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GEOLOGIC MAP OF THE PAINTBRUSH CANYON AREA, YUCCA MOUNTAIN, NEVADA

U.S. GEOLOGICAL SURVEY

Open-File Report 97–783

MASTER

Prepared in cooperation with the
NEVADA OPERATIONS OFFICE,
U.S. DEPARTMENT OF ENERGY, under
Interagency Agreement DE–AI08–97NV12033

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Geologic Map of the Paintbrush Canyon Area, Yucca Mountain, Nevada

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Denver, Colorado
1998

U.S. DEPARTMENT OF THE INTERIOR
BRUCE BABBITT, Secretary

U.S. GEOLOGICAL SURVEY
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[Plates are in pocket]

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CONVERSION FACTORS

Multiply	By	To obtain
inch	0.03937	millimeter (mm)
inch	0.3937	centimeter (cm)
foot	3.281	meter (m)
mile	0.6214	kilometer (km)

The following terms and abbreviations also are used in the report.

Ma millions of years before present
m.y. million years

Geologic Map of the Paintbrush Canyon Area, Yucca Mountain, Nevada

By Robert P. Dickerson *and* Ronald M. Drake II

Abstract

This geologic map is produced to support site characterization studies of Yucca Mountain, Nevada, site of a potential nuclear waste storage facility. The area encompassed by this map lies between Yucca Wash and Fortymile Canyon, northeast of Yucca Mountain. It is on the southern flank of the Timber Mountain caldera complex within the southwest Nevada volcanic field.

Miocene tuffs and lavas of the Calico Hills Formation, the Paintbrush Group, and the Timber Mountain Group crop out in the area of this map. The Calico Hills Formation is composed of nonwelded pyroclastic flow and fallout deposits, lava flows, and fused tuffs, the buried source of which is likely located in Fortymile Wash. The proximal facies of the voluminous Paintbrush Group pyroclastic flow deposits that compose Yucca Mountain crop out within the mapped area; these include the Topopah Spring Tuff, the Pah Canyon Tuff, and the Tiva Canyon Tuff. The source of these tuffs probably was the Timber Mountain caldera complex north of the map area. Numerous Paintbrush Group tuff cones and lava domes adjacent to the caldera complex also crop out within the map area; these include the rhyolite of Delirium Canyon, the rhyolite of Black Glass Canyon, the rhyolite of Vent Pass, and the rhyolite of Comb Peak. Similar tuff cones and lava domes of the Timber Mountain Group also crop out within the map area and include the rhyolite of Waterpipe Butte and the rhyolite of Pinnacles Ridge. The source vents of the tuff cones and lava domes commonly are located beneath the thickest deposits of pyroclastic ejecta and lava flows. The thickness of fused tuff beneath the lava domes is typically greatest adjacent to the source vents for the tuffs and lavas. Source vents for the rhyolites of Delirium Canyon, Black Glass Canyon, Vent Pass, and Comb Peak are located within the mapped area.

The rocks within the mapped area have been deformed by north- and northwest-striking, dominantly west-dipping normal faults and a few east-dipping normal faults. Vertical separation across faults increases towards the south. Faults commonly are characterized by well developed fault scarps, thick breccia zones, and hanging-wall grabens. Latest movement as preserved by slickensides on west-dipping fault scarps is oblique down towards the southwest. Two of these faults, the Paintbrush Canyon fault and the Bow Ridge fault, are major block-bounding faults here and to the south at Yucca Mountain. Offset of stratigraphic units across faults indicates that faulting occurred throughout the time these volcanic units were deposited.

INTRODUCTION

Yucca Mountain is on the southern flank of the Timber Mountain-Oasis Valley caldera complex in the southwest Nevada volcanic field. Yucca Mountain is composed of pyroclastic outflow deposits of the Paintbrush Group that originated from calderas in the Timber Mountain-Oasis Valley caldera complex. The area north of Yucca Mountain is dominated by the thin, proximal facies of these pyroclastic outflow deposits, by small volume pyroclastic flow and fallout deposits located near their source vents, and by tuff cones and lava domes adjacent to the caldera complex. These rocks exhibit greater lithologic variety, more pronounced facies changes, and larger thickness variations in a smaller region than do the pyroclastic deposits of Yucca Mountain. This map displays the geology of the region just north of Yucca Mountain, between Yucca Wash and Fortymile Wash.

Yucca Mountain, located at the Nevada Test Site, is the site designated for study as a potential repository for high-level radioactive waste. Geologic maps are one of the primary data sets for site characterization studies. The geologic map of the Paintbrush Canyon area was completed using the appropriate technical procedures to support the development of regional tectonic models and three-dimensional geologic models for the U.S. Geological Survey Yucca Mountain project.

Christiansen and Lipman (1965) completed the early geologic mapping of the Paintbrush Canyon area (fig. 1). The major volcanic formations were defined and the significant structures were mapped at a scale of 1:24,000 (fig. 2). Scott and Bonk (1984) completed a later phase of mapping at a scale of 1:12,000 for Yucca Mountain and part of the Paintbrush Canyon and Yucca Wash area. This more detailed mapping identified smaller faults that display only modest amounts of offset. The present geologic map of the Paintbrush Canyon area was completed at a scale of 1:6,000 and expands on the structural and stratigraphic detail of earlier geologic maps.

STRATIGRAPHIC RELATIONS

The stratigraphic framework of the southwest Nevada volcanic field has been established and refined by numerous workers (Lipman and others, 1966; Byers and others, 1976b; Carr and others, 1986; Byers and others, 1989; Ferguson and others, 1994; Sawyer and others, 1994). The stratigraphy of the Yucca Mountain region was refined more recently by Moyer and Geslin (1995), Buesch and others (1996), and Moyer and others (1996). The stratigraphic nomenclature used here is modified from Ferguson and others (1994), Sawyer and others (1994), and Buesch and others (1996).

Some of the geologic contacts shown on this map are more uncertain than other contacts. The contacts between the voluminous pyroclastic flow deposits are usually distinct, though locally they are obscure. The contacts between and within the tephra cones and lava domes may be indistinct because of fusing (sintering) of tuffs beneath thick lava flows (Christiansen and Lipman, 1966) and because devitrification of both the densely fused tuffs and lava flows causes these lithologies to look the same. The upper and lower contacts of lava flows locally exhibit a vitrophyre and/or a carapace of autoclastic flow-breccia. Where the rhyolite lava flow of one formation overlies that of a similar formation the contact can be exceedingly difficult to identify. Despite these uncertainties, most contacts portrayed on this map are accurate to within 1 or 2 meters.

Calico Hills Formation

The oldest rocks exposed within the mapped area are the pyroclastic rocks and lava flows of the Calico Hills Formation (12.9 Ma, Sawyer and others, 1994). The Calico Hills Formation and the equivalent tuffs and lavas of Area 20 (Warren, 1983) represent volcanism that postdates Crater Flat Group caldera-forming volcanism and originated from source vents north and south of the Timber Mountain caldera complex (Sawyer and others, 1994). A thick sequence of lava flows (Tacl) is exposed in Fortymile Canyon in the eastern part of the mapped area, and a thick sequence of pyroclastic flow deposits is exposed near Prow Pass a kilometer west of the mapped area. In upper Paintbrush Canyon in the north-central part of the mapped area the Calico Hills Formation is well exposed and encompasses five separate lava flow-bearing horizons intercalated with massive (Tacm) and bedded (Tact) pyroclastic flow, fallout, and surge deposits. The upper contacts of the lava flows locally are obscure because of the similarity between the devitrified and hydrothermally altered (zeolitized) autoclastic lava flow-breccia and the blocky, zeolitized massive tuff. Most of the lava flow-bearing horizons contain a single lava flow. Lava flows compose the lowest and highest stratigraphic horizons within the Calico Hills Formation in upper Paintbrush Canyon. The third lava flow-bearing horizon from the bottom contains two separate lava flows, and one of these lava flows is a composite flow of at least two individual

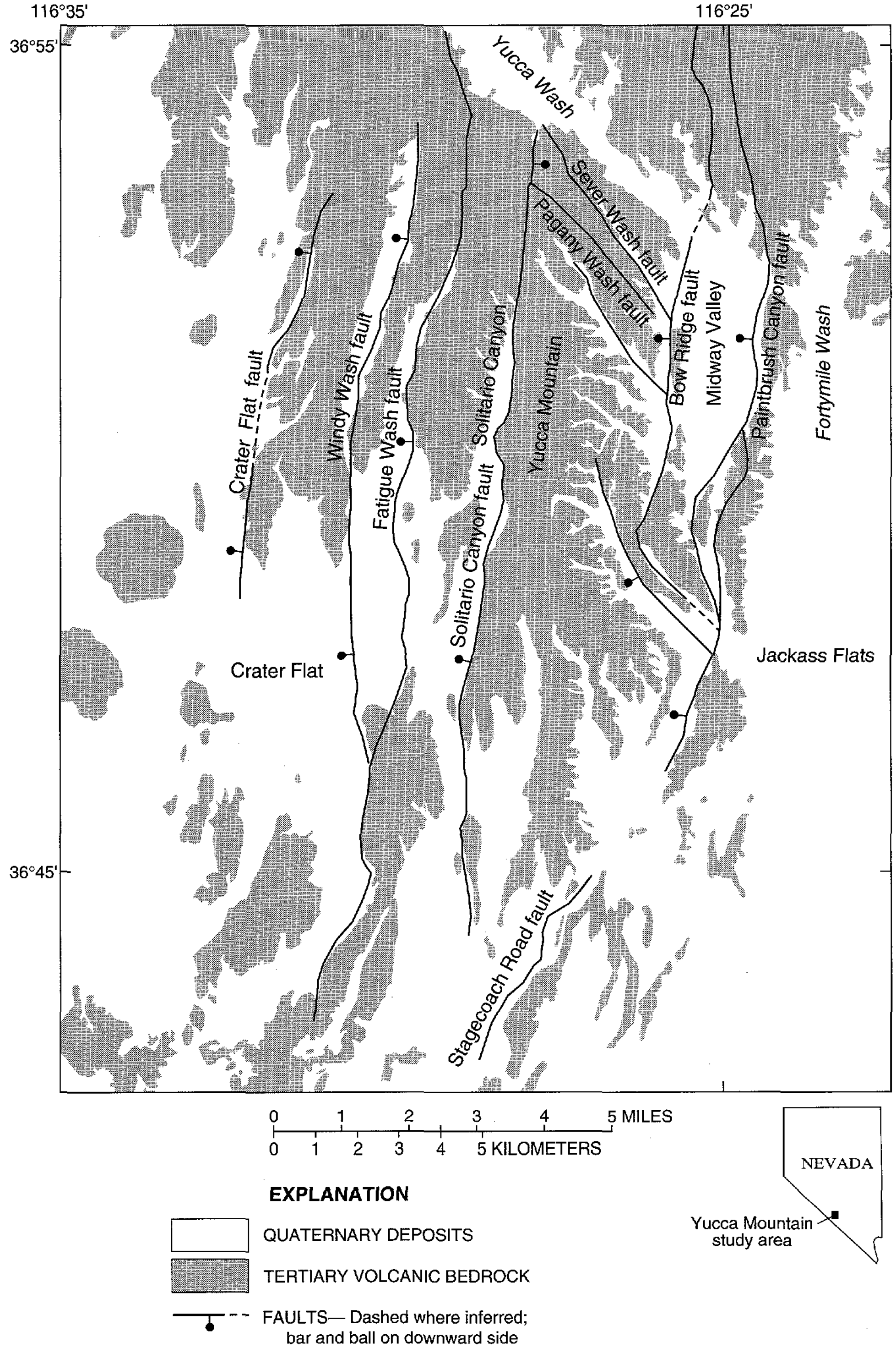

Figure 1. Location of study area and local features.

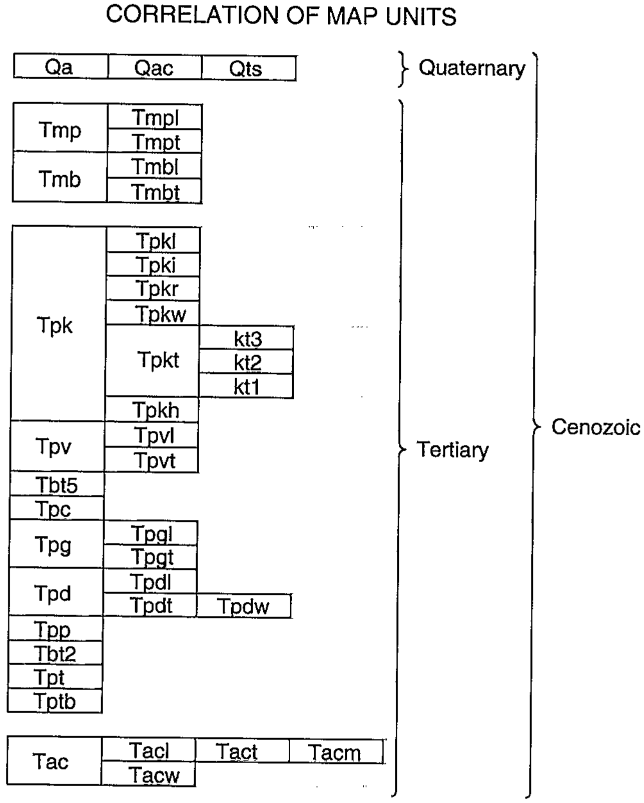

Figure 2. Correlation of map units.

lava flows partly separated by a thin, discontinuous pyroclastic deposit. Between the two lowest lava flows, there is a thick sequence of bedded tuffs that contains one major and several minor angular unconformities (Buesch and Dickerson, 1993a and 1993b). Moyer and Geslin (1995) have noted seven stratigraphic horizons including five separate pyroclastic flow units within the Calico Hills Formation in outcrops at Busted Butte, 14 kilometers south of upper Paintbrush Canyon. These five pyroclastic deposits at Busted Butte are the distal facies of pyroclastic flows and may correlate to the five lava flow-bearing horizons in upper Paintbrush Canyon (Moyer and Geslin, 1995). Each of the five lava flows in Paintbrush Canyon may be related to the subjacent pyroclastic deposits, indicating a repeated pattern of violent eruption of volatile-rich magma that forms pyroclastic deposits, followed by more sedate eruption of volatile-poor magma that forms lava flows. At least one of these eruptive cycles coincided with other tectonic activity that formed an angular unconformity. The prominent angular unconformity of 10° of discordance observed in the bedded tuffs in upper Paintbrush Canyon can be correlated to a similar angular unconformity in the same stratigraphic position north of Comb Peak.

The only welded tuffs known to exist within the Calico Hills Formation are found in Fortymile Canyon (Dickerson and Hunter, 1994). This welded tuff lies beneath a lava flow and may represent a fused tuff. Part of this fused tuff contains a megabreccia with clasts as large as 3 to 4 m. This is the only known megabreccia of Calico Hills Formation rocks within the map area. Studies have shown that fused tuff beneath lava flows may indicate proximity to eruptive vents (Dickerson and Drake, 1995). The fused tuff and megabreccia within Fortymile Canyon is consistent with the location of a source vent for the Calico Hills Formation tuffs and lavas in Fortymile Canyon. There are probably other source vents for Calico Hills Formation tuffs and lavas as well, such as in the Calico Hills and possibly in upper Yucca Wash. The thick sequence of lava flows in Fortymile Canyon thins westward toward Paintbrush Canyon to the five separate lava flows intercalated within the thick sequence of pyroclastic rocks. Further west at Prow Pass and in upper Yucca Wash the Calico Hills Formation is dominated by pyroclastic rocks in the upper part of the formation and by lava flows in the lower part of the formation. Borehole data (Lobmeyer and others, 1983; Maldonado and Koether, 1983; Rush and others, 1984; Muller and Kibler, 1986) show Calico Hills lavas thinning to the south beneath Yucca Mountain and pinching out altogether in the vicinity of Drill Hole Wash. Geologic data from the Calico Hills area (F.W. Simonds, U.S. Geological Survey, written commun., 1980) indicate that both lava flows and pyroclastic rocks are thickest in the northwestern part of the Calico Hills, adjacent to Fortymile Canyon, and they thin to the east and south. Isochore data and facies relations within the Calico Hills Formation tuffs beneath Yucca Mountain indicate thickening of tuffs to the north of Yucca Mountain (Moyer and Geslin, 1995). This internal geometry of the Calico Hills Formation is consistent with an eruptive source in the Fortymile Canyon area and possibly another one in upper Yucca Wash, with lava flows thinning to the southwest, south, and east, and pyroclastic rocks dominating the formation away from the proposed eruptive centers. Moyer and Geslin (1995) suggest that the deposition and thickness of the Calico Hills Formation was controlled in part by a south-striking paleovalley located on the eastern edge of Yucca Mountain.

Topopah Spring Tuff

Within the region of the map, the Topopah Spring Tuff (Tpt) lies directly upon rocks of the Calico Hills Formation and has been dated at 12.8 Ma using the $^{40}Ar/^{39}Ar$ method (Sawyer and others, 1994). The internal stratigraphy of the Topopah Spring Tuff at Yucca Mountain is based on lithophysal-bearing zones in the crystal-poor rhyolite member and on the pumice-bearing zones within the crystal-rich quartz latite member (Buesch and others, 1996). These subunits are poorly developed or not present at all within the Topopah Spring Tuff in the region north of Yucca Wash. However, the lowest portion of the Topopah Spring Tuff, a lithic-rich tuff breccia, forms a mappable unit (Tptb) not found further south at Yucca Mountain. Deposits of this lithic-rich, poorly-sorted pyroclastic flow deposit are thickest in the Fortymile Canyon and the Black Glass Canyon areas where it fills paleovalleys eroded into Calico Hills Formation rocks; thinner deposits exist in Paintbrush Canyon and west of Black Glass Canyon. The lithic-rich tuff breccia at the base of the Topopah Spring Tuff likely results from a violently explosive eruption that cleared the vent immediately prior to the eruption of the bulk of the Topopah Spring Tuff. Such a deposit would contain a high percentage of lithic clasts and would fill paleotopographic depressions.

Within the map the Topopah Spring Tuff is thinnest in upper Paintbrush Canyon (1 to 2 m) and upper Black Glass Canyon (12 m) and increases in thickness to the southeast (83.7 m), south (96.6 m), and southwest (69.2 m) (R.W. Spengler, U.S. Geological Survey, written commun., 1995). The welded part of the Topopah Spring Tuff has a more tabular geometry than the basal lithic-rich tuff breccia and does not exhibit the dramatic local changes in thickness that result from the underlying paleotopography in the way that the lithic-rich tuff breccia does. Previous workers (Byers and others, 1976b) have suggested that the Topopah Spring Tuff is related to the Claim Canyon caldera. Sawyer and others (1994) indicate that the Claim Canyon caldera is related to the Tiva Canyon Tuff. The facies relations and thickness distribution of the Topopah Spring Tuff indicates a source caldera in the same general vicinity as the Claim Canyon caldera. The thinning of this pyroclastic flow deposit in the direction of the Claim Canyon caldera rim in upper Paintbrush and Black Glass Canyons, and the increase in number and size of lithic clasts within both the lithic-rich tuff breccia and the Topopah Spring Tuff support this hypothesis. The Topopah Spring Tuff increases in thickness from 69.2 m thick 1 km north of Yucca Wash to 287 m thick 1 km south of Yucca Wash (Maldonado and Koether, 1983). The change in thickness of the Topopah Spring Tuff across Yucca Wash likely results from the onlap of this pyroclastic outflow deposit onto a thick pile of Calico Hills Formation tuffs and lavas to the north, and the filling in of the paleo-Crater Flat basin to the south (Fridrich, in press).

The overlying bedded tuff (Tbt2) is a thin but distinctive light gray, ledge-forming nonwelded tuff that is easy to identify in the field. Although the lower part of Tbt2 is probably the nonwelded top of the pyroclastic flow deposit and the uppermost fallout deposit associated with the underlying Topopah Spring Tuff, this unit has been mapped separately because it forms a distinctive marker bed useful in defining structural offset. The bedded tuff within the upper part of Tbt2 exists only intermittently within the map area. Tuff Tbt2 is about 1 m thick throughout the mapped area but thickens to 3 m on northeast side of Yucca Wash.

Pah Canyon Tuff

A complete section of the Pah Canyon Tuff (Tpp) is exposed adjacent to Yucca Wash north of Isolation Ridge. At this location the Pah Canyon Tuff is composed of, in ascending order, a lower, 5- to 10-m-thick, light gray, nonwelded tuff, a middle, 15- to 25-m-thick, light grayish-brown, partly to densely welded tuff that grades upward into an orange, moderately welded tuff, and an upper, 10- to 15-m-thick, light gray to lavender, nonwelded, pumiceous tuff. The differences in welding characteristics and pumice content between the lower, middle, and upper units indicate that the Pah Canyon Tuff is a compound eruptive unit composed of several pyroclastic flows (Moyer and others, 1996). At Yucca Mountain south of the map the Pah Canyon Tuff is a simple cooling unit (Moyer and others, 1996), and west of the map area it is a compound cooling unit (C.J. Fridrich, U.S. Geological Survey, written commun.,1996). Throughout most of the area of this map, the data are equivocal, but the Pah Canyon Tuff appears to be a simple cooling unit. However, on the north side of Yucca Wash there is a cooling break associated with a thin, ashfall parting in the lower, partly- to moderately-welded tuff. A similar cooling break at this same stratigraphic horizon also is exposed within the Pah Canyon Tuff in upper Fortymile Wash in the northeast corner of the map.

Adjacent to Yucca Wash the lower nonwelded tuff and the middle welded tuff fill a north-trending paleovalley in the subjacent Topopah Spring Tuff. Throughout the rest of the mapped area, however, the partly to moderately welded, distinct orange tuff that composes the upper half of the middle welded tuff is the dominant lithology of the Pah Canyon Tuff. In upper Paintbrush and Fortymile Canyons, this distinctive orange tuff is a cliff-former and attains its greatest thickness (33 m and 42 m, respectively). On the east side of upper Fortymile Wash the Pah Canyon Tuff exhibits a densely welded zone that is at least 25 m thick and contains a lithophysal-bearing zone similar to lithophysal zones within the Topopah Spring and Tiva Canyon Tuffs. In Paintbrush and Fortymile Canyons the orange Pah Canyon Tuff is deposited directly upon the rocks of the Calico Hills Formation and contains a distinct 1- to 3-m-thick lithic-rich horizon at its base. This same orange tuff maintains a thickness of at least 20 m to the southwest in the direction of northern Isolation Ridge, but thins to the south to about 10 m in the vicinity of Alice Point. In upper Paintbrush and Fortymile Canyons, the upper, light-gray to lavender, nonwelded tuff and the lower light-gray, nonwelded tuff are very thin or absent altogether, but they are present as thin, slope-forming deposits in lower Paintbrush Canyon and lower Black Glass Canyon. The lower nonwelded tuff thickens to the south and southwest within the map area, whereas the upper nonwelded tuff thickens mostly to the southwest.

Sawyer and others (1994) were uncertain as to the source of the Pah Canyon Tuff, but Byers and others (1976b) located it in the Claim Canyon caldera area. The thickness and facies relations indicate a source north of the map in the region of the Claim Canyon Caldera. Thickness and distribution of the various pyroclastic flow units that form the Pah Canyon Tuff within the map are strongly affected by paleotopography. Thickness maps of the Pah Canyon Tuff (Buesch and others, 1996; Moyer and others, 1996) indicate that regionally the formation thins to the south, pinching out near Split Wash at Yucca Mountain.

Rhyolite of Delirium Canyon Tuff and Tuff Tpbt3

Within the area of this map, there is a thick nonwelded tuff between the Pah Canyon Tuff (Tpp) and the Tiva Canyon Tuff (Tpc) that is not part of the Yucca Mountain Tuff. South of Yucca Wash, the Yucca Mountain Tuff and tuff Tpbt3E of Moyer and others (1996) occupy this stratigraphic position. North of Yucca Wash, the tuff in this stratigraphic position is a nonwelded to partly welded pyroclastic flow deposit that forms tan colored bluffs, cliffs, and steep slopes in Paintbrush Canyon, in Black Glass Canyon, and in Yucca Wash. This tuff is well indurated, devitrified, lithic-rich, and moderately well sorted. Lithic and pumice clasts are matrix supported. Within the lower two-thirds of this tuff, lithic clasts predominate over pumice clasts. The size of the clasts does not vary greatly vertically, but there is a subtle increase in size of lithic clasts towards the northeast. There are numerous individual horizons that are locally lithic-rich or pumice-rich within this tuff. Within the region north of Yucca Wash, this tuff is laterally persistent and largely unvarying, exhibiting few of the facies changes common to other tuffs within the Paintbrush Group. However, in upper Fortymile Canyon this tuff becomes very thick, and the lithic clasts become quite coarse grained. The greatest change within this stratigraphic interval exists across Yucca Wash. South of Yucca Wash tuff Tpbt3E of Moyer and others (1996) is not well indurated, is light gray, vitric, contains sparse lithic clasts but more and larger pumice clasts, and the pumice clasts increase in size upward. Near the top, tuff Tpbt3E is so pumiceous as to be nearly clast-supported. North of Yucca Wash, the tuff looks very similar in color, welding, devitrification, and lithic and pumice clast content to the tuff of the rhyolite of Delirium Canyon in Fortymile Wash, but tuff Tpbt3E does not. South of Yucca Wash, tuff Tpbt3E is laterally very persistent throughout the northern Yucca Mountain area, attaining a maximum thickness of 43 m in upper Yucca Wash. Neither tuff Tpbt3E nor the Yucca Mountain Tuff has been recognized north of Yucca Wash.

Broxton and others (1993) have developed petrographic and chemical data from samples of nonwelded tuffs collected above the Pah Canyon Tuff south of Yucca Wash that indicate some of these pyroclastic flow deposits are correlative with both the rhyolite of Delirium Canyon and the rhyolite of Black

Glass Canyon. Internal facies changes are subtle within the tan tuff overlying the Pah Canyon Tuff north of Yucca Wash, but the increase in lithic clast size towards the northeast indicates a source in that direction. The similarity in stratigraphic position of this tuff in Yucca Wash, Black Glass Canyon, and Paintbrush Canyon with the stratigraphic position of the tuffs of the rhyolite of Delirium Canyon in Fortymile Wash and upper Paintbrush Canyon indicates this tuff probably is part of the rhyolite of Delirium Canyon. This correlation is supported by the lithologic similarities between these two tuffs. The source vent of the rhyolite of Delirium Canyon is located in Fortymile Canyon. In conclusion, the tuff north of Yucca Wash is correlative with the tuffs of the rhyolite of Delirium Canyon (Tpdt), and tuff Tpbt3E south of Yucca Wash is a different deposit.

Within the map area tuff Tpdt is about 43 m thick in upper Paintbrush Canyon, less than 20 m thick in lower Paintbrush Canyon, 62 m thick west of Black Glass Canyon and in Yucca Wash, and variably 60 to 90 m thick in Fortymile Canyon, defining a southward thinning pyroclastic flow deposit that extends much further south and west than the overlying lava flows.

Rhyolite of Delirium Canyon-Lava Dome

In the northeast corner of the mapped area, a lava dome of the rhyolite of Delirium Canyon forms the mountain northeast of Comb Peak. The rhyolite of Delirium Canyon has been dated using K/Ar isotopic methods at 12.6 Ma (Warren and others, 1988), but regional stratigraphic relations indicate that it is younger than the Pah Canyon Tuff and older than the 12.7 Ma Tiva Canyon Tuff and the rhyolite of Black Glass Canyon (Ferguson and others, 1994). Rhyolite of Delirium Canyon tuff (Tpdt) lies beneath the rhyolite of Black Glass Canyon tuff; however, field relations do not show if this tuff is older or younger than the Yucca Mountain Tuff.

The rhyolite of Delirium Canyon forms a stratigraphic sequence similar to the rhyolite of Comb Peak, where a thick pyroclastic deposit is overlain by a thick lava flow deposit (Tpdl). The tuffs associated with the rhyolite of Delirium Canyon are 15 to 91 m thick and composed of welded (Tpdw) and nonwelded (Tpdt) pyroclastic flow deposits. In a tributary to Fortymile Canyon in the very northeast corner of the map, there are at least three welded tuffs of limited lateral extent within a sequence of nonwelded tuff, and in Fortymile Canyon there are two welded tuffs of limited lateral extent. These welded tuffs of limited lateral extent may represent local, small volume but very hot pyroclastic eruptions that deposited material close to the source vent. These tuffs are overlain by as much as 250 m of rhyolitic lava. The rhyolitic lava of Delirium Canyon is underlain everywhere by fused or welded pyroclastic rocks 6 to 60 m thick. These fused tuffs may represent pyroclastic rocks fused by the heat of the overlying lava flows, as demonstrated at Comb Peak (Chistiansen and Lipman, 1966; Dickerson and Drake, 1995), or they may represent normal welded tuffs.

Delirium Canyon east of the mapped area exposes 150 m of pyroclastic rocks that are overlain by as much as 290 m of rhyolitic lavas (Orkild and O'Conner, 1970). The thickness and areal extent of both the tuffs and lavas of this unit indicate the source vent for the rhyolite of Delirium Canyon is in the vicinity of Delirium Canyon. However, the thick deposit of tuff and lava northeast of Comb Peak indicates that a second vent probably exists beneath this lava dome. Locally, there are subtle differences in pumice content in the tuff beneath the lava dome on the west side of Fortymile Canyon relative to the tuff beneath the lava dome on the east side of Fortymile Canyon. Geophysical data support the interpretation of a second vent. Aeromagnetic data (McCafferty and Grauch, 1997) show a very large-magnitude magnetic low centered directly on this dome, but it does not extend north or eastward to where thinner deposits of the rhyolite of Delirium Canyon crop out.

Rhyolite of Black Glass Canyon

The rhyolite of Black Glass Canyon is composed of pyroclastic deposits (Tpgt) overlain by lava flows (Tpgl). However, the outcrop exposures of this unit are limited to one area in Black Glass Canyon, making it the most areally restricted unit on the map. The precise stratigraphic and regional relations of this unit within the Paintbrush Group are difficult to determine. The basal tuff of the rhyolite of Black Glass Canyon is deposited upon the tuff of the rhyolite of Delirium Canyon with no angular discordance, the contact between these two tuffs being fairly easy to identify and map in Black Glass Canyon. Near this same location the Tiva Canyon Tuff also lies upon the tuff of the rhyolite of Delirium Canyon. Locally the rhyolite of Black Glass Canyon is in fault contact with the Tiva Canyon Tuff, but the fault itself does not yield any data about relative direction of offset. Hence, there is no direct field evidence to determine the stratigraphic relation between the rhyolite of Black Glass Canyon and the Tiva Canyon Tuff. However, petrographic and chemical data from Broxton and others (1993) indicate that tuffs associated with the rhyolite of Black Glass Canyon lie between the subjacent rhyolite of Delirium Canyon and the superjacent Yucca Mountain Tuff in outcrops on the south side of Yucca Wash. This implies that the rhyolite of Black Glass Canyon is older than the Tiva Canyon Tuff.

Tiva Canyon Tuff

The areal distribution is more restricted within the mapped area for the Tiva Canyon Tuff (Tpc) than it is for any other volumetrically significant pyroclastic flow deposit of the Paintbrush Group. The Tiva Canyon Tuff does not extend as far north in Black Glass and Paintbrush Canyons as the Topopah Spring Tuff, the Pah Canyon Tuff, or the tuff of the rhyolite of Delirium Canyon, or as far eastward in Fortymile Canyon as the Topopah Spring Tuff and Pah Canyon Tuff. Additionally, the Tiva Canyon Tuff is thinner than the Topopah Spring Tuff in the map area and thinner than the Pah Canyon Tuff and the tuff of the rhyolite of Delirium Canyon in upper Paintbrush Canyon, in Black Glass Canyon, and in Yucca Wash. Only in the southern part of the map area, between lower Paintbrush and Fortymile Canyons, is the Tiva Canyon Tuff thicker (37 m) than the Pah Canyon Tuff (18 m) or the tuff of the rhyolite of Delirium Canyon (19 m).

The internal stratigraphy of the Tiva Canyon Tuff at Yucca Mountain is based on lithophysal-bearing zones in the crystal-poor rhyolite member, and on pumice-bearing zones in the crystal-rich quartz latite member (Buesch and others, 1996). These zones are poorly developed or not present within the Tiva Canyon Tuff in the area north of Yucca Wash. Where the Tiva Canyon Tuff is thickest within the mapped area, it is composed of a crystal-poor lower nonlithophysal zone, and a crystal-poor lithophysal zone that grades upwards into the crystal-rich transition zone, a crystal-rich mixed pumice zone, and a crystal-rich pumice-poor zone.

To clarify the details of Tiva Canyon Tuff stratigraphy, the lithologies recognized within the Tiva Canyon Tuff for the region north of Yucca Wash are discussed below in terms used to describe them south of Yucca Wash (Day and others, in press). A common marker bed at the base of the Tiva Canyon Tuff at Yucca Mountain is a red paleosol at the top of unit Tpbt4 described by Moyer and others (1996). In the northern part of Yucca Mountain this paleosol is overlain by a 1- to 10-cm-thick, light-gray, nonwelded, crossbedded, reversely-graded surge deposit and a light gray, vitric, tephra fallout deposit. The marker bed composed of the red paleosol and the overlying light-gray surge deposit are not found north of Yucca Wash. The light-gray, vitric, tephra fallout deposit is present only within the southern part of the map area where it is less than 1 m thick. This fallout deposit is equivalent to the lowest part of unit cpv at Yucca Mountain. The lower nonlithophysal zone is thin (less than 7 m) but contains rocks that are correlative to the crystal-poor vitric zone (unit cpv) and lower nonlithophysal zone (unit cpln) mapped at Yucca Mountain (Day and others, in press). The lithophysal zone in the map area contains rocks that are correlative at Yucca Mountain to the crystal-poor lower lithophysal zone (unit cpll) and the crystal-poor upper lithophysal zone (unit cpul) and locally contains the lithophysal-bearing lower part of the crystal-rich transition zone (unit cr1). The crystal-rich transition zone (unit cr1) is present only locally in thicknesses up to 2 m. The crystal-rich mixed pumice zone (unit cr2) is 5 m to 7 m thick, which is typical of this same zone to the south at Yucca Mountain. The crystal-rich pumice-poor zone (unit cr3) is thin (less than 1 m) and atypical in appearance (purplish brown and densely welded) compared to this same zone at Yucca Mountain where it is red and moderately welded. A thin (less than 1 m thick), partly welded, partly vitric caprock (possibly correlative to unit cr4) is present locally in the southern part of the map area.

The source for the Tiva Canyon Tuff was the Claim Canyon caldera (Byers and others, 1976b, Sawyer and others, 1994). Tiva Canyon Tuff has been dated at 12.7 Ma using the $^{40}Ar/Ar^{39}$ method (Sawyer and others, 1994). In the map area the Tiva Canyon Tuff was deposited upon a volcanic rampart composed of older Paintbrush Group rocks adjacent to the caldera complex. The Tiva Canyon Tuff thickens southward into the Crater Flat basin, and extends nearly as far south and east as the Topopah Spring Tuff

(Bentley and others, 1983; Byers and others, 1976b; Fridrich, in press; Maldonado and Koether, 1983; Thordarson and others, 1984).

Rhyolite of Vent Pass

The rhyolite of Vent Pass crops out as lava flows (Tpvl) and basal pyroclastic deposits (Tpvt) in the northern part of the map. Field relations indicate that the rhyolite of Vent Pass is younger than the Tiva Canyon Tuff and older than rocks of the Timber Mountain Group. The rhyolite of Vent Pass is distributed beneath the rhyolite of Pinnacles Ridge north of Yucca Wash from upper Paintbrush Canyon on the east to upper Yucca Wash on the west (Christiansen and Lipman, 1965). The lava flows of the rhyolite of Vent Pass are characterized by extensive development of spherulites and secondary silica. The rhyolite of Vent Pass lava flow contains a basal autoclastic flow breccia, and the underlying pyroclastic deposits characteristically exhibit a fused zone where they contact the overlying lava flow. The fused tuff is thickest on the ridge between upper Paintbrush Canyon and upper Black Glass Canyon. A vitrophyre, either within the base of the lava flow, within the top of the fused tuff, or containing both the base of the lava flow and the top of the fused tuff is common for the rhyolite of Vent Pass, and only locally is the vitrophyre absent. The tuffs of the rhyolite of Vent Pass look very similar to those of the Calico Hills Formation, and it is difficult to discriminate between the two based on lithologic criteria. In areas where tuffs of the rhyolite of Vent Pass overlie tuffs of the Calico Hills Formation, the contact must be traced in from adjacent areas where it is characterized by gentle angular discordance.

Tuffs and lavas of the rhyolite of Vent Pass are adjacent to the rhyolite of Comb Peak in Paintbrush and Black Glass Canyons (Christiansen and Lipman, 1965) and stratigraphically occupy a similar position within the Paintbrush Group rocks in the area north of Yucca Wash. Ferguson and others (1994) indicate that the rhyolite of Vent Pass is stratigraphically subjacent to the rhyolite of Comb Peak, but the field relations are equivocal concerning the relative ages of these two rhyolites. Petrographic and chemical data demonstrate that these two lavas are quite similar (R. Warren, Los Alamos National Laboratory, written commun. 1995), but the pyroclastic deposits are distinct. The temporal, spatial, and compositional similarities between these two units may indicate a possible common genesis from the same source magma and temporally related eruptions, although the two rhyolites remain separate stratigraphic units.

Rhyolite of Comb Peak

The rhyolite of Comb Peak is the youngest unit in the Paintbrush Group (Ferguson and others, 1994). It is mapped here in great detail because the map contains nearly all of the known outcrops of the rhyolite of Comb Peak and because it composes nearly 50 percent of all exposed bedrock within the map area. The rhyolite of Comb Peak forms one of several tuff cone-lava dome features exposed in the map area; others include the rhyolite of Delirium Canyon, the rhyolite of Vent Pass, the rhyolite of Waterpipe Butte, and the rhyolite of Pinnacles Ridge. Within the region of this map, however, the rhyolite of Comb Peak is the most completely developed and best exposed example of a tuff cone and related pyroclastic outflow deposits overlain by a lava dome (Dickerson and Drake, 1995).

Comb Peak itself is composed of a thick deposit of tuff (Tpkt) overlain by a thick deposit of rhyolite lavas (Tpkl). The tuff at Comb Peak exceeds 225 m in thickness, and thins to 90 m thick 1 km to the east and to 30 m thick 3 km to the south. A distinctive, lithic-rich horizon containing 2–3 m lithic blocks marks the base of the pyroclastic deposits. The overlying tuff forms the proximal facies of pyroclastic flow deposits within which are local, discontinuous, poorly-sorted beds of lithic clasts as large as 2 m. The lithic-rich layers, including the basal lithic-rich horizon, decrease in thickness and in lithic clast size to the south and east away from Comb Peak. Locally there are portions of the vertical to steeply inward-dipping crater rim preserved on the north, east, and south sides of Comb Peak. Near the crater rim, bedding planes within the tuff at Comb Peak dip inward toward the crater; farther out from the rim they dip outward (Dickerson and Drake, 1995).

At Comb Peak the pyroclastic deposits are overlain by as much as 230 m of rhyolitic lava flows that exhibit contorted flow-banding throughout and locally contain a basal autoclastic breccia. There are small-volume lava flows and at least one vitric intrusion (Tpki) contained within the pyroclastic deposits on the eastern side of Comb Peak. The small-volume lava flows are surrounded by a carapace of autoclastic breccia and exhibit cooling fractures oriented normal to the surface of the lava flow (Dickerson and Drake, 1995). The intrusion is surrounded by the halo of thermally altered tuff that results from incipient contact metamorphism. The intrusion also exhibits a flow lineation in the rhyolite vitrophyre that is parallel to the sides of the intrusion but exits the side of Comb Peak at an angle of 30 degrees from horizontal. On the southeast ridge of Comb Peak there is a jagged spine of rock with vertically oriented flow foliations that are indicative of a feeder dike for the rhyolite lava flows. These field relations are consistent with a source vent for the rhyolite of Comb Peak located beneath Comb Peak itself. This interpretation is supported by aeromagnetic data from McCafferty and Grauch (1997), which show a magnetic low centered over the part of Comb Peak inferred to be the vent.

At Comb Peak the pyroclastic deposits are nonwelded at the base and grade upward into partly fused to densely fused tuff (Tpkw). This change involves a gradual loss of visible porosity, an increase in density, and a change from undeformed pumice to flattened pumice with a flattening ratio of 6:1. The upper portions of the densely fused tuffs have been devitrified. At Yucca Mountain the welding zones of all the welded tuffs are roughly parallel to the flow boundaries of these deposits. However, the fused zone of the tuff at Comb Peak crosscuts bedding within the tuff, but is parallel to the contact with the overlying lava flow. Additionally, the degree of fusing increases with proximity to the contact with the overlying lava flow. Comb Peak is the model for the fusing (sintering) of pyroclastic deposits from the heat of overlying lava flows (Christiansen and Lipman, 1966), and this relation is confirmed by field observations of the rhyolite of Comb Peak throughout the map area. The thickness of the fused zone beneath the lava flow decreases from 205 m at Comb Peak to as thin as 1 to 2 m, 3 km to the southwest in Yucca Wash. The relative thickness of fused tuffs beneath lava flows can be used as an indicator of relative distance from a source vent for the superjacent lava flow.

The fused tuff at Comb Peak exhibits flattened pumice derived from heating and compaction described above on the northwest, north, east, and south sides of the peak. However, on the southwest side of Comb Peak, the densely fused tuff near the base of the lava flows exhibit extreme pumice deformation (flattening ratios of 20:1 interpreted here as resulting from shear), as well as a parallel flow foliation and lineation similar to and parallel with the flow foliation of the overlying lava flows. These textures indicate that this tuff was locally remobilized (Chapin and Lowell, 1979; Henry and Wolff, 1992) and is interpreted here to be a local rheomorphic tuff (Tpkr) within the tuff cone sequence. The lava flows of the rhyolite of Comb Peak are distributed to the south and southwest of the source vent at Comb Peak. The rheomorphic tuff was presumably fused by the heat from the overlying lava flow and subsequently sheared and partially remobilized by the southwestward flow of this lava.

The rhyolite of Comb Peak contains pyroclastic flow deposits in addition to those composing the tuff cone at Comb Peak. Three separate pyroclastic flow deposits are identified on the ridge southwest of Comb Peak. Here the rhyolite of Comb Peak tuff is composed of a lower nonwelded pyroclastic flow deposit (kt1), a middle partly to moderately welded pyroclastic flow deposit (kt2), and an upper nonwelded pyroclastic flow deposit (kt3). The middle welded tuff is the thickest and most widespread of these three tuffs, cropping out on the north side of Yucca Wash 3.5 km to the south and southwest of Comb Peak. The upper and lower light-gray nonwelded pyroclastic flow deposits are areally more restricted in the map area. However, 6.5 km to the south, in trenches and boreholes adjacent to Exile Hill and in the north portal of the Exploratory Studies Facilities (ESF) at Yucca Mountain, tuff X was identified and tentatively correlated with the pyroclastic deposits of the rhyolite of Comb Peak (Buesch and others, 1994). Petrographic data from samples of tuff X obtained from boreholes near Exile Hill support the correlation of tuff X with one of the nonwelded pyroclastic flow deposits (kt1 or kt3) of the rhyolite of Comb Peak (R. Warren, Los Alamos National Laboratory, written commun. 1995). Tuff X was labeled "Tpki" (rhyolite of Comb Peak ignimbrite) by earlier workers (Buesch and others, 1996). However, the term ignimbrite is defined (Jackson and Bates, 1987) as ash flow rocks that were either welded or indurated by vapor-phase mineralization, neither of which describes tuff X. The label "Tpki" as used in this report follows more conventional labeling for mapped intrusive rocks than for pyroclastic rocks. This revised usage of the label "Tpki" reflects the evolving understanding of the stratigraphy at Yucca Mountain.

Lahar deposits (Tpkh) related to the rhyolite of Comb Peak exist on the lower slopes of Comb Peak in

Fortymile Canyon. The lahar deposits appear similar to portions of the underlying Calico Hills Formation, but differ chiefly in the size and content of the lithic fragments and lack zeolitic alteration. The basal contact of the lahar deposit assists in defining the paleotopographic surface at the time of emplacement.

Rhyolite of Waterpipe Butte

Tuffs and lavas of the rhyolite of Waterpipe Butte overlie the rhyolite of Delirium Canyon in the very northern part of the map, near upper Paintbrush Canyon. The rhyolite of Waterpipe Butte is part of the Timber Mountain Group and is younger than all Paintbrush Group rocks (Ferguson and others, 1994). The largest exposures of the rhyolite of Waterpipe Butte in the region are located north of the map in the mountains between Paintbrush Canyon and upper Fortymile Canyon. Here the rhyolite of Waterpipe Butte forms a large lava dome (Tmbl) as thick as 350 m underlain by basal pyroclastic deposits (Tmbt) from 3 to 50 m thick (Christiansen and Lipman, 1965). The source vent for these rocks is most likely near the center of the lava dome, about 1 km north of the map. The rhyolite of Waterpipe Butte is characterized by a higher phenocryst content than any other eruptive unit in the map area (33 percent phenocrysts as compared to 2 to 15 percent phenocrysts for all other map units except the rhyolite of Pinnacles Ridge. The high phenocryst content indicates greater heat loss from crystallization within the magma chamber prior to eruption and probable cooler eruption temperature. The cooler lavas must have exhibited more viscous flow that resulted in the unusually thick (as much as 10 m) basal autoclastic flow breccia and in the lack of fused tuffs beneath this lava flow.

Rhyolite of Pinnacles Ridge

The rhyolite of Pinnacles Ridge is part of the Timber Mountain Group and is the youngest lava dome in the map area. The lava flows of the rhyolite of Pinnacles Ridge (Tmpl) contain a distinctive phenocryst content and exhibit a pervasive parallel flow banding. Within the area of this map, the rhyolite of Pinnacles Ridge contains pyroclastic deposits (Tmpt) similar to the other lava domes in the region. The pyroclastic deposits lie beneath the lava flows and are overlain by a vitrophyre of rhyolite lava as thick as 60 m. This thick basal vitrophyre is characteristic of the rhyolite of Pinnacles Ridge within the map area. Additionally, the rhyolite of Pinnacles Ridge is one of the most voluminous lava domes in the region between Yucca Wash and Fortymile Canyon (Christiansen and Lipman, 1965). Although most of the exposures of the rhyolite of Pinnacles Ridge exist northwest of the area of this map, the regional distribution of the lava dome indicates that a likely source vent lies beneath the 1820 m high ridge west of Black Glass Canyon.

STRUCTURAL RELATIONS

Description of Mapped Faults

Previous workers have mapped the structural relations in and north of Yucca Wash in part (Scott and Bonk, 1984) or in total (Christiansen and Lipman, 1965), and other workers have compiled the geology at a more regional scale (Byers and others, 1976a; Frizzell and Shulters, 1990). The current map builds upon the previous work and is a refinement of it. Planar structural features were not mapped as faults unless vertical separation of strata or horizontal displacement of rocks could be determined from field relations or unless tectonic breccias could be identified. Consequently, there are more faults mapped within bedded tuff sequences than within lava flow sequences. It is possible that unmapped faults exist within areas dominated by rhyolite lava flows. The projection of mapped bedrock faults into areas dominated by Quaternary surficial deposits has been refined based on recent geophysical data (Langenheim and others, 1993; Langenheim and Ponce, 1994; Ponce, 1993; Ponce and others, 1993; Ponce, 1996). This geologic map and recent geophysical data (Langenheim and others, 1993; Langenheim and Ponce, 1994) refine the interpretation of possible buried structures in Yucca Wash (see discussion below).

Paintbrush Canyon Fault

The Paintbrush Canyon fault is the largest structure on the map. This fault extends for 7 km in the map area and trends southward for 12 km to its intersection with the southwest-trending Stagecoach Road fault. The combined length of the Paintbrush Canyon-Stagecoach Road fault is 32 km. Vertical separation along the Paintbrush Canyon fault has been calculated from fault-scarp attitudes and the location of marker beds in middle Paintbrush Canyon to be about 210 m. At a location 6.5 km south of middle Paintbrush Canyon, the vertical separation has been calculated from drill hole data as about 360 m (Dickerson and Spengler, 1994). North of Yucca Wash the main strand of the Paintbrush Canyon fault is exposed as a discontinuous, west-dipping fault scarp along 30 percent of its 7-km length within the map area. The dip of this fault scarp varies nonsystematically from 41 to 74 degrees to the west. Individual exposures of this scarp range from 3 to 200 m in length and from 0.3 to 4 m in height. In most places the footwall forms the exposed scarp; however, in a few places the hanging wall forms a west-dipping, east-facing, overhanging fault scarp. The fault scarp is typically characterized by either a polished planar surface with or without slickensides, or as a tabular, well indurated breccia zone with or without interior shear planes. The fault breccias are a heterogeneous mixture of both clast-supported and matrix-supported breccia. Clasts and matrix consist of poorly sorted fragments dominated by hanging-wall lithologies, ranging in shape from subrounded to angular, but most commonly subangular. Clast size ranges from a minimum of 4 mm to a maximum of 40 cm, but rarely exceeds one order of magnitude in any one location. The fault breccias are commonly cemented with silica and locally may stand out as linear ridges as high as 4 m. While the breccias themselves are cemented with silica, pedogenic calcite may locally exist as a surface coating on fault scarps or as concentrations of white caliche in surface deposits along the trace of the fault. Locally, the main strand of the Paintbrush Canyon fault is a 1- to 4-m-wide zone of polished fault planes and fault breccias. The fault zones commonly exhibit several parallel fault planes stacked like playing cards, each with a uniquely oriented set of slickenside striations. Striations on these and other surfaces along the Paintbrush Canyon fault indicate mostly left-lateral oblique-slip movement down to the southwest and locally dip-slip movement down to the west (Dickerson and Spengler, 1994).

In northern Paintbrush Canyon, numerous elongate, north-, northwest-, and west-trending grabens exist in the hanging wall of the fault. These grabens range from 30 to 180 m wide and from 135 to 900 m long. Vertical offset along the faults that define these grabens is a few meters to a few tens of meters, and slickensides indicate the movement on them was largely dip-slip. These hanging wall grabens are best exposed in the bedded tuffs of upper Paintbrush Canyon (Dickerson and Spengler, 1994). Similar structures may exist in middle and lower Paintbrush Canyon, but may be obscured by the similarity of lithologies where similar-looking rhyolitic lavas exist on both sides of the fault. Several lineaments parallel and adjacent to the Paintbrush Canyon fault were observed in rhyolitic lava flows on aerial photographs, but these could not be confirmed as faults in outcrop exposures. Hence, there may be more hanging wall deformation along the Paintbrush Canyon fault than is shown on this map. In addition to these larger grabens, there are smaller grabens located along bends in the main trace of the fault. These smaller grabens resemble the rhombic pull-apart grabens found at similar points along the Solitario Canyon fault, the Windy Wash fault, and the Bow Ridge fault in the Yucca Mountain region (O'Neill and others, 1991).

Black Glass Canyon Faults

The features described above for the Paintbrush Canyon fault are typical of most other major faults in this region. There are two faults located in Black Glass Canyon, one fault in upper Black Glass Canyon with about 36 m of vertical offset and another fault in lower Black Glass Canyon with over 100 m of vertical offset. Another north-trending fault with over 60 m of vertical offset exists in the nameless canyon south of Comb Peak. Following the Paintbrush Canyon fault, these are the largest north-trending, down-to-the-west normal faults on the map. Each of these faults exhibits some degree of hanging wall deformation, development of grabens, and multiple fault planes and fault breccia within a 1- to 4-m-wide fault zone. The fault in upper Black Glass Canyon (here called the Midway Valley fault, see discussion below) contains a pull-apart graben at a bend in the fault north of Yucca Wash. Silicification of fault breccia and of wall rock along major and minor faults is common in upper Paintbrush and Black Glass Canyons, but is less evident in other parts of the map area. One anomalous aspect of the Midway Valley fault in upper Black Glass Canyon is that it exhibits void-filling botryoidal silica in planar cavities within the fault zone, which is the only such open-space feature within a fault in the mapped area. The fault in lower Black Glass Canyon is called here the Black Glass Canyon fault. The vertical offset across this fault diminishes southward from 100 m in the middle of Black Glass Canyon to a few tens of meters of vertical offset distributed among several fault splays in Yucca Wash.

Yucca Wash Faults

Northwest-striking strike-slip faults have been mapped in the northern part of Yucca Mountain south of the map area. Three faults are exposed in bedrock outcrops in Sever Wash, Pagany Wash, and in subsurface exposures in the ESF beneath Drill Hole Wash. These northwest-striking faults are associated with the northwest-trending valleys in which they are located. Some workers have speculated that a major northwest-striking fault is buried in the northwest-trending Yucca Wash and that it may be a dextral strike-slip fault (Scott and Bonk, 1984; Scott, 1990). Two geologic cross sections projecting across Yucca Wash parallel to regional strike were prepared to evaluate the vertical offset of beds across a structure buried in Yucca Wash. One cross section approximately parallel to the strike of the units indicates that the base of the Tiva Canyon Tuff changes elevation by only 3 m in a horizontal distance of 1 km, and the base of the Pah Canyon Tuff changes elevation by about 10 m. Another cross section through drill hole WT-6 in Yucca Wash indicates that the base of the Pah Canyon Tuff varies by only 6 m in 0.8 km of horizontal distance along regional strike. The amount of vertical change for both the Tiva Canyon Tuff and the Pah Canyon Tuff is about the same as variation based solely on paleotopography and does not indicate vertical disruption of strata across Yucca Wash. In contrast, the northwest-striking strike-slip faults exhibit a maximum vertical separation of 10 and 30 m for various splays of the Sever Wash fault, a vertical separation of 10 m for the Pagany Wash fault, and a vertical separation of 4 to 15 m for the Drill Hole Wash fault (Dickerson, 1996). It is difficult to postulate the existence of a major northwest-striking fault beneath the alluvium in Yucca Wash.

The available data from recent geologic mapping indicate very little vertical disruption of strata across Yucca Wash as would exist if strike-slip faulting occurred after the strata were tilted. Geophysical data also address the possibility of strike-slip movement along a fault buried in the wash as shown by Scott and Bonk (1984). Langenheim and others (1993) acquired ground-based gravity and magnetic data from four traverses across Yucca Wash and three parallel traverses along the length of Yucca Wash. Those data reveal a distinct magnetic anomaly trending across Yucca Wash near drill hole WT-6 (pl. 2). That magnetic anomaly is nowhere offset, nor is a distinct magnetic plateau southeast of this anomaly offset to the northwest or southeast. The ground-based geophysical data do, however, trace several north-striking normal faults across the wash, where they crop out in bedrock exposures on both sides of Yucca Wash. Recently compiled aeromagnetic data by McCafferty and Grauch (1997) show northwest-trending magnetic highs and lows parallel to the northwest-striking faults in Drill Hole Wash, Pagany Wash, and Sever Wash. Conversely, the aeromagnetic anomalies and gradients trend north-south in the Yucca Wash area, parallel to mapped normal faults. These data indicate that the structure in Yucca Wash is dominated by north-striking normal faults. If a northwest-striking strike-slip fault exists, it exhibits only very minor vertical or lateral offset in the Paintbrush Group rocks. Older structures that predate the Paintbrush Group rocks may exist, buried beneath the Topopah Spring Tuff, but such structures were quiescent during and subsequent to deposition of the Paintbrush Group tuffs and lavas (Dickerson, 1996).

Northern Extension of the Bow Ridge Fault

The northern extension of the Bow Ridge fault is the major north-trending, down-to-the-east fault on the map. This fault exhibits about 70 m of down-to-the-east vertical offset just north of Yucca Wash. Ground-based gravity and magnetic data from Langenheim and others (1993) and Langenheim and Ponce (1994) have been used to trace this fault south-southeastward to where it bends around the eastern end of Isolation Ridge. Subsurface data from drill hole WT#16 (pl. 1) indicates that at this location there is 65 m of down-to-the-east vertical offset (Muller and Kibler, 1986). Ground-based gravity and magnetic data from Ponce (1993) and Ponce and others (1993) indicate that from the location east of Isolation Ridge the Bow Ridge fault splays into numerous smaller strands. The Bow Ridge fault reverses direction of offset, from down-to-the-east adjacent to Isolation Ridge to 130 m of down-to-the-west offset adjacent to Exile Hill (fig. 1) (Buesch and others, 1994). East of the down-to-the-east northern extension of the Bow Ridge fault north of Yucca Wash, there are 3 to 4 splays of parallel, down-to-the-west normal faults of modest offset that may represent hanging wall deformation.

Midway Valley Faults

Several major and minor faults on the map strike southward towards Midway Valley where they are buried by Quaternary surficial deposits while maintaining appreciable offset. Ground-based gravity and magnetic surveys by Langenheim and others (1993), Langenheim and Ponce (1994), Ponce and others (1993), and Ponce (1993, 1996) trace many of these faults beyond the outcrop exposures into Midway Valley. These data and subsurface data from the RF drill holes located east of Exile Hill (Gibson and others, 1992) indicate they locally form horsts and grabens beneath the Quaternary deposits in Midway Valley.

The fault in upper Black Glass Canyon bends southeastward out of Black Glass Canyon, then southward through a nameless valley and into Yucca Wash. Where this fault disappears beneath Quaternary surficial deposits, it juxtaposes dense rhyolite lava flow rock down on the west side against less dense nonwelded tuff on the east side, resulting in an apparent east-side-down gravity signature on line YB of Langenheim and others (1993). Geophysical line YA of the same report traces this same fault further southward into Midway Valley, where Ponce (1993, 1996) traces it the full length of Midway Valley as the Midway Valley fault. The north-south trending Black Glass Canyon fault, a normal fault in lower Black Glass Canyon, lies west of the Midway Valley fault. Data from geophysical lines YB and YA of Langenheim and others (1993) indicate that this fault splays into numerous smaller faults, one of which trends southeastward and splays into the Midway Valley fault in Yucca Wash. Another splay of this fault trends southward through several outcrops of the rhyolite of Comb Peak. Field observations indicate that the rock is sheared, brecciated, and faulted along this splay, but offset cannot be quantified as similar rocks crop out on both sides of the fault. The geophysical data indicate that other closely spaced splays of this fault system exist, trending southward into Midway Valley as small faults, but they are all obscured by the Quaternary surficial deposits.

West of the Paintbrush Canyon fault a small down-to-the-east normal fault is exposed in the 8-meter-high cliff on the north side of Yucca Wash. Although this fault displays only a few meters of vertical offset, it is exactly on strike with an apparent down-to-the-east fault on geophysical line YA of Langenheim and others (1993). This particular fault is traced southward on additional geophysical lines (Ponce and others, 1993) as part of the "Midway Valley feature" of Ponce (1993), an apparent horst in Midway valley that is parallel to and west of the Paintbrush Canyon fault.

Small Faults

West of Black Glass Canyon near the northern extension of the Bow Ridge fault, there are numerous north-, northeast-, and northwest-trending normal faults of modest offset (less than 1 m to a few m). Similarly, there are numerous minor faults located within the bedded tuffs in upper Paintbrush Canyon. Most of these lesser faults are parallel to the major structures, though some of them are at large angles to the principal structures. Such minor faults may exist throughout the map area, but are visible only in the areas where bedded tuffs are exposed. These minor faults that exist between the major faults record intrablock strain.

Timing of Faults

Deformation accompanied volcanic activity in the Yucca Mountain region. Within the map area, the faulting of rocks of different ages assists in understanding the development of these structures through time. The areas underlain by bedded tuffs and containing several tuffs or lavas of different ages in upper Paintbrush Canyon and around Comb Peak are particularly useful in illustrating how faults developed through time. For example, there is a small fault in the hanging wall of the main fault south of Comb Peak that forms a small graben of Tiva Canyon Tuff. This graben is overlain by unfaulted basal tuff of the rhyolite of Comb Peak, indicating that this graben developed subsequent to deposition of the Tiva Canyon Tuff but prior to eruption of any of the rhyolite of Comb Peak. The main fault south of Comb Peak, of which this graben is a part, offsets the Tiva Canyon Tuff by over 60 m, but offset of the overlying rhyolite of Comb Peak is only 4 m distributed between 2 splays. An extension of this same fault north of Comb Peak offsets the basal tuff of the rhyolite of Comb Peak by about 10 m, offsets the underlying rhyolite of Delirium Canyon by about 35 m, and offsets the older Pah Canyon Tuff by about 45 m. The amount of deformation for the main fault through Comb Peak was greatest for the period of time between the deposition of the Pah Canyon Tuff and rhyolite of Comb Peak, with modest amounts of deformation before and after this time period.

In upper Paintbrush Canyon a northeast-striking fault offsets lava flow rock of the rhyolite of Delirium Canyon by 3 m, offsets tuff of the rhyolite of Delirium Canyon by about 17 m, and offsets the Topopah Spring Tuff by about 24 m. Similarly, a north-striking fault in upper Paintbrush Canyon 460 m east of the Paintbrush Canyon fault produced 2 m of offset in the rhyolite of Vent Pass and about 6 m of offset in a bedded tuff of the Calico Hills Formation. These faults indicate that the rate of deformation in the Paintbrush Canyon area probably peaked during the middle of the deposition of the Paintbrush Group rocks.

The structural deformation accompanying volcanic activity in the Yucca Mountain region manifested itself as westward extension that increased to the south, and by clockwise rotation about a vertical axis located in the northwestern part of Yucca Wash (Scott, 1990). Paleomagnetic data (Rosenbaum and others, 1991; Hudson and others, 1994) indicate that the vertical axis rotation also increases from north to south in the Yucca Mountain region. These data also indicate that the northern Yucca Mountain region was not rotated relative to the rest of the southwest Nevada volcanic center. Paloemagnetic data indicate that most of the vertical axis rotation occurred after cooling of the Tiva Canyon Tuff (12.7 m.y.; Sawyer and others, 1994), but before the deposition and cooling of the Ammonia Tanks Tuff (11.45 m.y.; Sawyer and others, 1994) (Rosenbaum and others, 1991; Hudson and others, 1994). The field data shown on this map, however, indicate that deformation was occurring throughout the eruption and deposition of all of the Paintbrush Group rocks, and that the greatest amount of deformation may have occurred during the middle of Paintbrush time. Some faults were relatively inactive after the deposition of the Tiva Canyon Tuff. However, the amount of vertical separation of the rhyolite of Comb Peak indicates that much of the deformation on the four major faults north of Yucca Wash (the Paintbrush Canyon, Black Glass Canyon, Midway Valley, and Bow Ridge faults) postdates deposition of the Paintbrush Group rocks.

The faults depicted on this map most likely resulted from tectonic stress related to the east-west tension, and to a lesser extent to volcanic activity. The area of this map is adjacent to the caldera complex that was the continual source of volcanic material deposited here. As such, tumescence and subsidence related to the movement and eruption of magma likely resulted in much of the pre-Tiva Canyon Tuff faulting activity preserved in these rocks. Such synvolcanic tectonic stress likely was more intense adjacent to the caldera complex than it was farther to the south where the regional tensional tectonic stress predominated.

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APPENDIX

DESCRIPTION OF MAP UNITS

Phenocrysts listed in order of decreasing abundance

QUATERNARY SURFICIAL DEPOSITS

Qa **Alluvial deposits**—Pale-yellowish-brown to pale-brownish-gray to dark-brown boulders, cobbles, and gravel, and light-gray sand and silt; unconsolidated to partly consolidated; poorly to moderately well sorted; poorly to moderately bedded; subangular to rounded; locally crossbedded, and locally cemented with caliche; clasts consist of volcanic rock; composes deposits in active ephemeral streams and washes; 1 to 50 m thick.

Qac **Alluvial and colluvial deposits**—Pale-yellowish-brown to pale-brownish-gray boulders, cobbles, gravel, sand, and silt; unconsolidated to consolidated; poorly to moderately well-sorted; poorly to moderately bedded; angular to rounded; clasts consist of volcanic rock; 0 to 52 m thick.

Qts **Talus and slope-failure deposits**—pale-brownish-gray to pale-yellowish-brown boulders, cobbles, gravel, and sand in slope-failure deposits, and boulders, cobbles, and gravel in talus deposits; unconsolidated; poorly sorted; angular to subangular; nonbedded; 0 to 4 m thick.

MIOCENE VOLCANIC ROCKS
TIMBER MOUNTAIN GROUP

Tmp **RHYOLITE OF PINNACLES RIDGE**

Tmpl **RHYOLITE LAVA FLOWS**—light-gray to dark-gray to black vitric rhyolitic lava flow, and light grayish-tan devitrified lava flow; crystal-rich, with parallel flow-banding; 30 to 35 percent phenocrysts of quartz, sanidine, plagioclase, biotite, and magnetite; exhibits thick basal vitrophyre; as much as 300 m thick.

Tmpt **ASH-FLOW TUFF**—light-gray to pink pyroclastic flow and fallout deposit; nonwelded; bedded; vitric and devitrified; with 15 to 30 percent phenocrysts of quartz, sanidine, plagioclase, biotite, and magnetite.

Tmb **RHYOLITE OF WATERPIPE BUTTE**

Tmbl **RHYOLITE LAVA FLOWS**—light-gray to dark-gray, rhyolitic lava flow; vitric (locally perlitic) to devitrified; crystal-rich, with irregular and parallel flow-banding, and locally silicified flow-banding; 33 percent phenocrysts of plagioclase, sanidine, quartz, biotite, hornblende, and sphene, phenocrysts as large as 6 mm; locally exhibits a basal vitrophyre, and/or a basal auto-clastic breccia; as much as 175 m thick.

Tmbt **ASH-FLOW TUFF**—light brownish-gray to tan, nonwelded ash-flow tuff; devitrified; massive; some bedded, lithic-rich and crystal-rich, fallout tephra, and minor reworked tuff; 5 to 20 percent lithic fragments, light-gray, dark-gray, and dark grayish-brown devitrified volcanic rock fragments, 0.5 to 5 cm, locally as large as 20 cm, and blocks of tan to light-gray tuff, as large as 30 cm; as much as 15 percent pumice, pale greenish-yellow and white, devitrified, partly vapor-phase altered; 12 to 15 percent phenocrysts, plagioclase, sanidine, quartz, biotite; 0 to 60 m thick.

PAINTBRUSH GROUP

Tpk **RHYOLITE OF COMB PEAK**

Tpkl **RHYOLITE LAVA FLOWS**—light-gray to pinkish-gray, rhyolitic lava flow; devitrified, with contorted and parallel flow-banding; basal vitrophyre with spherulitic zone; 4 percent phenocrysts of sanidine, plagioclase, hornblende, sphene, and biotite; as much as 230 m thick.

Tpki **INTRUSIVE VITROPHYRIC RHYOLITE**—black, vitrophyric rhyolite intrusion; exhibits needle-like flow lineation; 5 percent phenocrysts of sanidine, plagioclase, hornblende, sphene, and biotite, up to 3 mm; intrusive vitrophyre is mantled by an envelope of intrusive breccia, and thermally altered and discolored tuff.

Tpkr **RHEOMORPHIC FUSED TUFF**—tan to grayish-brown, pinkish-gray, densely fused (sintered), rheomorphic tuff; vitric to devitrified; flow-banded; 4 percent phenocrysts of sanidine, plagioclase, hornblende, sphene, and biotite; extremely flattened and elongated pumice; rheomorphic tuff characterizes a transition from fused ash-flow tuff below to lava flow with no basal vitrophyre or autoclastic breccia above; degree of fusing (sintering), devitrification, flattening of pumice fragments with flattening ratio as great as 20:1, and development of flow-foliation increase upward.

Tpkw **FUSED ASH-FLOW TUFF**—tan to grayish-brown to brownish-black, partly to densely fused (sintered) ash-flow tuff; partly devitrified to vitric ash-flow tuff lithologies of kt3, kt2, and/or kt1; lower contact of fused tuff commonly parallel to contact with overlying lava flow and locally crosscuts bedding; degree of fusing increases upward from partly- to moderately- to densely-fused tuff; 1 to 205 m thick.

Tpkt **ASH-FLOW TUFF**—light-gray, pink, grayish-brown, nonwelded to partly welded ash-flow tuff; devitrified; massive; pumiceous and lithic-rich; 5 percent phenocrysts of sanidine, plagioclase, hornblende, sphene, and biotite; pumice, white to light gray, pink, tan, devitrified, undeformed to partly deformed; lithic fragments, gray and brown devitrified rhyolite, and black, vitric volcanic rock fragments, as large as 15 cm; 1 to 30 m thick.

kt3 **ASH-FLOW TUFF**—white to light-gray, nonwelded, ash-flow tuff; devitrified; massive; pumiceous; 3 percent phenocrysts of sanidine, plagioclase, hornblende, sphene and biotite; pumice, white, devitrified, partly flattened; 0 to 21 m thick; upper contact characterized by blocky, vitric breccia with overlying autoclastic lava flow breccia.

kt2 **ASH-FLOW TUFF**—upper part grayish-brown to black, moderately to densely welded, vitric ash-flow tuff; lower part pink to tan, partly welded, devitrified ash-flow tuff; massive with planar bedding at top; characteristic pink cliff-former; 5 percent phenocrysts of sanidine, plagioclase, hornblende, sphene, and biotite; pumice, pink, tan, black, vitric, partly deformed to flattened, 2 to 4 cm; lithic fragments, black, vitric, 0.5 to 2 cm; 0 to 25 m thick; upper contact at top of local vitrophyre; lower contact below blocky, lithic-rich horizon with rhyolite and welded tuff blocks as large as 30 cm.

kt1	**ASH-FLOW TUFF**—light-gray, nonwelded ash-flow tuff; devitrified; pumiceous and lithic-rich; characteristically massive and very pumiceous; 5 percent phenocrysts of sanidine, plagioclase, hornblende, sphene, and biotite; pumice, white to light-gray, devitrified, undeformed, 1 cm; lithic fragments, gray and brown rhyolite and welded tuff, as large as 35 cm, concentrated in lithic-rich layers; 0 to 38 m thick; lower contact beneath fallout tephra underlying very coarse, very lithic-rich layer.
Tpkh	**LAHAR**—light brownish-gray to medium brownish-gray, mud-flow breccia or lahar; very poorly sorted; matrix-supported; 60 to 80 percent lithic clasts, heterogeneous mixture of volcanic rock fragments, subangular to subrounded, 2 cm to 3 m; 0 to 6 m thick.
Tpv	**RHYOLITE OF VENT PASS**
Tpvl	**RHYOLITE LAVA FLOWS**—medium-gray to dark brownish-gray to dark grayish-brown rhyolitic lava flow; vitric and devitrified; spherulitic; parallel and contorted flow-banding; oblate lithophysae parallel to flow-banding, lithophysae locally silicified; local basal autoclastic breccia; local basal vitrophyre; 2 to 3 percent phenocrysts of sanidine, plagioclase, biotite, and hornblende.
Tpvt	**ASH-FLOW TUFF**—light greenish-gray and light-gray to medium-gray, brownish-gray to dark purplish-brown ash-flow tuff; nonwelded; massive; locally bedded; devitrified; lithic-rich; locally pumice-rich; locally spherulitic; locally dark gray to black, vitric, partly to densely fused; 3 percent phenocrysts of sanidine, plagioclase, biotite, and hornblende; 10 to 35 percent lithic fragments, dark reddish-brown to brownish-gray devitrified volcanic fragments, 0.2 to 6 cm, locally as large as 20 cm; 0 to 150 m thick.
Tbt5	**BEDDED TUFF**—white to light-gray, nonwelded tuff; devitrified; locally bedded; 5 to 10 percent phenocrysts of sanidine, plagioclase, biotite; as much as 30 percent pumice, white, light-gray, and tan, devitrified, 3 to 40 mm; as much as 15 percent lithic fragments, gray, tan, and brown rhyolite and welded and nonwelded tuff, 3 to 35 mm; 0 to 3 m thick; lower contact at top of Tiva Canyon Tuff vitrophyre, upper contact above thin (12 cm), white, bedded tuff.
Tpc	**TIVA CANYON TUFF**—pale-brown, moderate reddish-orange, brownish-gray, light-gray, ash-flow tuff; partly to densely welded; rhyolite to quartz latite; vitric to devitrified; 3 to 15 percent phenocrysts of sanidine, plagioclase, biotite, pyroxene, sphene, trace of hornblende; 0 to 30 percent pumice, light-gray to dark-gray, yellowish-brown to reddish-brown, vitric to devitrified to vapor-phase altered, 1 to 15 cm; 0 to 3 percent lithic fragments of volcanic rock, light-gray to dark reddish-gray to brown, 1 to 10 mm; locally 0 to 40 percent, flattened to irregular lithophysae, 1 to 25 cm; locally spherulitic; locally with vapor-phase minerals in groundmass and lining lithophysae; ash-flow tuff characterized by upper crystal-rich quartz latite and lower crystal-poor rhyolite; contains lithophysal-rich layers; local upper or lower vitrophyre; local basal columnar-jointed layer; local white, nonwelded, fallout deposit; 3 to 30 m thick. (12.7 Ma, Sawyer and others, 1994).
Tpg	**RHYOLITE OF BLACK GLASS CANYON**
Tpgl	**RHYOLITE LAVA FLOWS**—medium-gray to purplish-gray, rhyolitic lava flow; devitrified; parallel and contorted flow-banding; local basal autoclastic breccia; 3 to 4 percent phenocrysts of sanidine, hornblende, sphene, and biotite; 2 to 14 m thick.

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