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Geologic Map of Oasis Valley Spring-Discharge Area and Vicinity, Nye County, Nevada

By C.J. Fridrich, S.A. Minor, J.L. Slate, and P.L. Ryder

Pamphlet to accompany Scientific Investigations Map 2957

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Introduction

This map report presents the geologic framework of an approximately 1,500 km^2 area in southern Nye County, Nevada. The study area extends across the Oasis Valley spring-discharge area and environs, and then further northeastward to the southwestern margin of the Pahute Mesa testing area, on the Nevada Test Site (fig. 1). This map incorporates new surficial mapping, adapted from Slate and others (2000), and updates to bedrock mapping previously published as U.S. Geological Survey Open-File Report 99–533-B (Fridrich and others, 1999b). Additionally, a much expanded discussion explains many of the interpretations that are presented graphically on the map and cross sections. Further discussion of the geologic framework of the Oasis Valley area can be found in an interpretive geophysical report by Mankinen and others (2003), and in a geologic report by Fridrich and others (1999a) that accompanied the earlier published version of this map.

The map covers nine 7.5-minute quadrangles centered on the Thirsty Canyon SW quadrangle (fig. 1). It is a compilation of one previously published quadrangle map (O'Connor and others, 1966) and eight new quadrangle maps, two of which were published separately during the earliest part of this study (Minor and others, 1997; 1998). The new bedrock and surficial mapping is partly a revision of several unpublished reconnaissance maps completed by Orkild and Swadley in the 1960s, and of previously published maps by Maldonado and Hausback (1990), Lipman and others (1966), and Sargent and Orkild (1976). Additionally, mapping of the pre-Tertiary rocks of northern Bare Mountain was compiled from Monsen and others (1992) with only minor modification.

The cross sections (see map sheet) were drawn to a depth of several kilometers at the request of hydrologists studying the Death Valley ground-water system. The interpretation of the geology below a depth of about 1 km is constrained primarily by geophysical data, and is model-dependent. The pattern of internal domino-style faulting shown on the east half of cross section *A–A′* is based on an interpretation of aeromagnetic data, but is strictly schematic. The estimated thickness of the Tertiary volcanic and sedimentary strata on both cross sections is shown with a heavy dashed blue line (gravity inversion line), which has a very rounded form because it was modeled from gravity data (Hildenbrand and others, 1999). The locations of major concealed structures were interpreted on the basis of gravity and magnetic data (Grauch and others, 1997; 1999; Mankinen and others, 1999).

The cross sections are generalized in several ways, relative to the map, for the sake of clarity. For example, several small faults that appear on the map were omitted from the cross sections. Some formations that are subdivided on the map are not subdivided on the cross sections. And the extent of Quaternary cover is simplified on the cross sections.

Other contributions to this map include the following: M.E. Berry assisted J.L. Slate in mapping the surficial deposits; R.G. Warren (Los Alamos National Laboratory) produced the point-counting results that were the basis of the phenocryst assemblage data quoted in the description of map units (Warren and others, 2000); T.G. Hildenbrand used gravity data to calculate profiles of depth to pre-Tertiary basement used as a constraint on the cross sections (Hildenbrand and others, 1999); D.A. Sawyer determined most of the $^{40}Ar/^{39}Ar$ dates that are cited; and P.P. Orkild completed preliminary unpublished maps of the Beatty Mountain and Thirsty Canyon SW quadrangles, which were refined with new field work, to produce the more detailed bedrock mapping presented here.

Geologic Summary

The predominant bedrock units exposed in the Oasis Valley area are widespread middle to upper Miocene ash-flow tuff sheets. These tuffs were erupted from calderas of the southwest Nevada volcanic field. Parts of six calderas are exposed in the map area (fig. 1) including the 9.4 Ma Black Mountain caldera and four calderas that comprise the central caldera complex of the volcanic field—the 11.45 Ma Ammonia Tanks, 11.6 Ma Rainier Mesa, 12.8–12.7 Ma Claim Canyon, and 13.7–13.3 Ma Silent Canyon calderas (Byers and others, 1976; 1989; Sawyer and others, 1994). The map area also includes an exposure of the 14.3 Ma Tolicha Peak caldera near the northwestern limit of the map, and the very small 11.55 Ma Twisted Canyon caldera, in the south-central part of the map (fig. 1). The Tolicha Peak caldera has been largely buried by younger volcanic rocks, and only a small remnant is exposed straddling the northern boundary of the map (fig. 1). The Twisted Canyon caldera is satellitic to the slightly older

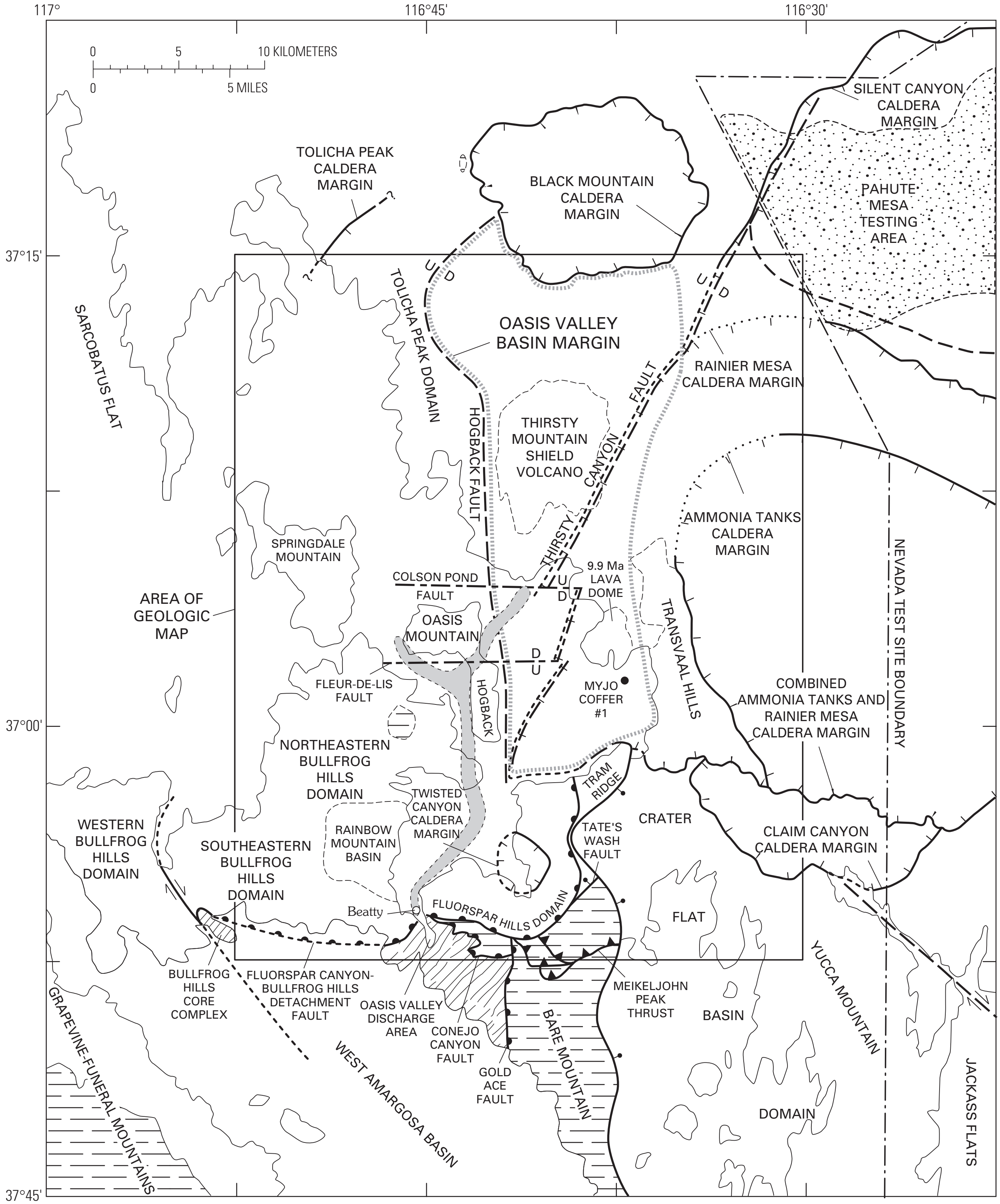
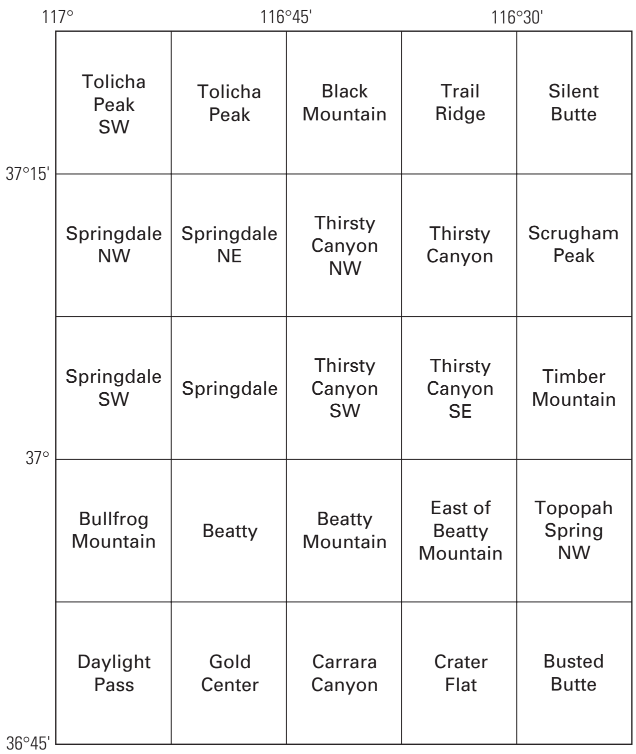
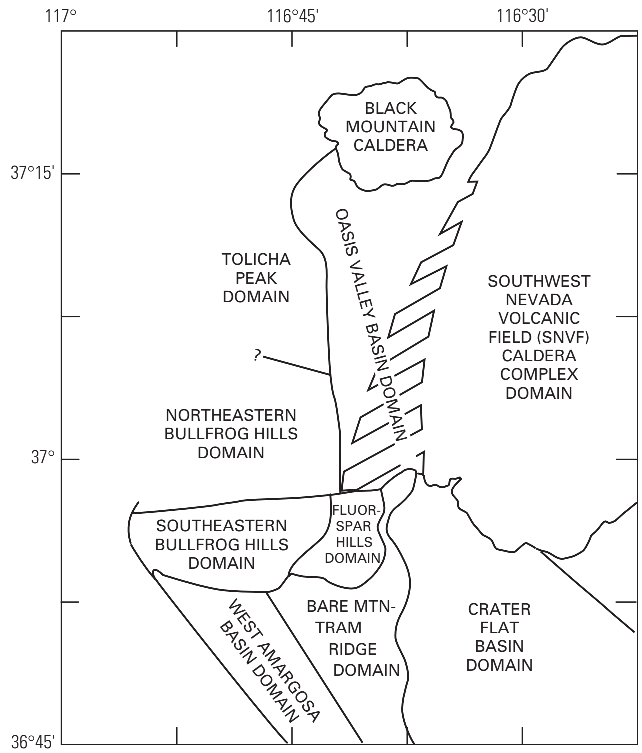


Figure 1 (above and following page). Index map of the Oasis Valley basin and vicinity showing the Pahute Mesa testing area, Oasis Valley spring-discharge area, caldera outlines, and selected faults. Figure covers the nine 7.5-minute quadrangles of the map, as well as a one-quadrangle-wide perimeter. The two smaller maps show the 25 quadrangles of this figure and a structural domain map of the area.

INDEX TO 7.5 MINUTE QUADRANGLES



STRUCTURAL DOMAIN MAP



EXPLANATION

Bedrock outline—Dashed where approximately located

Caldera margin—Dashed where approximately located; dotted where concealed. Queried where inferred

Detachment fault—Half-circles on upper plate; dashed where approximately located

Thrust fault—Sawteeth on upper plate

Normal fault—Dashed where approximately located; U, upthrown block; D, downthrown block. Bar and ball on downthrown side

Strike-slip fault—Dashed where approximately located. Bar and ball on downthrown side. Arrows show relative direction of lateral offset

Major geophysical lineament

Oasis Valley Basin margin

Spring discharge area

Underground nuclear testing area

Slate-nonmetamorphic—Paleozoic and Precambrian

Phyllite-schist—Paleozoic and Precambrian

Oil well

Rainier Mesa caldera, and is considered to be comagmatic because the intracaldera tuff of Twisted Canyon (Tmt) is petrographically indistinguishable from the Rainier Mesa Tuff (Tmr; R. Warren, unpub. data). The difference in the $^{40}Ar/^{39}Ar$ ages of these two tuffs is within the margin of analytical error, and it is only the presence of angular blocks of Rainier Mesa Tuff in the intracaldera tuff of Twisted Canyon that proves the latter unit is younger. The source areas of several major ash-flow tuff units in the map area are unknown, and probably are concealed by younger rocks and perhaps by younger calderas.

Sawyer and others (1994) concurred with previous workers that the Tiva Canyon Tuff (Tpc) was derived from the Claim Canyon caldera (fig. 1), but speculated that the other voluminous member of the Paintbrush Group, the Topopah Spring Tuff (Tpt), was derived from an older, buried caldera, located elsewhere. Only the southern part of the Claim Canyon caldera is preserved and exposed (fig. 1); the northern part was destroyed or buried by formation of the overlapping, younger Rainier Mesa caldera. Whereas half of the remnant of the Claim Canyon caldera lies to the east of the map area, we examined field relations throughout the caldera during this study. In widely spaced sites along the remaining margin of the Claim Canyon caldera, we found that the Topopah Spring Tuff has features that indicate close proximity to a vent. These features include the presence of boulder-size (to about 0.5 m) well-rounded lithics of Miocene-age granitoids, that presumably were blown out from deep parts of the vent walls, and unusual rhythmic welding reversals in the last-erupted part of the tuff, that resemble the pattern of welding found in proximal facies of agglutinated ash-fall tuffs. The development of these vent-facies features in the Topopah Spring Tuff is limited to very small areas, which lie immediately south of the topographic wall of the (Claim Canyon) caldera-collapse structure. Moreover, several tuff and lava units are exposed within the moat of the Claim Canyon caldera that were emplaced between the eruptions of the Topopah Spring (Tpt) and Tiva Canyon Tuffs (Tpc). These units thicken radically and abruptly across the outer margin of the caldera, and have proximal facies characteristics within the caldera. These relationships indicate that the Claim Canyon caldera initially formed during the eruption of the Topopah Spring Tuff, and was the source for all of the named members of the Paintbrush Group.

The major ash-flow tuff units exposed in the Oasis Valley area are intercalated with locally derived rhyolite, basalt, and trachyte lavas and related tephras, as well as alluvial and lake sediments, and landslide breccias. This predominantly volcanic sequence is overlain by younger alluvium containing minor amounts of upper Miocene to Quaternary basalts and small-volume tuffs, and is underlain by a pre-15-Ma Tertiary section that may locally be as thick as about 1 km. The underlying Tertiary section consists mostly of fluvial conglomerate and lesser freshwater limestone, but also includes minor distal tuffs and fine-grained clastic sediments; it predates the southwest Nevada volcanic field and is late Eocene to early Miocene in age. This underlying pre-15-Ma Tertiary section (Tog) is only locally exposed in the study area, as discussed below. It is mostly known from exposures to the west in the Grapevine and Funeral Mountains as the Titus Canyon Formation and the overlying "green conglomerate" (fig. 1; Reynolds, 1969; 1974; Fridrich, and others, 2000; Slate and others, 2000).

Whereas the Titus Canyon Formation is widely documented as being entirely Oligocene in age, the ≥40 to about 19 Ma age range of this formation, defined by fossil evidence and radiometric dates (Stock and Bode, 1935; Reynolds, 1969; 1974; Snow and Lux, 1999) is upper Eocene to lower Miocene on modern geologic age charts because the upper and lower age limits of the Oligocene epoch have been redefined by the International Commission on Stratigraphy, International Union of Geological Sciences (available at www.stratigraphy.org).

The Cenozoic section unconformably overlies a section of latest Proterozoic to late Paleozoic sedimentary rocks, consisting of limestone, dolomite, argillite, and quartzite. This mostly miogeoclinal (passive margin) section, which is as thick as 11 km in the Nevada Test Site region (Burchfiel, 1964), was deposited on the western continental shelf and slope of North America during the opening of the Pacific Ocean. These miogeoclinal strata are exposed on Bare Mountain, along the southern boundary of the map, and on a small, unnamed uplift in the west-central part of the map area, in the northeastern Bullfrog Hills (fig. 1). Additionally, a very small exposure of Paleozoic carbonate rocks (Ordovician Pogonip Group, Op) is located immediately north of the map area on the western margin of the Black Mountain caldera (fig. 1).

The only occurrence of Mesozoic rocks in the map area is a fault sliver of Cretaceous (about 100 Ma) granite (Kfi) exposed along the detachment fault that forms the northwestern margin of Bare Mountain (Monsen and others, 1992). Additionally, the latest Proterozoic to late Paleozoic sedimentary rocks of northwest Bare Mountain were moderately to strongly metamorphosed during the Cretaceous (Hoisch and others, 1997). Those metasedimentary rocks that are almost totally recrystallized could be considered to be Mesozoic rocks. We classify them here, however, by their time of deposition.

Hornblende gabbro dikes (Tvbi) in northwest Bare Mountain have yielded middle to late Tertiary K–Ar ages (Monsen and others, 1992), but strong discordance between the hornblende (about 26 Ma) and biotite (about 16 Ma) ages indicates these dates are problematic. If these are cooling ages, then the gabbro dikes may be as old as late Mesozoic, like the adjacent granite. Alternatively, the K–Ar ages may have been skewed by potassium loss accompanying hydrothermal alteration, and the true ages of the dikes may be younger. In that case, these gabbro dikes may be the intrusive lower-plate equivalents to the about 11 Ma basalt lava flows (Tvb) exposed to the north of Bare Mountain, in the upper plate of the Fluorspar Canyon-Bullfrog Hills detachment fault. This last alternative appears most likely because there are no known gabbros in the region that predate about 12 Ma.

The Oasis Valley area has a complex tectonic history that includes Mesozoic contractional events and a protracted, multi-stage history of Tertiary extension and strike-slip strain (Fridrich, 1999). Evidence of Mesozoic contraction in the map area is limited to Bare Mountain and consists of a thrust fault in the northeastern part of the mountain (Meiklejohn Peak thrust; fig. 1) and extensive folding of the rocks in the northwestern part of the mountain (Monsen and others, 1992).

In addition to the Fluorspar Canyon-Bullfrog Hills detachment fault that forms the northern boundary of Bare Mountain, two other detachment faults are exposed within Bare Mountain. These have been named the Gold Ace and Coñejo Canyon faults (fig. 1; Monsen and others, 1992). These faults separate strongly metamorphosed rocks of Cambrian and latest Proterozoic formations in their lower plates, from weakly metamorphosed to non-metamorphosed rocks of the same formations in their upper plates. This relationship requires at least a two-stage history involving thrust imbrication and variable metamorphism in an earlier (Mesozoic) stage, followed by low-angle normal faulting in a later (Tertiary) stage. Strongly metamorphosed and weakly to non-metamorphosed rocks of the same formations indicate either different thrust fault blocks or different structural levels in the same thrust block and thus different levels in the crust, when metamorphism occurred. Subsequently, different Mesozoic crustal levels have been juxtaposed by the two Tertiary detachment faults that are internal to Bare Mountain. The throws of these internal detachment faults are indicated by the metamorphic discordances across them, rather than by the displacement of formation boundaries.

Fridrich (1999) interpreted both the Coñejo Canyon and Gold Ace detachment faults as internal features within Bare Mountain that predated the Fluorspar Canyon-Bullfrog Hills detachment fault which forms the northern margin, and before erosion, the upper surface of the Bare Mountain uplift. An alternative possibility is that all three detachment faults are coeval structures. In that alternative case, the feature mapped as the Coñejo Canyon fault may be the lowermost strand of the same detachment fault that is mapped as the Fluorspar Canyon-Bullfrog Hills detachment fault at its uppermost strand in the same area. The rocks that intervene between these two strands of the detachment fault would thus represent an extremely attenuated sampling of the thick section that is faulted out.

The Gold Ace detachment fault appears to be a separate structure, as the geometry suggests it is truncated by the Fluorspar Canyon-Bullfrog Hills detachment fault (Fridrich, 1999). Moreover, the truncation suggests it is an older structure. It is possible however, that as the Fluorspar Canyon-Bullfrog Hills detachment fault was moving, the Gold Ace detachment fault was accommodating coeval internal deformation within its lower plate. Because Bare Mountain is composed almost entirely of Paleozoic rocks, field relations cannot be used to determine the relative ages of the detachment faults exposed in this uplift, and any interpretation of their relative ages is therefore model-dependent. For example, see Monsen and others (1992) for a very different interpretation that still satisfies all existing constraints.

Extension and related strike-slip deformation occurred in the map area throughout the latter half of the Tertiary Period. This late Tertiary deformation can be divided into three major intervals (1) deformation that preceded formation of the Fluorspar Canyon-Bullfrog Hills detachment fault system and the related Bare Mountain metamorphic core complex, (2) deformation while the detachment fault system was active, and (3) deformation that postdates activity on the detachment fault system.

Deformation associated with of the Fluorspar Canyon-Bullfrog Hills detachment fault system is discussed first because most of the structures exposed in the map area formed in this interval, which extended from about 12.5 to about 6.5 Ma. Stratigraphic relations in the vicinity of Bare Mountain indicate that this core complex was not uplifted until shortly after eruption of the 12.7 Ma Tiva Canyon Tuff (Tpc). Variation in thickness of the ≥12.7 Ma strata shows no relationship to the boundaries of this uplift, and the only sediments intercalated with the 14–12.7 Ma volcanic units on the flanks of Bare Mountain are very fine-grained, mostly lacustrine deposits, such as freshwater marls. Between 12.7 and 11.7 Ma, Bare Mountain was abruptly uplifted as is recorded by the emplacement of large wedges of rock-avalanche megabreccia that thicken and coarsen toward the uplift. These breccias are composed primarily of clasts of Paleozoic rocks, and to a much lesser extent of the late Eocene to middle Miocene Titus Canyon Formation and green conglomerate (which together comprise unit Tog), as well as some low-silica rhyolite porphyries that resemble the 14 Ma dikes of eastern Bare Mountain (Tli). Middle Miocene (14–12.7 Ma) rocks are almost completely absent from the rock-avalanche breccias, which is consistent with Hamilton's (1989) interpretation that Bare Mountain was tectonically denuded of most of its Tertiary cover as it was uplifted.

Fault-slip indicators on the Fluorspar Canyon-Bullfrog Hills detachment fault indicate that the upper plate was transported to the northwest. Low-silica rhyolite lavas (Tlp) exposed at about the 14 Ma stratigraphic level in the low hills immediately north of Bare Mountain are petrographically similar to the 14 Ma dikes (Tli) of eastern Bare Mountain (R. Warren, unpub. data). We propose that the dikes of eastern Bare Mountain are the intrusive underpinnings of these lavas, which have been displaced to the northwest, off the top of Bare Mountain, by slip on the detachment fault.

On the northeastern margin of Bare Mountain, the Fluorspar Canyon-Bullfrog Hills detachment fault bends to the north, cutting through volcanic rocks along a sinuous, generally north-striking trace. The currently exposed position of the detachment fault in this area is only slightly west of where it originally intersected the surface. To the south, however, the detachment fault is interpreted to have extended over the top of most, if not all, of Bare Mountain, and it probably also extended a short distance into western Crater Flat basin, immediately east of Bare Mountain.

The exposed trace of the original (about 12.5–11.6 Ma) breakaway of the Fluorspar Canyon-Bullfrog Hills detachment fault is truncated about 8 km north of Bare Mountain by the 11.6 Ma Rainier Mesa caldera. The detachment fault continued, however, to be active after 11.6 Ma. On the north side of Bare Mountain, the breakaway for this detachment fault shifted about 4–5 km to the west after 11.6 Ma. The 11.6–11 Ma breakaway is concealed under alluvium and is expressed only as an eroded west-facing scarp that extends between the Oasis Valley basin and the northern limit of Bare Mountain (see map sheet and fig. 1). Two successively younger breakaways for this detachment fault are found progressively further westward (see fig. 6 in Fridrich, 1999).

The Bare Mountain range-front fault forms the eastern boundary of the exposed, tectonically denuded footwall block of the Fluorspar Canyon-Bullfrog Hills detachment fault. Within this footwall block, the degree of metamorphism of the Late Proterozoic and Paleozoic lower-plate rocks increases discontinuously to the northwest; Bare Mountain is thus an example of a metamorphic core complex (Crittenden and others, 1980). As discussed above, large abrupt changes in metamorphic grade are present across the Gold Ace and Coñejo Canyon faults of northwestern Bare Mountain. Within the fault blocks on either side of these internal faults, the degree of metamorphism within the Bare Mountain core complex increases northwestward in a continuous pattern, indicating that the Fluorspar Canyon-Bullfrog Hills detachment fault cut down through the crust to the northwest, and was rotated to shallower dips as the upper plate of the detachment fault was transported to the northwest and the Bare Mountain uplift was tectonically denuded.

Uniformly non-metamorphosed middle Miocene rocks in the upper plate of the detachment, along the north side of Bare Mountain, are thus juxtaposed against Paleozoic and latest Proterozoic rocks having northwestward-increasing degrees of metamorphism in the lower plate. This laterally increasing degree of metamorphic discordance across the Fluorspar Canyon-Bullfrog Hills detachment fault indicates that fault displacement increases to the west. This is consistent with the strongly extended character of the upper-plate rocks relative to the lower-plate rocks. The upper-plate rocks are cut by a plexus of normal faults along which the rocks have been tilted, in some cases to vertical dips. The tilting and faulting in the upper plate immediately north of Bare Mountain occurred mainly between about 12–10 Ma, based on fanning dips, angular unconformities, and growth faulting in the strata of this age range. Normal faults in the upper plate are typically concave upwards (listric), and apparently sole downward into the Fluorspar Canyon-Bullfrog Hills detachment fault.

Proceeding northwestward from Bare Mountain, the timing of upper-plate extensional tectonism (faulting and related tilting) associated with the Fluorspar Canyon-Bullfrog Hills detachment fault was progressively younger, both in the time of initiation and of cessation of tectonism. Deformation associated with this detachment fault system migrated like a wave advancing westward or northwestward through the upper-plate rocks. The youngest extension that is associated with detachment faulting in this region occurred at about 6.5 Ma and affected only the northwesternmost part of the map area.

During movement along the detachment fault, the upper-plate rocks were not only extended, but also incurred strong right-lateral strike-slip strain. Strike-slip deformation is manifest by significant horizontal components of slip, indicated by moderate-angle rakes, along many of the extensional faults, as well as by a small number of nearly pure strike-slip faults in the upper plate. This strike-slip deformation is consistent with paleomagnetic data, which show a history of progressive clockwise steep-axis rotation throughout the interval of extensional deformation (Hudson and others, 1994; unpub. data).

The tilted-domino pattern of extensional faulting in the upper-plate rocks, along the north side of Bare Mountain, continues westward across the Bullfrog Hills. A second, very small metamorphic core complex is exposed in the central Bullfrog Hills, to the west of the map (fig. 1). Based on data from mineral exploration holes drilled in the southeastern Bullfrog Hills (T. John, oral comm., 1997; Eng and others, 1996), the detachment fault exposed at the eastern limit of the Bullfrog Hills core complex is continuous with the detachment fault along the north side of Bare Mountain in Fluorspar Canyon; hence the name Fluorspar Canyon-Bullfrog Hills detachment fault. Given the magnitude of displacement along this detachment fault, it is reasonable to conclude that this very low-angle fault extends for several kilometers in the subsurface northwestward of where it is exposed. We propose that the detachment fault shallowly underlies all of the west-central part of the map area based on continuity of the gravity high associated with the area of detachment faulting (Grauch and others, 1997; 1999; Hildenbrand and others, 1999; Mankinen and others, 1999). This proposal is supported by the exposed structural style, which continues the supradetachment pattern of extreme extension and moderately strong strike-slip deformation present along the north side of Bare Mountain.

The geometry of the western part of the Rainier Mesa caldera has long been a subject of controversy (Byers and others, 1989, and references therein). This is mainly because the volcanic rocks exposed on the Oasis Mountain hogback (fig. 1) are outside of the footprint of the Ammonia Tanks and Rainier Mesa calderas, as defined by gravity data (Hildenbrand and others, 1999); yet they have features that suggest they are part of the caldera fill (Noble and others, 1991). These features include (1) exceptional thickness of the Ammonia Tanks Tuff (Tma), tuffs of Fleur-de-Lis Ranch (Tmf1 and Tmf2) and Cutoff Road (Tmc), and related lavas (Tmwr) in this area, (2) the presence of giant (≥5 m) lithics in the Ammonia Tanks Tuff, and of lake sediments (Tms) intercalated between the volcanic units of the hogback, and (3) rheomorphic features. The pattern of rheomorphic foliations and folding exposed on Oasis Mountain suggest that the Ammonia Tanks Tuff in this area ponded in a north-trending, ≈5 km wide trough that was sufficiently deep and steep-sided that the tuff was remobilized during welding. Flow lineations in the tuff show that the tuff flowed down the sides of the trough from both the east and west into its center which became a site of tight folding. Given the age constraints and other features present, the simplest explanation for this paleo-trough is that it was the western moat of the Rainier Mesa caldera, which was filled by the younger members of the Timber Mountain Group exposed in the Oasis Mountain hogback. Additionally, the base of the exposed section in the hogback consists of sedimentary breccias, some of which are megabreccias, possibly of caldera-collapse origin. Because these megabreccias underlie the Ammonia Tanks Tuff, they must be related to an earlier eruptive unit, presumably the Rainier Mesa Tuff (Tmr).

The exposed thickness of the volcanic section in the hogback is estimated at 3 km, measured from the base of the Ammonia Tanks Tuff (Tma) to the top of the Timber Mountain Group. This estimate is a minimum because it does not include the thickness of the Rainier Mesa Tuff (Tmr) which, although not exposed in the hogback, almost certainly underlies the Ammonia Tanks Tuff. As discussed above, the Rainier Mesa Tuff is presumably an intracaldera tuff in this area, and may have a thickness of 1.5 km or more. Thus the complete Timber Mountain Group section has a proven (exposed but incomplete) thickness of 3 km in the Oasis Mountain hogback and a probable total thickness of about 4.5 km. Despite the tremendous thickness of the Timber Mountain Group in the hogback, immediately to the west this group is nowhere thicker than about 200 m, and is in most places absent (see map sheet and cross section *A–A′*).

Gravity data over the area of the Oasis Mountain hogback indicate that the very thick, strongly east-tilted (about 25–45°) Tertiary section is truncated at about 1.0–1.5 km depth at a widespread subhorizontal surface (see cross section *A–A′*). This surface of truncation places the tilted Tertiary section against moderately high-density rocks, probably siliciclastic rocks of the Proterozoic and Paleozoic miogeoclinal section. This concealed surface evidently is a fault because it is roughly planar and truncates the Tertiary section at an angle. The gravity high under this area extends southward to the exposure of the Fluorspar Canyon-Bullfrog Hills detachment fault at the north end of Bare Mountain, as discussed above. The simplest explanation for the shallow subhorizontal truncation of the exceptionally thick-tilted volcanic section exposed on the hogback is that the detachment fault extends under the area of the hogback (cross section *A–A′*), as proposed above. If that is true, then the hogback section has been transported westward or northwestward on the detachment fault from where it was originally emplaced, and it thus would restore back to a pre-extensional position inside the gravity footprint of the Rainier Mesa caldera.

In the area of the Oasis Valley hogback, there are two roughly east-striking faults that are inferred from a combination of field and geophysical data—the Fleur-de-Lis and Colson Pond faults (fig. 1 and map sheet). The strike of these structures is unclear from the field relations and is based on geophysical data (Hildenbrand and others, 1999). The Fleur-de-Lis fault is expressed on the surface as a north-dipping paleoscarp, which has a throw of about 1.5 km based on a combination of structural offset and stratigraphic growth of the Ammonia Tanks Tuff (Tma) and related younger units across it. The Colson Pond fault is very strongly expressed in the gravity data but coincides with an area of complete cover by upper Miocene and Pliocene alluvial fan deposits, which are virtually untilted and unfaulted. On the south side of the Colson Pond fault, the Timber Mountain Group has a proven, minimum thickness of 3 km and an estimated total thickness of about 4.5 km, as discussed above. On the north side of this fault the maximum thickness of this group, as a whole, is only about 50 m. It appears probable that the Colson Pond fault has a strong strike-slip component, and it evidently juxtaposes intracaldera and extracaldera sections. Thus the difference between the thickness of the Timber Mountain Group sections on either side of this fault is not a measure of the throw of the Colson Pond fault by itself; rather, it also includes the throw of the caldera margin fault.

The origin of the Fleur-de-Lis and Colson Pond faults is unclear. Both share the facts that (1) they were clearly active only during the time of emplacement of the Rainier Mesa (Tmr) and Ammonia Tanks Tuffs (Tma) and related younger units (the tuffs of Fleur-de-Lis Ranch, Tmf1 and Tmf2; and Cutoff Road, Tmc), (2) they are both east-striking and thus roughly parallel to each other, and roughly perpendicular to the predominant strike of local extensional faulting, (3) they have anomalously large offsets relative to their lengths, and (4) the vertical offsets calculated from gravity data are significantly less than the offsets indicated by field relationships, and the misfit between those two is much too large to be caused merely by lateral density changes in the Tertiary sections across these faults. We have considered that these two east-striking faults may be tear faults that accommodated strong lateral changes in development of the detachment fault, or that they may be caldera structures of some type; however, the characteristics of these faults do not fit well-documented models for either of these alternatives. These faults formed within the area in which the Rainier Mesa caldera overlapped the detachment fault system, both of which were simultaneously active during the same interval in which the faults were active.

Significant evidence is present in the study area for one or more episodes of extension that preceded the initial (about 12.5 Ma) formation of the Fluorspar Canyon-Bullfrog Hills detachment fault system and the related Bare Mountain metamorphic core complex. In the northwestern part of the map, oblique extension and clockwise rotation occurred along a set of mostly northeast-striking left-oblique-slip faults between about 14.5–13 Ma (Minor and others, 1993; Minor and Hudson, unpub. data). A number of northeast-striking normal or oblique-slip faults of the same age are buried under Yucca Mountain, southeast of the map area, based on gravity and subsurface data (Fridrich, 1999). Between these two areas, northeast of Bare Mountain, a 25° angular unconformity (see Correlation of Map Units on map sheet) is locally present between the 14 Ma Lithic Ridge Tuff (Tlt) and the about 13.5 Ma Tram Tuff (Tct). In the Bullfrog Hills, relationships in rocks of the 15.5–13.5 Ma range are much less clear; however, the 15.5–14 Ma rocks are much more deformed and hydrothermally altered than are adjacent rocks that are <14 Ma.

Tertiary rocks older than about 15.5 Ma are exposed only in the vicinity of Bare Mountain and around the small uplift of Paleozoic rocks in the northeastern Bullfrog Hills. In a small sector graben at the northeast corner of Bare Mountain, a 45° angular unconformity is present between the about 16–15 Ma "green conglomerate" (the uppermost, middle Miocene part of "old fluvial conglomerates"—Tog) and the about 15–14 Ma rocks of Pavits Spring (Tos). In the northeastern Bullfrog Hills, strata correlative with units Tog and Tos are present only as giant blocks in landslide breccias, and thus are included in unit Tyx. The internal disruption present in these mega-slide-blocks precludes recognition of angular unconformities or other evidence of syndepositional tectonism. In summary, the field evidence indicates that significant extension occurred in the Oasis Valley area during the approximately 15–12.5 Ma interval (immediately predating formation of the Fluorspar Canyon-Bullfrog Hills detachment fault system); however, the evidence is currently too fragmentary to develop an understanding of the structural framework at that time.

Evidence of tectonism postdating movement on the Fluorspar Canyon-Bullfrog Hills detachment fault is limited to minor, widely spaced, mostly north-striking, west-dipping faults that slightly offset the youngest volcanic formations and surficial deposits. Evidence of much stronger post-7-Ma tectonism has been documented along the Bare Mountain fault, immediately south of the map area, and on Yucca Mountain to the southeast (USGS, 1996; Fridrich, 1999; Fridrich and others, 1999c).

Tertiary Stratigraphic Nomenclature

The stratigraphic nomenclature used in this study for the Tertiary rocks differs somewhat from previous usage in the Nevada Test Site/Death Valley region. Mainly, we redefine the Timber Mountain and Paintbrush Groups of the southwest Nevada volcanic field. Sawyer and others (1994) originally defined the Paintbrush Group (Tp) as consisting dominantly of four major ash-flow tuff sheets, from oldest to youngest, the Topopah Spring (Tpt), Pah Canyon (Tpp), Yucca Mountain (Tpy), and Tiva Canyon Tuffs (Tpc), which range in age from 12.8 to 12.7 Ma. They originally defined the Timber Mountain Group as consisting of two major ash-flow tuff sheets, the 11.6 Ma Rainier Mesa Tuff (Tmr) and 11.45 Ma Ammonia Tanks Tuff (Tma), along with some small-volume tuffs and lavas that intervene between the two. We add a number of units to each of these groups because field relationships and $^{40}Ar/^{39}Ar$ age constraints indicate that these additional units are products of the same resurgent cauldron cycles (a term defined by Smith and Bailey, 1968). The new stratigraphic definitions we propose here are consistent with those used by Slate and others (2000) in their study of the entire Nevada Test Site region; however, they never formalized their redefinition of the units (from Sawyer and others, 1994), because their map was published as an Open-File Report.

To the Paintbrush Group (Tp) we add the rhyolite of Windy Wash (Tpn), a group of felsic domes and related tuffs that range in age from about 12.6 to about 12.5 Ma (Sawyer and others, 1994). The lava domes of this unit are entirely restricted to the southern moat of the Claim Canyon caldera, which is the source of the four major tuffs of the Paintbrush Group, listed above. Whereas the related tuffs that surround and intervene between the Windy Wash lava domes are mostly tuff-ring deposits, some water-reworked deposits are locally present that provide sparse paleohorizontal indicators. Dips in these lenses of water-lain tuff reflect the form of the resurgent dome of the Claim Canyon caldera, which the moat cumulodome as a whole is buttressed against, and these dips decrease upsection. These relationships, along with the close timing of this caldera-moat lava sequence to the final caldera-forming eruption, indicate that the rhyolite of Windy Wash was emplaced during resurgent doming of the Claim Canyon caldera. Moreover, the feeder dikes for the lava domes are partly exposed. These dikes are entirely restricted to the Claim Canyon caldera, and most were intruded along faults that are part of the internal structure of the resurgent dome. The dikes are locally sheared within these fault zones. By the criteria set out in Smith and Bailey (1968), the rhyolite of Windy Wash is a resurgent lava sequence. It is part of the Paintbrush resurgent cauldron cycle, and thus we include it in the Paintbrush Group.

Sawyer and others (1994) used the name "rhyolite of the Loop" for a small cluster of domes that represent the last-erupted part of the unit that Christiansen and Lipman (1965) named the rhyolite of Windy Wash. We have retained the original definition, which groups the whole cumulo-dome and its related surrounding tuff apron as the rhyolite of Windy Wash (Tpn). Sawyer and others (1994) classified the "rhyolite of the Loop" as the earliest member of the Timber Mountain Group, based solely on petrographic criteria. We disagree with this for two reasons. First, field relationships unequivocally show that the rhyolite of Windy Wash, as a whole, represents the final phase of evolution of the Claim Canyon caldera, source of the Paintbrush Group (Tp), as discussed above. Second, a volcanic hiatus of 750 k.y. separated the rhyolite of Windy Wash from the pre-Rainier Mesa rhyolite (Tmrf)—the first unit erupted during the Timber Mountain resurgent cauldron cycle.

Sawyer and others (1994) included a unit they called the rhyolite of Fluorspar Canyon in their original definition of the Timber Mountain Group, but there is a lack of clarity in their definition because they considered both this unit and the rhyolite of the Loop to constitute a transitional sequence between the Paintbrush and Timber Mountain volcanic cycles. We redefine the rhyolite of Fluorspar Canyon, which we call the pre-Rainier Mesa rhyolite (Tmrf), as a member of the Timber Mountain Group. Moreover, to the Timber Mountain Group, we also add the tuffs and related lavas of Fleur-de-Lis Ranch (Tmf1, Tmf2, and Tmwr), the tuff of Cutoff Road (Tmc), and the tuffs and lavas of Twisted Canyon (Tmt).

The unit that Sawyer and others (1994) named the rhyolite of Fluorspar Canyon, on the southwest side of the Rainier Mesa caldera, has long been informally referred to by USGS geologists working on the Nevada Test Site as the pre-Rainier Mesa rhyolite (Tmrf), a unit that also includes the tuff of Holmes Road, on the northwest side of the caldera. This sequence of rhyolite lavas and tuffs was erupted from the area immediately in and around the site of the Rainier Mesa caldera, within the 100 k.y. interval that immediately preceded the caldera-forming eruption of the 11.6 Ma Rainier Mesa Tuff (Tmr). The pre-Rainier Mesa rhyolite includes some nonwelded ash-flow tuffs that buried pre-existing topography and thus have thickness variations that reflect the topography they buried. These thickness variations show that the site of the future Rainer Mesa caldera was at the center of a broad dome that formed in the 100 k.y. interval (from 11.7 to 11.6 Ma) that preceded formation of the caldera. The tuffs of the pre-Rainier Mesa rhyolite (Tmrf) were evidently derived from source vents within the area that became the Rainier Mesa caldera (perhaps along an early development of its ring fracture zone), based on two lines of evidence (1) progressive increase in the size of pumice lumps and lithics in the tuffs toward the caldera, and (2) the provenance of the lithics, which indicate radial transport of the tuffs away from the site of the future caldera. Despite having been sourced from the area of the future caldera, these tuffs initially thicken away from it, reflecting burial of a pre-caldera tumescent dome, and then thin outward at greater distances, reflecting diminishing transport away from the source.

Additionally, the chemistries of the numerous eruptive units that comprise the pre-Rainier Mesa rhyolite closely resemble that of the first-erupted, most silicic part of the Rainer Mesa Tuff (Tmr), except that they are more chemically evolved, in general. Thus the pre-Rainier Mesa rhyolite extends the high-silica-rhyolite to quartz-latite-compositional zonation of the Rainier Mesa Tuff, supporting the field relationships and indicating that they are comagmatic units. In Smith and Bailey's (1968) resurgent cauldron cycle model, the pre-Rainier Mesa rhyolite represents the tumescent phase of caldera evolution, and thus should be considered part of the Timber Mountain Group. We have reinstated the informal name pre-Rainier Mesa rhyolite (Tmrf) because a Paleozoic carbonate unit in Bare Mountain was named the Fluorspar Canyon Formation by Monsen and others (1992); hence the formation name used by Sawyer and others (1994) was pre-empted. The 750 k.y. volcanic hiatus that separated the Paintbrush and Timber Mountain resurgent cauldron cycles represents a large and unequivocal break between the two cycles. Thus, we cannot agree with the concept advanced by Sawyer and others (1994) that there are units that are transitional between the Paintbrush and Timber Mountain Groups.

The tuffs and lavas of Twisted Canyon (Tmt) are only preserved and exposed within the very small (about 3-km-diameter) Twisted Canyon caldera (fig. 1 and map sheet), discussed above. In previous maps of the area, the Twisted Canyon units were mapped as part of the pre-Rainier Mesa rhyolite (Tmrf), whereas they actually are part of the volcanism that intervened between the caldera-forming eruptions of the Rainier Mesa (Tmr) and Ammonia Tanks Tuffs (Tma), in the immediate environs of the resultant calderas. These intervening units, which are mostly moat lavas, were defined as part of the Timber Mountain Group by Sawyer and others (1994), and we retain that definition with the inclusion of the rhyolite of Twisted Canyon.

The tuffs of Fleur-de-Lis Ranch (Tmf1 and Tmf2) and of Cutoff Road (Tmc) are units that directly overlie the 11.45 Ma Ammonia Tanks Tuff (Tma), and that are indistinguishable in age from it by $^{40}Ar/^{39}Ar$ dating (Sawyer and others, 1994; D. Sawyer, USGS, pers. comm., 1999). Thick, proximal facies of these units are limited to the Oasis Mountain hogback and, to a lesser extent, the western margin of the Transvaal Hills (fig. 1). Both of these areas, at least originally, were inside the boundaries of the Rainier Mesa caldera, as discussed above, but lie to the west of the nested Ammonia Tanks caldera. Outside of the Rainier Mesa caldera, these tuffs are found only as widely scattered thin distal deposits locally present around the western caldera perimeter. We estimate that at least 99 percent of the exposed volume of these three tuffs was emplaced in this western caldera moat area, which was not included in the resurgent doming of either the Rainier Mesa or Ammonia Tanks calderas. Based on the very close timing of the tuffs of Fleur-de-Lis Ranch and Cutoff Road to the Ammonia Tanks Tuff, and the fact that they are found almost exclusively as intracaldera units, they evidently represent a late stage of co-resurgent (or late-resurgent) volcanism in the Timber Mountain resurgent cauldron cycle. Their petrologic similarity to the major Timber Mountain units supports the idea that they are comagmatic. We thus include them here in the Timber Mountain Group.

In Sawyer and others (1994) and Slate and others (2000), the tuff of Cutoff Road (Tmc) was included as part of the Beatty Wash Formation (Tvw). This formation is mostly sedimentary, but includes numerous distal tuffs, mainly ash-fall tuffs of the about 11–10.5 Ma rhyolite of Rainbow Mountain (Trt, Trl, and Tri), a unit that consists mostly of lava domes erupted from a broad source area in the eastern Bullfrog Hills. Unlike the tuff of Cutoff Road, the rhyolite of Rainbow Mountain is totally unrelated to the Timber Mountain resurgent cauldron cycle. We do not object to the definition of the Beatty Wash Formation; sometimes practical considerations necessitate grouping sediments and intercalated thin distal tuffs into single map units, even when the tuffs that are thus grouped are unrelated. But in those areas where the tuff of Cutoff Road is thick enough to map as an individual unit, it should be grouped with the other tuffs of the Timber Mountain Group, not with the unrelated rhyolite of Rainbow Mountain.

In summary, we have redefined the stratigraphic nomenclature based on two concepts we believe nearly all experts in volcanic rocks would agree with (1) that the resurgent cauldron cycle (Smith and Bailey, 1968) is the best model to use in defining and grouping formations related to ash-flow calderas, and (2) that petrographic groupings should never override field relationships and radiometric dating as the basis for defining stratigraphic nomenclature.

Description of Map Units

Volcanic rock names were adopted primarily from Minor and others (1993), who used the International Union of Geological Sciences (IUGS) total alkali-silica classification (Le Bas and others, 1986). Volcanic rock names are, however, based on field criteria when chemistry is unavailable. Modifiers are sometimes added, such as high-silica rhyolite for rhyolites with >75 percent SiO^2, and quartz trachyte for tuffs that have the major-element bulk composition of trachyte in the IUGS classification scheme, but abundant modal quartz. Phenocryst abundances are median values determined by Warren and others (2000) by point-counting thin sections of samples collected throughout the southwestern Nevada volcanic field, and may therefore represent a broader compositional range than is found in the map area. For rocks that vary in porosity, owing to variable welding in tuffs, the median phenocryst abundances were determined predominantly from dense samples; hence, abundances in nonwelded equivalents have similar proportions of phenocrysts but lower abundances. Descriptions of the Paleozoic and Late Proterozoic rock units are condensed from the more complete version by Monsen and others (1992), except for the Eleana Formation, which was rewritten based on new work by Trexler and others (1996).

Tertiary volcanic nomenclature is modified from Sawyer and others (1994) and Warren and others (2000), as discussed above. Reported ages are based mainly on $^{40}Ar/^{39}Ar$ age determinations (see Wahl and others, 1997, and references therein). Magnetic polarity data were determined primarily by M. Hudson and are compiled here from Wahl and others (1997).

Surficial Deposits

Qa **Young alluvial deposits (Holocene)—**Gravel, sand, and silt; intermixed and interbedded. Grayish brown, pale yellowish brown, light brownish gray to light gray, unconsolidated to poorly consolidated, poorly to moderately well-sorted, nonbedded to well-bedded, locally crossbedded. Clasts are angular to subrounded, mostly <0.5 m in diameter, but up to 2 m in diameter near mountain fronts. Sand and silt present as matrix and lenses; rarely forming continuous beds. Where gravelly, forms irregular surfaces with bar-and-swale topography and braided channels. Where sandy, surface is flat and smooth. Little or no pavement, varnish, or soil development. Maximum thickness about 10 m

Qp **Playa deposits (Holocene)—**Silt, fine sand, and clay; poorly to moderately well-consolidated, light grayish brown, calcareous, moderately well-sorted, thin-bedded, polygonal desiccation cracks common. Contains sparse thin beds and lenses of pebbly coarse sand. At least 20 m thick

Qe **Eolian sand deposits (Quaternary)—**Silty fine to medium sand, pale yellowish or grayish brown to pale orange, well-sorted, massive to poorly bedded; locally includes a few cobbles and pebbles near bedrock outcrops. Forms sheets, ramps, and vegetation-stabilized mounds. Locally reworked by slopewash and intermittent streams. Older deposits have soil development. Thickness as much as 30 m

Qlb **Lacustrine beach deposits (Holocene and late Pleistocene)—**Pebbly sand beach deposits of late Pleistocene pluvial lakes, which form low discontinuous ridges near playas. Sand is yellowish gray, moderately sorted, mostly medium-to coarse-grained, weakly consolidated, slightly pebbly. Ridges are 1–3 m high, commonly covered with a pebble to coarse-sand lag; surface clasts have a weakly developed desert varnish. Thickness less than 3 m

Qs **Middle alluvial deposits (Pleistocene)—**Gravel, sand, and silt; intermixed and interbedded, light gray, pinkish gray, and yellowish to grayish brown, weakly to moderately well-consolidated, nonbedded to well-bedded. Clasts are unsorted to moderately well-sorted, angular to subrounded. Clasts commonly less than 0.5 m in diameter, but locally as much as 2 m in diameter; matrix is sandy to silty. Sand is discontinuously to moderately well-bedded, locally crossbedded, moderately well-sorted. Surface is planated with moderately packed to densely packed pavement; pavement clasts are moderately to well varnished. In places, thin eolian sand deposits mantle the surface. Soil development varies from a cambic B horizon and a stage I–II carbonate horizon to an argillic B horizon and an approximately 1-m-thick, stage III–IV carbonate horizon. Thickness less than 1 m to at least 10 m

QTc **Colluvium (Holocene to Pliocene)—**Angular to subangular granule- to boulder-sized clasts with variable amounts of sand, silt, and clay as matrix. Generally unsorted and nonbedded to poorly bedded; locally cemented by carbonate. Matrix probably partly of eolian origin. Forms talus deposits and thin mantles of debris along flanks of steep slopes; deposited chiefly by mass-wasting processes. Colluvium-mantled surfaces commonly have ribbed or fluted appearance due to gullying and development of stony-surface lags. Mainly Holocene to middle Pleistocene age. Thickness generally less than 3 m

QTs **Old alluvial deposits (early Pleistocene and Pliocene)—**Gravel, sand, and silt; intermixed and interbedded, light brownish gray to light gray, mostly poorly sorted, nonbedded to poorly bedded, and moderately to well cemented with carbonate. Clasts are angular to subrounded, mostly <0.5 m in diameter, but up to 1 m near mountain fronts. Locally consists of moderately well-bedded, poorly to moderately well-sorted pebble to cobble gravel in a sand and silt matrix. Surface is eroded and dissected; commonly forms rounded ridges or ballenas. Pavement, where preserved, is generally densely packed and includes tabular fragments cemented by pedogenic carbonate and opaline silica; varnish on pavement clasts is variable but commonly strongly developed. Soils typically consist of a stage III–IV carbonate horizon as much as 2 m thick; argillic horizons are mostly eroded. Thickness may be greater than 40 m

Cenozoic Bedrock

Qby **Pleistocene basalt—**Trachybasalt, black to reddish brown; median 1.7 percent total phenocrysts of olivine and rare to absent plagioclase. Occurs as two cinder cones with associated aa flows known as Little Black Peak and Hidden cones; only slightly dissected. Dated at about 0.35 Ma (Fleck and others, 1996; Crowe and others, 1995). Normal magnetic polarity. Maximum thickness about 200 m

Typ **Basalt of the Thirsty Mountain shield volcano (Pliocene)—**Sequence of black to reddish-brown basaltic trachyandesite lavas, lesser scorias, and rare high-level dikes forming a broad, moderately dissected shield volcano at Thirsty Mountain. Median 12.5 percent total phenocrysts: 7.5 percent plagioclase, 5 percent olivine, and traces of apatite and clinopyroxene. Reversed magnetic polarity. Dated at 4.63 Ma (Fleck and others, 1996). Linear, northeast-trending master-feeder vent is inferred to be mostly buried beneath capping lava flows based on northeast-elongate crest of the shield volcano and roughly coincident-pronounced aeromagnetic anomalies (Grauch and others, 1997). Maximum thickness of about 200 m

Tgs **Older gravels (lower Pliocene and Miocene)—**Yellowish-gray to grayish-tan gravel deposits, mostly of alluvial-fan origin; poorly to partially consolidated, commonly calcareous; poorly sorted, mostly with sandy matrix, and with local thin interbeds of sandstone and mudstone. Clasts are angular to subrounded, consisting of various tuffs, lavas, and sedimentary rocks from surrounding highlands; pebbles predominate but cobbles and boulders up to 2 m are common; clasts as large as 5 m are rare. Locally includes intercalated playa deposits in middle part of unit, southeast of Oasis Mountain hogback, as well as widely scattered bedded tuffs and landslide breccias, which are more common in lower part of unit. Deeply dissected but poorly exposed; erosional slopes are typically covered with lag gravels. Unit is generally only slightly tilted and faulted; however, significant faulting and tilting of beds up to 20° is locally present in northwestern Crater Flat, below an ashfall tuff dated at 10.5 Ma. Unit is everywhere younger than the 11.6 Ma Rainier Mesa Tuff (Tmr); locally interbedded with volcanic units including volcanic rocks of Twisted Canyon caldera (Tmt; about 11.55 Ma), tuffs and lavas of the Thirsty Canyon Group (Tt; 9.43–9.15 Ma), and Spearhead Member of the Stonewall Flat Tuff (Tsp; 7.5 Ma). Locally interfingers at top with 4.63 Ma basalt of Thirsty Mountain (Typ). Maximum exposed thickness at least 200 m and probably much thicker locally in subsurface, in western part of Oasis Valley basin

Tba **Younger bedded tuffs (Miocene)—**White to cream-colored and light-gray nonwelded rhyolite tuffs that are intercalated within older gravels (Tgs) in the vicinity of Oasis Mountain and in northeastern Bullfrog Hills. Tuffs are mostly of ash-fall origin but also include ash-flow and water-lain tuffs, including distal tephras correlative with rhyolite of Rainbow Mountain (Trt, Trl, and Tri), rhyolite of Obsidian Butte (Tsr), and Spearhead Member of the Stonewall Flat Tuff (Tsp). The lowermost part of unit is a lateral equivalent to uppermost part of the Beatty Wash Formation (Tvw) mapped further east, based on intercalated tuffs. Maximum exposed thickness about 10 m

Tsp **Spearhead Member of the Stonewall Flat Tuff (Miocene)—**Mildly peralkaline rhyolite ash-flow tuff; light to very light brown where nonwelded and, rarely, light to medium reddish brown where moderately welded; erupted from Stonewall Mountain caldera at 7.5 Ma (Sawyer and others, 1994). Median 3.2 percent total phenocrysts: 0.2 percent quartz, 2.4 percent sanidine, 0.4 percent plagioclase, 0.1 percent clinopyroxene, and traces of biotite, hornblende, and fayalite which together total about 0.1 percent. Intercalated in unit Tgs. Commonly concealed on hillsides by colluvial lag gravels derived from overlying older gravels (Tgs). Tuff is commonly reworked and interbedded with tuffaceous gravel lenses. Thin white ash layer commonly present at base of map unit may be an ashfall deposit related to the rhyolite of Obsidian Butte (Tsr). Normal magnetic polarity. Maximum exposed thickness of about 20 m

Tsb **Basalts generally of Thirsty Canyon age (Miocene)—**Widespread mafic lava flows, eroded cinder cones, and local feeder dikes erupted from numerous centers between about 8.5 and about 10 Ma. Consists of dark-gray to reddish-brown trachybasalt, basalt, and basaltic andesite, and subordinate hawaiite and mugearite. Variable phenocryst content of olivine and plagioclase, with lesser to absent clinopyroxene, biotite, and orthopyroxene, and rare kaersutitic amphibole and apatite. Majority of these mafic rocks were erupted immediately before, during, or after emplacement of the Thirsty Canyon tuffs in close proximity to Black Mountain caldera; however, a number of these basalts interfinger either with the 9.5–9.9 Ma rhyolite of Oasis Valley (Tso) or with the about 8.8 Ma rhyolite of Obsidian Butte (Tsr). Maximum exposed thickness at least 100 m

Tsr **Rhyolite of Obsidian Butte (Miocene)—**Generally aphyric, flow-laminated rhyolite lava flows and subordinate related pyroclastic and sedimentary rocks exposed only in northwest corner of map area. Some flows contain sparse feldspar and biotite. Dated at 8.8 Ma (Noble and others, 1991). Maximum exposed thickness of about 150 m

Tt **Thirsty Canyon Group (Miocene)—**Peralkaline assemblage of ash-flow tuffs, lavas, and related nonwelded tuffs erupted from Black Mountain caldera between 9.15 and 9.43 Ma. The oldest member of Group, comendite of Ribbon Cliff (Ttc), was emplaced as a precaldera complex of flows and domes. The Trail Ridge (Ttt) and Pahute Mesa Tuffs (Ttp) are the largest volume units and likely the major, and possibly the only units associated with caldera collapse. Following caldera collapse, trachyte lavas of Pillar Spring (Tts) and the Gold Flat Tuff (Ttg) accumulated in caldera and the latter overflowed mainly to north and south (Minor and others, 1998). Group is everywhere subdivided on the map and is used as a unit only on cross sections

Ttg **Gold Flat Tuff—**Strongly peralkaline silicic (pantelleritic) welded ash-flow tuff erupted at 9.15 Ma and deposited in and adjacent to moat of Black Mountain caldera. Light bluish green; weathers greenish-ochre-yellow. Median 12.7 percent total phenocrysts: 0.4 percent quartz, 11.1 percent sanidine and lesser anorthoclase, 1 percent plagioclase, and traces of clinopyroxene, fayalite, biotite, and arfvedsonite totaling about 0.2 percent. Contains rare primary fluorite and enigmatite. Anomalous normal magnetic polarity. Maximum thickness of 30 m in caldera

Tts **Trachyte lavas of Pillar Spring—**Crystal-rich to very crystal-rich trachyte to quartz trachyte lava flows, associated tuff and tuff breccia, and porphyritic syenite intrusive rocks that partly fill and overlap Black Mountain caldera. Lavas contain abundant to very abundant alkali feldspar (sanidine and lesser anorthoclase), moderately abundant plagioclase, and traces of clinopyroxene, fayalite, and rare biotite. Magnetic polarity is reversed. Maximum exposed thickness of 125 m

Ttt **Trail Ridge Tuff—**Widespread welded comendite (peralkaline rhyolite) ash-flow tuff; typically tan or pink where nonwelded; rusty red or greenish brown where welded. Median 13 percent total phenocrysts: 12 percent sanidine and lesser anorthoclase, 0.5 percent plagioclase, and traces of clinopyroxene, fayalite, and quartz, totaling about 0.5 percent. Anomalous reversed magnetic polarity. Maximum exposed thickness about 80 m

Ttp **Pahute Mesa Tuff—**Comendite ash-flow tuff; typically tan or pink where nonwelded; rusty red or greenish brown where welded. Median 4.9 percent total phenocrysts: 0.1 percent quartz, 4.4 percent sanidine and lesser anorthoclase, 0.2 percent plagioclase, and about 0.1 percent each of Fe-rich clinopyroxene and fayalite. Subjacent and closely related cooling unit, Rocket Wash Tuff, found north of map area, dated at 9.4 Ma (Sawyer and others, 1994). Magnetic polarity is anomalous reversed. Maximum exposed thickness of about 35 m

Ttc **Comendite of Ribbon Cliff—**Precaldera crystal-rich to very crystal-rich comendite and trachyte lava flows and domes exposed marginal to Black Mountain caldera. Median 20.8 percent total phenocrysts: 17.9 percent sanidine and lesser anorthoclase, 2.9 percent plagioclase, and traces of clinopyroxene and fayalite, and rare biotite. Maximum exposed thickness of about 100 m

Tsa **Andesite of Sarcobatus Flat (Miocene)—**Local sequence of andesitic lava flows with intercalated minor tuffaceous sedimentary rocks exposed in low hills along edge of Sarcobatus Flat in northwestern part of map area. Lava is medium to dark gray, weathers to dark brown, and is commonly platy and flow-folded with phenocrysts of plagioclase and subordinate orthopyroxene and hornblende. Dated at 9.3 Ma (unpub. data of Fleck cited by Minor and others, 1997). Maximum exposed thickness about 100 m

Tvmu **Volcanic units intervening between the Ammonia Tanks and Pahute Mesa Tuffs in Oasis Valley basin (Miocene)—**Collective unit used only on cross sections that includes rhyolite of Oasis Valley (Tso) and Beatty Wash Formation (Tvw)

Tso **Rhyolite of Oasis Valley (Miocene)—**Rhyolite lavas and lesser related ash fall and block-and-ash flow tuffs erupted in Oasis Valley area between 9.5–9.9 Ma. Lavas typically are medium gray whereas tuffs are white or light tan. Exposed at mouth of Thirsty Canyon and immediately west of Transvaal Hills. Median 12.7 percent total phenocrysts: 4.5 percent quartz, 3.8 percent sanidine, 3.8 percent plagioclase, 0.3 percent biotite, and 0.3 percent hornblende, and a trace of clinopyroxene. Maximum exposed thickness of about 70 m

Tld **Lavas of Dome Mountain (Miocene)—**Black vesiculated trachybasalt and trachyandesite lava with phenocrysts of olivine, plagioclase, and lesser clinopyroxene. One small exposure in southeastern part of map is westernmost tip of a large mesa-like volcanic edifice (Dome Mountain) of basaltic lavas formed in southern moat of Ammonia Tanks caldera between about 11 and 10 Ma. A larger exposure is a separate, petrographically correlated volcanic edifice in the northwestern moat of same caldera. Exposed thickness is about 35 m

Tdu **Upper Lava of Springdale Mountain (Miocene)—**Rhyolite lava forming upper part of a sequence of late differentiates related to underlying Trachyte of Donovan Mountain (Tdt). Lava is light gray, flow-banded and -foliated, locally lithophysal, and contains abundant sanidine, sparse plagioclase, biotite, and rare clinopyroxene phenocrysts. Commonly vitrophyric at base; unit locally includes a nonwelded to moderately welded trachyte ash-flow tuff. Maximum preserved thickness about 150 m

Tdl **Lower Lava of Springdale Mountain (Miocene)—**Dacite lava forming lower part of a sequence of late differentiates related to trachyte of Donovan Mountain (Tdt). Lava is medium to dark gray, weathering to dark brown; flow-foliated and -folded, with sparse to abundant sanidine and plagioclase, biotite, and lesser clinopyroxene. Includes local pyroclastic deposits. Maximum exposed thickness about 125 m

Tdb **Tuffaceous sedimentary breccia of Springdale Mountain (Miocene)—**Poorly to moderately well-bedded breccia, conglomerate, pebbly sandstone, and minor siltstone with a reworked tuffaceous matrix, and rare thin interbeds of silicic ash-fall tuff. Contains subangular clasts as large as 0.5 m, mostly of trachyte of Donovan Mountain (Tdt). Maximum exposed thickness about 35 m

Tdt **Trachyte of Donovan Mountain (Miocene)—**Sequence of crystal-rich mafic trachyte flows, and lesser local basaltic flows in southwestern part of map. Flows are about 10 m thick on average and form resistant ledges owing to alternation of dense flow interiors with rubbly, oxidized flow tops and bases. Trachyte is dark brown to dark gray or red (in oxidized flow margins) and has median 19.6 percent total phenocrysts: 10.4 percent plagioclase, 7.6 percent sanidine, 0.8 percent biotite, and 0.8 percent clinopyroxene. Normal magnetic polarity dated at 10.4 Ma (Sawyer and others, 1994). Maximum exposed thickness about 300 m

Tvw **Beatty Wash Formation (Miocene)—**Sequence of nonwelded rhyolitic bedded tuffs, lowest of which are related to the youngest lavas of Timber Mountain Group (rhyolite of Coffer's Well; Tml) and the youngest of which are distal tuffs of the rhyolite of

Rainbow Mountain (Trt). Includes interbeds of tuffaceous alluvium and of breccias derived from rhyolite of Coffer's Well. Maximum exposed thickness at least 200 m

Trl **Rhyolite lavas of Rainbow Mountain (Miocene)—** Rhyolite lavas erupted from vent areas in eastern Bullfrog Hills in southwest part of map. Stratigraphic constraints and existing geochronology suggest sequence dates from about 10.5–11 Ma (Connors and others, 1998). Ranges in composition from crystal-poor to crystal-rich and from high- to low-silica rhyolite. Distinguished from other post-11 Ma quartz- and biotite-bearing rhyolites of the southwest Nevada volcanic field by a very high plagioclase-to-sanidine ratio (sanidine commonly absent) and by absence or rarity of hornblende except in lowest-silica and most crystal-rich flows. Intimately interbedded with related rhyolite tuffs (Trt). Maximum exposed thickness of rhyolite lavas and tuffs of Rainbow Mountain together is at least 400 m

Trt **Rhyolite tuffs of Rainbow Mountain (Miocene)—** Tuffs related to, and mostly interbedded with above lavas, but extending beyond them; includes ash flow, block-and-ash flow, ash fall, and water-lain tuffs. Locally includes partly consolidated alluvium that is interbedded with tuffs near base of unit

Tri **Felsic intrusions of rhyolite of Rainbow Mountain (Miocene)—**Intrusive rhyolite ranging from crystal-poor, flow-banded rhyolite to crystal-rich porphyry with an aphanitic groundmass; typically strongly hydrothermally altered

Tyx **Younger landslide breccias (Miocene)—**Includes both rock-avalanche breccias and giant gravity-slide blocks in west-central and southern part of map. In northern Bullfrog Hills, unit includes overlying and intercalated ash fall tuffs petrographically correlated to rhyolite tuffs of Rainbow Mountain (Trt). Elsewhere, breccias of this unit are older, such as at Oasis Mountain where they underlie Ammonia Tanks Tuff (Tma). Most if not all of the older breccias of this group include clasts of Rainier Mesa Tuff (Tmr). Breccia clasts and slide blocks include rock units ranging from Paleozoic sedimentary rocks through entire sequence of Tertiary units that predate rhyolite of Rainbow Mountain (Trl, Trt, and Tri). Breccias are highly variable in color but most commonly are bleached white or stained bright red owing to common strong hydrothermal alteration. Thickness uncertain because tilting and especially faulting are difficult to discern in breccias

Tvb **Basalts (Miocene)—**Black to dark-gray extrusive rocks, including vesiculated to dense lavas and reddened flow-margin breccias and scorias, erupted between about 10.5–11.4 Ma. Stratigraphically constrained as being roughly coeval with or younger than tuff of Cutoff Road (Tmc) and older than trachyte of Donovan Mountain (Tdt), or constrained to same interval by radiometric dates. Locally contains interbeds of alluvium, rock-avalanche breccia (Tyx), and tuff of Cutoff Road (Tmc). Contains moderate amounts of plagioclase, olivine, and lesser clinopyroxene phenocrysts. Maximum exposed thickness of about 500 m

Tvbi **Gabbro dikes (Miocene(?))—**Dark green hornblende gabbro dikes that resemble dikes just south of map that have been dated at 26.1 Ma and 16.6 Ma (K/Ar, hornblende, and biotite, respectively; Monsen and others, 1992). These dates are untrustworthy owing to strong chloritic alteration and associated potassium loss. In composition, the closest match for these dikes is to basalts erupted between about 10.5 and 11.4 Ma (unit Tvb) nearby, to north and northwest, in upper plate of the Bullfrog Hills-Fluorspar Canyon detachment fault. Those basalts must have been fed by dikes that cut the lower plate, and that are likely to be uplifted and exposed nearby as a result of tectonic denudation along detachment fault

Timber Mountain Group (Miocene)—Assemblage of rocks that range in composition from high-silica rhyolite to trachyte and were erupted from Timber Mountain caldera complex between 11.4–11.7 Ma. Includes two very large volume ash-flow tuffs, Ammonia Tanks (Tma) and Rainier Mesa Tuffs (Tmr), as well as numerous minor tuffs and lavas erupted before, after, and between emplacement of these major caldera-forming eruptive units

Tmc **Tuff of Cutoff Road—**Rhyolite ash-flow tuff, pink, incipiently welded. Median 10.6 percent total phenocrysts: 4.6 percent sanidine, 5.2 percent plagioclase, 0.7 percent biotite, 0.1 percent sphene, trace of hornblende and notably contains almost no quartz. Normal magnetic polarity. Maximum exposed thickness of about 250 m

Tmf2 **Upper tuff of Fleur-de-Lis Ranch—** Rhyodacitic-welded ash-flow tuff, typically greenish gray or brownish gray, and containing median 15.5 percent total phenocrysts: 13.4 percent plagioclase, 0.4 percent sanidine, 1.5 percent biotite, and 0.2 percent clinopyroxene. Uppermost of three petrographically indistinguishable units erupted on west side of Timber Mountain caldera complex and consisting of a lava sequence sandwiched between two tuffs. Normal magnetic polarity. Maximum exposed thickness of about 200 m

Tmwr **Lavas of Fleur-de-Lis Ranch and of West Cat Canyon—**Unit includes two physically separated but petrographically, chemically, and temporally similar sequences of rhyodacitic lava flows. Lava of Fleur-de-Lis Ranch is exposed in northern half of the Oasis Mountain, whereas lava of West Cat Canyon is exposed in western moat of Ammonia Tanks caldera. Both have normal magnetic polarity. Maximum exposed thicknesses of about 350 m for lava of Fleur-de-Lis Ranch and about 250 m for lava of West Cat Canyon

Tmf1 **Lower tuff of Fleur-de-Lis Ranch—**Rhyodacitic-welded ash-flow tuff that is petrographically indistinguishable from upper tuff of Fleur-de-Lis Ranch (Tmf2) and is distinguished based on stratigraphic position and magnetic polarity. Reversed magnetic polarity. Maximum exposed thickness of about 150 m

Tmai **Subcaldera intrusion of the Ammonia Tanks caldera—**Batholithic intrusion inferred to be present under Ammonia Tanks caldera and shown only on cross sections. Geometry of this body is based on a model of gravity data (Hildenbrand and others, 1999). Hypabyssal microgranite intrusions that may be cupolas of this batholith are exposed locally on east flank of Timber Mountain, about 4 km east of map

Tml **Rhyolite of Coffer's Well—**Post-caldera rhyolite lavas erupted in moat of Ammonia Tanks caldera; typically gray, red, or black (where vitreous); moderately crystal rich with subequal sanidine and plagioclase, biotite, conspicuous sphene, sparse hornblende, and rare local quartz. Normal magnetic polarity. Maximum exposed thickness of at least 50 m

Tma **Ammonia Tanks Tuff—**Crystal-rich, most commonly lavender-gray, welded ash-flow tuff erupted 11.45 Ma (Sawyer and others, 1994) from Ammonia Tanks caldera. Compositionally zoned from lower high-silica rhyolite (median 17.51 percent total phenocrysts: 3.8 percent quartz, 11.2 percent sanidine, 2.3 percent plagioclase, 0.2 percent biotite, 0.01 percent clinopyroxene, with commonly cryptic (small, sparse sphene) to upper quartz trachyte (median 24.55 percent total phenocrysts: 2.7 percent quartz, 13.0 percent sanidine, 7.5 percent plagioclase, 1.1 percent biotite, 0.25 percent clinopyroxene, with conspicuous sphene). Commonly difficult to distinguish from Rainier Mesa Tuff (Tmr); distinguished by its higher stratigraphic position, normal magnetic polarity, presence of sphene, as well as common basalt lithics and chatoyant sanidine. Unusual features of unit include strong rheomorphic lineation near crest of Oasis Mountain and high abundance of lithics on hogback immediately south of Oasis Mountain. Maximum exposed thickness of at least 1,000 m on Oasis Mountain

Tmri **Subcaldera intrusion of the Rainier Mesa caldera—**Batholithic intrusion inferred to be present under Rainier Mesa caldera and shown only on the cross sections as it is nowhere exposed. Geometry of this body is based on a model of gravity data (Hildenbrand and others, 1999)

Tmat **Rhyolite of Tannenbaum Hill—**Rhyolite lavas emplaced in moat of Rainier Mesa caldera prior to caldera-forming eruption of Ammonia Tanks Tuff (Tma). Median about 8 percent total phenocrysts: 3 percent quartz, 5 percent sanidine, traces of plagioclase and biotite, and conspicuous sphene. Typically gray, commonly flow banded. Maximum exposed thickness of about 100 m

Tmt **Tuffs and lavas of Twisted Canyon caldera—**Sequence of volcanic rocks, erupted in Twisted Canyon caldera at about 11.55 Ma, which includes one rhyolite ash-flow tuff unit, and numerous rhyolite lavas and related ash-fall tuffs emplaced above and below ash flow. Ash-flow tuff is petrographically and chemically indistinguishable from Rainier Mesa Tuff (Tmr) but is clearly a separate unit because it includes lithics and wedges of caldera-collapse breccia composed of poorly to densely welded Rainier Mesa Tuff. Exposed only as fill of Twisted Canyon caldera. Caldera fill also includes some interbedded alluvium which is included in unit, caldera-collapse breccias (Tmrx), and two small dissected olivine basalt cinder cones (Tmb). Maximum exposed thickness of about 140 m

Tmr **Rainier Mesa Tuff—**Crystal-rich welded ash-flow tuff erupted 11.6 Ma from Rainier Mesa caldera. Compositionally zoned from lower high-silica rhyolite (median 10.3 percent total phenocrysts: 4.0 percent quartz, 4.3 percent sanidine, 1.9 percent plagioclase, and 0.1 percent biotite) to upper more crystal-rich quartz trachyte (median 23.9 percent total phenocrysts: 3.3 percent quartz, 9.9 percent sanidine, 9.3 percent plagioclase, 1.2 percent biotite, 0.2 percent clinopyroxene, and traces of hornblende and orthopyroxene). Unit distinguished from Ammonia Tanks Tuff (Tma) by high quartz content, rare accessory monazite, and lack of sphene. Lower nonwelded zone is salmon pink; welded part is brown, gray, or red. Reverse magnetic polarity. Maximum exposed thickness of at least 250 m

Tmrf **Pre-Rainier Mesa rhyolite—**Sequence of mostly white to pink nonwelded tuffs, including ash-flow, ash-fall, surge, and water-lain tuffs, as well as related, petrographically similar, typically gray lavas, all of high-silica rhyolite composition. Several eruptive units of this unit have yielded ages ranging from 11.62 to 11.7 Ma ($^{40}Ar/^{39}Ar$, sanidine; Sawyer and others, 1994; M.A. Lanphere, USGS, unpub. data). Syntectonic nature of unit is reflected in prevalent fanning dips, locally with as much as 35° of decrease in dips upsection, as well as common interfingering of unit with older landslide breccias (Tox). Small fraction of tuffs and lavas in unit are petrographically similar to first-erupted part of Rainier Mesa Tuff (Tmr), whereas majority are more evolved and crystal-poor. Median phenocryst assemblage for dominant crystal-poor facies is 5.5 percent total phenocrysts: 2.1 percent quartz, 2.0 percent sanidine, 1.3 percent plagioclase, and about 0.1 percent biotite. Maximum exposed thickness of about 400 m

Tms **Lake sediments of Oasis Mountain—**Interbedded shale, sandstone, marl, and freshwater limestone, all tuffaceous; ivory, ochre, yellowish green, and tan in color; thinly laminated, with ripple marks and mud cracks locally preserved. Mapped only on Oasis Mountain where it overlies Ammonia Tanks Tuff (Tma) and underlies the lower tuff of Fleur-de-Lis Ranch (Tmf1). Maximum exposed thickness of about 80 m

Tmb **Basalts of Timber Mountain age—**Black to reddish-brown basalt lavas and lesser scoria deposits and feeder dikes emplaced between eruptions of Rainier Mesa (Tmr) and Ammonia Tanks Tuffs (Tma), or immediately below Rainier Mesa Tuff (Tmr) and immediately above Pre-Rainier Mesa rhyolite (Tmrf) or breccias associated with Timber Mountain tuffs (Tmrx). Typically phenocryst-poor with ≤5 percent olivine and lesser plagioclase phenocrysts. Maximum exposed thickness of about 60 m

Tmrx **Breccia associated with Timber Mountain tuffs—**Caldera-collapse breccias associated with the Rainier Mesa Tuff (Tmr) and the tuff of Twisted Canyon (Tmt); typically bright red or bleached white where hydrothermally altered or dark purplish brown where relatively unaltered. In the Transvaal Hills, caldera-collapse breccia is intercalated with intracaldera Rainier Mesa Tuff (Tmr) and consists predominantly of large, internally shattered clasts of Paintbrush Group (Tp) tuffs. Similar breccias are exposed along southwestern margin of Rainier Mesa caldera. Caldera-collapse breccias also form an inboard-thinning wedge around eastern margin of Twisted Canyon caldera, in south-central map area; these breccias are composed predominantly of clasts of Rainier Mesa Tuff (Tmr) and of lava of pre-Rainier Mesa rhyolite (Tmrf). Maximum exposed thickness of about 70 m in southern Transvaal Hills

Tox **Older landslide breccia (Miocene)—**Rock-avalanche megabreccias and subordinate talus breccias deposited before emplacement of 1.6 Ma Rainier Mesa Tuff (Tmr). Dominant volume was deposited in a major tectonic event between 12.7–11.6 Ma, and breccia is locally interbedded with the pre-Rainier Mesa rhyolite (Tmrf). Most breccias of this interval are composed of clasts of Tiva Canyon Tuff (Tpc) and other units of the Paintbrush Group (Tp). One large breccia wedge of this age is exposed along north side of Bare Mountain and is composed predominantly of clasts of Paleozoic rocks and of lower Miocene and Oligocene sediments (Tos and Ttc), and 14 Ma quartz-trachyte porphyries (Tli). In the north-central part of map, breccias of this unit predate 12.7 Ma Tiva Canyon Tuff (Tpc), mantle the eroded scarp of the Hogback fault (fig. 1), and are composed mainly of clasts of rhyolite lavas of Quartz Mountain (Tqc and Tqh) and tuff of Sleeping Butte (Tqs). Maximum exposed thickness of at least 100 m

Tps **Sedimentary fill of Claim Canyon caldera (Miocene)—**Tuffaceous sedimentary breccias and water-lain tuffs that fill moat of Claim Canyon caldera, source of Paintbrush Group (Tp). Most of tuffaceous material in unit is probably derived from rhyolite of Windy Wash (Tpn) based on phenocryst assemblage. Stratal tilts in unit indicate that much of exposed sequence was deposited during caldera resurgence; dips reflect resurgent doming but are less than dips in underlying intracaldera Tiva Canyon Tuff (Tpc) and decrease upsection. Thickness uncertain owing to poor exposure

Tp **Paintbrush Group (Miocene)—**Sequence of alkali-rhyolite to trachyte tuffs and lavas erupted from Claim Canyon caldera between 12.7–12.8 Ma. Group consists of one unit only on cross section *B–B′*, where it includes a lava sequence that postdates Tiva Canyon Tuff (Tpc) but that petrographically resembles crystal-rich trachyte subunit (Tpcr) of that formation

Tpn **Rhyolite of Windy Wash—**Predominantly a complex of rhyolite lava domes and related tuffs erupted in southern moat of Claim Canyon caldera. Lavas are light gray or tan whereas the tuffs are off-white; from a distance, both are a yellow-greenish cream color. Main group of flows have a median of 20.45 percent total phenocrysts: 5 percent quartz, 9.6 percent sanidine, 5.4 percent plagioclase, 0.4 percent biotite, and 0.05 percent sphene; whereas the lesser uppermost group of flows (“rhyolite of the Loop”; Sawyer and others, 1994) have a median of 14.6 percent total phenocrysts: 5.1 percent quartz, 5.2 percent sanidine, 3.7 percent plagioclase, 0.6 percent biotite, and no sphene. Oldest flows and tuffs appear to be tilted by resurgent doming of caldera; whereas youngest flows, dated at about 12.5 Ma, are apparently untilted. Maximum exposed thickness of about 200 m

Tpi **Intrusive facies of rhyolite of Windy Wash—**Feeder dikes for lavas and tuffs, many which have both massive and pyroclastic facies within single dikes. Most dikes are emplaced in faults formed during resurgence of Claim Canyon caldera and cut intracaldera Tiva Canyon Tuff (Tpc). Intrusive/extrusive transition is locally exposed

Tpc **Tiva Canyon Tuff—**Voluminous, densely welded ash-flow tuff erupted at 12.7 Ma from Claim Canyon caldera. Reverse magnetic polarity. Unit is compositionally zoned from lower crystal-poor, high-silica rhyolite (Tpcp) to upper crystal-rich trachyte (Tpcr), wherein the compositional change between these two units typically is developed over 1–5 m with no cooling break. Locally, mafic-upward compositional zonation is repeated above a partial cooling break and subunit above that break has been called tuff of Pinyon Pass (Tpcy; Christiansen and Lipman, 1965), which is only very locally preserved outside Claim Canyon caldera, but is mapped in major extracaldera exposure (at about 116° 37′ W. and 36° 58′ N.). Within Claim Canyon caldera alone, Tiva Canyon Tuff is divided into three compositional subunits (Tpcp, Tpcr, and Tpcy), all of which are different mixtures of the same bimodal group of high-silica rhyolite- and trachyte-pumice lapilli and ash. Maximum exposed thicknesses of entire unit inside and outside caldera are at least 1,500 m and at least 200 m, respectively

Tpcy **Tuff of Pinyon Pass—**Low-silica rhyolite; typically medium rusty red where densely welded and light yellow where nonwelded. Compositionally intermediate between crystal-rich trachyte (Tpcr) and crystal-poor rhyolite (Tpcp) subunits, described below. Bulk tuff varies from about a 95:5 to 70:30 mixture of high-silica rhyolite- and trachyte-pumice lapilli and ash, from base to top, respectively

Tpcr **Crystal-rich trachyte—**Typically dark rusty brown, dark red, or dark purplish gray; and densely welded throughout. Median about 13.7 percent total phenocrysts: about 10 percent sanidine, 3 percent plagioclase, 0.5 percent biotite, 0.2 percent clinopyroxene, and traces of sphene, fayalite, and rare hornblende and quartz. Bulk tuff is roughly a 70:30–50:50 mixture of high-silica rhyolite- and trachyte-pumice lapilli and ash, respectively

Tpcp **Crystal-poor rhyolite—**Typically light gray or light to medium red, very lithic-poor, densely welded except at base. Outside caldera, subunit is characteristically strongly lithophysal near upper contact with Tpcr. Median 3.0 percent total phenocrysts: 2.9 percent sanidine, and traces of clinopyroxene, plagioclase, sphene, biotite, and rare hornblende and quartz, totaling about 0.1 percent. Subunit is almost purely derived from high-silica-rhyolite pumice lapilli and ash, but locally includes rare (<1 percent) trachyte pumices in upper part

Tpy **Yucca Mountain Tuff—**Welded high-silica rhyolite ash-flow tuff that is aphyric (median <0.1 percent phenocrysts of sanidine, biotite, plagioclase, and sphene), but otherwise resembling lower rhyolitic part of Tiva Canyon Tuff (Tpc) in range of colors, welding, lithophysae development, and groundmass crystallization in hand specimens. From a distance, unit appears dark brown as compared to rusty medium brown of Tiva Canyon Tuff (Tpc). Reversed magnetic polarity. Maximum exposed thickness of about 200 m inside Claim Canyon caldera and about 75 m outside

Tpet **Rhyolite of Echo Peak—**Consists of a rhyolite lava flow and petrographically similar overlying ash-flow tuff found only inside Claim Canyon caldera. Median 10.74 percent total phenocrysts: 0.14 percent quartz, 6.3 percent sanidine, 3.8 percent plagioclase, 0.5 percent biotite, and traces of clinopyroxene and sphene. Reversed magnetic polarity. Maximum exposed thickness of about 300 m

Tpp **Pah Canyon Tuff—**Variably welded low-silica rhyolite ash-flow tuff with two partial cooling breaks evident in many exposures. Typically light to dark rusty orange. Brownish medium gray where very thick—inside Claim Canyon caldera. Median 7.3 percent total phenocrysts: 0.1 percent quartz, 3.3 percent sanidine, 3.5 percent plagioclase, 0.4 percent biotite, and traces of clinopyroxene and rare sphene. Reversed magnetic polarity. Maximum exposed thickness of about 200 m inside caldera, and <40 m outside caldera

Tpt **Topopah Spring Tuff—**Voluminous welded ash-flow tuff sheet erupted at 12.8 Ma from Claim Canyon caldera; light orange (nonwelded base) to dark olive brown (welded) in color, or black where dense and vitrophyric. Compositionally zoned from lower crystal-poor, high-silica rhyolite (median 0.93 percent total phenocrysts: 0.3 percent sanidine, 0.6 percent plagioclase, 0.03 percent biotite, and trace quartz) to upper crystal-rich trachyte (median 11.67 percent total phenocrysts: 7.2 percent sanidine, 3.8 percent plagioclase, 0.45 percent biotite, 0.12 percent clinopyroxene, and <0.1percent quartz). Distinguished from the Tiva Canyon Tuff (Tpc) by absence of sphene and lower minimum phenocryst abundance (comparing lower, rhyolitic parts). Very locally contains well-rounded pebble- to boulder-size lithics of light greenish-gray Miocene granite in several sites around margins of Claim Canyon caldera. At one of these sites, near a locality named Prospector's Pass in northwestern Crater Flat, an additional compositional (hornblende-bearing) subunit is locally present at top of tuff and consists of a largely vitrophyric section with six partial cooling breaks. Where lithophysal, the characteristic vug size is about 10 cm, as compared to about 5 cm or less for Tiva Canyon Tuff (Tpc). Normal magnetic polarity. Maximum exposed thickness of about 180 m

Tpx **Breccias associated with tuffs of Paintbrush Group—**Caldera-collapse breccias that crop out as wedges and irregular masses intercalated with all three subunits of Tiva Canyon Tuff (Tpcp, Tpcr, and Tpcy) within Claim Canyon caldera. Consists predominantly of large, internally shattered clasts from volcanic units predating Tiva Canyon Tuff (Tpc), especially Yucca Mountain (Tpy) and Topopah Spring Tuffs (Tpt), most commonly in a matrix of nonwelded Tiva Canyon Tuff. The largest exposure is in northwestern moat of Claim Canyon caldera, where giant (commonly >100 m) lenticular breccia masses are suspended in a matrix of nonwelded tuff and are aligned parallel to subvertical caldera margin. Maximum exposed thickness of at least 100 m

Tht **Calico Hills Formation (Miocene)—**Sequence of numerous thin high-silica rhyolite block-and-ash flows and other bedded tuffs, typically very light yellow, characteristically zeolitized and bearing abundant lithic fragments of flow-banded red and gray lava that is petrographically similar to tuffs. Predominant crystal-poor facies has median 2.29 percent total phenocrysts: 0.9 percent quartz, 0.9 percent sanidine, 0.45 percent plagioclase, and 0.04 percent biotite. Dated at 12.9 Ma (Sawyer and others, 1994). Maximum exposed thickness of about 100 m

Tc **Crater Flat Group (Miocene)—**Sequence of metaluminous rhyolite tuffs and lavas erupted between 13.1 and 13.5 Ma from vents in general area of central caldera complex of southwest Nevada volcanic field (Sawyer and others, 1994). Collective unit used only on cross section *B–B′*

Tcb **Bullfrog Tuff—**Rhyolite ash-flow tuff; generally lavender or pale orange where poorly to moderately welded and dark red where densely welded. Median 13.34 percent total phenocrysts: 2.5 percent quartz, 4.7

percent sanidine, 5.7 percent plagioclase, 0.34 percent biotite, and 0.1 percent hornblende; wormy resorbed quartz is characteristic. Dated at 13.25 Ma (Sawyer and others, 1994). Normal magnetic polarity. Maximum exposed thickness of about 200 m

Tcr **Rhyolite of Prospector's Pass—**Unit consists primarily of lava flows found only in northwestern Crater Flat, and tuffs interbedded with lavas and extending several kilometers beyond them. Petrographically similar to Bullfrog Tuff (Tcb) except that hornblende contents are more variable, ranging from absent to much more abundant. Lavas are flow banded and are typically pale olive gray but local dense parts of flows, which escaped the otherwise pervasive zeolitization, are black, medium green-gray (vitrophyric), or brick red (devitrified). Most tuffs are pervasively zeolitized, bedded, block-and-ash-flow tuffs, petrographically similar to lava facies, and contain abundant lithic fragments of lava facies. Dated at 13.35 Ma (M.A. Lanphere, USGS, unpub. data). Maximum exposed thickness of at least 100 m

Tct **Tram Tuff—**Rhyolite ash-flow tuff, mostly densely welded. Median 10.6 percent total phenocrysts: 3.6 percent quartz, 3.2 percent sanidine, 3.4 percent plagioclase, and 0.4 percent biotite. Dated at 13.4 Ma. Reversed magnetic polarity. Maximum exposed thickness of at least 250 m in northwestern Crater Flat

Tbg **Grouse Canyon Tuff of Belted Range Group (Miocene)—**Peralkaline rhyolite (comendite) welded ash-flow tuff erupted from Silent Canyon caldera complex (fig. 1) at 13.7 Ma. Basal ash-fall tuff is white; welded ash-flow tuff is typically dark rusty red, greenish black (vitrophyre), or dark bluish green where densely welded and devitrified but not oxidized. Compositionally zoned from lower aphyric comendite to upper crystal-rich comendite. Median 0.5 percent total phenocrysts, mostly alkali feldspar with rare quartz, plagioclase, clinopyroxene, and fayalite. Groundmass arfvedsonite is common in devitrified welded upper part. Anomalous normal magnetic polarity. Maximum exposed thickness of 100 m in northwestern part of map

Tob **Older basalts (Miocene)—**Olivine basalts consisting of thin localized flows immediately below Grouse Canyon Tuff (Tbg). Maximum exposed thickness of about 20 m

Tlt **Lithic Ridge Tuff (Miocene)—**Rhyodacitic ash-flow tuff, poorly to moderately welded, and characteristically very rich in intermediate-composition lithic fragments. Typically greenish gray or yellow-greenish tan. Median of 9.46 percent total phenocrysts: 0.5 percent quartz, 3.4 percent sanidine, 5.3 percent plagioclase, 0.26 percent biotite, and conspicuous sphene. Locally included are numerous thin nonwelded bedded tuffs that directly underlie ash-flow tuff and resemble it petrographically. Anomalous reverse magnetic polarity. Maximum exposed thickness of about 200 m

Tlp **Lavas and associated tuffs, Rhyolite of Picture Rock—**Rhyodacitic to dacitic, and lesser rhyolitic lava flows, typically dark gray-green, dark red, gray, or dark brown and coarsely porphyritic, and related light yellowish-tan and light green bedded tuffs. Related to Lithic Ridge Tuff (Tlt) based on petrographic similarity. Median 17.38 percent total phenocrysts: 0.2 percent quartz, 0.7 percent sanidine, 15 percent plagioclase, 1.3 percent biotite, 0.17 percent hornblende, and 0.01 percent sphene. Reversed magnetic polarity. Maximum exposed thickness of about 200 m

Tli **Intrusive facies, Rhyolite of Picture Rock—**Dikes that are presumed feeders for Tlp lavas, described above, based on petrographic similarity; dated at 14 Ma (Sawyer and others, 1994). Mostly found intruding Paleozoic rocks in eastern Bare Mountain. Similar dikes are found intruding unit Tot in southwestern corner of map, however strong hydrothermal alteration makes this assignment speculative

Volcanic rocks of Quartz Mountain (Miocene)—Informal group of two major ash-flow tuffs, Tqs and Tqt, along with a local sequence of rhyolite lavas emplaced immediately before and after, and between them. Lavas erupted before Tqt are only exposed to north of map. Units of this informal group probably are products of a single resurgent cauldron cycle; however, this is speculative owing to strong subsequent tectonic deformation, along with extensive burial by younger volcanic units.

Tqc **Late rhyolite of Quartz Mountain—**Rhyolite lava flows and associated tephra envelope; flow-foliated and -banded, partly vitric. Crystal-poor with sparse alkali feldspar and rare plagioclase and clinopyroxene. Exposed only in northwestern part of map where unit has a maximum exposed thickness of about 60 m

Tqs **Tuff of Sleeping Butte—**Sequence of two lithic-rich rhyolite ash-flow tuffs and associated ash-fall tuffs exposed mainly in northwest part of map; distal facies are included in units Tot and Tos, described above. Lower tuff is thicker, more widespread, more densely welded, and zoned from a lower mafic-poor rhyolite to an upper mafic-rich and phenocryst-rich, low-silica rhyolite. Lower tuff has a median of 18.94 percent total phenocrysts: 4.2 percent quartz, 9.5 percent sanidine, 4.6 percent plagioclase, 0.4 percent biotite, and 0.24 percent hornblende, and locally includes characteristic alaskitic granite lithics. Upper tuff is petrographically similar. Dated at 14.3 Ma. Normal magnetic polarity. Maximum exposed thickness of about 1,000 m

Tqh **Middle rhyolite of Quartz Mountain—**Rhyolite to lesser dacite lava flows and related bedded tuffs and local tuffaceous sedimentary rocks; flow-foliated and -banded. Contains phenocrysts of sanidine, plagioclase, quartz, and sparse hornblende. Reverse magnetic polarity. Maximum exposed thickness of about 200 m

Tqt **Tuff of Tolicha Peak—**Very crystal- and lithic-poor welded rhyolite ash-flow tuff. Median 0.5 percent total phenocrysts: plagioclase > sanidine > quartz > biotite. In northwesternmost corner of map, uppermost part is significantly more phenocryst-rich and especially biotite-rich, and includes internally shattered lithic blocks, as long as 50 m, derived from older volcanic formations; unit is evidently an intracaldera tuff in this locale. Normal magnetic polarity. Dated at about 14.3 Ma (Sawyer and others, 1994). Maximum exposed thickness of at least 300 m

Tot **Older tuffs and intercalated sediments—**Section of rhyolitic to dacitic ash-flow and ash-fall tuffs and lesser sedimentary rocks. Upper part commonly includes 14.3 Ma tuffs of Sleeping Butte (Tqs) and Tolicha Peak (Tqt), along with numerous minor tuffs probably related to rhyolite lavas of Quartz Mountain (Tqc and Tqh). Tuffs in lower part are mostly unidentified but include about 15.2 Ma tuff of Yucca Flat (not mapped separately or described here). Tuffs are interbedded with tuffaceous arkoses, sandstones, shales, and freshwater limestones. Typically strongly altered hydrothermally and ochre colored. Unit was mapped as tuff of Sawtooth Mountain and tuff of Buck Spring by Maldonado and Hausback (1990). Age equivalent to Tos in eastern part of map which is mostly sedimentary rocks, but includes many of the same tuffs. Maximum exposed thickness of at least 600 m

Tos **Rocks of Pavits Spring (Miocene)—**Thick sequence of mostly tuffaceous sedimentary rocks: arkoses, shales, freshwater limestones, marls, and lesser tuffs; laterally transitional into unit Tot, described above, in which tuffs dominate. Typically light-yellowish tan on surface; commonly black in unoxidized samples obtained by drilling in hydrothermally altered zone on north side of Bare Mountain. Locally, in sector graben on northeastern Bare Mountain, includes small exposures of 13.9 Ma Lithic Ridge Tuff (Tlt) near top that are too small to map separately. Maximum exposed thickness of at least 200 m

Tog **Older fluvial conglomerates (Miocene and Oligocene)—**Roundstone cobble conglomerates, moderately consolidated, commonly with red lateritic clay matrix in lower part (equivalent to upper Eocene to lower Miocene–Oligocene Titus Canyon Formation) and green dacitic tuffaceous-sandstone matrix in upper part (equivalent to middle Miocene “green conglomerate” of Reynolds, 1969; and to Panuga Formation of Snow and Lux, 1999). Cobbles consist of quartzites and lesser carbonates and argillites, with rare rhyolite lava cobbles in upper part alone. Mapped only in sector graben at northeastern corner of Bare Mountain where maximum exposed thickness is at least 200 m. Rocks of lower part are also found within mega-slide blocks mapped as Tyx in northeastern Bullfrog Hills, where conglomerate is interbedded with lesser freshwater limestones and intruded by andesite porphyry sills correlative with unit Tli (fig. 1 and map sheet). Rocks of both upper and lower parts are found as blocks in rock-avalanche megabreccias immediately north of Bare Mountain, mapped as Tox

Pre-Cenozoic Bedrock

Kfi **Granite (Cretaceous)—**Weakly foliated, very pale orange to pale-yellowish-orange, medium-grained, equigranular granitic rock. Contains roughly 50 percent quartz, 30 percent orthoclase, 15 percent plagioclase, and 5 percent alteration products, mainly sericite and iron oxides. Dated by U/Pb (zircon) at 98 ± 27 Ma (Monsen and others, 1992). Found only as a fault-block sliver along north flank of Bare Mountain

PzZ **Pre-Cenozoic sedimentary rocks, undivided (Paleozoic and late Proterozoic)—**Very thick sequence of mostly miogeoclinal sedimentary rocks including limestones, dolomites, quartzites, and argillites. Locally metamorphosed. Mapped as a collective unit only on cross sections. Thickness before Mesozoic compression estimated at about 11 km

MDe **Eleana Formation (Mississippian and Upper Devonian(?))—**Thick sequence of clastic rocks consisting predominantly of argillite and cherty argillite. Two exposures of unit, in two different fault blocks in northern Bare Mountain, are separated by the Meiklejohn Peak thrust and are lithologically distinct, suggesting that they were deposited in settings far apart before thrust faulting (Trexler and others, 1996). Western fault block, in upper plate of thrust, consists of thinly bedded chert-lithic sandstone, bedded chert, siltstone, and mudstone. Eastern, parautochthonous section consists of a coarse debris-flow boulder conglomerate (an olistostrome) at base, overlain by dolomitic siltstone, bedded chert, argillite, and cherty wackestone and mudstone (Trexler and others, 1996)

Df **Fluorspar Canyon Formation (Devonian)—**Layered light to dark gray, fine- to medium-grained dolomite and limy dolomite containing limestone and quartzite beds in some intervals. Consists of four subunits which, in descending order have the following distinctive features (1) interbeds as much as 2 m thick of medium- to light-brown weathering quartzite, (2) interbeds containing abundant *Amphipora*, (3) sparse layers of pebble conglomerate, and (4) sparse to moderately abundant light-brown chert nodules. Grades downward into Lone Mountain Dolomite (Sl); lower contact is indistinct. Exposed (incomplete) thickness of about 250 m

Sl **Lone Mountain Dolomite (Silurian)—**Craggy dolomite, very light gray with a distinct medium-gray interval near middle of unit. Dolomite is fine- to medium-grained, indistinctly bedded, and commonly brecciated; sparsely fossiliferous with common poorly preserved crinoid debris. Basal contact is gradational and is distinguished from a distance by a distinct downward darkening into underlying Roberts Mountain Formation (Sr). Total thickness is about 490 m

Sr **Roberts Mountains Formation (Silurian)—**Slope-forming, light brownish-gray to medium-gray dolomite and limestone containing interbedded silty and sandy dolomite and sparse beds of dolomite-pebble conglomerate. Thinly to thickly bedded, commonly flaggy. Silicified brachiopods and corals are present throughout unit. Thickness is about 200 m

Oes **Ely Springs Dolomite (Ordovician)—**Ledge-forming, medium- to dark-gray dolomite and limy dolomite containing abundant dark-gray chert layers and nodules 5–20 cm thick. Basal contact is marked by abrupt gradation from dark-gray dolomite to reddish Eureka quartzite (Oe). Thickness of about 125 m

Oe **Eureka Quartzite (Ordovician)—**Ledge-forming, light-gray to pale-red quartzite and sandstone. Fine-grained, well-sorted, medium- to thick-bedded, containing thin intervals of limy sandstone near top and base. Basal contact is placed at downward transition to limestone. Thickness of about 110 m

Op **Pogonip Group (Ordovician) —**Grouping of three related formations

Oav **Antelope Valley Formation—**Ledge- to cliff-forming unit of medium gray, predominantly nodular, finely to coarsely crystalline limestone and silty limestone, massive to laminated and platy-splitting rock. Pale-orange-weathering silty partings are common near top and base. Basal contact is abrupt transition to siltstone of Ninemile Formation (On). Estimated thickness of about 200 m

On **Ninemile Formation—**Slope-forming, light- to moderate-brown siltstone and olive-black to dark-medium-gray silty limestone or dolomite. Irregular thin platy layers of siltstone alternate with nodular interbeds of silty carbonate rocks. Basal contact is abrupt transition to pure carbonate of Goodwin Limestone (Og). Estimated thickness of 85 m

Og **Goodwin Limestone—**Ledge-forming, medium- to dark-gray limestone and lesser silty limestone. Contains pale-orange silty laminae and partings, and brown-weathering chert lenses. Basal contact is placed at top of ledge-forming dolomite of the Nopah

Formation (Ꞓnsh). Estimated thickness of 135 m

Ꞓnsh **Nopah Formation, undivided (Cambrian)—** Cliff-forming light- and medium-gray, saccharoidal dolomite and much lesser shale, subdivided into Smoky, Halfpint, and Dunderberg Shale Members

Ꞓns **Smoky Member—**Cliff-forming, very light-gray to medium-gray dolomite in indistinct medium-to-thick beds. Upper part is alternating dark- to medium-gray dolomite containing sparse light-gray beds. Lowermost 70 m is white to very light-gray dolomite. Estimated thickness of 305 m

Ꞓnh **Halfpint Member—**Predominantly medium- to dark-gray, thin- to thick-bedded, finely to coarsely crystalline dolomite locally containing abundant black chert nodules and layers, bedding generally indistinct. Estimated thickness of 185 m

Ꞓnd **Dunderberg Shale Member—**Greenish-brown, fissile shale containing subordinate medium-gray to pale-brown thinly bedded limestone. Thickness of 30 m

Ꞓb **Bonanza King Formation, undivided (Cambrian)—**Combined unit used mainly on cross sections, divided on most parts of map into

Ꞓbbu **Banded Mountain Member, upper part—**Cliff-forming, finely to medium crystalline, thickly bedded light- to dark-gray dolomite. From a distance, appears as three color bands of approximately equal thickness that are, in descending order, medium gray, very light gray, and dark gray. Thickness of about 180 m

Ꞓbbl **Banded Mountain Member, lower part—**Cliff-forming dolomite and limestone, distinctively striped in alternating light- to dark-gray bands ranging from 0.5 to 6 m thick. Basal contact is mapped at top of silty carbonate interval that appears pale orange from a distance. Thickness of about 395 m

Ꞓbp **Papoose Lake Member—**Cliff-forming, white to dark-gray dolomite and limestone intercalated with sparse but distinctive rusty yellowish-orange silty and sandy intervals, which are concentrated at top and base. Estimated thickness is 580 m

Ꞓc **Carrara Formation, undivided (Cambrian)—** Heterogeneous unit of slate, phyllite, or schist, and fine-grained micaceous quartzite; contains prominent intervals of limestone and silty limestone. Oncoids are common in limestone beds whereas trilobite fossil hash is common in pelitic beds. Combined unit used mainly on cross sections, divided on most parts of map into

Ꞓcu **Upper part—**Intercalated thin- to medium-bedded, dark-greenish-gray phyllite or schist, micaceous quartzite, and medium-dark-gray limestone. Pelitic rocks are typically dark greenish brown and increase in abundance downsection, whereas limestone beds are dark greenish gray. Thickness of 200 m

Ꞓcm **Middle part—**Cliff-forming, thickly bedded, dark-gray limestone, *Girvenella* characteristically are present. Thickness about 60 m

Ꞓcl **Lower part—**Similar to upper part of formation. Thickness about 90 m

Ꞓz **Zabriskie Quartzite (Cambrian)—**Cliff-forming unit of pale-red to dusky-red, fine- to medium-grained orthoquartzite, thick bedded and commonly cross-stratified. *Scolithus* common in lower part. Thickness of about 350 m

ꞒZw **Wood Canyon Formation (Cambrian and Late Proterozoic)—**Mostly slope-forming sequence of siltstones and lesser quartzites with distinctive thin orange dolomite marker beds in upper and lower parts of formation. Middle member (Ꞓwm) of this formation is faulted out in map area. Divided into

Ꞓwu **Upper member (Cambrian)—**Steep slope-forming sequence of interbedded quartzite and siltstone with thin orange, oolitic dolomite beds in lower part. Basal contact is base of upper dolomite beds. Thickness about 260 m

Zwl **Lower member (Late Proterozoic)—**

Zwld **Unit D—**Thickly bedded, brownish-black to moderate-brown, very fine grained micaceous siltstone and quartzite containing sparse interbeds of light-green siltstone. Thickness about 50 m

Zwlc **Unit C—**Thin to medium interbeds of greenish-gray, very fine grained micaceous siltstone and quartzite, capped by 25 m of thick pale-orange dolomite and limestone. Thickness about 80 m

Zwlb **Unit B—**Thin to medium interbeds of greenish-gray, very fine grained micaceous quartzite and siltstone, capped by 20-m-thick pale-orange, medium- to thick-bedded dolomite and limestone. Thickness about 110 m

Zwla **Unit A—**Thin to medium interbeds of greenish-gray, very fine grained micaceous quartzite and siltstone, capped by about 10-m-thick pale-orange dolomite and limestone. Basal contact gradational, defined as horizon at which quartzite becomes dominant. Thickness about 100 m

Stirling Quartzite (Late Proterozoic)—Divided into

Zse **E member—**White to pale-yellowish-brown, medium- to thick-bedded, fine-grained orthoquartzite, commonly laminated and cross-laminated. Moderate ridge-forming unit. Maximum exposed thickness of about 50 m

Zsd **D member—**Medium to thick interbeds of light-brown siltstone and quartzite and yellowish-brown dolomite. Only the upper about 50 m of unit exposed in map area

References Cited

Burchfiel, B.C., 1964, Precambrian and Paleozoic stratigraphy of the Specter Range quadrangle, Nye County, Nevada: American Association of Petroleum Geologists Bulletin, v. 48, no. 1, p. 40–56.

Byers, F.M., Jr., Carr, W.J., and Orkild, P.P., 1989, Volcanic centers of southwestern Nevada: Evolution of understanding, 1960–1988: Journal of Geophysical Research, v. 94, no. B5, p. 5908–5924.

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

Christiansen, R.L., and Lipman, P.W., 1965, Geologic map of the Topopah Spring NW quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-444, scale 1:24,000.

Connors, K.I., Weiss, S.I., and Noble, D.C., 1998, Geologic map of the northeastern Bullfrog Hills and vicinity, southern Nye County, Nevada: Nevada Bureau of Mines and Geology Map 112, scale 1:24,000.

Crittenden, M.D., Jr., Coney, P.J., and Davis, G.H., eds., 1980, Cordilleran metamorphic core complexes: Geological Society of America Memoir 153, 490 p.

Crowe, B.M., Perry, F., Geissman, J., McFadden, L., Wells, S., Murrell, M., Poths, J., Valentine, G.A., Bowker, L., and Finnegan, K., 1995, Status of volcanism studies for the Yucca Mountain Site Characterization Project: Los Alamos National Laboratories Report LA-12908-MS, 363 p.

Eng, Tony, Boden, D.R., Reischmann, M.R., and Biggs, J.O., 1996, Geology and mineralization of the Bullfrog Mine and vicinity, Nye County, Nevada: *in* Coyner, A.R., and Fahey, P.L., eds., Geology and Ore Deposits of the American Cordillera: Geological Society of Nevada Symposium proceedings, Reno, Nev., p. 353–402.

Fleck, R.J., Turrin, B.D., Sawyer, D.A., Warren, R.G., Champion, D.E., Hudson, M.R., and Minor, S.A., 1996, Age and character of basaltic rocks of the Yucca Mountain region, southern Nevada: Journal of Geophysical Research, v. 101, p. 8205–8227.

Fridrich, C.J., 1999, Tectonic evolution of the Crater Flat basin, Yucca Mountain region, Nevada: *in* Wright, L.A., and Troxel, B.W., eds., Cenozoic basins of the Death Valley region, California and Nevada, Geological Society of America Special Paper 333, p. 169–196.

Fridrich, C.J., Minor, S.A., and Mankinen, E.A., 1999a, Geologic evaluation of the Oasis Valley basin, Nye County, Nevada: U.S. Geological Survey Open-File Report 99–533-A, 55 p.

Fridrich, C.J., Minor, S.A., Ryder, P.L., Slate, J.L., Warren, R.G., Hildenbrand, T.G., Sawyer, D.A., Orkild, P.P., Grunwald, D.J., 1999b, Geologic map of the Oasis Valley basin and vicinity, Nye County, Nevada: U.S. Geological Survey Open-File Report 99–533-B, 43 p., scale 1:62,500.

Fridrich, C.J., Thompson, R.A., Machette, M.N., and Miggins, D.P., 2000, Late Cenozoic stratigraphic record of tectonic evolution, volcanism, and climate change in the Death Valley region, California and Nevada: EOS, Transactions, American Geophysical Union Fall Meeting Supplement, v. 81, no. 48, p. F1127.

Fridrich, C.J., Whitney, J.W., Hudson, M.R., and Crowe, B.M., 1999c, Space-time patterns of late Cenozoic extension, vertical axis rotation, and volcanism in the Crater Flat basin, southwest Nevada: *in* Wright, L.A., and Troxel, B.W., eds., Cenozoic basins of the Death Valley region, California and Nevada, Geological Society of America Special Paper 333, p. 197–212.

Grauch, V.J.S., Sawyer, D.A., Fridrich, C.J., and Hudson, M.R., 1997, Geophysical interpretations west of and within the northwestern part of the Nevada Test Site: U.S. Geological Survey Open-File Report 97–476, 45 p.

Grauch, V.J.S., Sawyer, D.A., Fridrich, C.J., and Hudson, M.R., 1999, Geophysical framework of the southwestern Nevada volcanic field and hydrogeologic implications: U.S. Geological Survey Professional Paper 1608, 39 p.

Hamilton, W.B., 1989, Detachment faulting in the Death Valley region, California and Nevada: *in* Carr, M.D., and Yount, J.C., eds., Geologic and hydrologic investigations of a potential nuclear waste disposal site at Yucca Mountain, southern Nevada: U.S. Geological Survey Bulletin 1790, p. 51–86.

Hildenbrand, T.G., Langenheim, V.E., Mankinen, E.A., and McKee, E.H., 1999, Inversion of gravity data to define the pre-Tertiary surface of the Pahute Mesa-Oasis Valley region, Nye County, Nevada: U.S. Geological Survey Open-File Report 99–0049, 26 p.

Hoisch, T.D., Heizler, M.T., and Zartman, R.E., 1997, Timing of detachment faulting in the Bullfrog Hills and Bare Mountain area, southwest Nevada: Inferences from $^{40}Ar/^{39}Ar$, K–Ar, U–Pb, and fission track thermochronology: Journal of Geophysical Research, v. 102, no. B2, p. 2815–2833.

Hudson, M.R., Sawyer, D.A., and Warren R.G., 1994, Paleomagnetism and rotation constraints for the middle Miocene southwestern Nevada volcanic field: Tectonics, v. 13, p. 258–277.

Le Bas, M.J., Maitre, R.W., Streckheisen, A., and Zannetin, B., 1986, A chemical classification of volcanic rocks based on the total alkali-silica diagram: Journal of Petrology, v. 27, p. 745–750.

Lipman, P.W., Quinlivan, W.D., Carr, W.J., and Anderson, R.E., 1966, Geologic map of the Thirsty Canyon SE quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-489, scale 1:24,000.

Maldonado, F., and Hausback, B.P., 1990, Geologic map of the northeast quarter of the Bullfrog 15-minute quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Investigations Series I-2049, scale: 1:24,000.

Mankinen, E.A., Hildenbrand, T.G., Dixon, G.L., McKee, E.H., Fridrich, C.J., and Laczniak, R.J., 1999, Gravity and magnetic study of the Pahute Mesa and Oasis Valley region, Nye County, Nevada: U.S. Geological Survey Open-File Report 99–303, 57 p.

Mankinen, E.A., Hildenbrand, T.G., Fridrich, C.J., McKee, E.H., and Scheckel, C.J., 2003, Geophysical setting of Pahute Mesa-Oasis Valley region, southern Nevada: Nevada Bureau of Mines and Geology Report 50, 45 p.

Minor, S.A., Orkild, P.P., Sargent, K.A., Warren, R.G., Sawyer, D.A., and Workman, J.B., 1997, Digital Geologic map of the Springdale quadrangle, Nye County, Nevada: U.S. Geological Survey Open-File Report 97–93, scale 1:24,000.

Minor, S.A., Orkild, P.P., Swadley, WC, Warren, R.G., and Workman, J.B., 1998, Preliminary Digital Geologic map of the Thirsty Canyon NW quadrangle, Nye County, Nevada: U.S. Geological Survey Open-File Report 98–623, scale 1:24,000.

Minor, S.A., Sawyer, D.A., Wahl, R.R., Frizzell, V.A., Jr., Schilling, S.P., Warren, R.G., Orkild, P.P., Coe, J.A., Hudson, M.R., Fleck, R.J., Lanphere, M.A., Swadley, WC, and Cole, J.C., 1993, Preliminary geologic map of the Pahute Mesa 30′ × 60′ Quadrangle, Nevada: U.S. Geological Survey Open-File Report 93–299, scale 1:100,000.

Monsen, S.A., Carr, M.D., Rehies, M.C., and Orkild, P.P., 1992, Geologic map of Bare Mountain, Nye County, Nevada: U.S. Geological Survey Geologic Investigations Series I-2201, scale 1:24,000.

Noble, D.C., Weiss, S.I., and McKee, E.H., 1991, Magnetic and hydrothermal activity, caldera geology, and regional extension in the western part of the southwestern Nevada volcanic field: *in* Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., eds., Geology and Ore Deposits of the Great Basin, Geological Society of Nevada, Reno, Nev., p. 913–934.

O′Connor, J.T., Anderson, R.E., and Lipman, P.W., 1966, Geologic map of the Thirsty Canyon quadrangle, Nye County, Nevada: U.S. Geological Survey Geologic Quadrangle Map GQ-524, scale 1:24,000.

Reynolds, M.W., 1969, Stratigraphy and structural geology of the Titus and Titanothere Canyons area, Death Valley, California: Unpub. Ph.D. dissertation, University of California, Berkeley, 310 p.

Reynolds, M.W., 1974, Recurrent middle and late Cenozoic deformation, northeastern Death Valley, California–Nevada: Geological Society of America Abstracts with Programs, v. 6, no. 3, p. 241.

Sargent, K.A. and Orkild, P.P., 1976, Preliminary geologic map of the Springdale NW quadrangle, Nye County, Nevada: U.S. Geological Survey Miscellaneous Field Studies Map MF-751, scale 1:24,000.

Sawyer, D.A., Fleck, R.J., Lanphere, M.A., Warren, R.G., Broxton, D.E., and Hudson, M.R., 1994, Episodic caldera volcanism in the Miocene southwestern Nevada volcanic field: Revised stratigraphic framework, $^{40}Ar/^{39}Ar$ geochronology, and implications for magmatism and extension: Geological Society of America, v. 106, no. 10, p. 1304–1318.

Slate, J.L., Berry, M.E., Rowley, P.D., Fridrich, C.J., Williams, V.S., and many others, 2000, Digital Geologic map and data base of the Nevada Test Site and vicinity, Nye, Lincoln, and Clark Counties, Nevada, and Inyo County, California: U.S. Geological Survey Open-File Report 99–554-A, 56 p.

Smith, R.L., and Bailey, R.A., 1968, Resurgent cauldrons: Geological Society of America Memoir 116, p. 613–662.

Snow, J.K., and Lux, D.R., 1999, Tectono-sequence stratigraphy of Tertiary rocks in the Cottonwood Mountains and northern Death Valley region, California and Nevada: *in* Wright, L.A., and Troxel, B.W., eds., Cenozoic basins of the Death Valley region, California and Nevada, Geological Society of America Special Paper 333, p. 17–64.

Stock, C., and Bode, F.D., 1935, Occurrence of lower Oligocene mammal-bearing beds near Death Valley, California: National Academy of Sciences Proceedings, v. 21, p. 571–579.

Trexler, J.H., Jr., Cole, J.C., and Cashman, P.H., 1996, Middle Devonian–Mississippian stratigraphy on and near the Nevada Test Site: Implications for hydrocarbon potential: American Association of Petroleum Geologists Bulletin, v. 80, no. 11, p. 1736–1762.

USGS, 1996, Seismotectonic framework and characterization of faulting at Yucca Mountain, Nevada (J.W. Whitney, coordinator): U.S. Geological Survey Report to the U.S. Department of Energy, v. 1–4, variously paginated.

Wahl, R.R., Sawyer, D.A., Minor, S.A., Carr, M.D., Cole, J.C., Swadley, WC, Laczniak, R.J., Warren, R.G., Green, K.S., and Engle, C.M., 1997, Digital geologic map of the Nevada Test Site area, Nevada: U.S. Geological Survey Open-File Report 97–140, scale 1:120,000.

Warren, R.G., Sawyer, D.A., Byers, F.M., Jr., and Cole, G.L., 2000, A petrographic/geochemical database and stratigraphic framework for the southwestern Nevada volcanic field, Los Alamos National Laboratory Report LA-UR-00-3791. Available online at http://queeg.ngdc.noaa.gov/seg/swnvf/.