are limited to local areas. The local areas are primarily near nuclear test sites on the Nevada Test Site and in the vicinity of Yucca Mountain, where a high-level-nuclear-waste repository has been proposed. Thus, many important questions remain that are pivotal to defining ground-water flow paths beyond these local areas (Laczniak and others, 1996). In particular, the deep ground-water system south and southwest of Pahute Mesa is poorly characterized. Better subsurface knowledge of this area is crucial for evaluating the possible flow paths away from the testing areas at Pahute Mesa (fig. 1).

In the absence of drill-hole information, geophysical methods provide the best information on major subsurface features that may be controlling ground-water flow. Moreover, where drill-hole information is present, geophysical methods provide important tools for interpolating data between drill holes. In this report we use geophysical data, especially gravity and magnetic data, to develop an integrated geophysical framework of the southwestern Nevada volcanic field. The framework is based on the extensive geophysical interpretations by previous investigators and on recent interpretations from new geophysical, geological, and rock-property information west of the Nevada Test Site. We identify subsurface features that have potential hydrogeologic importance and provide more detailed evaluation of features in the vicinity of potential flow paths from Pahute Mesa.

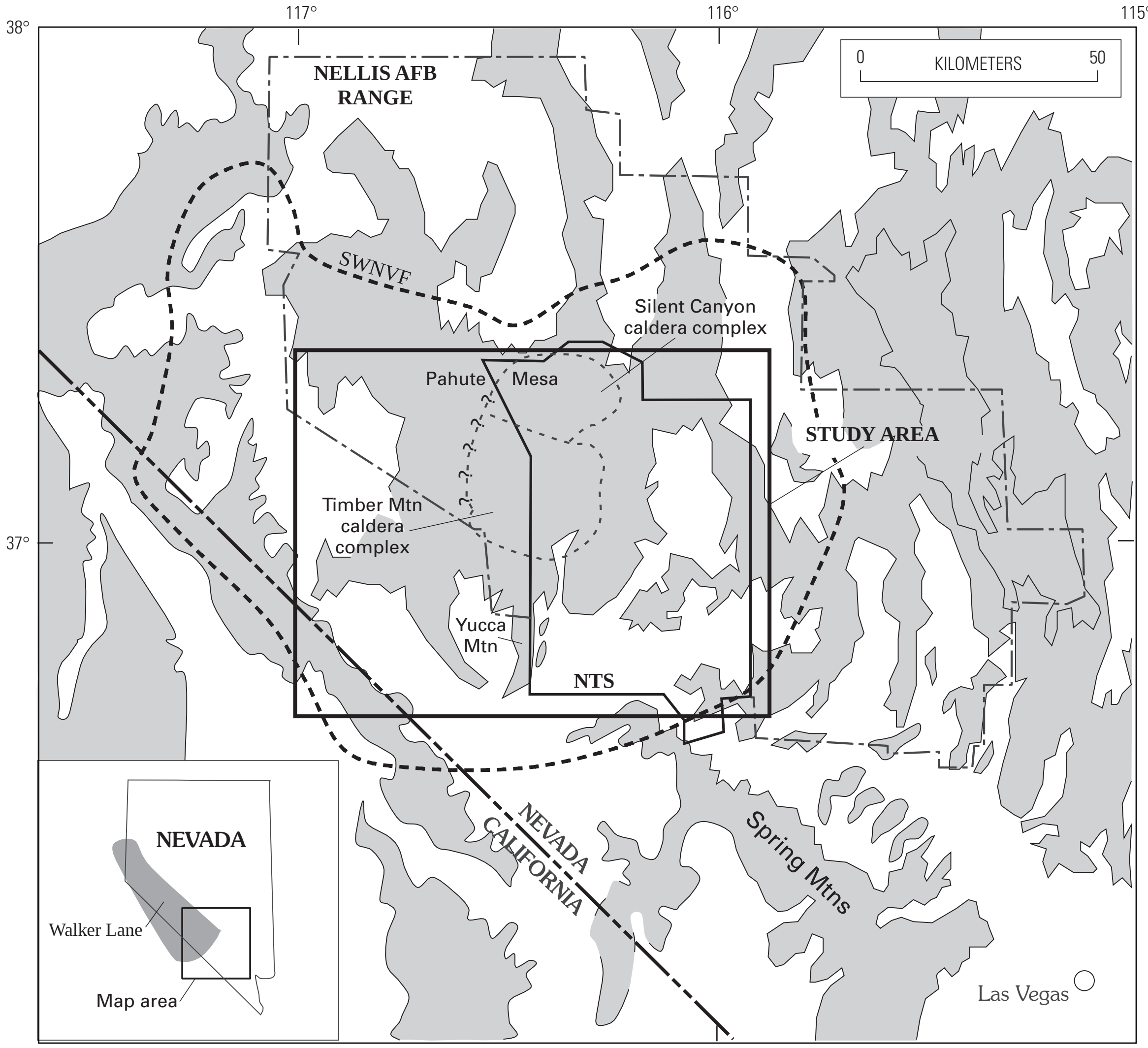

Figure 1. Map showing approximate extent of the southwestern Nevada volcanic field (SWNVF, thick dashed line) in relation to major geographic features. Upland areas are shaded; alluvial areas are shown in white. Also shown are the study area (figs. 3–7; bold solid line), Nevada Test Site (NTS, solid line), Nellis Air Force Base Range (dash-dot line) and Yucca Mountain. Inset shows location of map area and Walker Lane belt.

Regional Setting

The southwestern Nevada volcanic field is in the southwestern Great Basin near and within several sensitive Federal facilities, including the Nevada Test Site, Yucca Mountain, and Nellis Air Force Base Range (fig. 1). The Great Basin, with its pronounced pattern of elongated mountain ranges and intervening basins, evolved as a result of regional crustal extension that took place during middle to late Cenozoic time. This extension represents the latter stages of a diverse history of tectonism, volcanism, and sedimentation, where younger events overprinted older events in ways that are sometimes difficult to unravel.

In Late Proterozoic and early Paleozoic time, nearly 5.5 km of marine carbonate and clastic sediments were deposited on Proterozoic crystalline basement in the southwestern Nevada volcanic field region. An additional 2.5 km of sediments were deposited during Devonian to Mississippian time, when marine sedimentation was intermixed with periods of major compressional tectonics throughout the Great Basin (Trexler and others, 1996). In Late Cretaceous time, small granitic stocks intruded major thrust faults and related folds in Paleozoic sedimentary rocks. The thrust faults may be Mesozoic, or perhaps as old as Permian (Snow, 1992). In the early Tertiary, from 45 to 17 Ma, while much of the rest of the Great Basin was experiencing widespread ash-flow eruptions and episodes of extension (Noble, 1972; Christiansen and Yeats, 1992), the southwestern Nevada volcanic field region experienced minor volcanism and perhaps major episodes of tectonism.

From 17 to 9 Ma, the southwestern Nevada volcanic field developed as a result of episodic, voluminous magmatism and variably intense extension (Sawyer and others, 1994; Hudson and others, 1994). The first part of this tectonism predates the southwestern Nevada volcanic field, at perhaps 16 Ma (Fridrich, 1999). Magmatism began at about 15.2 Ma and culminated in voluminous rhyolite eruptions from a complex of large ash-flow calderas between 12.8 and 11.4 Ma. After this period of intense volcanism, activity began to wane and change to bimodal rhyolite-basalt magmatism followed by entirely basaltic eruptions. The silicic ash-flow tuffs and lesser silicic and mafic lava flows of the southwestern Nevada volcanic field cover an area of >10,000 km^2 and reach thicknesses of 4 km or more in the center of the field (Ferguson and others, 1994). Each of the silicic ash-flow tuffs is associated with one or more calderas in the center of the volcanic field. Extension around the perimeters of the southwestern Nevada volcanic field occurred during and after the episode of magmatism but varied in intensity, timing, and style from area to area (Hudson and others, 1994). From 9 Ma to the present, volcanism and tectonism in the southwestern Nevada volcanic field have progressively declined.

The southwestern Nevada volcanic field is associated with some distinctive geophysical characteristics that are unique to Nevada. The central area of overlapping caldera complexes corresponds to a large, regional gravity low that includes the lowest values in the State (Saltus, 1988a). This gravity minimum led to the discovery of the mostly buried Silent Canyon caldera complex (Healey, 1968). Along the southern edge of the southwestern Nevada volcanic field, a change in upper-crust lithology and mantle elevation is expressed as major east-trending gradients in topography, gravity, heat flow, crustal thickness, and aeromagnetic data (Eaton and others, 1978; Saltus and Thompson, 1995). The southwestern Nevada volcanic field area is situated at the southeastern termination of the Walker Lane belt, a 100- to 300-km-wide by 700-km-long northwest-trending zone of irregular topography, discontinuous strike-slip faults, and northwest-trending linear magnetic anomalies near the southern Nevada–California border (fig. 1) (Stewart, 1988; Blakely, 1988). To the east of the southwestern Nevada volcanic field, including most of eastern Nevada, is a region of generally low magnetic character known as the "quiet zone," the significance of which is still unclear (Blakely, 1988).

Hydrogeologic Background

Regional Hydrology

The study area is within the Death Valley ground-water system (Winograd and Thordarson, 1975; Waddell and others, 1984; Harrill and others, 1988; Laczniak and others, 1996). Recharge areas for the system are the high mountain ranges of central and southern Nevada, primarily to the north of the southwestern Nevada volcanic field. Ground water is transmitted generally southward at depths of more than 500 m through predominantly carbonate aquifers on the east and through predominantly volcanic aquifers and possibly alluvial aquifers on the west. Ground water within the eastern, carbonate-aquifer-dominated area discharges at springs in Ash Meadows (fig. 2) (Winograd and Thordarson, 1975; Laczniak and others, 1996). Ground water within the western, volcanic-aquifer-dominated area discharges at springs in Oasis Valley and through evaporative processes at Alkali Flat (fig. 2) (Waddell and others, 1984; Laczniak and others, 1996). Within the Nevada Test Site, the two different aquifer areas are separated by a long, nearly continuous structural block of Paleozoic confining units that create a northerly trending ground-water divide marked by a regional-scale hydraulic gradient (fig. 2) (Laczniak and others, 1996).

In the area of extensive drill-hole control at Pahute Mesa, Blankennagel and Weir (1973, plate 1) identified a prominent, 120-m change in water level that they considered to be a hydraulic barrier. More recently, O'Hagan and Laczniak (1996) have reclassified the feature as a water-level discontinuity (fig. 2). Based on subsurface geologic data (Healey, 1968; Orkild and others, 1968; Sawyer and others, 1994), the location of the discontinuity coincides with the western margin of the Silent Canyon caldera complex (fig. 1). However, no hydrologic data exist to constrain the southern extent of the discontinuity.

Hydrogeologic Units

Although the region can be generally divided into carbonate-aquifer-dominated versus volcanic-aquifer-dominated systems, the hydrogeology of these systems is not simple. Large lateral changes in subsurface thickness and character of rocks are common. These variations mostly result from (1) primary variations in geometry and thickness of rock units, (2) structural deformation of pre-Tertiary and, to a lesser extent, Tertiary rocks, (3) secondary thermal-related or diagenetic processes that have altered the mineralogy or physical properties of the rocks, and (4) fracturing that has changed permeability (Laczniak and others, 1996). In addition, faults can be important either as conduits for or as barriers to ground-water flow.

From a regional perspective, the southwestern Nevada volcanic field region can be subdivided into nine hydrogeologic units (Laczniak and others, 1996). The following brief descriptions of these hydrogeologic units are from Laczniak and others (1996) and Cole and others (1994).

The sedimentary rocks of Late Proterozoic and Paleozoic age, which have a total undeformed thickness of about 10 km in the southwestern Nevada volcanic field region, comprise four of the hydrogeologic units: the quartzite confining unit (3 km thick), the lower carbonate aquifer (4.2 km thick), the Eleana confining unit (as much as 2 km thick), and the upper carbonate aquifer (1 km thick, only locally preserved). The quartzite confining unit forms the hydrologic basement of the Death Valley flow system, above which the lower carbonate aquifer transmits the greatest flow of ground water relative to other aquifers in the region. The Eleana confining unit, designated by Laczniak and others (1996), includes rocks that were previously considered part of the Eleana Formation but are now considered to be part of the Chainman Shale (Cashman and Trexler, 1991). However, we keep the Eleana name for the sake of consistency. The unit consists of clastic sedimentary rock that is as much as 2 km thick in this area, but, due mostly to structural deformation in the subsurface, the unit is confined to a narrow band ringing the southern and eastern interface between the southwestern Nevada volcanic field and the carbonate aquifer system. The upper carbonate aquifer is not geographically significant.

The hydrogeologic unit termed "granite" consists of granitic intrusions that are scattered throughout the region.

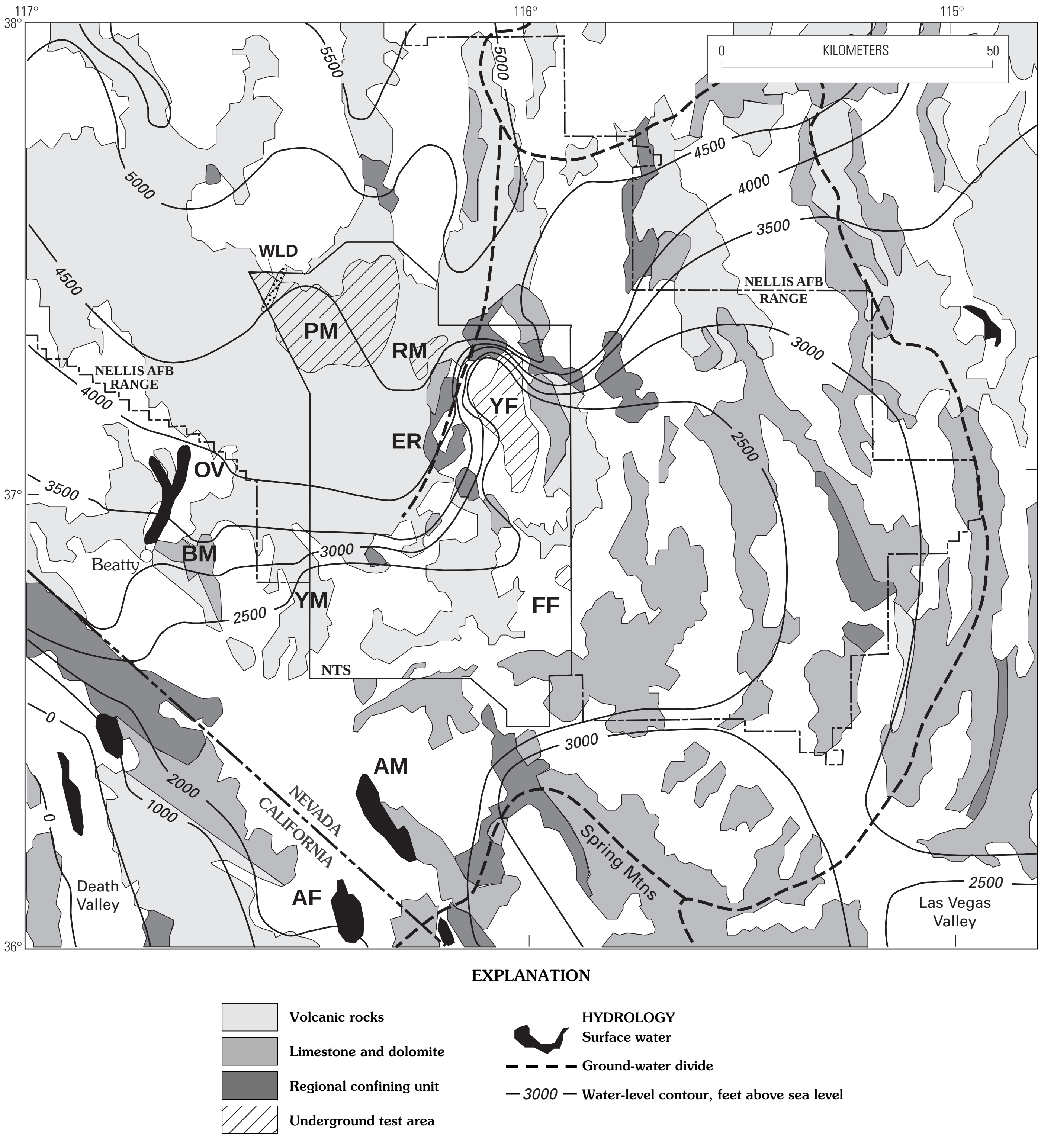

Figure 2. Map showing major aquifer systems, major surface discharge areas (black), water-level contours (in feet above sea level), and underground test areas (cross hatched) in the vicinity of southwestern Nevada volcanic field and the Nevada Test Site (solid line). AF, Alkali Flat; AM, Ash Meadows; BM, Bare Mountain; ER, Eleana Range; FF, Frenchman Flat; OV, Oasis Valley; PM, Pahute Mesa; RM, Rainier Mesa; YF, Yucca Flat; YM, Yucca Mountain. From Laczniak and others (1996). Also shown is the water-level discontinuity (WLD) of O'Hagan and Laczniak (1996).

These include Mesozoic intrusions that intrude pre-Tertiary sedimentary rocks and Tertiary intrusions related to caldera resurgence or late-stage magmatism. Intrusions consist of crystalline rocks that, in this region, are generally impermeable to ground-water flow.

The Tertiary section is a complex assemblage that includes welded and nonwelded tuffs, lava flows, and minor clastic and carbonate sedimentary rocks. Individual rock units may be variable in hydrologic properties both vertically and laterally. Thus, although particular geologic units cannot easily be assigned to one hydrogeologic unit, three hydrogeologic units are generally characterized by rock type: lava-flow aquifer, welded-tuff aquifer, and tuff confining unit. Welded-tuff and lava-flow aquifers transmit ground water primarily through fracture permeability. Although somewhat less productive than the carbonate aquifers, these volcanic aquifers dominate in the western part of the southwestern Nevada volcanic field. The tuff confining unit mainly refers to nonwelded tuffs in which the primary permeability was destroyed during alteration of the volcanic glass to zeolites and other secondary minerals.

The valley-fill aquifer, which consists of upper Miocene to Holocene alluvium, is an important component of the saturated-zone hydrologic system of the southwestern Nevada volcanic field region only within a few deep alluvial basins where the water table is generally shallow. Outside of these basins, alluvium represents the unsaturated zone.

Geophysical Background

Geophysical studies of the southwestern Nevada volcanic field have been conducted for decades concurrently with geologic and hydrologic studies and have provided constraints on the subsurface distribution of rock types in the upper crust. The geophysical methods that have been employed include gravity; ground-based and airborne magnetic methods; seismic reflection and refraction; teleseismic, heat-flow, borehole-geophysical, and a variety of deep-looking electrical methods, primarily the magnetotelluric method. Major results of these studies for the Yucca Mountain area are summarized in Oliver, Ponce, and Hunter (1995). Geophysical results from other areas of the southwestern Nevada volcanic field and the Nevada Test Site are scattered in the literature (much of which is not easily available), although some early results are summarized in Eckel (1968).

Although results derived from these different types of geophysical data provide invaluable constraints on knowledge of the subsurface, all but gravity and magnetic data are acquired either at individual locations or along profiles, so that information is concentrated only in certain areas. In this report, we focus on the gravity and magnetic data to give a regional map view of the subsurface. The interpretations of the gravity and magnetic data, however, result from integration with the results of other geophysical methods, subsurface drilling information, and geologic mapping. Many of the interpretations rely heavily on the efforts of previous workers. Our detailed discussions concentrate on recently reported interpretations that incorporate new aeromagnetic data west of the Nevada Test Site (Grauch and others, 1997).

Gravity Data

Data for more than 19,000 stations were extracted from Bouguer gravity data compiled from Saltus (1988a) and Harris and others (1989) by McCafferty and Grauch (1997) then interpolated onto a grid at 100-m intervals. A regional field based on an isostatic model was removed to isolate the gravity effects of rocks in the upper crust (Simpson and Jachens, 1989; fig. 3). The parameters used for the regional field were the same as those used by Saltus (1988b) for the State of Nevada.

The typical value of 2,670 kg/m^3 that is used to reduce gravity data is too large to be representative of subsurface densities for large areas of the southwestern Nevada volcanic field (Kane and others, 1981; Snyder and Carr, 1982; table 1). Measurements within boreholes indicate that local density variations can be abrupt and unpredictable, depending on depth, structure, degree of welding, alteration (particularly zeolitization, which decreases density significantly), and water saturation (Healey, 1968; Snyder and Carr, 1982, 1984; Carroll, 1989; Ferguson and

Table 1. Estimated reduction densities for different rock types of certain areas within the southwestern Nevada volcanic field and the probable hydrogeologic units associated with those rock types.

[Hydrogeologic units are from Laczniak and others (1996) with the following modifications: Volcanic aquifers include welded-tuff aquifers and lava-flow aquifers; volcanic confining units include tuff and other volcanic confining units; carbonate aquifer includes lower and upper carbonate aquifers. SWNVF, southwestern Nevada volcanic field; NTS, Nevada Test Site]

Reduction density (kg/m^3)	Lithology and area	Probable hydrogeologic units	References
2,000	Nonwelded tuff and alluvium, especially in Crater Flat and Yucca Mountain area	Volcanic confining units; valley-fill aquifers	Snyder and Carr (1982, 1984); Ponce and Oliver (1995)
2,200	Tuff and volcanic rocks for central caldera complexes, except for resurgent areas	Volcanic aquifers and confining units	Kane and others (1981); Healey (1968)
2,400	Partially welded to welded tuff and other volcanic and intrusive rocks, especially associated with resurgent domes and around the outer margins of caldera complexes.	Volcanic aquifers	Kane and others (1981); Ponce and Oliver (1995); this study
2,670	Undivided pre-Tertiary sedimentary and igneous rocks surrounding SWNVF	Eleana and quartzite confining units, granite	Healey (1983); Ponce and Oliver (1995)
2,750	Pre-Tertiary carbonates and metamorphic rocks, especially in eastern NTS and in Bare Mountain and Funeral Mountains area	Carbonate aquifers, quartzite confining unit	Langenheim (in press); Healey and others (1984)

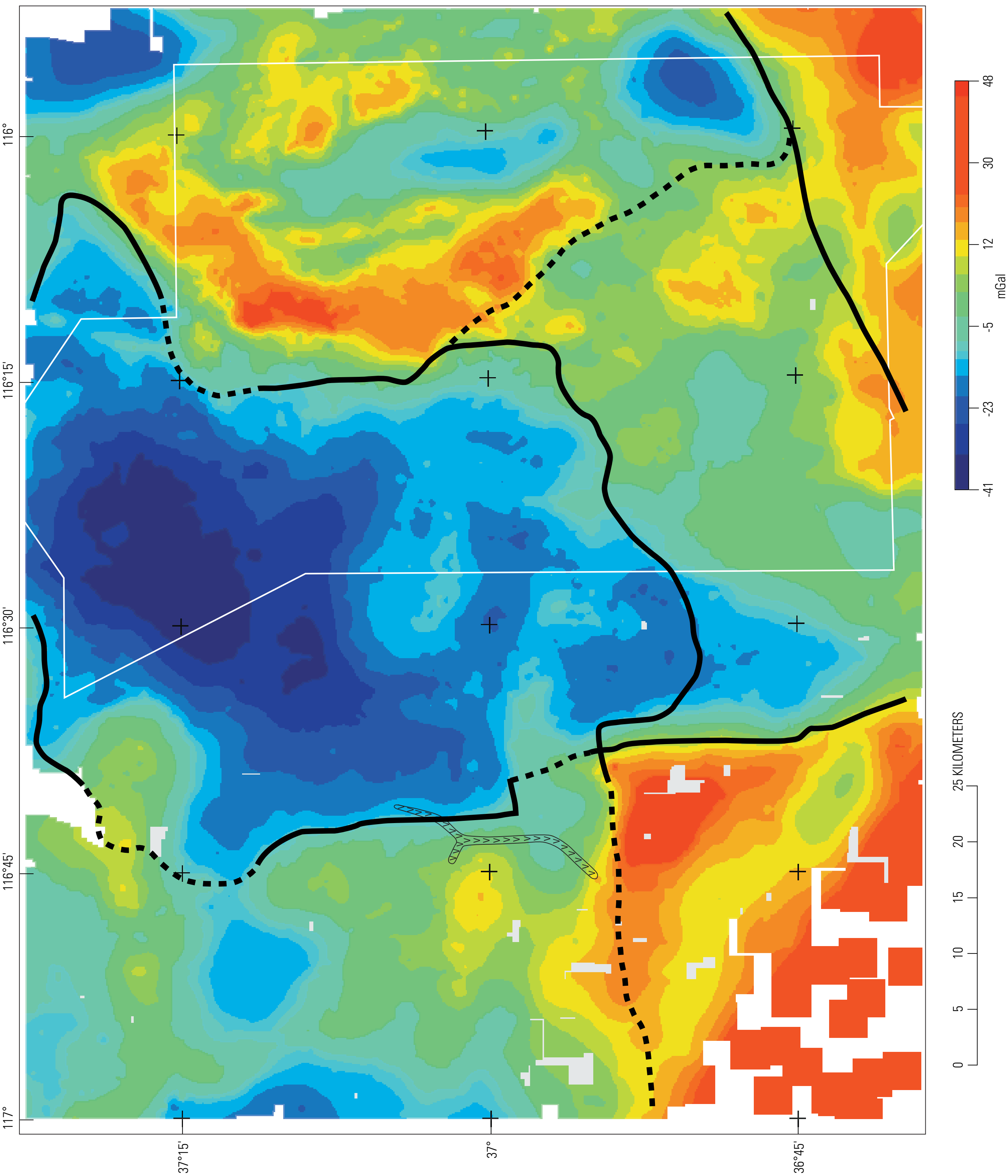
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Figure 3 (facing page). Color map of isostatic residual gravity using a reduction density of 2,400 kg/m^3 (see text for discussion). White areas show where data coverage was too coarse for interpolation. The boundary of the Nevada Test Site is shown in white, thick black lines are domain boundaries discussed in the text and shown on figure 6. The Oasis Valley discharge area is shown as the "v" pattern.

others, 1994). However, rock types can be divided into several general groups of density ranges that are useful for looking at bulk-density averages of the upper crust in the southwestern Nevada volcanic field (table 1). In figure 3, the isostatic residual gravity data is based on a reduction density of 2,400 kg/m^3, which provides a compromise between the areas of high density surrounding the southwestern Nevada volcanic field versus areas of low density within the southwestern Nevada volcanic field.

The gravity signatures of hydrogeologic units are neither consistent nor unique. However, a few general statements can be made: (1) pre-Tertiary aquifers and confining units have similar densities and therefore cannot be distinguished by gravity signature; (2) tuff confining units, if they confine because of strong zeolitization, are generally less dense than tuff aquifers (Carroll, 1989) because the aquifers generally consist of welded or partly welded tuffs; and (3) valley-fill aquifers and tuff confining units have the lowest densities and may not be distinguishable within alluvial basins (Saltus and Jachens, 1995).

Aeromagnetic Data

Aeromagnetic data for this study were extracted from the compilation prepared by McCafferty and Grauch (1997), who merged 14 individual surveys onto a common observation altitude of 122 m above ground. Most of the area for the present study is covered by two detailed surveys, both flown at 122 m above ground with east-west flight lines spaced 400 m apart (Kane and others, 1981; Grauch and others, 1993, 1997). A lower resolution survey covers the area from lat 36°45′N. to lat 37°N. and long 116°37.5′W. to long 116°45′W. It was originally flown at 300 m above ground with north-south flight lines spaced 800 m apart (Langenheim and others, 1991).

Interpretation of aeromagnetic data for the southwestern Nevada volcanic field must account for highly variable remanent magnetization and topography composed of magnetic rocks (Grauch and others, 1997). Remanent magnetization of volcanic rocks and ash-flow tuffs in particular can be quite variable, ranging from low to high intensities, sometimes within the same unit. Thus, the total magnetization (vector sum of induced and remanent component) is important to consider rather than just magnetic susceptibility or paleomagnetic direction (Bath, 1968; Grauch, 1987a). Total magnetizations are the vector sums of induced and remanent magnetization components, which can be estimated from natural remanent magnetization and magnetic susceptibility measurements and the intensity of the Earth's field. In this report we commonly refer to positive- or negative-inclination total magnetization. Inclinations are measured down from horizontal and are positive if greater than 25°, negative if less than –25° and anomalous if in between. Total magnetization intensities are classified as suggested by Bath and Jahren (1984): nonmagnetic, <0.05 A/m; weak, between 0.05 and 0.5 A/m; moderate, between 0.5 and 1.5 A/m; and strong, >1.5 A/m. Relative total magnetizations of selected volcanic units for the study area are presented in table 2.

In general, the total magnetizations of units in the study area are collinear with the Earth's field direction within 25°, a criterion suggested by Bath (1968) and discussed for this area by Grauch and others (1997). Given this general collinearity, the magnetic data were transformed by reduction-to-the-pole (fig. 4) in order to place anomalies directly over their sources (see Blakely, 1995).

Magnetic interpretation in areas of rugged topography can use relations between anomaly shapes and topographic shapes to determine whether the source of the anomaly composes the topography or is at depth (Grauch, 1987b). Positive correlation with topography indicates that rocks composing the topography have positive-inclination total magnetization; inverse correlation indicates negative-inclination total magnetization. Lack of correlation with topography or with mapped extent of geologic units suggests that the magnetic source underlies units exposed at the surface. Thus, magnetic interpretation in the southwestern Nevada volcanic field was accomplished by inspection of magnetic anomalies compared to topographic shapes, extent of mapped units, and using input from rock-magnetic-property measurements (Grauch and others, 1997).

The magnetic signatures of hydrogeologic units, like their gravity signatures, are neither consistent nor unique. However, several general statements can be made: (1) welded-tuff aquifers commonly have strong total magnetization; (2) lava-flow aquifers commonly have strong total magnetization but are limited spatially; (3) tuff confining units are not expected to produce magnetic anomalies because of alteration; and (4) valley-fill aquifers, if they are composed primarily of alluvium, have negligible magnetization relative to volcanic units.

Geophysical-Structural Domains

To a first order, the isostatic residual gravity map (fig. 3) shows fundamental differences in bulk density of the crust that are related to structural relief on the pre-Tertiary basement. The high values show where dense, pre-Tertiary rocks are near the surface; the low values show where these rocks are at great depths, buried by 3 km or more of low-density volcanic rocks (Saltus and Jachens, 1995). Minor variations in gravity values can be due to minor relief on the top of pre-Tertiary rocks or density variations within pre-Tertiary rocks (table 1).

Regional variations in the magnetic map (fig. 4) are harder to see than in the gravity map because the magnetic data are sensitive to shallow sources. In order to see regional variations, we computed the magnetic potential of the data (fig. 5). The magnetic potential is an integration of the data (often called pseudogravity—Baranov, 1957; Blakely, 1995). The operation is a low-pass filter that maximizes the broad variations in the data and minimizes the local ones. The map has been further filtered by the terracing method of Cordell and McCafferty (1989) in order to bring out discrete areas that have similar values, analogous to a terraced hillside.

Table 2. Selected volcanic units of the southwestern Nevada volcanic field and their descriptions and relative total magnetizations.

Related caldera (if applicable)	Geologic unit[1]	Approx. age (Ma)[2]	Description of unit[2]	Maximum[2] thickness (m)	Total magnetization[3]
			Younger Tertiary basalts Tb		
	Typ Pliocene and youngest Miocene basalt at Thirsty Mountain (TH) and Buckboard Mesa (BU)	TH: 4.65 BU: 2.87	Basaltic trachyandesite, cinder cones, lava flows, and feeder dikes	TH: >200 BU: 100	TH: negative, strong[4, 5] BU: positive, strong[4]
	Tyb Thirsty Canyon and younger basalts	9.9-7.4	Widespread basalts spatially and temporally bracketing Thirsty Canyon Group peralkaline caldera volcanism	100	At Coba Ridge: negative, strong;[6] elsewhere: mixed polarities, strong[6]
			Thirsty Canyon group Tt		
Black Mountain	Ttg Gold Flat Tuff	9.15	Strongly peralkaline, welded ash-flow tuff		anomalous positive, weak[6]
	Tth Trachyte of Hidden Cliff	9.3	Sequence of very crystal rich trachyte lavas emplaced as exogenous dome within a collapse depression in Black Mountain caldera	>500	positive, strong[6]
	Tts Trachytic rocks of Pillar Spring and Yellow Cleft	9.3	Trachyte to rhyolite lava flows, associated tuff and tuff breccia, and porphyritic syenite intrusive rocks; rocks partly fill and overlap Black Mountain caldera	180	negative, moderate[6]
Black Mountain	Ttt Trail Ridge Tuff	9.3	Widespread welded, comendite ash-flow tuff	65	shallow negative, moderate[6]
	Ttc Comendite of Ribbon Cliff	9.4	Pre-caldera comendite and trachyte lava flows and domes exposed marginal to Black Mountain caldera	320	positive, strong[6]
			Volcanics of Fortymile Canyon Tf		
	Tfu Upper Fortymile rhyolite lavas	10.5-9.5	Rhyolite flows, domes, plugs, and associated tephra	175	negative, moderate[4]
	Tfn Trachyte of Donovan Mountain	10.4	Trachyte lava flows and subordinate feeder dikes, sills, and flow-margin tephra present in the Bullfrog Hills area	>200	positive, strong[6]
	Tfb Beatty Wash Formation	11.4-11.2	Rhyolite lavas and related tuff erupted in moat of Timber Mountain caldera complex	lavas: 300-430; tuff: 60	positive, moderate[6]
	Tff Rhyolite of Fleur-de-lis Ranch	11.4	Rhyolite lavas and welded ash-flow tuff erupted on west side of Timber Mountain caldera complex	300	positive, moderate[6]
			Timber Mountain group Tm		
Ammonia Tanks	Tma Ammonia Tanks Tuff	11.45	Widespread metaluminous, welded ash-flow tuff; resurgently domed to form Timber Mountain	intracaldera: >900; outflow: <150	positive, moderate-strong[6, 7]

Table 2. Selected volcanic units of the southwestern Nevada volcanic field and their descriptions and relative total magnetizations—*Continued.*

Related caldera (if applicable)	Geologic unit[1]	Approx. age (Ma)[2]	Description of unit[2]	Maximum[2] thickness (m)	Total magnetization[3]
			Timber Mountain group Tm—*Continued*		
	Tmat Rhyolites of Tannenbaum Hill	11.55	Rhyolite lavas and related subordinate nonwelded tuff erupted in the moat of the Rainer Mesa caldera before collapse of the Ammonia Tanks caldera	>180	negative, strong[4]
Rainier Mesa	Tmr Rainier Mesa Tuff	11.6	Voluminous and widespread, metaluminous, welded ash-flow tuff	intracaldera: >500; outflow: 150, locally ponded to 400	negative, moderate-strong[4, 6]
			Paintbrush group Tp		
	Tpu Post-Tiva Canyon rhyolites	12.7	Post-caldera rhyolite lavas and related nonwelded tuff. Includes the rhyolite of Benham.	300	negative, strong[6]
Claim Canyon	Tpc Tiva Canyon Tuff	12.7	Widespread metaluminous welded ash-flow tuff. Locally hydrothermally altered in Bullfrog Hills	110	shallow negative, strong[8]
Unknown source	Tpt Topopah Spring Tuff	12.8	Widespread metaluminous welded ash-flow tuff	350	positive, moderate[8]
			Volcanics of Area 20		
	Tac Calico Hills Formation	12.9	Sequence of metaluminous rhyolite lavas and related tuff erupted from vents in the Calico Hills area and in the Area 20 caldera.	200, locally ponded to >2200.	Lavas: positive, moderate;[6] tuffs: positive, weak[6]
			Crater Flat group Tc		
Area 20	Tcb Bullfrog Tuff	13.25	Widespread metaluminous, variably welded, rhyolite ash-flow tuff. Hydrothermally altered and locally brecciated in Bullfrog Hills	intracaldera: 680; outflow: 120	Near Yucca Mt.: positive, strong[8] At Pahute Mesa: positive, weak-moderate[6]
Prospector Pass?	Tct Tram Tuff	13.4	Widespread welded rhyolite ash-flow tuff		negative, moderate;[8] strong near Tram Ridge[6]
			Belted Range group Tb		
	Tbd Deadhorse Flat Formation	13.7-13.5	Lavas and related tuff erupted and ponded within Grouse Creek Canyon caldera	1,600	negative and mostly positive units, weak[6]
Grouse Canyon	Tbg Grouse Canyon Tuff	13.7	Peralkaline welded ash-flow tuff	intracaldera: 575; outflow: 110-150	shallow positive, weak[6]
			Volcanics of Quartz Mountain Tq		
Unknown source	Tqs Tuff of Sleeping Butte	14.3	Sequence of two metaluminous rhyolite ash-flow tuffs and associated bedded tephra	400	lower tuff: positive, strong;[6] other units: weak[4]
Unknown source	Tqt Tuff of Tolicha Peak	14.3	Metaluminous, welded rhyolite ash-flow tuff	300	positive, moderate-strong[4, 6]

Table 2. Selected volcanic units of the southwestern Nevada volcanic field and their descriptions and relative total magnetizations—*Continued.*

Related caldera (if applicable)	Geologic unit[1]	Approx. age (Ma)[2]	Description of unit[2]	Maximum[2] thickness (m)	Total magnetization[3]
			OLDER VOLCANICS ON THE WEST		
	Tqm Dacite of Mount Helen	?	Lava flows and intrusive masses		positive, moderate[4]
			OLDER VOLCANICS ON THE EAST		
			Volcanics of Big Dome		
Unknown source	Tub Tub Spring Tuff	14.9	Peralkaline welded ash-flow tuff	90	positive shallow, weak-moderate[6]
			Volcanics of Oak Spring Butte To		
Unknown source	Toy Tuff of Yucca Flat	15.05	Nonwelded to partly welded, metaluminous rhyolite ash-flow	80	negative shallow, weak-moderate[6]
Unknown source	Tor Redrock Valley Tuff	15.3	Welded, metaluminous, rhyolite ash-flow sheet	125	negative shallow, weak-moderate[6]
Unknown source	Tot Tuff of Twin Peaks	15.5	Rhyolite ash-flow tuff	475	negative, weak-moderate[6]

[1] Unit names and groupings follow Sawyer and others (1995) and Ferguson and others (1994).

[2] From Sawyer and others (1995) and Fleck and others (1996).

[3] Total magnetization is the vector sum of induced and remanent magnetization components, estimated from natural remanent magnetization and magnetic susceptibility measurements and the intensity of the Earth's field. Results are presented qualitatively only. Inclinations are measured down from horizontal and are considered positive if > 25°; anomalous positive if < 25° and > 0°; negative if < -25°, and anomalous negative if > -25° but < 0°. Intensities are classified as suggested by Bath and Jahren (1984): nonmagnetic, < 0.05 A/m; weak, between 0.05 and 0.5 A/m; moderate, between 0.5 and 1.5 A/m; strong, >1.5 A/m.

[4] Total magnetization information not available from measurements. Total magnetization inferred from inspection of magnetic map compared to geologic contacts and topography.

[5] Negative-inclination total magnetization is corroborated by a reversed polarity remanent direction reported by Fleck and others (1996).

[6] From M.R. Hudson, unpub. data, 1996.

[7] From Bath (1968).

[8] From Rosenbaum and Snyder (1985).

The values on the magnetic potential map (fig. 5) can be viewed as a general indicator of the relative bulk magnetization of the upper crust. At great depth, bulk magnetization is likely dominated by the induced component due to thermal demagnetization of the remanent component (McElhinny, 1973). Thus, high bulk magnetization may imply the presence of large volumes of igneous rocks of intermediate composition at depth.

The broad regional variations in character on the gravity, magnetic, and magnetic potential maps show general correspondence to areas that have fundamental differences in the style, timing, and magnitude of structural deformation and magmatism recognized in the southwestern Nevada volcanic field region (Fridrich and others, 1996). Thus, for ease of discussion of the geophysical framework, we have divided the region into six geophysical-structural domains (fig. 6). These domains are not strictly defined but are generally (and sometimes subjectively) based on differences in geophysical characteristics that relate to differences in structural style.

Within each domain, we used gravity and magnetic evidence integrated with other available geologic, geophysical, and rock-property information to identify and delineate many of the features shown on figure 7. Precise locations of the outlines on figure 7 were guided primarily by the maximum horizontal gradients of the gravity or magnetic-potential data, which are commonly associated with the surface projections of near-vertical physical-property boundaries (Cordell, 1979; Cordell and Grauch, 1985; Blakely and Simpson, 1986). These locations can be offset downdip if the boundaries have shallower dip (Grauch and Cordell, 1987). We have only included major features that cover fairly large areas or have significant linear extent. Those that can be confidently identified geologically are explained in table 3 and keyed to the letter labels on figure 7. Those that are buried and (or) have not been confidently identified geologically are discussed in table 4 and keyed to the number labels on figure 7. Explanations of the interpretations are confined to the tables where possible. More detailed discussion is given to those features within and south and southwest of Pahute Mesa that may have bearing on regional ground-water flow from Pahute Mesa.

In the following discussions of features within each domain, we will simplify parenthetical references to features that are apparent on a particular geophysical figure by listing the feature number or letter from figure 7 along with the appropriate geophysical figure number or numbers. For example, the gravity feature labeled as 24 on figure 7 and described under feature 24 in table 4 will be referenced parenthetically as "(24 compared to fig. 3)." Reference to figure 7 and the appropriate table is implied. To identify features without comparison to geophysical figures, the label number or letter will appear with reference to figure 7, such as "(ATT, fig. 7)." To locate the features on the geophysical figures, we highly recommend that the reader prepare a transparency of figure 7 for use as an overlay.

Timber Mountain Domain

The major domain of the study area is the Timber Mountain domain (fig. 6), which consists of a central area of caldera complexes and bordering areas of thick Tertiary rocks. The domain is characterized by its voluminous Tertiary magmatism (maximum eruption rate of thousands of km^3/m.y.) and a lack of the moderate-to-strong late Miocene structural deformation that is evident in adjacent domains (Hudson and others, 1994). The boundaries of the Timber Mountain domain are mostly defined as the limit of the strong gravity low (fig. 3), which locally extends beyond the area of identified calderas. A notable exception to this definition is the Black Mountain caldera, which is associated with a gravity high (BM compared to fig. 3). The domain is also characterized by moderate to high bulk magnetization (fig. 5) and numerous high-amplitude magnetic anomalies (fig. 4), caused primarily by widespread ash-flow tuffs.

The area of low gravity that generally defines the Timber Mountain domain—and, by inference, the area of thick Tertiary rocks—extends beyond the margins of the identified calderas (fig. 7 compared to fig. 3). These surrounding areas probably represent additional buried calderas in some places and volcanic and sedimentary fill within tectonic basins in other places. Buried (unidentified) calderas are likely present because several of the older (pre-13 Ma) ash-flow tuff units of the volcanic field have sufficient volume to infer that they were ejected from large calderas, yet no caldera sources for these units have been identified (Sawyer and others, 1994). Geophysical evidence for buried calderas are arcuate gravity gradients, such as along the northern part of the western domain boundary (west of feature 12 compared to fig. 3). Evidence that tectonic subsidence has occurred in the area are (1) thick (> 600 m) Tertiary basin-filling volcanic and sedimentary sequences deposited during the earliest period of evolution of the southwestern Nevada volcanic field (pre-13.5 Ma) that are in the vicinity of the Rock Valley fault (RV, fig. 7) (Hinrichs, 1968) and in two places near Bare Mountain (fig. 6) (Swadley and Carr, 1987; Monsen and others, 1992); (2) a buried, pre-13-Ma graben identified in the subsurface in Crater Flat (26, fig. 7) (Fridrich, Dudley, and Stuckless, 1994); and (3) linear segments of the boundary of the Timber Mountain gravity low, which is typical of the gravity signature of a tectonic fault, such as along the central part of the western boundary of the Timber Mountain domain (24 compared to fig. 3).

Calderas and Caldera-Related Features

The predominant features of the Timber Mountain domain are calderas and caldera-related features (fig. 7 compared to fig. 6). Identified calderas include the Area 20 and Grouse Canyon calderas (A20 and GC, fig. 7), comprising the Silent Canyon caldera complex (fig. 1); the nested Ammonia Tanks and Rainier Mesa calderas (ATT, ATS and RMT, RMS, respectively, fig. 7), comprising the Timber Mountain caldera complex (fig. 1); Black Mountain caldera (BM, fig. 7), and the Claim Canyon caldera (CC, fig. 7). The outlines for these calderas are from Sawyer and others (1994, 1995), who based their locations on surface geologic contacts, thickness differences between caldera-forming and post-caldera units, and on scattered to tightly constrained subsurface drill-hole information (Warren and others, 1985; Ferguson and others, 1994). Ferguson and others (1994) interpret slightly different locations for parts of the caldera margins within the Silent Canyon caldera complex. The caldera margins

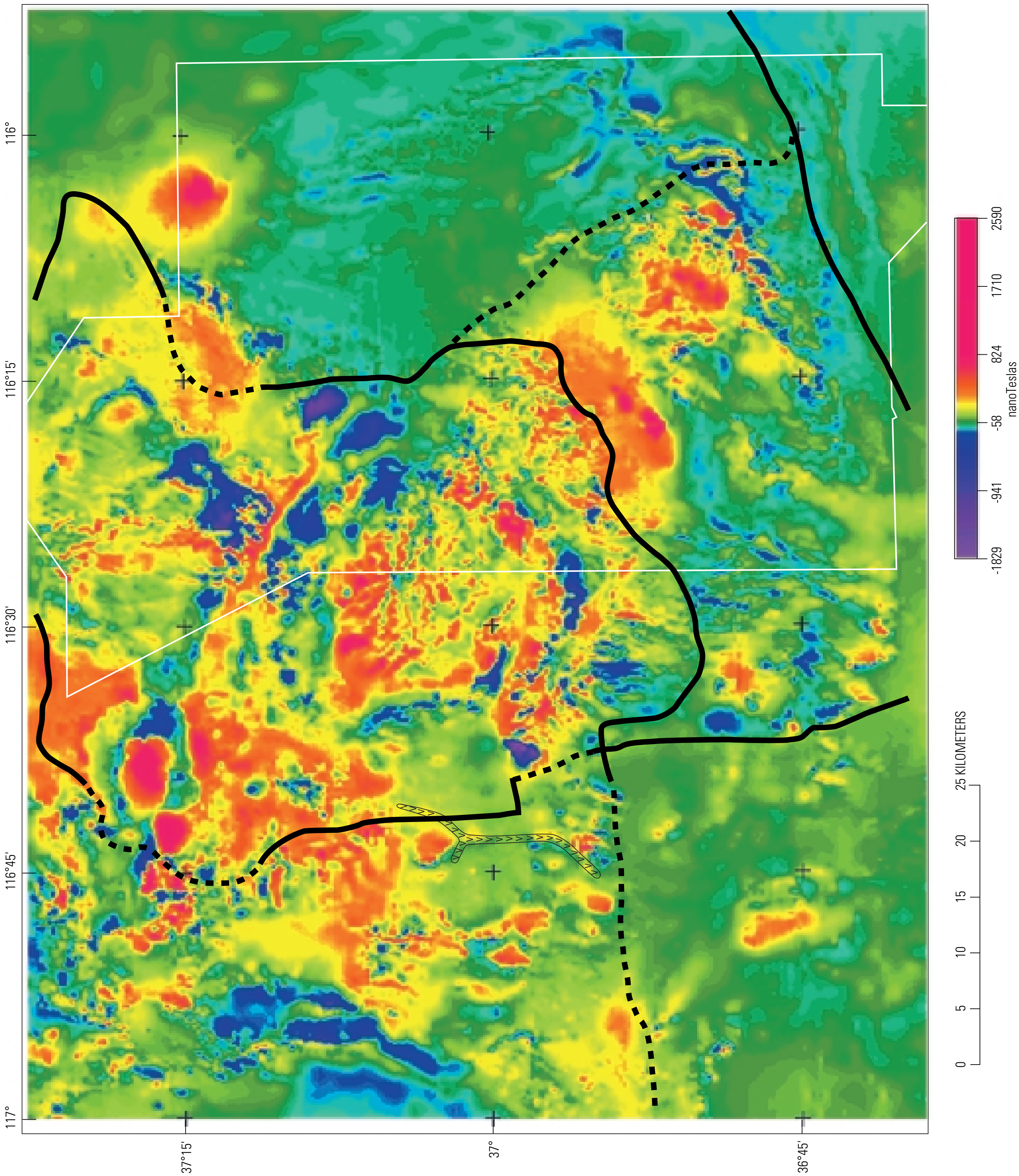

116°
116°15'
116°30'
116°45'
117°
37°15'
37°
36°45'
2590
1710
824
-58
-941
-1829
nanoTeslas
25 KILOMETERS
20
15
10
5
0

Figure 4 (facing page). Color map of reduced-to-pole aeromagnetic data. Inclination and declination of the Earth's field used in the transformation were 62° and 14.5°, respectively. The boundary of the Nevada Test Site is shown in white, thick black lines are domain boundaries discussed in the text and shown on figure 6. The Oasis Valley discharge area is shown as the "v" pattern.

are dashed on figure 7 where locations are based on previous geophysical arguments (Sawyer and others, 1994). In a modification to the margins of Sawyer and others (1994), we have not drawn the southwestern margin of the Rainier Mesa caldera on figure 7.

The Grouse Canyon (13.7 Ma; GC, fig. 7) and Area 20 (13.25 Ma; A20, fig. 7) calderas of the Silent Canyon caldera complex are beneath Pahute Mesa (fig. 1). Both calderas are completely buried by younger deposits and were first identified by gravity studies (Healey, 1968; Orkild and others, 1968). Subsequently, more than a hundred deep (> 600 m) drill holes have defined the subsurface distribution of volcanic units in the complex (Warren and others, 1985; Sawyer and Sargent, 1989; Ferguson and others, 1994; Sawyer and others, 1994). The eastern margin of the Grouse Canyon caldera and the northern topographic wall of the Silent Canyon caldera complex are reflected in abrupt changes in magnetic anomaly patterns (fig. 7 compared to fig. 4). The western margin of the complex coincides with a water-level discontinuity in northwestern Nevada Test Site (WLD, fig. 2) and a major gravity gradient, discussed under the section on NNE.-trending structures.

The oldest caldera of the Timber Mountain caldera complex, the Rainier Mesa caldera, formed in response to the eruption of the Rainier Mesa Tuff (Tmr, table 2) at 11.6 Ma. The topographic wall of the caldera (RMT, fig. 7) is not tightly constrained geologically except along the northeastern margin. The topographic wall of the younger Ammonia Tanks caldera (11.45 Ma) is probably superimposed on the structural wall of the Rainier Mesa caldera along the southeastern margin (RMS/ATT, fig. 7). Part of the resurgent, intracaldera dome of the Rainier Mesa caldera is exposed on the west side of the Ammonia Tanks caldera (near ATT western boundary), but the largest part of the caldera was stoped by the Ammonia Tanks caldera or is covered by younger rocks (Sawyer and others, 1994).

The younger caldera of the Timber Mountain caldera complex is the Ammonia Tanks caldera, associated with the Ammonia Tanks Tuff (Tma, table 2). The structural and topographic margins of the caldera (ATS and ATT, respectively, fig. 7) are well exposed around most of the caldera. It is a classic resurgent caldera of the type described by Smith and Bailey (1968), with isolated exposures of intrusive rocks related to resurgence located on the southeast side of Timber Mountain (fig. 6) (Byers, Carr, Christiansen, and others, 1976). The geologic evidence, combined with analysis of the gravity data, led Kane and others (1981) to conclude that the broad, low-amplitude gravity high in this area is the expression of the resurgent intrusion (TM compared to fig. 3). Electrical-data profiles collected over Timber Mountain also indicated rocks with high resistivities at depth, typical of intrusive rock (Zablocki, 1979).

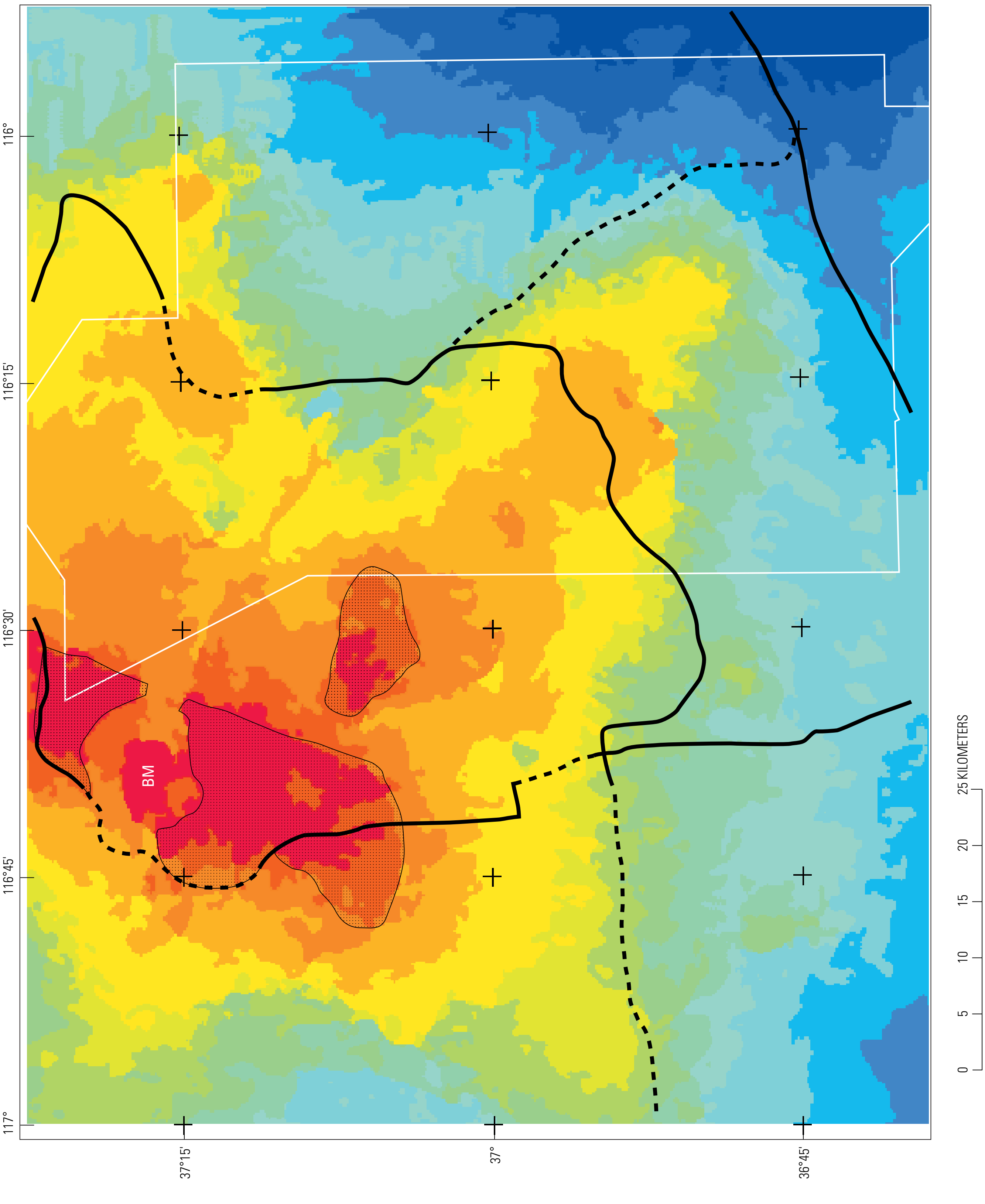
Outlining the lateral extent of the Timber Mountain resurgent intrusion is difficult. Gradients surrounding the gravity high are moderate, especially to the north, indicating that the intrusive contacts may slope gently downward and have no identifiable vertical "edges" that can be used to define the lateral extent. Another approach considers the lateral extent most important for understanding the hydrogeologic implications of the intrusion. Inversion of regional gravity data (V. Langenheim, written commun., 1997) indicate that the caldera fill is less than 1 km thick within the map area generally outlined by the gravity contour level of –10 mGal (TM compared to fig. 3). Comparison of these thickness estimates to ground-water depths expected for the surrounding area (Laczniak and others, 1996) suggests that the underlying intrusion may interact with ground water near the margins of this area. Therefore the outline of the area (TM, fig. 7) is considered the hydrogeologically important lateral extent of the intrusion. However, the location is approximate because none of the depth estimates are well constrained.

The Claim Canyon caldera (Byers, Carr, Orkild, and others, 1976; Christiansen and others, 1977; Sawyer and others, 1994; Fridrich, 1999) collapsed at 12.7 Ma, accompanied by the eruption of the Tiva Canyon Tuff (Tpc, table 2). Part of the intracaldera dome is exposed south of Timber Mountain, but most of the caldera is beneath the younger Timber Mountain caldera complex. Gravity values within the exposed part of the caldera are higher compared to surrounding areas (CC compared to fig. 3), suggesting the presence of a resurgent intrusion, analogous to the one under Timber Mountain. The caldera margins correspond with an abrupt change in magnetic-anomaly pattern (CC compared to fig. 4).

The Black Mountain caldera is associated with several eruptive events (Sawyer and others, 1994). The topographic margin produced by the most recent event (9.4 Ma; BM, fig. 7) is a contact with precaldera rocks, well-exposed for more than half of its boundary. A fairly thick (>500 m) sequence of mafic trachyte present within the caldera (Sawyer and others, 1995) produces a strong magnetic high (BM compared to figs. 4 and 5). A circular gravity high corresponds fairly well to the caldera outline (BM compared to fig. 3). Gravity models assuming a high-density fill within the caldera cannot entirely explain the lateral extent of the gravity high. Therefore, an intrusion is inferred at depth (Grauch and others, 1997).

Faults at Pahute Mesa

The eastern part of Pahute Mesa has been the site of extensive underground weapons tests (fig. 2), which in many places were detonated near or below the water level (Laczniak and others, 1996). Extensive drill-hole information, in conjunction with gravity and seismic reflection data, gives good control on the identification of important faults and rock units in the subsurface near testing areas (Ferguson and others, 1994). Some of the subsurface faults are also expressed in the magnetic data by changes in magnetic character that occur across the faults in places but are not consistent along the lengths of the faults (fig. 8). This inconsistency and the strong amplitudes imply that the magnetic expressions are primarily due to the juxtaposition of rocks of different magnetic properties at shallow depths. In particular, the Boxcar (*B*), Almendro (*A*), and Scurgham Peak (*SP*) faults are expressed as



116°
116°15'
116°30'
116°45'
117°
37°15'
37°
36°45'
BM
0
5
10
15
20
25 KILOMETERS

Figure 5 (facing page) Color map of magnetic potential (pseudogravity) data to which the terracing operator of Cordell and McCafferty (1989) has been applied. This can be viewed as an indicator of the relative values (in arbitrary units) of bulk magnetization of the subsurface (except where low values correspond to strong negative anomalies that have wide lateral extent). High values correspond to warm colors; low values to cool colors. The dotted pattern shows areas of regionally high values (excluding the Black Mountain caldera, BM), discussed in the text. The boundary of the Nevada Test Site is shown in white, thick black lines are domain boundaries discussed in the text and shown on figure 6.

major changes in magnetic values (fig. 8), primarily reflecting relative differences in elevation of the shallowest, magnetically significant units.

A prominent WNW.-trending lineament in the magnetic data can be traced from the eastern side of Black Mountain to the eastern side of the Timber Mountain domain (18 compared to figs. 4 and 6). The western part of the lineament is expressed as the boundary between strong negative anomalies on the northern side juxtaposed against high magnetic values on the southern side (fig. 8). The central and eastern parts are expressed as linear positive anomalies, in places flanked on either side by strong negative anomalies. The extreme western and eastern parts are also expressed by subtle gravity gradients (Kane and others, 1981) (fig. 8). From its linearity, a structural origin is inferred. However, its genesis and age in relation to caldera development are not well constrained.

North-Northeast-Trending Structures

The western margin of the Silent Canyon caldera complex coincides with a NNE.-trending gravity gradient (14 and 14/SCC compared to fig. 3) (Sawyer and Sargent, 1989; Ferguson and others, 1994) and a water-level discontinuity (O'Hagan and Laczniak, 1996) (WLD, fig. 2). The gravity gradient extends south of the complex and past the western side of the Timber Mountain caldera complex to the valley east of Oasis Mountain (23, fig. 7). Nearly parallel to and west of the gravity gradient is a magnetic gradient (13 compared to fig. 4). The magnetic gradient is best evidenced from the magnetic potential map as the edge of regional magnetic highs (10 and 11 compared to fig. 5). The coherency and linearity of these gradients, the abrupt changes in geophysical character across them (13, 14, and 14/SCC compared to figs. 3 and 4), and the relation between the gravity gradient and the Silent Canyon caldera margin (14/SCC compared to fig. 3) indicate that they represent major faults at depth that probably controlled caldera formation.

Regional magnetic highs that are bounded on the east by the NNE.-trending structures correspond to moderately low gravity values (10 and 11 compared to fig. 3). Rough depth estimates made by models of gravity data, and corroborated by magnetic gradient analysis, indicate that the source rocks of these regional magnetic highs extend at least 2 km below the surface. Grauch and others (1997) concluded that the most likely sources of the northern regional magnetic high (10 compared to fig. 4) are the dacite of Mount Helen (Tqm, table 2), the tuff of Tolicha Peak (Tqt, table 2), and locally the comendite of Ribbon Cliff (Ttc, table 2) on the basis of comparisons to rock-property, geologic-mapping, and limited drill-hole information. In addition, they used the absence of negative magnetic anomalies combined with geologic evidence of absent or thinning Rainier Mesa Tuff (Tmr, table 2) to suggest the general absence of the tuff in the area of the regional magnetic high. Where exposed elsewhere in the study area, the Rainier Mesa Tuff is commonly thick, widespread (Sawyer and others, 1995), and consistently associated with strong negative anomalies on the aeromagnetic map (Grauch and others, 1997).

A simple model of a magnetic profile that crosses from the northern regional magnetic high into the Silent Canyon caldera complex (fig. 9) shows that three magnetically significant units (such as the dacite lavas (Tqm), the tuff of Tolicha Peak (Tqt), and the Rainier Mesa Tuff (Tmr)) can explain most of the variations in the magnetic data. Variations not modeled can be explained by variations in thicknesses and magnetizations of shallow rocks. The first-order variations along the profile can be explained by the configuration of the bodies attributed to be dacite lavas. This is especially evident by comparing the fit between observed values after upward continuation by 1 km and the model values calculated at the same high level (fig. 9).

The regional magnetic high that is south of Black Mountain and in the Thirsty Mountain area (11 compared to fig. 4) cannot be explained by exposed units, and therefore the sources cannot be determined definitively. However, Grauch and others (1997) determined probable sources based on similarities and proximity to the regional magnetic high northeast of Black Mountain (10 compared to fig. 4) and expected magnetic properties (table 2). The probable sources include (from table 2) the dacite of Mount Helen (Tqm), the tuff of Tolicha Peak (Tqt), Ammonia Tanks Tuff (Tma), the rhyolite of Fleur-de-lis Ranch (Tff), and locally the comendite of Ribbon Cliff (Ttc).

Oasis Valley Basin

The large area east of Oasis Valley discharge area and west of Timber Mountain (fig. 6) is an area of low gravity values (23 compared to fig. 3), reflecting a thick sequence of moderately low density rocks, likely Tertiary in age. We call the area "Oasis Valley basin" to avoid confusion with the name "Oasis Valley," which has been informally used to include this area as well as the discharge area. Oasis Valley basin is an area of alluvium surrounded by exposures of Tertiary volcanic units (fig. 10). The area shows very little magnetic signature (23 compared to fig. 4). Estimates from gravity data indicate a 5-km thickness of low-density rocks within the area (V. Langenheim, written commun., 1997). Drill hole MYJO Coffer #1, drilled for oil exploration, penetrated about 240 m of alluvium in the middle of this area. The alluvium lies above Ammonia Tanks Tuff, volcanics of Fortymile Canyon, and younger units (fig. 10). Many of these units are exposed at the surface nearby (fig. 10).

The area of thick, low-density rocks is bounded (1) on the west by the major, inferred, north-striking fault, mainly evident as a major gravity gradient (24 compared to fig. 3), which we informally name the Hogback fault; (2) on the south by an east-trending inferred structure evident in both magnetic and gravity

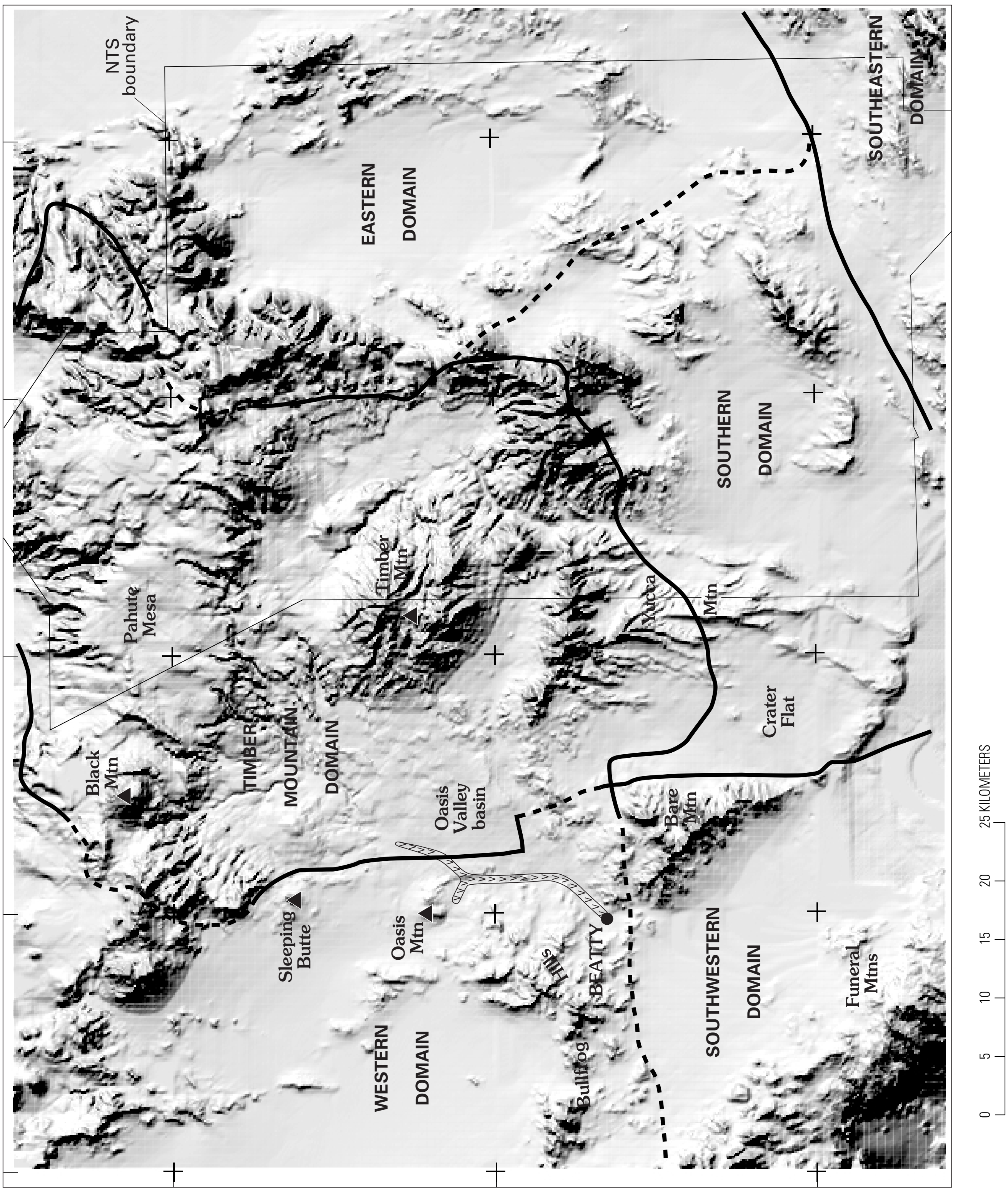


Figure 6. Shaded-relief topographic map showing the six geophysical-structural domains discussed in the text. Solid lines denote well-defined boundaries between domains; dotted lines are gradational or poorly defined boundaries. The Oasis Valley discharge area is shown as the "v" pattern.

maps (7 compared to figs. 3 and 4), which we informally name the Hot Springs fault; and (3) on the north by the abrupt, southern edge of a regional magnetic high (southern boundary of the stippled area labeled 11 compared to fig. 4). The eastern boundary and the origin of the thick sequence of low-density rocks beneath this area are unclear.

The linearity of the gravity gradient that delineates the Hogback fault (24 compared to fig. 3) suggests a tectonic origin rather than a caldera origin. The lack of low gravity values to the west of the Hogback fault and the uninterrupted extent of its associated gravity gradient do not support the presence of a major caldera collapse west of the fault. Preliminary models for the gravity gradient indicate a boundary dipping about 45°, which may represent one or a series of normal faults, down to the east. This configuration is similar to the stepped-fault model of the Bare Mountain fault (8, table 4 and references given therein). The northern extent of the Hogback fault, where it passes along the west side of the area of Thirsty Mountain basalts (TH, fig. 7), is parallel to faults mapped at the surface (Minor and others, 1996) and nearly coincides with an east-facing paleoscarp where Ammonia Tanks Tuff was emplaced against volcanics of Quartz Mountain (Noble and others, 1991; Sawyer and others, 1995). Previous workers have interpreted this paleoscarp as evidence for a caldera topographic wall, although they disagree on the age of the caldera (Byers, Carr, Orkild, and others, 1976; Noble and others, 1991). The paleoscarp may be surface evidence of the inferred tectonic fault or of caldera collapse that was controlled by the fault.

Evidence suggests that the Hot Springs fault (7, fig. 7) is a near-vertical transverse fault or accommodation zone (Grauch and others, 1997). Such evidence includes the steepness of the gravity gradient on the eastern half of the fault, abrupt change in magnetic character and linearity across the entire fault, change in slope of the gravity gradient on either side of the Hogback fault, and configuration of the Hot Springs fault in relation to the Hogback and Bare Mountain faults (8 and 24, fig. 7). Geologic evidence south of the fault indicates a paleoscarp there, with a depositional basin to the north during and perhaps before the time of deposition of the Rainier Mesa Tuff (C. Fridrich, unpub. data, 1996).

Other Domains

Western Domain

The western domain (fig. 6) is characterized by relatively moderate to high gravity values (fig. 3), indicating generally elevated pre-Tertiary rocks; low to moderate bulk magnetization (fig. 5); and local, high-amplitude magnetic anomalies (fig. 4). Preliminary models of gravity data indicate that the pre-Tertiary rocks are generally about 1 km below the surface. The gravity highs in the northern part of the area and in the northern Bullfrog Hills (2 and BH compared to fig. 3) indicate shallower depths—less than 500 m below the surface. A depth estimate from magnetotelluric data (Furgerson, 1982) indicates a depth of about 1 km to resistive basement at the northeastern end of Springdale Mountain, the range just northwest of Oasis Mountain (fig. 6).

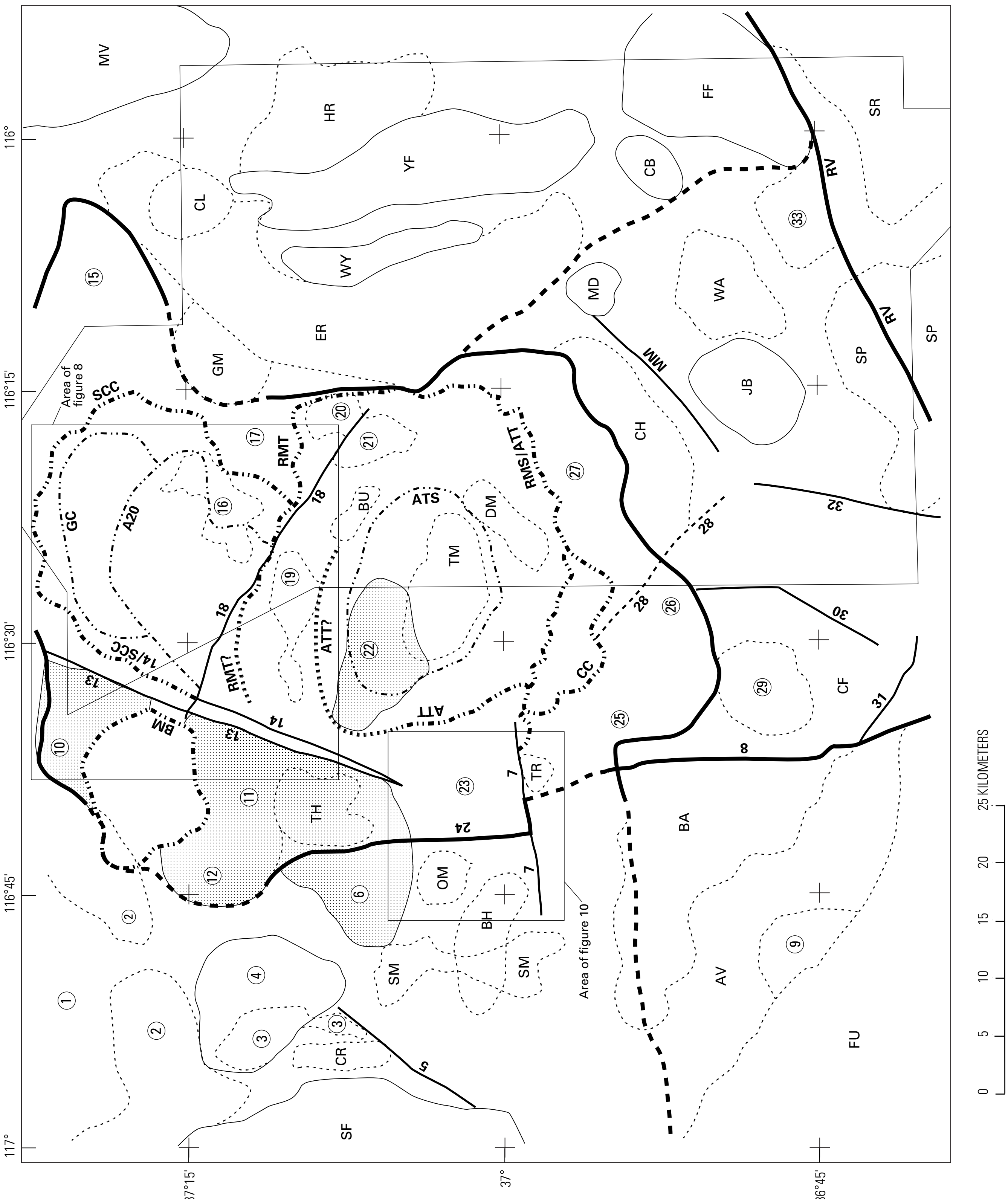
The western domain underwent a complex middle Miocene tectonic and volcanic history, followed by deposition of young (post-10 Ma) volcanic rocks and alluvium that cover much of the area. The southern boundary of the western domain (fig. 6) is generally located along the Bullfrog Hills–Fluorspar Canyon detachment fault (Maldonado, 1990). The repeated faulting of the upper plate of this fault is especially evident in the magnetic data in the southern Bullfrog Hills by the striped pattern of north-trending anomalies (the area between BA and 7 compared to fig. 4), similar to the pattern in Crater Flat and Yucca Mountain (the area between CF and 28 compared to fig. 4) (Bath and Jahren, 1984). Although many minor faults can be interpreted from the striped magnetic patterns, only one major fault has been identified within the western domain (5, fig. 7). This fault marks an abrupt change between north-south orientation (on the northwest) and northeast orientation (on the southeast) of the grain of tilted fault blocks (5 compared to fig. 4). On the extreme west side of the domain is Sarcobatus Flat (SF, fig. 7), a basin that developed post-10 Ma (Minor and others, 1991). The low gravity values indicate that this is a deep basin (SF compared to fig. 3); the strong, broad, low magnetic anomaly indicates a down-dropped block of volcanic rock having negative-inclination magnetization (SF compared to fig. 4) (Grauch and others, 1997).

In the areas of outcrop, the magnetic expression of volcanic units can be identified by inspection (CR, OM, SM compared to fig. 4). Other areas show high-amplitude magnetic anomalies indicative of volcanic units but are covered entirely by Quaternary alluvium (3 and 6 compared to fig. 4). Many exposed volcanic units in the northwestern part of the study area (1, fig. 7) do not correspond in location to magnetic anomalies (1 compared to fig. 4), suggesting that the magnetic sources are buried.

The prominent, elliptical gravity low in the north-central part of the domain (4 compared to fig. 3) is in an area with very few rock exposures and is associated with discontinuities or changes in character in the magnetic map (4 compared to fig. 4). Analysis of gravity and magnetic data in this area indicates a depression in the high-density pre-Tertiary rocks (Grauch and others, 1997). Evidence that supports a caldera origin for the depression is primarily the presence of rhyolite domes within the gravity low. The depression may be the caldera source of the tuff of Sleeping Butte (Tqs, table 2), but uncertainties in geologic and rock-property data prevent definitive conclusion (Grauch and others, 1997).

Southwestern Domain

The southwestern domain (fig. 6) includes Bare Mountain, the Funeral Mountains, and the intervening Amargosa Valley (BA, FU, AV, fig. 7). The high to very high gravity values characteristic of the domain reflect near-surface and exposed Paleozoic and Precambrian sedimentary and metamorphic rocks. At Bare Mountain, the pre-Tertiary rocks are considered to be the exhumed lower plate (i.e., footwall) of the Fluorspar Canyon–Bullfrog Hills detachment fault (Maldonado, 1990; Hoisch and others, 1997), which is generally located along the northern boundary of the domain. Within the study area in the Funeral Mountains, the exposed pre-Tertiary rocks represent thin, upper-plate rocks above the Boundary Canyon detachment fault



MV
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FF
SR
YF
CB
RV
CL
WY
33
15
MD
WA
ER
GM
SCC
Area of figure 8
JB
SP
CH
20
21
17
RMT
RMS/ATT
27
16
GC
A20
18
BU
ATS
DM
TM
19
32
28
26
30
14/SCC
RMT?
ATT?
22
CC
29
CF
31
13
BM
14
ATT
25
10
8
23
TR
7
11
TH
24
BA
12
6
OM
BH
2
4
AV
9
SM
1
3
CR
FU
5
SF
Area of figure 10
116°
116°15'
116°30'
116°45'
117°
37°15'
37°
36°45'
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25 KILOMETERS

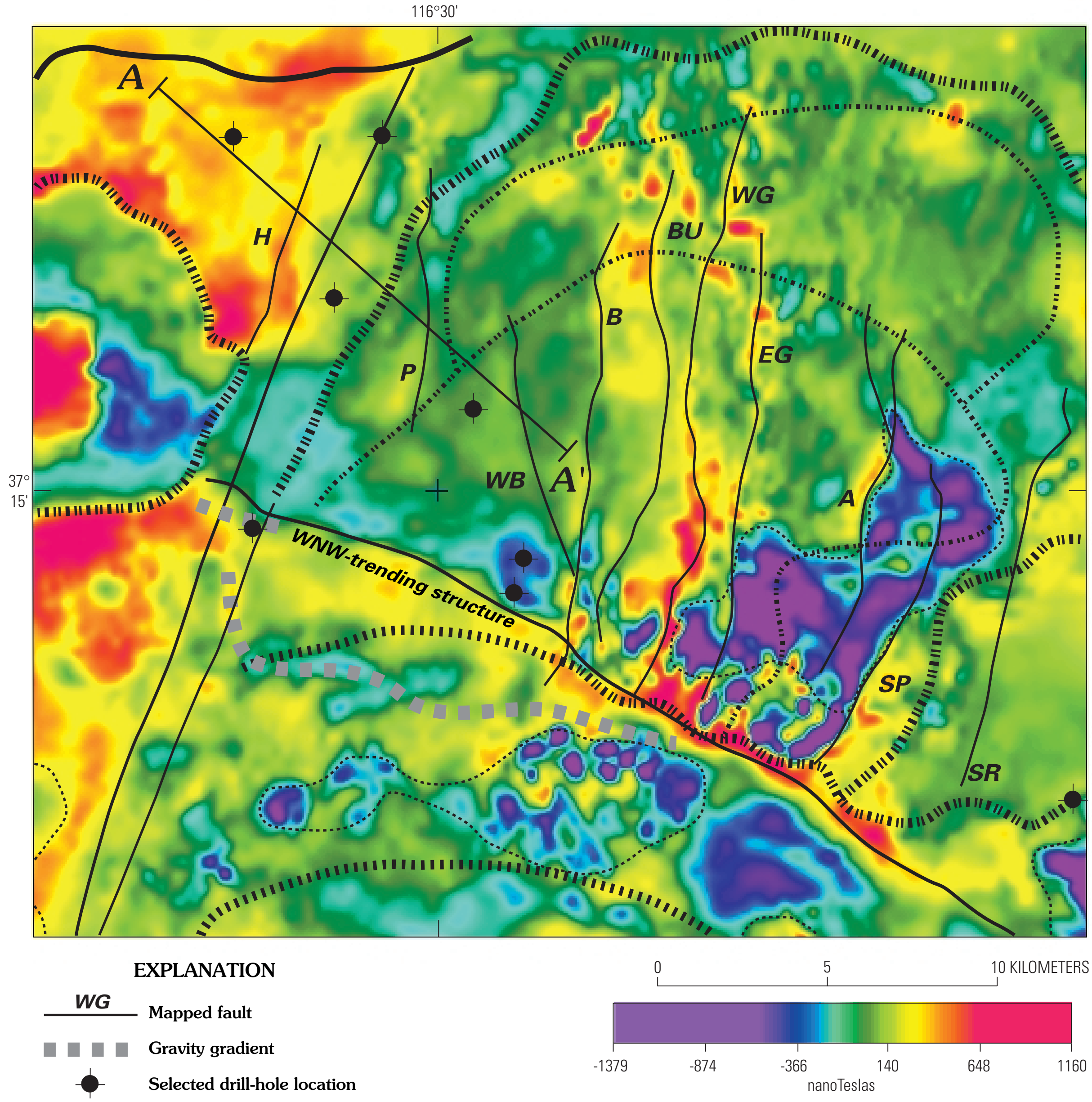

Figure 8. Reduced-to-pole magnetic map of the Pahute Mesa area (map area shown by rectangle on fig. 7), showing interpreted features from figure 7, labeled faults, locations of selected major gravity gradients near the northwestern corner of the Rainier Mesa caldera, and the location of profile *A-A′* of figure 9. The gravity gradient locations were determined from maxima of the magnitudes of the horizontal gradient (Cordell, 1979; Blakely and Simpson, 1986). *A*, Almendro fault; *B*, Boxcar fault; *BU*, Buteo fault; *EG*, East Greeley fault; *H*, Handley fault; *P*, Purse fault; *SP*, Scurgham Peak fault; *SR*, Split Ridge fault; *WB*, West Boxcar fault; *WG*, West Greeley fault.

Figure 7 (facing page). Outlines of interpreted subsurface features to be used as an overlay to figures 3 and 4. The lettered codes are keyed to table 3; the numbered ones to table 4. The numbered labels are circled when referring to a feature other than a fault. The line types for classes of features are generally as follows: domain boundary, thick solid line where well-defined, thick dashed line where poorly defined; inferred faults, medium-thickness solid line where well defined, medium-thick dashed line where poorly defined; caldera topographic walls, thick dash-dot-dot line where well defined, thick short-dash line where poorly defined; caldera structural margins, medium-thick dash-dot-dot line; basins, thin solid line; other features, thin dashed line. The small rectangles in the northern and central parts of the figure show the areas of figures 8 and 10, respectively.

(Wright and Troxel, 1993). The two areas are grouped here as one domain because of their similarity in geophysical character. The high gravity values associated with Bare Mountain (BA compared to fig. 3) extend north of the domain boundary and the Fluorspar Canyon–Bullfrog Hills detachment fault, reflecting the moderate to shallow dip of the fault to the north and northwest.

Low magnetic values throughout the domain and over most of Amargosa Valley (AV compared to fig. 3) indicate a general absence of volcanic rocks. One exception is the large positive magnetic anomaly on the Funeral Mountains side of the Amargosa Valley, of undetermined origin (9 compared to fig. 3).

Table 3. Identified geologic features shown on figure 7 that have geophysical expression.

[Inferred hydrogeologic unit is based on the lithologic type inferred in the subsurface. In some cases, the subsurface feature may be expected to have limited depth extent, so that assignment of a hydrogeologic unit is not applicable. Hydrogeologic units are from Laczniak and others (1996) with the following modifications: Volcanic aquifers include welded-tuff aquifers and lava-flow aquifers; volcanic confining units include tuff and other volcanic confining units; and carbonate aquifer includes lower and upper carbonate aquifers]

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Description/comments	Reference(s)
		Intrusions **Geophysical expression: broad, high-amplitude positive magnetic anomaly with corresponding, somewhat circular, positive or negative gravity anomaly.**	
CH northern part of southern domain	Granite	Calico Hills—Highest amplitude magnetic anomalies are caused by contact-metamorphosed Mississippian black shale (formerly considered part of the Eleana Formation, now as Chainman Shale) discovered through drilling. Contact metamorphism here is considered indirect evidence of an underlying intrusion. Scattered exposures of approximately 10-Ma rhyolite plugs are spatially related to the contact metamorphism. However, the main body of the intrusion must be deep, as indicated by depth estimates of about 3 km for the broader component of the magnetic high. Gravity values in the area are moderate, but intrusive rocks cannot be distinguished from pre-Tertiary sedimentary rocks because the expected densities are similar.	Bath and Jahren (1984); Snyder and Oliver (1981); Snyder and Carr (1984); Carr and others (1986); Oliver, Ponce, and Hunter (1995); Fridrich, Dudley, and Stuckless (1994); Maldonado and others (1979); Baldwin and Jahren (1982) Chainman versus Eleana Formation references: Cashman and Trexler (1991); Trexler and others (1996)
CL northern part of eastern domain	Granite	Climax stock—Cretaceous composite granitic intrusion expressed primarily by a positive magnetic anomaly. Gravity values associated with the stock are somewhat lower than higher values that correspond to surrounding Paleozoic carbonate rocks, but the density contrast is not large enough to resolve the stock.	U.S. Geological Survey (1983); Maldonado and others (1988)
GM northern part of eastern domain	Granite	Gold Meadows—Cretaceous quartz monzonite stock intruded into Precambrian and Paleozoic quartzite where exposed. The gravity data cannot distinguish between these two rock types; the circular gravity high reflects the contrast with overlying and surrounding volcanic rocks on the west. The positive magnetic anomaly coinciding with moderate gravity values may better reflect the extent of the stock, although negative anomalies produced by shallow, Rainier Mesa Tuff (Tmr, table 2) probably mask its signature on the northwest side.	Healey and Miller (1963); Wahl (1969); Maldonado and others (1988).
TM central Timber Mountain domain	Granite	Timber Mountain—Intrusion related to resurgence of the Ammonia Tanks caldera evidenced by structural dome, outcrops of granitic intrusive rocks, and a broad, low-amplitude gravity high. The intrusion is shallowest on the southern side of the caldera, as generally indicated by the outline on fig. 7. However, it probably has lateral extents in the subsurface that correspond to the extents of the gravity high. Electrical data indicate the intrusion is fairly impermeable.	Byers, Carr, Orkild, and others (1976); Byers, Carr, Christiansen, and others (1976); Kane and others (1981); Maldonado and others (1988). Electrical data: Zablocki (1979)
WA eastern part of southern domain	Granite	Wahmonie intrusion—Tertiary granodiorite intrusion associated with both gravity and magnetic highs.	Ponce (1984); Maldonado and others (1988)
		Calderas **Geophysical expression: generally arcuate shape of geophysical anomalies or of discontinuities defining abrupt changes in magnetic anomaly character or values of gravity; low gravity values; variable magnetic expression in detail, but moderate to high values of bulk magnetization of crust (fig. 5).**	
A20 northern Timber Mountain domain	Volcanic aquifers and confining units	Area 20 caldera—Caldera is entirely buried and part of the Silent Canyon caldera complex that was first revealed by the extremely low gravity values. The Area 20 caldera was confirmed through drilling. Magnetic expression is dominated by abrupt changes in character between structural blocks within the caldera complex (fig. 8).	Healey (1968); Orkild and others (1968); Sawyer and Sargent (1989); Ferguson & others (1994). Magnetic expression: Grauch & others (1997).

Table 3. Identified geologic features shown on figure 7 that have geophysical expression—*Continued.*

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Description/comments	Reference(s)
		Calderas—*Continued*	
ATS and ATT central Timber Mountain domain	Volcanic aquifers and confining units; granite	Ammonia Tanks caldera – Inside the structural margin (ATS) of the Ammonia Tanks caldera is a magnetic-anomaly pattern of high amplitudes and steep gradients. This is consistent with the strong, positive-inclination total magnetization expected for the associated Ammonia Tanks Tuff (Tma, table 2). The broad gravity high associated with the caldera is one piece of evidence for a resurgent intrusion (TM). The topographic wall (ATT) is well constrained geologically only on the south and west sides. On the southeastern side it is probably superposed on the structural wall of the older Rainier Mesa caldera (RMS/ATT).	Kane and others (1981); Sawyer and others (1994)
BM northwestern Timber Mountain domain	Volcanic aquifers and confining units	Black Mountain caldera—The topographic wall is well defined in aeromagnetic data by juxtaposition of negative-inclination units inside the caldera, such as the trachytic rocks of Pillar Spring and Yellow Cleft (Tts, table 2), and positive-inclination units outside the caldera, such as the Comendite of Ribbon Cliff (Ttc, table 2). The strong positive anomaly in the center of the caldera corresponds to a thick (>500 m) sequence of the positive-inclination, mafic, Trachyte of Hidden Cliff (Tth, table 2). The higher densities expected for this mafic sequence compared to surrounding units can partially explain the circular gravity high associated with the caldera, but cannot account for its broad lateral extent. Therefore an underlying intrusion is inferred. Grauch and others (1997) argue that the caldera fill on the west side is probably thin, because evidence suggests the magnetic anomalies crossing the western topographic margin have sources that are shallow and older than the caldera.	Sawyer and others (1994, 1995); M. Hudson (unpub. rock-property data, 1996); Grauch and others (1997)
CC southern Timber Mountain domain	Volcanic aquifers and granite	Claim Canyon caldera—The boundary shown is the approximate structural boundary of the resurgent intracaldera block as inferred from geologic evidence. Within the caldera segment, magnetic-anomaly patterns are dominated by the strong, negative-inclination Tiva Canyon Tuff (Tpc, table 2). The patterns have dominantly southeasterly trends, which differ in orientation from surrounding areas. Broad low-amplitude gravity highs probably reflect the remnants of an intrusion related to resurgence of the caldera, which was later fragmented by subsequent caldera collapses.	Sawyer and others (1994); Fridrich, Dudley, and Stuckless (1994); Fridrich (1999); Kane and others (1981); Snyder and Carr (1984); Christiansen and others (1977); Byers, Carr, Orkild, and others (1976)
GC northern Timber Mountain domain	Volcanic aquifers and confining units	Grouse Canyon caldera—Caldera is entirely buried and part of the Silent Canyon caldera complex that was first revealed by the extremely low gravity values. The Grouse Canyon caldera was defined through drilling. Magnetic expression is dominated by differences between structural blocks within the caldera complex (fig. 8).	Healey (1968); Orkild and others (1968); Sawyer and Sargent (1989); Ferguson and others (1994)
RMS and RMT central and southern Timber Mountain domain	Volcanic aquifers and confining units; lava-flow aquifers	Rainier Mesa caldera—The topographic wall (RMT) is well constrained geologically on the northeastern, eastern, and southern sides of the caldera. Geophysical expression is confined to high-amplitude negative magnetic anomalies associated with the strong, negative-inclination Rainer Mesa Tuff (Tmr, table 2). Possible geophysical expression of the northwestern margins of the caldera may be related to buried structures expressed in the geophysical data (13, 14, and 18, fig. 7). On the southeastern side the topographic wall of the Ammonia Tanks caldera is probably superposed on the structural wall of the Rainier Mesa caldera (RMS/ATT).	Sawyer and others (1994); Grauch and others (1997)
SCC northern Timber Mountain domain	See GC and A20	Silent Canyon Caldera margin—The topographic margin surrounding the nested caldera complex consisting of Area 20 and Grouse Canyon calderas, determined from drill-hole information. The western margin coincides with a gravity gradient (14/SCC).	Warren and others (1985); Sawyer and Sargent (1989); Ferguson and others (1994); Sawyer and others (1994)

Table 3. Identified geologic features shown on figure 7 that have geophysical expression—*Continued*.

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Description/comments	Reference(s)
Basalt flows and volcanoes — **Geophysical expression: high-amplitude magnetic anomalies (positive or negative) usually correlating with topography and/or mapped geologic contacts. Where flow is thin, magnetic expression may be absent. No gravity expression.**			
BU east-central Timber Mountain domain	Volcanic aquifers	Buckboard Mesa—Elongate area of high-amplitude positive magnetic anomalies corresponding to mapped basaltic rocks (Typ, table 2) of young Tertiary age.	Kane and others (1981); Grauch and others (1997). Description of unit: Sawyer and others (1995)
CR west-central part of western domain	N/A	Coba Ridge—A high-amplitude negative magnetic anomaly corresponds to topography and exposures of Tertiary basalt that has a strong, negative-inclination total magnetization (Tyb, table 2).	Grauch and others (1997)
DM southeastern Timber Mountain domain	Volcanic aquifers	Dome Mountain—Elongate area of high-amplitude positive magnetic anomalies corresponding to mapped lavas of Dome Mountain. The geometry of the zone suggests structural control on their emplacement.	Kane and others (1981)
TH west-central Timber Mountain domain	N/A	Thirsty Mountain—Basaltic shield volcano outlined on fig. 7 by mapped extent of the associated basalt (Typ, table 2). Negative magnetic anomalies are limited in extent around the vent of the volcano despite surface samples that indicate reversed-polarity rocks are more extensive. This suggests that the basalt thins away from the vent.	Grauch and others (1997). Description of volcano and paleomagnetic measurements: Fleck and others (1996)
Tertiary basins — **Geophysical expression: generally elongate or elliptical negative gravity anomalies, bounded at least in part by steep gradients that have fairly linear trend. Basins filled primarily with volcanic rocks may exhibit many high-amplitude magnetic anomalies. Sedimentary basins lack many high-amplitude magnetic anomalies and have low values of bulk magnetization of crust (fig. 5).**			
AV central part of southwestern domain	Valley-fill aquifer	Northwestern end of Amargosa Valley—A shallow alluvial basin evidenced by moderate gravity values surrounded by high gravity values. The moderate values and the general lack of magnetic anomalies suggest that pre-Mesozoic rocks similar to those in Bare Mountain and the Funeral Mountains floor this valley.	Snyder and Carr (1982; 1984); Carr (1990); Wright (1989); Kane and Bracken (1983); Electrical data: Greenhaus and Zablocki (1982); Klein (1995); Seismic reflection data: Brocher and others (1996)
CB southern part of eastern domain	Valley-fill aquifer	CP Basin—An alluvial basin elongated in the northeast direction with a maximum depth of about 640 m based on estimates of gravity data.	Miller and Healey (1986)
CF western part of southern domain	Valley-fill aquifer and volcanic aquifers and confining units	Crater Flat—A basin defined by low gravity values and that contains thick piles of volcanic rock and alluvium. The basin has been proposed alternatively as the result of caldera collapse or of tectonic extension (either through normal faulting or detachment faulting). Gravity, seismic reflection and refraction, and magnetotelluric data indicate the thickness of the basin fill to be 2.5 to 4 km. The area is associated with low values of crustal bulk magnetization (fig. 5) that suggest the absence of a large volume of intrusive rocks at depth. The ribbed magnetic pattern reflects the fault blocks of volcanic units within the basin.	Oliver, Ponce, and Hunter (1995); Snyder and Carr (1984); Carr (1988); Scott (1989); Kane and Bracken (1983); Bath and Jahren (1984); Fridrich, Dudley, and Stuckless (1994); Langenheim and Ponce (1995); Brocher and others (1996)

Table 3. Identified geologic features shown on figure 7 that have geophysical expression—*Continued*.

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Description/comments	Reference(s)
		Tertiary basins—*Continued*	
FF southern part of eastern domain	Valley-fill aquifer	Frenchman Flat basin – A probable pull-apart basin filled mainly with alluvium. The subsurface configuration of the basin is known primarily from gravity data, but supplemented by sparse shallow drill holes, electrical, seismic refraction data and, to limited extent, magnetic data. It is elongate to the northeast, with the deepest part located about 3 km to the north of the present-day valley minimum and having a maximum depth of about 1.4 km. Magnetic anomalies and geologic extrapolation indicate that volcanic rocks compose the floor of the basin primarily on the western side.	Miller and Healey (1986); V. Grauch and M. Hudson (unpub. report)
JB central part of southern domain	Valley-fill aquifer	Jackass Basin – A shallow alluvial basin evidenced by low gravity values, drill-hole information, and seismic refraction data. The alluvium is about 150 m thick, and depth to Paleozoic basement estimated at about 1.0 to 1.3 km.	Snyder and Carr (1982, 1984); Mooney and Schapper (1995)
MD northeastern part of southern domain	Valley-fill aquifer, volcanic aquifer	Mid Valley – A 1- to 1.5-km-deep basin filled with alluvium and tuff, evidenced by low gravity values and few magnetic anomalies. An extensive geologic, geochemical, and geophysical study showed that the basin is elongate in the north-south direction and truncated and offset by left-lateral faults (MM) on the northwest side.	McArthur and Burkhard (1986)
MV northeastern part of eastern domain	Valley-fill aquifer	Migrant Valley (in some places called Emigrant Valley) – An alluvial basin evidenced by a strong gravity low and lack of aeromagnetic anomalies.	Snyder (1983)
SF west-central part of western domain	Valley-fill aquifer	Sarcobatus Flat – Deep basin, inferred from low gravity values, that corresponds to a broad negative magnetic anomaly within the study area. Estimates of basin depth are about 1.5 to 2.0 km. The negative anomaly probably reflects a down-dropped volcanic unit with negative-inclination total magnetization. Regionally, the basin extends in a wide area west of the study area.	Basin inferred from gravity values: Jachens and Moring (1990); Saltus and Jachens (1995)
WY central part of eastern domain	Valley-fill aquifer	West Yucca basin – An alluvial basin subparallel to and not as deep as the Yucca Flat basin. Its associated gravity low is separated from Yucca Flat basin by a gravity high, described next (YF).	Ferguson and others (1988); Carr (1984); Cole and others (1989); Faults: Dockery and others (1984); Cole (1987)
YF central part of eastern domain	Valley-fill aquifer	Yucca Flat basin – An alluvial basin well-defined by subsurface drilling and by detailed east-west gravity profiles collected by D. Healey and R. Wahl, (USGS). It is an asymmetric, west-tilted basin formed by down-to-the-east normal faults. The pattern of faults is evident in the aeromagnetic data by the linear anomalies parallel to the basin axis. The higher amplitude gravity low in the southern end of the basin corresponds to the greatest accumulation of alluvium, estimated from drill-hole isopach maps to be 1.3 km. The Yucca Flat basin formed after the eruption of the Ammonia Tanks Tuff at 11.45 Ma with active tectonism continuing today on Yucca fault, which bisects the basin. The principal boundary fault on the west is the Carpetbag-Topgallant fault zone, which has as much as 2 km of normal slip on the pre-Tertiary surface. Yucca Flat basin is separated from West Yucca basin by a Paleozoic structural high, which is reflected by a north-northwest trending gravity high (fig. 3).	Ferguson and others (1988); Carr (1984, 1990); Laczniak and others (1996); Cole and others (1989); Faults: Dockery and others (1984); Cole (1987); Alluvial thickness: V. Williams (USGS, unpub. data, 1997)

Table 3. Identified geologic features shown on figure 7 that have geophysical expression—*Continued*.

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Description/comments	Reference(s)
		Structurally high, pre-Tertiary rocks **Geophysical expression: broad areas of high gravity values and low values of bulk magnetization of crust (fig 5).**	
BA southwestern domain	Carbonate aquifer and quartzite confining unit	Bare Mountain—Exposed Paleozoic and Precambrian bedrock associated with high gravity values. Extrapolation of the area of the gravity high to the north of an exposed detachment fault on the north side of Bare Mountain indicates the shallow dip of the fault.	Snyder and Carr (1982, 1984); Detachment fault: Maldonado (1990); Carr and others, 1996
BH south-central part of western domain	Volcanic aquifers and confining units	Northern Bullfrog Hills—Site of extensive faulting of Tertiary volcanic units that may be part of the upper plate of the detachment fault north of Bare Mountain (BA, fig. 7). Estimates from the gravity data give depths to pre-Tertiary rocks of less than 500 m. The notable lack of magnetic anomalies on the eastern side of BH, despite the presence of units that commonly produce anomalies, probably reflects the effects of multiple periods of hydrothermal alteration.	Grauch and others (1997). Geology: Minor and Fleck (1994); Noble and others (1991); Minor and others (1997)
ER western part of eastern domain	Primarily Eleana confining unit	Eleana Range—Paleozoic rocks are exposed in many places in the Eleana Range and to the south, ending at the CP Hills. The rocks consist mainly of Mississippian clastic units, which hydrogeologically comprise a confining unit. Along the western side of the gravity high of the Eleana Range is a strong gradient indicating faulting that also coincides with a Mesozoic thrust fault, the CP thrust.	Laczniak and others (1996); Cashman and Trexler (1991)
FU southwestern domain	Carbonate aquifer	Funeral Mountains—Exposed Paleozoic and Precambrian bedrock associated with high gravity values.	Snyder and Carr (1982, 1984)
HR central part of eastern domain	Carbonate aquifer and granite	Halfpint Range—Gravity highs in the northern part of the Halfpint Range indicate that Paleozoic rocks are beneath a thin cover of Tertiary volcanic rocks. Includes the Twin Ridge pluton.	Laczniak and others (1996); Maldonado and others (1988)
SP southern edge of NTS; in southern and southeastern domains	Carbonate aquifer and quartzite confining unit	Specter Range—Gravity highs reflect shallowly buried and exposed Paleozoic rocks. The southern part of the range within the study area is composed of lower Paleozoic carbonates. Late Precambrian sedimentary rocks underlie the northern side. Gravity, seismic-reflection, and electrical data indicate that the pre-Cenozoic rocks are downdropped at a fault on the west end (32, fig. 7).	Sawyer and others (1995); Laczniak and others (1996); Snyder and Carr (1982); Miller and Healey (1986); Mooney and Schapper (1995); Brocher and others (1996); Greenhaus and Zablocki (1982)
SR southeastern domain	Carbonate aquifer	Spotted Range—Gravity highs reflect shallowly buried and exposed Paleozoic carbonate rock.	Sawyer and others (1995); Laczniak and others (1996); Mooney and Schapper (1995)
		Faults and fault zones **Geophysical expression: gravity or magnetic gradients along a linear trend or linear discontinuities between anomalies.**	
RV southeastern corner of study area	Fault	Rock Valley fault zone—Zone of left-lateral shear evidenced in the gravity and magnetic data by gradients, east-northeast alignments of anomalies, and a change in magnetic anomaly pattern from many high-amplitude anomalies on the north to low-amplitude broad anomalies on the south (fig. 4).	Burchfiel (1965); O'Leary (in press)
MM northeastern part of southern domain	Fault	Mine Mountain fault—A left-lateral fault zone that separates subtle changes in magnetic and gravity character.	Carr (1984); O'Leary (in press)

Table 3. Identified geologic features shown on figure 7 that have geophysical expression—*Continued*.

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Description/comments	Reference(s)
Magnetic expressions of miscellaneous volcanic units			
Geophysical expression: correlation of magnetic anomalies to the shape of topography and the extent of mapped volcanic units that correspond to measured magnetic properties for the unit (table 2).			
OM east-central part of western domain	Volcanic aquifers and confining units(?); valley-fill aquifers	Identified and unknown units at Oasis Mountain—Magnetic highs correspond to rhyolite of Fleur-de-lis Ranch (Tff, table 2) on the eastern side and Ammonia Tanks Tuff (Tma, table 2) on the western side. The source of the negative anomaly in between these two highs is not known.	Grauch and others (1997)
SM south-central part of western domain	Volcanic aquifers?	Fortymile volcanics at Springdale Mountain and Donovan Mountain—Mapped upper Fortymile rhyolite lavas (Tfu, table 2) have good correspondence to negative magnetic anomalies and topographic shapes at Springdale Mountain except on the eastern side where the trachyte of Donovan Mountain (Tfn, table 2) is mapped. This area needs reexamination.	Grauch and others (1997) Geologic map: Minor and others (1997)
TR southwestern Timber Mountain domain	N/A	Tram Tuff near Tram Ridge—Exposed, 150-m-thick Tram Tuff, which has negative-inclination total magnetization (Tct, table 2), as is evidenced by a high-amplitude negative magnetic anomaly. However, the negative anomaly does not extend over the southwestern exposures where it is hydrothermally altered.	Grauch and others (1997); Kane and Bracken (1983); Fridrich, Orkild, and others (1994); M. Hudson (unpub. magnetic rock-property data, 1996).

Table 4. Description of subsurface features from figure 7 that are inferred or interpreted from geophysical, geological, and rock-property information.

[Inferred hydrogeologic unit is based on the lithologic type inferred in the subsurface. In some cases, the subsurface feature may be expected to have limited depth extent, so that assignment of a hydrogeologic unit is not applicable. Hydrogeologic units are from Laczniak and others (1996) with the following modifications: Volcanic aquifers include welded-tuff aquifers and lava-flow aquifers; volcanic confining units include tuff and other volcanic confining units; and carbonate aquifer includes lower and upper carbonate aquifers]

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Interpretation	Explanation
1 northern part of western domain	Volcanic aquifers or confining units or valley-fill aquifer	Area of moderately uplifted pre-Tertiary rocks southeast of Stonewall Mountain and north of Obsidian Butte.	Moderate gravity values indicate moderately thick Tertiary rocks. Strong negative magnetic anomalies do not correspond to mapped young Tertiary basalts; instead they are probably related to Rainier Mesa Tuff (Tmr, table 2), which is exposed locally.
2 northern part of western domain	Quartzite confining unit or carbonate aquifer	Structurally high pre-Tertiary rocks west of Black Mountain.	Moderate to high gravity values indicate pre-Tertiary rocks are within 500 m to 1 km of the surface (Grauch and others, 1997). An isolated exposure of Paleozoic carbonate rocks (Cole, 1997) occurs just west of Black Mountain caldera (BM).
3 north-central part of western domain	Valley-fill aquifer	Volcanic unit(s) with negative-inclination total magnetization that is/are older than Ammonia Tanks Tuff. Probably the Rainier Mesa Tuff, which has been structurally repeated.	A collection of strong negative magnetic anomalies that have similar orientation and proximity to each other. Based on anomaly correspondence to mapped units in the area, magnetic properties, and age relations of the units, Grauch and others (1997) concluded that the source(s) is a unit with negative-inclination magnetization that is older than the basalt of similar magnetic character to the southwest at Coba Ridge (CR).
4 north-central part of western domain	Volcanic aquifers or confining units	Possible caldera south of Tolicha Peak, perhaps the source of the Sleeping Butte tuff (Tqs, table 2).	Suggested by Grauch and others (1997) from analysis of the elliptical gravity low in an area of low magnetic values. Evidence for a caldera origin is the occurrence of rhyolite lava domes and their magnetic expressions confined to the area of the gravity low. Westward thickening of the tuff of Sleeping Butte toward the area suggests an association, but the magnetic properties of the unit are not well determined (Tqs, table 2), precluding a definitive association with the magnetically low area (Grauch and others, 1997).
5 central part of western domain	N/A	A northeast-striking fault zone that does not have major offset east of Sarcobatus Flat.	A marked change between negative and positive magnetic anomalies that probably represents a fault between volcanic units. A lack of expression in the gravity data indicates no major vertical offset in the underlying pre-Tertiary rocks (Grauch and others, 1997).
6 west-central part of western domain	Volcanic aquifers and confining units; valley-fill aquifer	Magnetic volcanic rocks 500 to 1000 m thick overlying pre-Tertiary rocks north of Oasis Mountain.	A region of high magnetic values that corresponds mainly to Quaternary alluvium at the surface and occurs within the domain of structurally high pre-Tertiary rocks. Grauch and others (1997) suggested that the likely magnetic sources are tuff of Tolicha Peak (Tqt, table 2) or other units older than Fortymile Canyon rocks (based on anomaly trends and expected orientation of structures in the area).
7 southern part of boundary between western and Timber Mountain domains	Fault	East-striking fault or transverse zone, informally called the Hot Springs fault, that crosses the boundary between the Timber Mountain and western domains and apparently truncates other, major north-striking faults (8, 24).	In the Timber Mountain domain, a gravity gradient separates low gravity values on the north from moderate gravity values on the south. In the western domain, the extension of the gradient separates moderate gravity values on the south from high gravity values on the north. Abrupt changes in magnetic character coincide with the gravity gradients. The linearity suggests a structure, but its geometry and relation to other structures is unclear (Grauch and others, 1997).

Table 4. Description of subsurface features from figure 7 that are inferred or interpreted from geophysical, geological, and rock-property information—*Continued*.

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Interpretation	Explanation
8 boundary between southwestern and southern domains	Fault	North-striking, probably stepped, down-to-the-east, normal fault just east of Bare Mountain.	The strong, linear gravity gradient indicates a major, tectonic fault. However, the steepest part of the gradient and corresponding changes in character of the magnetic data occur 1-2 km east of the mapped range-front fault. The geometry of this fault has been proposed as (1) a stepped normal fault, with most of the throw near the steepest part of the gravity gradient (Snyder and Carr, 1984); (2) a shallowly dipping detachment surface (Oliver and Fox, 1993); or (3) a normal fault developed at the range front that has high-density alluvium within the basin fill near the range front (Langenheim, in press). From gravity modeling, all three models are viable, but the magnetic and seismic-reflection data support the stepped normal fault model (Langenheim, in press; Brocher and others, 1996). Snyder and Carr (1984) and Carr (1988) proposed that this fault was related to a Crater Flat caldera.
9 center of south-western domain	?	Local, fairly thick accumulation of probable volcanic rocks within the Amargosa Valley.	Grauch and others (1997) suggested that this broad, magnetic high is produced by a source that is 100-500 m below the surface and over 1 km thick, probably fault-bounded on the northeast side.
10 along northwestern margin of Timber Mountain domain	Volcanic aquifers and confining units	Thick section of magnetic, low- to moderate-density, probably volcanic rocks, evidenced primarily by a region of high magnetic values.	Grauch and others (1997) examined the likely sources of a region of high magnetic values extending along the western margin of the Silent Canyon caldera complex to Black Mountain caldera (BM). Based on magnetic-property and limited drill-hole information, they suggested the primary magnetic sources are dacite lavas of Mt. Helen, tuff of Tolicha Peak, and locally the comendite of Ribbon Cliff (Tqm, Tqt, and Ttc, table 2). In addition, the general absence of Rainier Mesa Tuff (Tmr, table 2) helps explain the high magnetic values. The magnetic sources are truncated by NNE.-trending structures on the eastern side (13 and 14). Region corresponds to low gravity values, indicating a thick pile of low- to moderate-density volcanic rocks.
11 along western margin of Timber Mountain domain	Volcanic aquifers and confining units	Thick section of magnetic, low- to moderate-density, probably volcanic rocks, evidenced primarily by a region of high magnetic values.	A region of high magnetic values extending along the western margin of the Timber Mountain caldera complex, overprinted by the expression of the Thirsty Mountain shield volcano (TH). Based on comparisons to rock-property, geologic mapping, and limited drill-hole information, Grauch and others (1997) consider the primary sources of the regional magnetic high could include (from oldest to youngest, table 2) dacite of Mount Helen (Tqm,) or similar intermediate-composition rock at depth, the tuff of Tolicha Peak (Tqt), the tuff of Sleeping Butte (Tqs), Ammonia Tanks Tuff (Tma), the rhyolite of Fleur-de-lis Ranch (Tff), and the comendite of Ribbon Cliff (Ttc; northern part of 11 only). In addition, the Rainier Mesa Tuff (Tmr, table 2) is either absent or present at great depth.
12 northwestern margin of Timber Mountain domain	Volcanic aquifers or confining units	Possible Tolicha Peak caldera (Tqt, table 2), southwest of Black Mountain.	A circular embayment in the Timber Mountain domain gravity low south and southeast of thick tuff of Tolicha Peak (Tqt, table 2) and strong positive magnetic highs due to sources below the surface suggest a buried caldera source of the strongly magnetic tuff of Tolicha Peak (Tqt, table 2; Grauch and others, 1997).
13 northwestern Timber Mountain domain	Fault	NNE.-trending structural zone bounding the areas of regional magnetic highs (10 and 11) on the east and probably associated with the nearly parallel gravity gradient 1 km to the east (14 and 14/SCC).	The linearity of the NNE. magnetic gradient, especially evident on figure 5, suggests a structural origin (Kane and others, 1981). A magnetic model of the structure (fig. 9) shows a major, down-to-the-east fault parallel to and west of the margins of the Silent Canyon caldera complex (Grauch and others, 1997).

Table 4. Description of subsurface features from figure 7 that are inferred or interpreted from geophysical, geological, and rock-property information—*Continued*.

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Interpretation	Explanation
14 northwestern Timber Mountain domain	Fault	NNE.-trending structural zone bounding the Silent Canyon and Timber Mountain caldera complexes on the west and probably associated with the nearly parallel magnetic gradient 1 km to the west (13).	Major, NNE.-trending gradient between primarily low gravity values on the west and very low gravity values on the east associated with the Silent Canyon and Timber Mountain caldera complexes (Kane and others, 1981). The gradient corresponds in part to the Silent Canyon caldera margin, known from drilling (Healey, 1968; Sawyer and Sargent, 1989).
15 northeastern Timber Mountain domain	Volcanic aquifers or confining units or pre-SWNVF sedimentary aquifer	Possible Tub Spring caldera or Tertiary basin in Kawich Valley.	A northeast-elongated part of the Timber Mountain domain gravity low with little expression in the magnetic data. Variations in the gravity low that inversely correlate with topography suggest that rocks in the subsurface have low density and could be explained by a thick pile of ash-flow tuffs. Proximity to the source area of the Tub Spring Tuff, based on outflow thickness, contact relations, and distribution of the Tub Spring Tuff suggest that a fragment of the Tub Spring caldera is in this area. However, a Tertiary basin filled with volcanic rocks and alluvium could also produce the same geophysical signature.
16 east-central Timber Mountain domain	Volcanic aquifers	Probable thick accumulation of welded Rainier Mesa Tuff and Paintbrush tuffs near Silent Canyon.	Strong negative magnetic anomalies correspond to Rainier Mesa Tuff (Tmr, table 2) that overlies Paintbrush tuffs that exhibit strong negative-inclination magnetization (Grauch and others, 1997). Rainier Mesa Tuff is as much as 300 m thick in drill holes in the northern part of the anomalous area, whereas elsewhere within the Silent Canyon caldera complex, it averages about 100 m thick (appendix of Ferguson and others, 1994).
17 east-central part of Timber Mountain domain	Valley-fill aquifer	Probable Tertiary basin, filled with alluvium and volcanic rocks near Kawich Canyon.	Moderate to low gravity values outside the Silent Canyon caldera complex margins indicate moderately thick Tertiary rocks. The gravity model of Ferguson and others (1994) combined with the lack of magnetic character, favor a tectonic basin interpretation. The moderate magnetic values at the eastern end of the profile and at the northern end of the gravity low may indicate the Gold Meadows stock (GM) extends west under the basin.
18 central Timber Mountain domain	Fault	WNW.-trending structure extending from Stockade Wash to Black Mountain caldera of unknown relation to caldera formation.	A linear discontinuity marked by abrupt differences in magnetic character or by linear positive anomalies. It has only subtle gravity expression (Kane and others, 1981). The change in magnetic character is probably due primarily to the juxtaposition of magnetic rocks having different magnetization directions within the top 1 km of the surface (Grauch and others, 1997). However, it is unclear which units are juxtaposed, especially on the western and eastern ends of the lineament where sources are buried. The linearity of the feature suggests it has a structural origin; the coincidence with the topographic wall of the Rainier Mesa caldera in the central part suggests that it is related in some way to caldera structures.
19 central Timber Mountain domaiin	Volcanic aquifers	An area of post-Rainier Mesa rhyolite domes near Tannenbaum Hill. The rhyolite may actually be more extensive throughout the northern Rainier Mesa moat but covered by younger rocks.	Exposures of negative-anomaly-producing rhyolite (Tmat, table 2) generally correspond to small, circular, strong negative anomalies. Kane and others (1981) suggested that the entire northwestern corner of the Rainier Mesa caldera is underlain by these lavas. They may also be the sources of other strong negative anomalies in the northern moat (such as 20, 21, and the anomalies surrounding BU). However, the broad, wide character of these latter anomalies preclude a domal morphology.

Table 4. Description of subsurface features from figure 7 that are inferred or interpreted from geophysical, geological, and rock-property information—*Continued*.

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Interpretation	Explanation
20 east-central Timber Mountain domain	Volcanic aquifers	Probable thick accumulation of Rainier Mesa Tuff underlying a thin veneer of Ammonia Tanks Tuff near Stockade Wash.	A high-amplitude negative magnetic anomaly that coincides with exposures of the positive-anomaly-producing Ammonia Tanks Tuff (Tma, table 2) indicates that the exposed tuff is not the source. The likely source is the Rainier Mesa Tuff (Tmr, table 2) which is exposed nearby, although older negative-inclination units, such as those within the volcanics of Oak Spring Butte (Toy, Tor, and Tot, table 2) are also possibilities. The associated gravity values that are higher than the adjacent caldera complexes suggest that the area is outside the structural margin of the Rainier Mesa caldera (Grauch and others, 1997).
21 east-central Timber Mountain domain	Volcanic aquifers	Probable thick accumulation of Rainier Mesa Tuff or moat lavas having strong, negative-inclination total magnetization, near Stockade Wash.	High-amplitude negative magnetic anomaly within the Rainier Mesa caldera, which is associated with low gravity values typical of caldera fill in the Timber Mountain domain. The source is not exposed, but is likely a unit with strong negative-inclination magnetization, such as the Rainier Mesa Tuff (Tmr, table 2; Grauch and others, 1997).
22 central Timber Mountain domain	Volcanic aquifers	Probably a thick section of welded Ammonia Tanks Tuff northwest of Timber Mountain.	A region of high magnetic values with no corresponding expression in the gravity data within the Ammonia Tanks caldera but extending outside the structural margin on the northwest. Grauch and others (1997) suggest that the source is Ammonia Tanks Tuff (Tma, table 2) based on exposures at the surface, magnetic depth estimates, and lack of gravity signature.
23 west-central part of Timber Mountain domain	Volcanic aquifers or confining units or valley-fill aquifer	Tertiary basin fill and (or) caldera fill in Oasis Valley basin.	An area of low gravity values bounded on the south and west by strong gravity gradients (7 and 24), which indicate a fault-bounded, thick sequence of Tertiary volcanic and (or) sedimentary rocks. The area is at the southwestern termination of the NNE.-trending structural zone (13 and 14). The western Rainier Mesa caldera margin is within or is east of this area (Grauch and others, 1997).
24 central part of boundary between Timber Mountain and western domains	Probably a barrier	Major buried, north-striking, down-to-the-east, normal fault or series of faults extending 15 km from southern Oasis Valley to north of Sleeping Butte. Informally called the Hogback fault.	A linear gravity gradient discussed by Grauch and others (1997) that marks a major change in subsurface composition from primarily low-density volcanic rocks on the east to high-density pre-Tertiary sedimentary rocks on the west. Based on exposures at Oasis Mountain, the pre-Tertiary rocks are probably quartzite confining unit. The linearity and long extent implies a tectonic fault as opposed to a caldera-collapse origin, which is contrary to geologic interpretations of a nearly coincident paleoscarp near Sleeping Butte (Noble and others, 1991; Byers, Carr, Orkild, and others, 1976; Byers, Carr, Christiansen, and others, 1976). On the other hand, part of the fault could have been reused during caldera collapse.
25 southwestern Timber Mountain domain	Volcanic aquifers and confining units	Prospector Pass caldera, possible source of the Tram Tuff (Tct, table 2) in northern Crater Flat.	Suggested by Snyder and Carr (1982) and Carr (1986) based on subsurface geologic information and low gravity values. The area is contained within high values of bulk magnetization of the crust (fig. 5), which is consistent with the presence of intrusive roots to a caldera at depth.
26 southern Timber Mountain domain	Volcanic aquifers or confining units or valley-fill aquifer	Tertiary graben or possible caldera source of Lithic Ridge Tuff in northern Crater Flat.	The low gravity values and inferences from subsurface geologic information suggest this may be a caldera, possibly associated with the Lithic Ridge Tuff (14 Ma). Fridrich, Dudley, and Stuckless (1994) argue that the area is a structural graben aligned in a northeasterly direction, based on subsurface information.

Table 4. Description of subsurface features from figure 7 that are inferred or interpreted from geophysical, geological, and rock-property information—*Continued*.

Feature label (fig. 7) and general location	Inferred hydrogeologic unit at depth	Interpretation	Explanation
27 southeastern Timber Mountain domain	Volcanic aquifers or confining units	Possible southeastern part of Topopah Spring caldera near Shoshone Mountain.	A gravity low on the southeastern margin of the Timber Mountain domain is accompanied by magnetic anomalies that arise from volcanic units mapped at the surface (cf. Sawyer and others, 1995). Variations in the gravity low that inversely correlate with topography (Kane and others, 1981) indicate that rocks in the subsurface have low density, such as a thick pile of ash-flow tuffs. This likelihood and the proximity to the source area of the Topopah Spring Tuff (based on thickness and extent of the tuff) suggest that a fragment of the Topopah Spring caldera is located in this area.
28 Timber Mountain and southern domains	Fault	A possible fault or accommodation zone that follows Yucca Wash, inferred based on a change in structural style. However, geophysical evidence does not support much offset.	Minor gravity gradients and a change in magnetic anomaly character on the north align with an inferred fault zone in Yucca Wash. Workers have debated whether the fault is right-lateral (Scott and others, 1984), separates areas of different structural style (Fridrich, 1999; Hamilton, 1994), has normal offset (Dickerson, 1996) or has significant offset at all (based on geophysical models: Langenheim and others, 1993; Ponce and Langenheim, 1994).
29 western part of southern domain	Granite?	Possible intrusion or unknown magnetic volcanic source below central Crater Flat.	Broad magnetic high in central Crater Flat could be thick volcanic units at depth (Kane and Bracken, 1983). Connor and others (1997) suggested the presenced of a buried volcano. Carr (1984; 1988) used the magnetic high as evidence of thick volcanic units composing a resurgent dome, interpreted as the Crater Flat caldera. However, magnetic models (Langenheim and Ponce, 1995) indicate that these units, which were encountered in drilling, can only be expected to account for part of the anomaly; a more likely explanation is a granitic intrusion in pre-Tertiary rocks within the basin floor (Langenheim, in press). The low gravity and bulk magnetization values argue against a large, intra-basin intrusion (figs. 3 and 5).
30 west-central part of southern domain	Fault	Down-to-the-west normal fault(s) on the east side of Crater Flat.	A segmented, linear gravity gradient on the eastern side of Crater Flat that corresponds to a main bounding fault as interpreted from gravity and seismic-refraction (Snyder and Carr, 1982; 1984), magnetotelluric (Klein, 1995) and seismic-reflection (Brocher and others, 1996) data. However, drilling at northern Yucca Mountain has not discovered such a major fault within the post-14-Ma volcanic section.
31 southwestern part of southern domain	Fault	Inferred fault along the southern end of Crater Flat (CF).	A gentle gravity gradient, abrupt termination of magnetic anomalies from the north, and a topographic scarp that delimits the southern extent of exposed Tertiary volcanic rock correspond to the southern end of the Crater Flat basin along Highway 95 (Snyder and Carr, 1982; Sawyer and others, 1995). Seismic-refraction data indicate that the thickness of the basin fill decreases from 3 km on the north, to 1 km in this area (Ackermann and others, 1988). The linearity of and abrupt changes along this gradient suggest it is structural in origin.
32 central part of southern domain	Fault	A north-northwest-striking buried fault on the west side of the Striped Hills, known colloquially as the “gravity fault.”	A linear gravity gradient interpreted and modeled by Snyder and Carr (1982) as a normal fault with 1 km of throw down to the west, corroborated by seismic-reflection and electrical data (Brocher and others, 1996; Greenhaus and Zablocki, 1982). Fault generally follows a change in magnetic values at its S. extent (fig. 4).
33 southeastern part of southern domain	Carbonate aquifer?	Structurally high pre-Tertiary rocks near Hampel Hill.	Gravity high indicates pre-Tertiary rocks near the surface (Miller and Healey, 1986). The Rock Valley fault zone (RV) truncates the structural high.

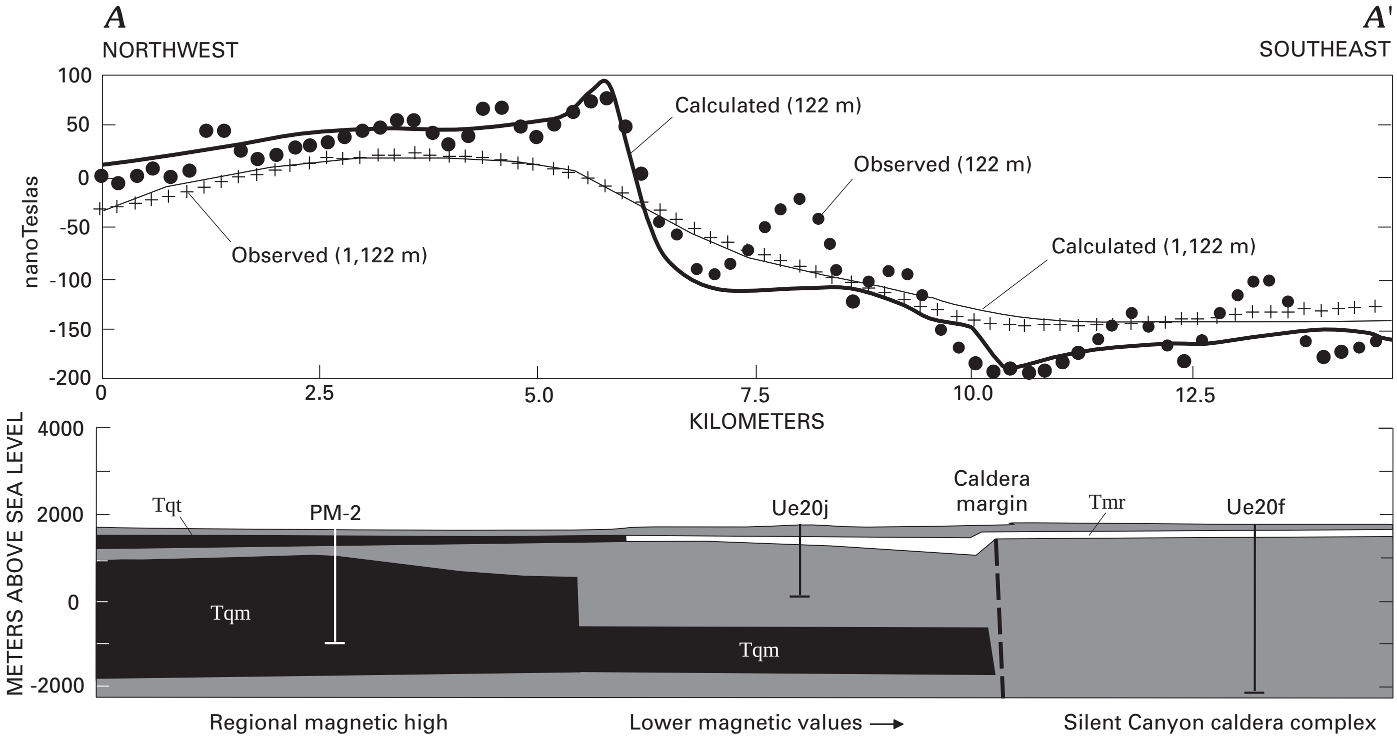

Figure 9. Simple magnetic profile model demonstrating possible sources of the regional magnetic high northeast of Black Mountain. The location of profile *A-A′* is shown on figure 8. The bold lines and dots are calculated and observed at 122 m above ground; the thin line and plusses are calculated and observed 1,122 m above ground. Total magnetizations assigned to the models are modified slightly from measured values (M. Hudson, unpub. data, 1996) in order to better fit the data. Declination/inclination and intensity (A/m) of total magnetization for tuff of Tolicha Peak (Tqt) = 24°/46° and 2.15; for Rainier Mesa Tuff (Tmr) = 157°/–32° and 1.08; for the shallower body of dacite lava of Mt. Helen (Tqm) = 357°/58° and 0.9; and for the deeper body 15°/62° and 0.5. The deeper body is assigned a lower remanent magnetization, likely due to its depth (McElhinny, 1973). For simplicity, the gray area (undetermined country rock) of the model has zero magnetization. Near the caldera margin, viable models require either thickening of the modeled Rainier Mesa Tuff (Tmr), changes in magnetization, or variations in other rock units in this area. However, only the model involving thickening of Tmr is shown.

Southern Domain

The southern domain (fig. 6) is one of the most extensively studied parts of the map area because it includes Yucca Mountain, site of the DOE-proposed high-level-nuclear-waste facility. Many previous workers have discussed geologic and geophysical studies in this area, which are too numerous to review in this paper. The domain is generally characterized by a moderate magnitude of extension, moderate magmatism (several to tens of km^3/m.y. extruded during the middle to late Miocene), and by a mixture of structural styles. Geophysically, this domain has low bulk magnetization (fig. 5), numerous moderately high amplitude magnetic anomalies (fig. 4), and variable gravity values (fig. 3).

The boundary between the southern and Timber Mountain domains in the northern part of Crater Flat is expressed by a subtle change in gravity values (fig. 3) and by abrupt changes in magnetic patterns (fig. 4). This boundary has also been recognized by previous workers as the southern limit of a broad, regional, east-trending magnetic high (e.g., Bath and Jahren, 1984; Oliver, Ponce, and Blank, 1995). However, the magnetic potential map indicates the southern limit of high bulk magnetization is actually about 10 km farther north (fig. 5). No evidence of this domain boundary is observed in surface geology nor in changes of thickness of pre-14-Ma rocks in the subsurface (Fridrich, 1999; Fridrich, Dudley, and Stuckless, 1994).

The origin of the broad, regional, east-trending magnetic high has been the subject of interest and debate because it extends across the northern part of Yucca Mountain and coincides with a hydraulic gradient (Fridrich, Dudley, and Stuckless, 1994). In the area of the Calico Hills (CH, fig. 7), argillite in the Eleana Formation has a unique magnetic expression that allows it to be distinguished from the carbonate units, whereas it cannot be distinguished from the carbonate units with gravity data, nor does it have a magnetic signature elsewhere. This unique magnetic signature prompted speculation that the western extension of the broad, regional magnetic high is caused by a subsurface extension of the magnetized Eleana unit (CH compared to fig. 4) (Bath and Jahren, 1984). The presence of the Eleana confining unit north of Yucca Mountain could also explain the hydraulic gradient (Fridrich, Dudley, and Stuckless, 1994). However, the magnetic source of the regional high is estimated at 1.5- to 3.0-km depth (Ponce and others, 1995; Oliver, Ponce, and Blank, 1995). At the depths indicated, a large volume of magnetic material is required to explain the magnetic high. Therefore, a granitic intrusion or batholith is more likely to be the primary source, perhaps with some contribution from magnetized argillite (Kane and Bracken, 1983; Carr and others, 1986; Oliver, Ponce, and Blank, 1995).

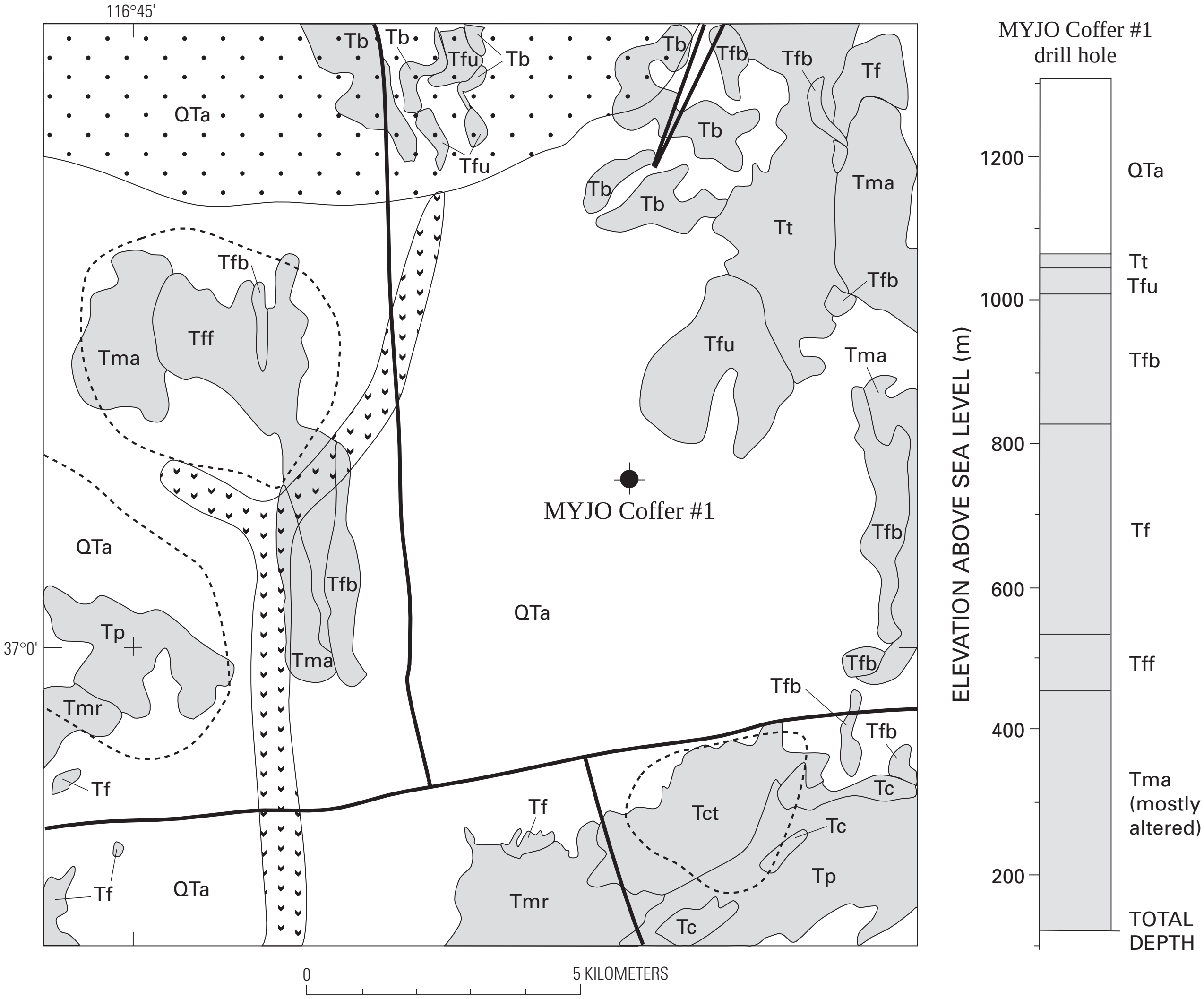

Figure 10. Geologic map of Oasis Valley basin area (map area shown by rectangle on fig. 7) generalized from Sawyer and others (1995). Also shown are Oasis Valley discharge area ("v" pattern), geophysical features from figure 7, and the location of and schematic stratigraphic section drilled in MYJO Coffer #1 well (R. Warren and D. Sawyer, written commun., 1992). Unshaded areas represent Quaternary alluvium and Tertiary gravels (QTa). Shaded areas are geologic units and groups from table 2: younger Tertiary basalts (Tb), Thirsty Canyon group (Tt), upper Fortymile rhyolite lavas (Tfu), Beatty Wash Formation (Tfb), rhyolite of Fleur-de-lis Ranch (Tff), Ammonia Tanks Tuff (Tma), Rainier Mesa Tuff (Tmr), Paintbrush group (Tp), Tram Tuff (Tct), and Belted Range group (Tb). Shaded areas also include units from Sawyer and others (1995) within the volcanics of Fortymile Canyon (Tf) and the Crater Flat group (Tc) that are not listed in table 2.

Eastern Domain

Another well studied area is the eastern domain (fig. 6), which locally was intensively drilled and investigated in studies associated with underground nuclear-weapons testing in Yucca Flat. The domain is characterized by late Miocene normal faulting and limited Tertiary magmatism. The eastern domain is more typical of basin-and-range structure than other parts of the study area, and the wealth of subsurface information, especially in Yucca Flat, provides an excellent model for this structural style elsewhere in the Great Basin. The style is evident in the gravity map (fig. 3), as shown by paired, north-trending highs and lows. The lows (MV, YF, WY, CB, and FF compared to fig. 3) are caused by alluvial basins filled with Miocene-Quaternary alluvium and underlain by distal tuffs erupted from the southwestern Nevada volcanic field. The gravity highs (ER, HR, and the area between YF and WY compared to fig. 3) reflect near-surface pre-Tertiary rocks. None of the relief on the pre-Tertiary sedimentary surface can be attributed to caldera tectonism.

The boundary of the Timber Mountain and eastern domains coincides with the interface between pre-caldera rocks on the east and caldera-related rocks on the west within the upper 3 km of crust. Thus, the boundary was drawn to include the inferred Gold Meadows stock at depth (GM, fig. 7) within the eastern domain. This stock, like the nearby Climax stock (CL, fig. 7) and some other small plutons not shown, is of Mesozoic age and therefore predates the main stage of volcanism. This western boundary of the eastern domain generally corresponds to the principal ground-water divide in the Nevada Test Site region (fig. 2), which separates the regional carbonate aquifer systems to the east from the regional volcanic aquifer systems to the west (Laczniak and others, 1996). The boundary of the eastern domain with the southern domain is gradational and does not correspond to any known structure. It generally marks a pronounced change in structural and magmatic style and values of bulk magnetization (fig. 5).

Southeastern Domain

The southeastern domain (fig. 6) includes structural styles and characteristic geophysical signatures that can be continued farther to the southeast of the study area to the Spring Mountains (fig. 1). The region is amagmatic, as evidenced by a subdued magnetic character (Blakely, 1988), and it is characterized by strike-slip faulting (Hudson, 1997). The high gravity values reflect structurally high pre-Tertiary sedimentary rocks (SP and SR, fig. 7), overlain locally by Cenozoic alluvium. The northern boundary of this domain is the Rock Valley fault zone (RV, fig. 7), which is an oblique, down-to-the-northwest fault zone (Burchfiel, 1965; O'Leary, in press).

Hydrogeologic Implications

The geophysical framework of interpreted, major geologic features (fig. 7, tables 3 and 4) provides constraints for understanding the geologic and hydrogeologic framework of the subsurface in the southwestern Nevada volcanic field and vicinity, especially where drill-hole control on subsurface geology is limited. Many of the geophysical features show evidence of major lateral changes in the physical properties of the crust that extend to depths of 1 km or greater. No matter what their geologic origin, these geophysical features remain as evidence of major changes in the nature of the subsurface that may be significant to the hydrogeology of the area.

Regional Hydrologic and Geophysical Features

Within the southwestern Nevada volcanic field, the change from volcanic aquifers to carbonate aquifers to the east and south corresponds to a steep hydraulic gradient (fig. 2) and the presence of the Eleana confining unit (Fridrich, Dudley, and Stuckless, 1994; Laczniak and others, 1996). This change is expressed geophysically primarily by a major change in gravity values between the Timber Mountain and eastern domains (compare figs. 3 and 6) and, secondarily, by a change in magnetic character (fig. 4). The gravity expression is related to the difference in subsurface densities between the volcanic rocks and pre-Tertiary sedimentary rocks in the subsurface.

The same gravity gradient continues to the south and west, generally defining the boundary between the Timber Mountain and southern domains (compare figs. 3 and 6). The gravity gradient also coincides with the regional magnetic gradient that corresponds to a change in water level seen in subsurface drilling (Fridrich, Dudley, and Stuckless, 1994), as discussed previously in the section on the southern domain.

Hydrogeologic Implications West of the Nevada Test Site

West of the Nevada Test Site, where drill-hole information is lacking, geophysical data provide the best information available about the subsurface hydrogeology. Interpretations of such data constrain the bulk physical properties of the subsurface from which hydrogeologic units have been inferred (fig. 11). The inferences are intended to help focus further work, not to redefine regional ground-water concepts.

Regional ground-water flow is southwestward from the main area of underground testing at Pahute Mesa toward the northern part of the western border of the Nevada Test Site (fig. 11) (Blankenagel and Weir, 1973; O'Hagan and Laczniak, 1996). Figure 11 shows a detail of the area of interest with interpretations and inferred hydrogeologic units that were developed from the geophysical framework. The interpretations are discussed primarily under the section on the Timber Mountain domain. The following geophysical features have hydrogeologic significance (referenced to the labels of figure 7 and tables 3 and 4): (1) the WNW.-trending inferred structure (18); (2) the resurgent intrusion associated with the Ammonia Tanks caldera (TM); (3) features near the northwestern margins of the Ammonia Tanks and Rainier Mesa caldera margins (RMT and gravity gradient); (4) the NNE.-trending structures on the west side of the Silent Canyon and Timber Mountain caldera complexes (13 and 14); and (5) the Hot Springs and Hogback faults bounding Oasis Valley basin (7 and 24) and the subsurface rocks that are juxtaposed at these faults.

The WNW.-trending inferred structure (18, fig. 7) may in part be related to the topographic wall of the Rainier Mesa caldera (RMT, fig. 7). Along the western part of the structure, where its trend is nearly perpendicular to regional ground-water flow (fig. 11), rocks having significantly different magnetization directions (as opposed to magnetization intensities) are juxtaposed within the top 1 km of crust. Their magnetic signatures are indicative of moderate to strong total magnetization, a signature typically associated with unaltered, welded ash-flow tuffs. The subtle gravity gradient (figs. 8 and 11) indicates only a minor change in bulk density of the crust. Thus, the lithology (but probably not the ages) of units on either side of the structure could be very similar, suggesting that the structure has minor hydrogeologic significance.

The area within which ground water intersects with the resurgent intrusion underneath the Timber Mountain area is approximated by the general outline of the elliptical gravity high (TM compared to fig. 3; fig. 11), as discussed under the section on the Timber Mountain domain. Electrical surveys across the center of Timber Mountain (fig. 11) indicate the intrusion and its volcanic cover have low interstitial and fracture porosities to depths of 1 km (Zablocki, 1979). If this electrical characterization is representative of the resurgent intrusion as a whole, then an extensive barrier to regional ground-water flow from the north of Timber Mountain could be present in the subsurface (fig. 11).

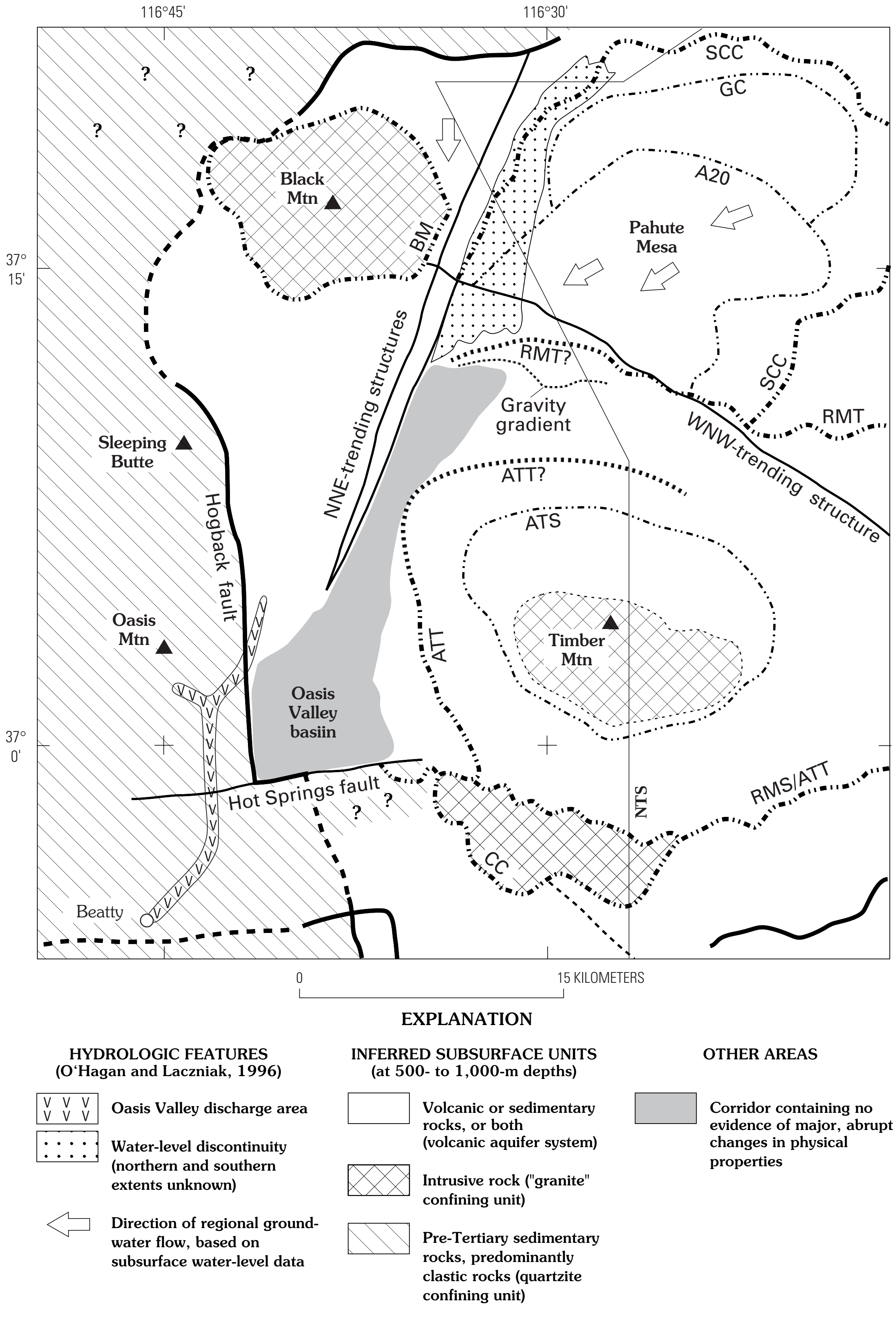

Figure 11. Detail of the northwestern part of the Nevada Test Site (NTS) and vicinity, showing geophysical features that may be hydrogeologically significant. Inferred hydrogeologic units at 500- to 1,000-m depth are based on the geophysical-geologic interpretations of figure 7. The text and tables 3 and 4 provide detailed discussion on the limitations and constraints associated with the interpretations of the NNE.-trending structures; WNW.-trending structure; Hot Springs and Hogback faults; resurgent and other intrusions at Black Mountain caldera, Timber Mountain, and associated with the Claim Canyon caldera and other caldera boundaries. The significances of the corridor (shown by shading), gravity gradient, and inferred pre-Tertiary rocks are discussed in the section on hydrogeologic implications. Hydrologic information is from O'Hagan and Laczniak (1996).

Between the inferred WNW.-trending structure and the Timber Mountain resurgent intrusion is a gravity gradient that generally trends east-west near the projected northwestern topographic margin of the Rainier Mesa caldera (fig. 11). The gradient reflects a subtle, but abrupt, change in subsurface density that may be related to differences in rocks across the topographic wall of the Rainier Mesa or Ammonia Tanks calderas, or across the structural margin of the Rainier Mesa or older caldera. From geologic inference, caldera margins should be present in this area, but they are not exposed.

The NNE.-trending structures along the western margins of the major caldera complexes (fig. 11) are probably related to each other and to caldera formation, as discussed previously in the section on the Timber Mountain domain. In particular, the structure that is expressed in the gravity data is coincident with caldera margins (14/SCC compared to fig. 7) and with the water-level discontinuity in the northwestern part of the Nevada Test Site (fig. 11), both of which are known from drill-hole data and hydrologic pump tests. Such coincident features suggest that the structure extends to the southwest, where it could also produce water-level discontinuities.

The structures bounding Oasis Valley basin include the inferred north-striking Hogback and east-striking Hot Springs faults (fig. 11) that compose the western boundary of the Timber Mountain domain. The gravity data indicate that the domain boundary here represents the interface between a subsurface composed primarily of pre-Tertiary sedimentary rocks on the west and south and primarily low- to moderate-density Tertiary rocks in Oasis Valley basin (fig. 11). The gravity information alone cannot distinguish pre-Tertiary confining units from carbonate aquifers. However, quartzite exposed near Oasis Mountain (Laczniak and others, 1996) and in the northern Bullfrog Hills (Minor and others, 1997) adds evidence that the pre-Tertiary sedimentary rocks west of the Hogback fault are likely composed mainly of the quartzite confining unit rather than carbonate aquifers. Thus, the Hogback fault probably acts as a barrier to ground water flowing westward from the Timber Mountain domain. No additional evidence on the composition of pre-Tertiary rocks in the shallow subsurface between the Hot Springs fault and Bare Mountain is available. If the pre-Tertiary rocks in this area are composed primarily of confining units, the Hot Springs fault could also represent a barrier. A barrier at the Hot Springs fault could explain the presence of springs along the east side of Oasis Mountain in Oasis Valley discharge area (figs. 6, 11). Ground water flowing southward in Oasis Valley basin might be diverted to the west by the Hot Springs fault and forced up the moderately dipping Hogback fault.

The configuration of the geophysical features that have potential hydrogeologic importance (fig. 11) supports the hypothesis of O'Hagan and Laczniak (1996) and the results of more recent hydrologic modeling (U.S. Department of Energy, 1997) that regional ground-water flow from the area of underground testing at Pahute Mesa follows a path southwestward to Oasis Valley discharge area. In particular, there is no geophysical nor geologic evidence for a significant change in subsurface physical properties within a corridor (shading on fig. 11) extending from the northwestern corner of the Rainier Mesa caldera to Oasis Valley basin.

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