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Preliminary Geologic Map of the Pahute Mesa 30' x 60' Quadrangle, Nevada

By
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INTRODUCTION

Work on a geologic compilation of the Pahute Mesa 30' x 60' quadrangle was conceptually proposed in 1984 as part a U.S. Geological Survey (USGS) programmatic initiative to conduct a geologic synthesis of the southern Great Basin in Nevada. One of the central objectives of the program was to compile the geology of four contiguous 1:100,000-scale, 30' x 60' minute quadrangles that cover the region of interest (Pahute Mesa, Beatty, Pahranagat Range, and Indian Springs quadrangles), and to produce a separate 1:100,000-scale geologic map of the NTS that overlaps all four quadrangles. Compilation of the Pahute Mesa sheet was initiated in 1984 under the USGS Geologic Framework Program. Digital compilation of the quadrangle began in 1990, with support coming entirely from the USGS Rad Waste Program. Two of the other targeted 1:100,000-scale geologic maps have been completed, the NTS map (Frizzell and Shulters, 1990) and the Pahranagat Range quadrangle map (Jayko, in press).

The Pahute Mesa compilation documents the interactions of diverse regional geologic elements; it covers most of the Miocene southwest Nevada volcanic field (SWNVF), and includes partly overlapping structures of the Timber Mountain and Silent Canyon caldera complexes, the Black Mountain caldera, and several domains of high- to low-angle Basin and Range extensional faulting. Including all major testing areas in the Nevada Test Site (NTS) and near the proposed Yucca Mountain high-level nuclear-waste repository, the map provides updated regional geologic information for nuclear-weapons test containment and radionuclide migration studies. A majority of the 86 map units shown on the compilation represent Miocene volcanic rocks of the SWNVF; the compiled geologic database incorporates the latest stratigraphic revisions of the SWNVF, which reflect the results of recent geochronologic, paleomagnetic, and petrographic research.

The Pahute Mesa digital geologic database from which the map was plotted allows for accurate and rapid updating of geologic information, generation of derivative maps at various scales, and layering with other Geographic Information System (GIS) databases to produce integrated thematic maps and 3-D models. The digital database is available, in GRASS ascii vector and DLG-3 (optional) formats, from the USGS, Denver, on-line repository on Internet (via 'anonymous ftp') at greenwood.cr.usgs.gov.

COMPILATION METHODS

The geologic map was compiled by S.A. Minor (principal compiler), R.R. Wahl, S.P. Schilling, D.A. Sawyer, and J.A. Coe using digital compilations methods developed by R.R. Wahl, S.A. Minor, and S.P. Schilling. The Pahute Mesa quadrangle incorporates mapping from two published and nine unpublished 1:24,000-scale quadrangle maps, parts of two 1:48,000-scale published maps, one 1:62,500-scale published map, and part of a 1:100,000-scale published map (see Sources of Geologic Data). Scale-stable copies or tracings of the original archival U.S. Geological Survey map publication sheets or stable-base author compilations were scanned and digitized using a Tektronics autovectorizing scanner with a resolution of 300 dpi. For each component map, different types of map data (i.e., geologic contacts, or "polygon" boundaries, faults and fold axes, and structural attitude symbols) were scanned as separate layers to facilitate editing and other compilation tasks. New geologic field data, which were mapped mostly by S.A. Minor in areas with uncertain geologic relations and map-join problems in the western half of the map area, were digitized directly from field-annotated aerial photographs using a digital photogrammetric plotter. All scanned and photogeologic digital files were imported into AutoCAD for editing and simplification for depiction at a scale of 1:100,000. Simplification entailed: 1) modifying or removing polygon boundaries as dictated by stratigraphic unit reassignments or legibility at the final reduced map scale, 2) removing non-contact-forming faults that have insignificant stratigraphic separation or trace length, and 3) removing some repetitive, closely spaced structural-attitude symbols and, for the remaining symbols, rounding off dip values greater than 10^{o} to the nearest 5^{o}. A preexisting vectorized polygon coverage (R.J. Laczniak, digital commun., 1990) of the recent 1:100,000-scale geologic map of the NTS (Frizzell and Shulters, 1990) provided geologic data for much of the eastern part of the Pahute Mesa compilation. This coverage was edited and revised in Geographic Resource Analysis Support System (GRASS), a GIS, to incorporate recent changes in stratigraphic assignment and geologic interpretation, and was eventually integrated with fault and attitude layers exported from AutoCAD. GRASS was used to transform all of the other component map files to Universal Transverse Mercator projections, merge the files in the appropriate composite map-data layers, conduct final editing and modification of map elements, build and tag polygons, and assign attributes to map elements. A vectorized, scanned raster image of the printed Pahute Mesa 1:100,000-scale topographic base map (U.S. Geological Survey, 1979) was imported into AutoCAD for minimal editing, and was then integrated with the geologic map layers in GRASS The completed GRASS map data layers were written to a customized plot file for final hard copy output on a CalComp 68436 color electrostatic plotter at 400 dpi resolution.

The map contains some minor labeling problems that reflect limitations of the algorithms used to automatically generate the labels; unit labels of some narrow polygons extend into adjoining polygons, and faults or fault decorations (e.g., ball and bars) locally overlie map unit labels or structure symbols. These labeling conflicts were not resolved for this version of the map because doing so would have caused considerable delay in release of the map without significantly improving its quality. Also, some details of the topographic base layer, in particular geographic place names, are ambiguous mainly due to unavoidable effects of scanning and vectorizing a composited base map. The reader is referred to a published copy of the base map (U.S. Geological Survey, 1979) for clarification of place names and other unclear map features.

The Tertiary map unit descriptions were largely compiled using recent petrographic, paleomagnetic, and geochronologic data provided by some of the authors (R.G. Warren/D.A. Sawyer, M.R. Hudson, and R.J. Fleck/M.A. Lanphere/D.A. Sawyer, respectively). The pre-Tertiary and Quaternary unit descriptions were chiefly compiled from information contributed by J.C. Cole and WC Swadley, respectively.

PREVIOUS INVESTIGATIONS

The region of the Pahute Mesa quadrangle has been the focus of geologic investigations intermittently since the pioneering work of Ball (1907) early in this century. Numerous, detailed geologic investigations were conducted mainly in the NTS area during the late 1950's, the 1960's, and the early 1970's in support of the U.S. Atomic Energy Commission and, later, the Department of Energy nuclear testing programs. Byers and others (1989) have summarized the history of geologic investigations and the evolution of concepts pertaining to the geology of the SWNVF, where all of the testing has been conducted. Thirty-four 1:24,000-scale (7.5') geologic quadrangle maps of the NTS area were published by the early 1970's to document the geologic framework of the region; sixteen of these maps provide coverage within the map area of the Pahute Mesa 30 by 60 minute quadrangle (see Sources of Geologic Data). Also prepared were 1:48,000-scale geologic compilations of the Timber Mountain caldera (Byers and others, 1976a), Pahute Mesa (Orkild, Sargent, and Snyder, 1969), and Wheelbarrow Peak-Rainier Mesa (Sargent and Orkild, 1973) areas, which summarize, with some refinements and modifications of mapped contact relations and stratigraphic nomenclature, the earlier 7.5' quadrangle mapping. The geology of portions of the remote northern part of the Pahute Mesa quadrangle and environs was mapped in reconnaissance by Rogers and others (1968; northern Black Mountain quadrangle, 1:62,500) and Ekren and others (1971; northern Nellis Air Force Bombing and Gunnery Range, 1:125,000). After more than 20 years much of this foundation mapping still remains the principal source of geologic data for inaccessible parts of the Nellis Range. A comprehensive description and interpretation of volcanic rocks of the Timber Mountain caldera complex region were reported in a landmark paper by Byers and others (1976b). An important subsequent report by Carr and others (1986) described several of the older stratigraphic units in the region and proposed new caldera sources for some of the major ash-flow tuffs. A recently compiled regional geologic map of the NTS (1:100,000 scale) by Frizzell and Shulters (1990) summarizes the geologic mapping of the area through the 1970's. An updated and modified version of this map was used for much of the eastern part of the present compilation.

DESCRIPTION OF MAP UNITS

Volcanic rock names are based on the IUGS total alkali-silica classification scheme of Le Bas and others (1986). Phenocryst content modifiers of volcanic rock names are based on the modal percentages shown in table 1 below; in basaltic rocks the modifiers "phenocryst-rich" and "-poor" are substituted for "crystal-rich" and "-poor", respectively, to distinguish phenocrysts and microphenocrysts from coarse groundmass crystals common in those rocks. Plutonic rock names are based on the IUGS classification scheme of Streckeisen (1976). Phenocrystic mineral abundances are from unpublished median data compiled for individual SWNVF units by R. G. Warren. Table 2 below shows terms used to indicate median abundances for felsic phenocrysts (quartz, K-feldspar = sanidine + anorthoclase, and plagioclase), for mafic minerals (biotite, hornblende, arfvedsonite, orthopyroxene, clinopyroxene, acmite, and olivine), and for accessory minerals (chiefly sphene) in intermediate to silicic volcanic rocks. Mineral abundance terms for basaltic rocks are listed in table 3 below, which differ only for mafic phenocrystic abundances; these median abundances include both phenocrysts and microphenocrysts. Generally, mineral contents are listed in order of decreasing abundance. Although the relative abundance terms shown in the tables are appropriate for descriptions of volcanic rocks from the SWNVF, they may be inappropriate when applied to other volcanic fields.

Table 1. Total phenocryst content

Term	(median modal %)
aphyric	<0.5
crystal-poor	0.5-5
(no modifier)	5-15
crystal-rich	15-25
very crystal-rich	>25

Table 2. Phenocrystic mineral abundances in intermediate to silicic volcanic rocks

Term	Felsics (median modal %)	Mafics (median modal %)	Accessories (median ppm/V)
rare	<0.5	<0.1	<20
sparse	0.5-2	0.1-0.5	20-150
common	2-10	0.5-1	150-300
abundant	10-20	1-2	>300
very abundant	>20	>2	

Table 3. Phenocrystic mineral abundances in basaltic volcanic rocks

Term	Felsics (median modal %)	Mafics (median modal %)	Accessories (median ppm/V)
rare	<0.5	<0.5	<20
sparse	0.5-2	0.5-2	20-150
common	2-10	2-5	150-300
abundant	10-20	5-10	>300
very abundant	>20	>10	

Tertiary volcanic stratigraphic nomenclature is from Sawyer and others (in press) and the Los Alamos National Laboratory (LANL) GEODES database (Warren and others, 1989). Some map unit descriptions and informal unit names cited within them are derived from descriptions in published USGS Geologic Quadrangle (1:24,000-scale) and Miscellaneous Investigations (1:48,000-scale) Series maps (see Sources of Geologic Data), from the GEODES data, or, in the case of central Nevada volcanic units, from

Scott and others (in press). The revised SWNVF stratigraphic framework used in this report is largely based on the reports of Ekren and others (1971), Byers and others (1976b), and Carr and others (1986), and from the 1:48,000 compilation maps of Orkild, Sargent, and Snyder (1969), Sargent and Orkild (1973), and Byers and others (1976a).

Stratigraphic nomenclature adopted for the pre-Tertiary sedimentary units is outlined in Cole and others (1989) and Guth (1986, 1990), and is based on numerous published studies cited by them. Descriptions of these units are largely summarized from published geologic map descriptions (see Sources of Geologic Data), and supplemented by Cole and others (1989), Miller (1989), Monsen and others (1990), Cole (1991), Cashman and Trexler (1991), and some unpublished data.

Reported ages are based mainly on new $^{40}Ar/^{39}Ar$ age determinations (Best and others, 1989; Sawyer and others, 1990; Fleck and others, 1991; Noble and others, 1991; Sawyer and others, in press). Also reported are new conventional K/Ar ages by R.J. Fleck supplemented by published results of Kistler (1968) and Marvin and others (1970), recalculated using current IUGS constants (Steiger and Jäger, 1977; Dalrymple, 1979). A few additional sources of radiometric ages are cited specifically in the map unit descriptions.

Magnetic polarity data are from published sources (Bath, 1968; Byers and others, 1976a and 1976b; Rosenbaum and Snyder, 1984; Noble and others, 1984; Carr and others, 1986; Hudson, 1992) or from unpublished data of M.R. Hudson and J.G. Rosenbaum. Normal polarity magnetizations have northerly declinations and moderate downward inclinations. Reversed polarity magnetizations have southerly declinations and moderate upward inclinations. Anomalous normal and reversed polarity magnetizations have downward or upward inclinations, respectively, but their directions lie at great ($>45^{o}$) angles to a time-averaged late Tertiary expected direction for the area.

Some geographic place names mentioned in the descriptions are not labeled on the 1:100,000-scale topographic base map but are present on the larger-scale component topographic and geologic quadrangle maps that have been published. Where cited place names are not labeled on the Pahute Mesa base map, the locations of the named geographic features are described with respect to features that *are* labeled on the map.

QTa **Surficial deposits (Quaternary and Pliocene?)**--Combined map unit that includes fan and stream alluvium, colluvium, and eolian, playa, and lacustrine deposits. Fan alluvium consists of coarse, poorly sorted and poorly bedded, angular gravel and sand; unconsolidated to moderately consolidated; older deposits are moderately dissected. Stream alluvium is composed of poorly sorted and poorly bedded, unconsolidated gravel and sand deposited along modern and recently active washes. Colluvium consists of coarse, angular, poorly sorted, nonbedded gravel and minor sand; chiefly unconsolidated to weakly consolidated rock-fall and slope-wash deposits below steep bedrock slopes. Eolian deposits are composed of unconsolidated, moderately sorted, mostly medium sand; they form dunes, irregular sand sheets, and sand ramps on the flanks of bedrock hills. Playa deposits consist of clayey, silty fine sand with minor amounts of pebbly coarse sand; thinly bedded, well compacted, calcareous;

underlie small, intermittently flooded areas in several closed basins. Lacustrine deposits are composed of unconsolidated, poorly sorted sand and pebbly sand; form low rounded ridges deposited along shore lines of lakes that occupied closed basins now marked by playas

Qb **Basalt (Quaternary)**--Generally isolated, phenocryst-poor cinder cones, lava flows, and feeder dikes at Little Black Peak and on the flank of Sleeping Butte about 12 km north of Oasis Mtn.; compositionally rocks are trachybasalt and basalt; more sodic varieties, including hawaiite, are uncommon. Phenocrysts consist of common olivine and sparse plagioclase. Distinguished by a low phenocryst abundance, almost exclusively olivine, by a youthful age (about 350 Ka) and geomorphic appearance of cinder cone vents, and by normal magnetic polarity

Tgo **Gravels of Oasis Valley (Pliocene and Miocene)**--Consists of basin-fill deposits and fan alluvium composed of coarse, poorly sorted and poorly to moderately bedded, angular to rounded gravel and sand in a locally tuffaceous matrix; weakly to well cemented; locally contains interbedded, partly tuffaceous sandstone and mudstone and layers of nonwelded tuff. Clasts composed of locally derived Tertiary volcanic rocks and lesser Paleozoic and Proterozoic sedimentary rocks; include boulders up to 3 m across. Unit is extensively dissected and moderately to deeply weathered. Distinguished from post-caldera moat-filling sediments (unit Tgm) by extracaldera distribution of gravels in the Oasis Valley area and in the northwest part of map area, and locally from older proximal (unit Tgx) and tuffaceous (unit Tgu) sedimentary rocks by unconformity at base of gravels. Unit deposited during at least 3 m.y.; distal, 7.5-Ma Spearhead Member of Stonewall Flat Tuff (unit Tsp) is intercalated with gravels in Beatty Wash just south of map area, whereas basalt flows of the 4.63-Ma Thirsty Mountain shield volcano (unit Typ) intertongue with gravels in lower Thirsty Canyon. Maximum known thickness of more than 150 m in Oasis Valley. Equivalent in part to Gravel of Sober-up Gulch of Maldonado and Hausback (1990)

Typ **Basalt (Pliocene)**--Basaltic trachyandesite cinder cones, lava flows, and feeder dikes forming Buckboard Mesa (2.82 Ma; normal magnetic polarity) and broad shield volcano at Thirsty Mountain about 10 km north of Oasis Valley (4.63 Ma; reversed polarity). Common to abundant olivine; phenocryst poor with rare plagioclase in Thirsty Mountain area; sparse plagioclase and variably sparse clinopyroxene in Buckboard Mesa area. Distinguished by marked preservation of constructional volcanic geomorphology, Pliocene age, and characteristic magnetic polarity of each center. Maximum thickness of more than 200 m at shield volcano

Tyb **Thirsty Canyon and younger basalts (Miocene)**--Widespread trachybasalt, basaltic trachyandesite, basalt, and basaltic andesite lava flows, eroded cinder cones, and feeder dikes erupted from several centers between 9.8 and 6.3 Ma. Distribution generally north and west of Timber Mountain in areas adjoining Black Mountain caldera and Stonewall Mountain volcanic center; unit includes two local basalt centers in northern Pahute Mesa at and east of Basalt Ridge (8.8-9.1 Ma). Basalts erupted just prior to, during, and following peralkaline volcanism of the Black Mountain caldera (Thirsty Canyon Group). Basalts adjoining Black Mountain caldera in west part of map area are variable in composition from basalt and alkali basalt to trachybasalt and trachybasaltic andesite, and include subordinate hawaiite, mugearite, and basaltic andesite. Petrography is also variable; phenocryst-rich varieties contain very abundant plagioclase and abundant olivine phenocrysts; subordinate phenocryst-poor varieties contain sparse to common olivine, sparse plagioclase; sparse to rare clinopyroxene, biotite, and orthopyroxene, rare kaersutitic amphibole, and very abundant apatite are locally present. Olivine and plagioclase contents, and stratigraphic range are distinctive. Maximum exposed thickness about 100 m

Tsc **Civet Cat Canyon Member of Stonewall Flat Tuff (Miocene)**--Comendite welded ash-flow tuff erupted from Stonewall Mountain caldera at 7.45 Ma [Hausback and others, 1990; recalculated using 513.9 Ma monitor age for MMHB-1 (Lanphere and others, 1990)]. Compositionally zoned from lower comendite, containing common alkali feldspar (anorthoclase and sodic sanidine) and rare clinopyroxene, plagioclase, and fayalitic olivine, to upper crystal-rich trachyte containing abundant alkali feldspar, common plagioclase, sparse biotite and clinopyroxene, and rare orthopyroxene; acmite or arfvedsonite is present in groundmass. Magnetic polarity reversed. Maximum exposed thickness 180 m

Tsr **Rhyolite of Stonewall Mountain (Miocene)**--Lava flows and domes adjoining Stonewall Mountain caldera. Rhyolite is crystal-rich, containing abundant biotite and common sanidine, plagioclase, and clinopyroxene; flow laminated and flow folded. Maximum preserved dome height exceeds 200 m

Tsp **Spearhead Member of Stonewall Flat Tuff (Miocene)**--Welded ash-flow tuff erupted from Stonewall Mountain caldera at 7.5 Ma. Compositionally zoned from lower crystal-poor comendite, containing common alkali feldspar, sparse clinopyroxene, and rare fayalitic olivine, plagioclase, and quartz, to upper comendite containing abundant alkali feldspar, sparse plagioclase, clinopyroxene, and fayalitic olivine, and rare quartz, biotite, and hornblende; upper zone is only locally present. Magnetic polarity normal. Maximum exposed thickness about 50 m

Tgm **Post-caldera moat-filling sediments (Miocene)**--Consists of intercalated fan alluvium and subordinate lacustrine deposits and nonwelded tuff. Fan alluvium composed of coarse, poorly sorted and poorly to moderately bedded, angular to rounded gravel and sand in a locally tuffaceous matrix; clasts consist of locally derived volcanic rocks; weakly to well cemented. Lacustrine deposits include interbedded, partly tuffaceous sandstone and mudstone and water-laid tuff. Tuff beds, as much as several meters thick, consist of pumice-bearing ash-fall and ash-flow tuff. Sediments distinguished from gravels of Oasis Valley (unit Tgo) by their limited extent within the Timber Mountain caldera complex and the Black Mountain caldera. Timber Mountain sediments overlie intracaldera, 11.45 Ma Ammonia Tanks Tuff (unit Tma), intertongue with Pahute Mesa (unit Ttp) and Trail Ridge (unit Ttt) Tuffs, and underlie 2.82 Ma basalt at Buckboard Mesa (unit Typ); in Black Mountain caldera unit postdates 9.15 Ma Gold Flat Tuff (unit Ttg) and underlies 7.5 Ma Spearhead Member of the Stonewall Flat Tuff (unit Tsp). Maximum thickness about 300 m in Timber Mountain caldera complex

Tyr **Rhyolite of Obsidian Butte (Miocene)**--Generally aphyric, flow-laminated and -folded rhyolite lava flows and subordinate related pyroclastic and sedimentary rocks in Obsidian Butte area in northwestern part of map area. Some flows contain sparse plagioclase, biotite, or olivine, or rare clinopyroxene, but overall aphyric nature is distinctive; locally rhyolite is conspicuously spherulitic. Pyroclastic rocks mainly consist of variously bedded, pumice- and lithic-rich tuff, tuff breccia, and reworked tuff; sedimentary rocks are generally well-bedded tuffaceous sandstone and conglomerate; clasts are predominantly locally derived rhyolite. Intertongues with and is at least in part comagmatic with basalt flows of unit Tyb. Age determinations on underlying and overlying units are 9.15 and 7.5 Ma, respectively. Maximum exposed thickness about 375 m

Tgu **Tuffaceous sedimentary rocks (Miocene)**--Generally well-bedded pebble to cobble conglomerate, sandstone, and locally reworked nonwelded tuff. Variously rounded clasts, predominantly of mixed volcanic provenance, supported in tuffaceous matrix; tuff is commonly silicic and contains pumice lapilli. Unit distinguished from proximal sedimentary rocks (unit Tgx) by typically smaller size and greater rounding of clasts and by greater tuffaceous input. Deposition of sedimentary rocks limited to local small paleobasins and paleochannels in western part of map area. Maximum exposed thickness about 100 m

Thirsty Canyon Group (Miocene)--Peralkaline assemblage of ash-flow sheets, lavas, and related nonwelded tuffs erupted from Black Mountain caldera in north-central part of quadrangle between 9.4 and 9.15 Ma. The Pahute Mesa (unit Ttp) and Trail Ridge (unit Ttt) Tuffs likely are the major units associated with caldera collapse. Following caldera collapse, the Pillar Spring, Yellow Cleft, and Hidden Cliff lavas and associated rocks (units Tts and Tth) and the Gold Flat Tuff (unit Ttg) accumulated within the caldera; the Gold Flat also overflowed the caldera mainly to the north and south. Late caldera collapse associated with the Gold Flat is uncertain. Thirsty Canyon Group is distinguished by its peralkaline mineralogy and chemistry; petrographically it is characterized by high alkali feldspar and low plagioclase contents, general absence of biotite and hornblende, and presence of Fe-rich clinopyroxene and fayalitic olivine; chemically it is distinguished by high iron and low aluminum contents for rhyolitic compositions, and anomalously high trace-element concentrations of zirconium, rare-earths, and other elements. Subdivided into:

Ttg **Gold Flat Tuff**--Strongly peralkaline (pantellerite) welded ash-flow tuff erupted at 9.15 Ma from Black Mountain caldera. Contains abundant alkali feldspar (anorthoclase and sodic sanidine), sparse plagioclase, Fe-rich clinopyroxene, and fayalitic olivine, and rare biotite, quartz, and hornblende. Arfvedsonite occurs both as sparse phenocrysts and as a devitrification product in groundmass. Contains rare primary fluorite and aenigmatite. Anomalous normal magnetic polarity. Deposited in caldera moat and present outside of it mainly to north and south; maximum thickness 70 m

Tth **Trachyte of Hidden Cliff**--Very crystal rich, thick (exposed part exceeds 500 m) sequence of trachyte lavas containing very abundant plagioclase and common to very abundant olivine and clinopyroxene. Distinguished by high plagioclase content. Normal magnetic polarity. Exogenous dome emplaced within a collapse depression nested within Black Mountain caldera

Tts **Trachytic rocks of Pillar Spring and Yellow Cleft**--Crystal-rich to very crystal rich trachyte to rhyolite lava flows, associated tuff and tuff breccia, and porphyritic syenite intrusive rocks; rocks partly fill and overlap Black Mountain caldera. Lavas contain abundant to very abundant alkali feldspar (mainly anorthoclase), common plagioclase, sparse clinopyroxene and olivine, and local rare biotite; syenite phenocrysts consist of abundant alkali feldspar (anorthoclase and sodic plagioclase) and lesser olivine and clinopyroxene. Magnetic polarity of Pillar Spring rocks is reversed. Maximum exposed thickness 180 m

Ttt **Trail Ridge Tuff**--Widespread welded, moderately crystal rich, comendite ash-flow tuff erupted from Black Mountain caldera. Contains abundant sodic sanidine, sparse Fe-rich clinopyroxene and fayalitic olivine, and rare plagioclase. Anomalous reversed magnetic polarity. Maximum exposed thickness about 65 m

Ttp **Pahute Mesa and Rocket Wash Tuffs**--Widespread Pahute Mesa Tuff consists of welded, moderately crystal-poor, comendite ash-flow tuff erupted from Black Mountain caldera. Contains common alkali feldspar, sparse Fe-rich clinopyroxene and fayalitic olivine, and rare plagioclase and quartz. Pahute Mesa has anomalous reversed magnetic polarity; maximum thickness about 60 m. Unit locally includes the Rocket Wash Tuff, a subjacent cooling unit erupted 9.4 Ma that has slightly more common alkali feldspar and a typical reversed magnetic polarity; maximum exposed thickness about 50 m

Ttc **Comendite of Ribbon Cliff**--Pre-caldera crystal-rich to very crystal rich comendite and trachyte lava flows and domes exposed marginal to the Black Mountain caldera. Contains abundant alkali feldspar, local common plagioclase, sparse clinopyroxene and fayalitic olivine, and local rare biotite. Normal magnetic polarity. Maximum exposed thickness 320 m

Tgx **Proximal sedimentary rocks (Miocene)**--Sedimentary breccia and conglomerate, and subordinate finer-grained tuffaceous sedimentary rocks and tuff. Unit present in western part of map area and in a limited area south of Syncline Ridge in Yucca Flat area. In Bullfrog Hills area largely consists of crudely bedded, polymictic, matrix-supported breccia containing lenses and sheets of monolithologic, clast-supported breccia having blocks up to 10 m or more in length. Conglomerate is poorly to well bedded and contains matrix-supported, poorly sorted, locally well-rounded pebbles, cobbles, and, rarely, boulders. Breccia and conglomerate clasts, locally derived from competent Miocene volcanic rocks and Proterozoic and Paleozoic sedimentary rocks, are enclosed in partly tuffaceous, sandy to silty matrix. Breccia and conglomerate probably deposited syntectonically as landslide debris, colluvium, and proximal fan alluvium adjacent to uplifted fault blocks. In Bullfrog Hills, rocks concordantly(?) underlie rhyolite of Rainbow Mountain (unit Tfr) tuff and have a maximum exposed thickness exceeding 400 m; sedimentary rocks underlie Rainier Mesa Tuff (unit Tmr) or Grouse Canyon Tuff (unit Tbg) at two local exposures south of Quartz Mtn; sedimentary unit is interlayered with or overlies Trail Ridge Tuff (unit Ttt) and (or) Pahute Mesa Tuff (unit Ttp) near Tolicha Peak and east of Mt Helen, respectively; near Syncline Ridge breccia directly overlies Redrock Valley Tuff (unit Tor)

Tfs **Rhyolite of Shoshone Mountain (Miocene)**--Generally aphyric sequence of rhyolite lavas and minor related tuffs containing rare plagioclase, sanidine, clinopyroxene, and biotite. Erupted at about 10.3 Ma from center southeast of Timber Mountain caldera complex; normal magnetic polarity. Maximum exposed thickness in quadrangle 150 m

Tfn **Latite of Donovan Mountain (Miocene)**--Sequence of crystal-rich latite to trachyte lava flows, feeder dikes, plugs, sills, and related tephra present in

Bullfrog Hills area. Lower flows contain abundant plagioclase, common sanidine, biotite, and clinopyroxene, and sparse olivine; flows become more silicic upward and contain abundant sanidine, sparse biotite, and rare clinopyroxene. Flow foliations and laminations locally conspicuous. Latite flows have normal magnetic polarity; age 10.4 Ma. Maximum exposed thickness exceeds 200 m. Flows overlie rhyolite of Rainbow Mountain (unit Tfr) with local angular discordance

Tfa **Andesitic lavas (Miocene)**--Local sequence of andesitic to basaltic lava flows and local interflow tuffaceous sedimentary rocks exposed near edge of Sarcobatus Flat in western part of quadrangle. Andesitic flows contain common plagioclase and sparse to common orthopyroxene and hornblende; in large exposure northeast of highway 95 they overlie basaltic rocks of unit. Includes intermediate-composition rocks of peralkaline affinity, probably close in age to rocks of Thirsty Canyon Group, exposed south and east of Black Mountain. Maximum exposed thickness about 100 m

Tfd **Lavas of Dome Mountain (Miocene)**--Interstratified trachybasalt, basaltic trachyandesite, and trachyandesite lava flows overlapping southern moat of Timber Mountain caldera complex. Different lava types are petrographically distinguishable; basaltic rocks contain abundant plagioclase, common olivine, and sparse clinopyroxene; trachyandesites contain sparse to common clinopyroxene, rare olivine and orthopyroxene, and local rare hornblende. Normal magnetic polarity. Maximum exposed thickness in quadrangle about 200 m

Tft **Post-Timber Mountain basaltic rocks (Miocene)**--Basalt, basaltic andesite, trachybasalt, and basaltic trachyandesite lava flows and dikes erupted between 11.45 and approximately 10 Ma. Flows generally contain common olivine, sparse plagioclase, and rare clinopyroxene. Maximum exposed thickness about 30 m

Tfr **Rhyolite of Rainbow Mountain (Miocene)**--Intercalated rhyolite and minor dacite/trachyte nonwelded ash-flow tuff and lava flows, and subordinate ash-fall tuff and tuffaceous sedimentary rocks, in Bullfrog Hills area. In map area dominated by thick (as much as about 150 m), massive ash-flow tuff that is crystal-rich and contains common plagioclase, quartz, sanidine, and biotite. Lava flows contain common plagioclase and biotite, sparse quartz, and local rare hornblende and clinopyroxene. Rests with angular discordance upon older volcanic units; concordantly(?) overlies proximal sedimentary rocks (breccia) of unit Tgx. Lavas have normal magnetic polarity; age about 11 Ma. Maximum exposed thickness in quadrangle about 250 m. Equivalent to rhyolite lava flows and tuffs of Rainbow Mountain of Maldonado and Hausback (1990)

Tfb **Beatty Wash Formation (Miocene)**--Post-caldera rhyolite lavas and related tuff erupted from 11.4 to 11.2 Ma within moat of Timber Mountain caldera complex. Includes rhyolite of Beatty Wash (normal magnetic polarity) and tuff of Cutoff Road (anomalous reversed magnetic polarity), which contain common sanidine and plagioclase, sparse to common biotite, local sparse hornblende, local rare quartz, and common sphene. Petrographically similar tephras are white and very pumice-rich in lower part and consist of brown basalt-rhyolite mixes in rhyolite of Chukar Canyon subunit of upper part. Quartz-poor character and abundance of sphene are diagnostic. Also includes overlying rhyolites of Max Mountain (reversed magnetic polarity) and Boundary Butte, which contain sparse quartz phenocrysts. Lavas as much as 300-430 m thick; tuff layers as much as 60 m thick

Tff **Rhyolite of Fleur-de-lis Ranch (Miocene)**--Post-caldera rhyolite lavas and welded ash-flow tuff erupted at about 11.4 Ma on west side of Timber Mountain caldera complex. Contains abundant plagioclase and biotite, sparse clinopyroxene, and local sparse hornblende. Distinguished by abundance of plagioclase and lack of sphene, especially in welded ash-flow subunits. Magnetic polarity normal. Stacked lavas and welded tuffs as much as 300 m thick. Includes rhyolite of West Cat Canyon

Timber Mountain Group (Miocene)--Calc-alkaline assemblage erupted from the Timber Mountain caldera complex between about 11.6 and 11.45 Ma. Group consists predominantly of rhyolite ash-flow tuff and includes subordinate, related rhyolite lava flows and domes that erupted before, between, and after emplacement of ash-flow units. Eruption of the voluminous Rainier Mesa Tuff (unit Tmr) and Ammonia Tanks Tuff (unit Tma) resulted in collapse of the Rainier Mesa and younger Ammonia Tanks calderas, respectively, which form the Timber Mountain caldera complex. The latter caldera is centered about Timber Mountain, which consists of the Ammonia Tanks resurgent dome. Rocks of this group are distinguished by high content of quartz phenocrysts in rhyolite units and high mafic contents in upper parts of zoned units. Subdivided into:

Tmi **Timber Mountain intrusive rocks (Miocene)**--Intrusive rhyolite and microgranite porphyry that intruded southeast flank of Timber Mountain dome following collapse of Ammonia Tanks caldera. Intrusive rhyolite is crystal-rich and contains abundant alkali feldspar, common quartz, sparse biotite and plagioclase, and sphene; strongly resembles rhyolite zone of Ammonia Tanks Tuff (Tma) compositionally. Microgranite porphyry is very crystal rich syenite and contains very abundant sanidine, abundant biotite, and common plagioclase and clinopyroxene

Tmay **Trachyte of East Cat Canyon**--Immediately post-caldera, very crystal rich trachyte lavas erupted prior to resurgence on margin of Ammonia Tanks resurgent dome. Contains very abundant plagioclase and biotite, abundant clinopyroxene, sparse sanidine and orthopyroxene, rare quartz and hornblende, and abundant apatite. Close temporal and compositional association with Ammonia Tanks Tuff (Tma) is distinctive, as is the presence of sanidine and quartz, which is unusual for an intermediate lava. Maximum thickness about 125 m. Includes rhyolite of Parachute Canyon

Tmaw **Tuff of Buttonhook Wash**--Post-caldera, crystal-rich rhyolite ash-flow tuff and subordinate bedded tuff erupted immediately after Ammonia Tanks subsidence, and confined within Timber Mountain caldera complex. Contains common sanidine, plagioclase, and quartz, sparse biotite and clinopyroxene, local rare hornblende, and abundant sphene. Virtually identical to intracaldera facies of unit Tma, but separated from it by a cooling break. Magnetic polarity normal. Maximum exposed thickness about 250 m. Includes petrographically indistinguishable tuff of Crooked Canyon

Tma **Ammonia Tanks Tuff**--Widespread calc-alkaline, welded ash-flow tuff sheet erupted at 11.45 Ma from younger Ammonia Tanks caldera of Timber Mountain caldera complex, and resurgently domed to form Timber Mountain. Compositionally zoned from lower, volumetrically dominant rhyolite (abundant sanidine, common quartz and plagioclase, sparse biotite, rare clinopyroxene, and sparse sphene) to upper crystal-rich trachyte (abundant sanidine and biotite, common plagioclase and quartz, and sparse clinopyroxene and sphene). Local basal bedded tuff unit resembles lower rhyolite but contains sparse hornblende and rare orthopyroxene, clinopyroxene, and Mg-rich olivine in association with basaltic lapilli. Distinguished by high quartz and mafic contents, sparse sphene, and normal magnetic polarity. Maximum intracaldera thickness of more than 900 m on Timber Mountain resurgent dome; outflow widely distributed in all directions, with a typical thickness of less than 150 m

Tmx **Timber Mountain landslide breccia**--Thickly bedded, poorly sorted breccia grading downward into megabreccia. Composed of angular, mainly pre-Ammonia Tanks volcanic clasts as much as 6 m across and variable proportions of coarse-grained tuffaceous matrix; clasts locally derived from rock units exposed on topographic wall of Timber Mountain caldera complex. Lower part of unit locally intertongues with upper Rainier Mesa Tuff (Tmr), and breccia is overlain by intracaldera Ammonia Tanks Tuff (Tma). Breccia, limited to caldera moat and base of caldera wall, emplaced as debris flows and rock avalanches shed off topograhic wall of caldera(s) following Rainier Mesa and, perhaps, Ammonia Tanks collapse. Maximum thickness exceeds 300 m

Tmt **Basalts in Timber Mountain Group**--Flows containing common olivine, common plagioclase, and local sparse clinopyroxene. Includes pre-

Rainier Mesa basalt of Tierra [normal magnetic polarity (Lawrence Livermore National Lab, unpublished data)] and basalt of Oasis Valley (reversed magnetic polarity) that occurs stratigraphically between Rainier Mesa (Tmr) and Ammonia Tanks (Tma) Tuffs. Maximum exposed thickness less than 30 m

Tmat **Rhyolite of Tannenbaum Hill**--Rhyolite lavas and related subordinate nonwelded tuff erupted between emplacement of Rainier Mesa Tuff (Tmr) and Ammonia Tanks Tuff (Tma) in northwest Timber Mountain caldera complex moat; chemically and petrographically similar to Ammonia Tanks. Contains common quartz and sanidine, rare plagioclase and biotite, and common sphene. Distinguished by sphene content, normal magnetic polarity, and stratigraphic position between major tuff units. Maximum thickness greater than 180 m

Tmr **Rainier Mesa Tuff**--Widespread calc-alkaline welded ash-flow tuff sheet erupted at 11.6 Ma from older Rainier Mesa caldera of Timber Mountain caldera complex. Compositionally zoned from lower, volumetrically dominant rhyolite (common sanidine and quartz, sparse plagioclase, and rare biotite) to upper crystal-rich trachyte (abundant biotite, common sanidine, plagioclase, and quartz, sparse clinopyroxene, and rare orthopyroxene and hornblende). Distinctive thin (about 10 cm) tephra layers directly beneath main eruptive unit consist of paired dacite and overlying trachybasalt tuff containing abundant hornblende, common plagioclase, and sparse orthopyroxene. Unit distinguished by high quartz and mafic contents, rare accessory monazite, and reversed magnetic polarity; lower nonwelded to partly welded zones are characteristically salmon pink. Maximum intracaldera thickness of more than 500 m; outflow, which is widely distributed in all directions, has a typical maximum thickness of 150 m and locally is ponded to a thickness of as much as about 400 m. Includes local overlying bedded Rainier Mesa Tuff; may locally include Ammonia Tanks Tuff (Tma) in Bullfrog Hills where tuff is brecciated and hydrothermally altered

Tmrl **Pre-Rainier Mesa rhyolites**--Widespread pre-caldera rhyolite lava and nonwelded tuff erupted prior to eruption of Rainier Mesa Tuff (Tmr). Contains common quartz and sanidine, sparse plagioclase, and rare biotite. Locally consists of thick nonwelded tuff deposits. Distinguished by high quartz content, reversed magnetic polarity, and rare accessory monazite, and from petrographically similar mafic-poor Rainier Mesa Tuff by lower lithic content. Maximum thickness about 200 m. Includes tuff of Holmes Road, a distinctive interlayered brown and pink to white phreatomagmatic deposit

Paintbrush Group (Miocene)--This calc-alkaline assemblage of alkali rhyolite tuffs and lavas was erupted from the vicinity of the Timber

Mountain caldera complex between 12.8 and 12.7 Ma. The Claim Canyon caldera, the well-established source of the younger Tiva Canyon Tuff (unit Tpc), overlaps the southern part of the Timber Mountain caldera complex and is exposed just south of the quadrangle, whereas the source of the older Topopah Spring Tuff (unit Tpt) is uncertain. Paintbrush Group rocks are distinguished by an absence or rarity of quartz phenocrysts in rhyolite units and the presence of sphene, except in the lower Topopah Spring. In addition to biotite, units in the upper part of the Paintbrush contain hornblende, whereas the lower units contain clinopyroxene. Subdivided into:

Tpu **Post-Tiva Canyon rhyolites**--Post-caldera rhyolite lavas and related nonwelded tuff exposed on northern topographic wall of Timber Mountain caldera complex. Contains common sanidine and common to sparse plagioclase and biotite. Includes the rhyolite of Scrugham Peak, which also contains abundant sphene, and the younger rhyolite of Benham, which additionally contains rare quartz and hornblende. Erupted at 12.7 Ma immediately after the Tiva Canyon Tuff; reversed magnetic polarity. Maximum exposed thickness 300 m

Tpc **Tiva Canyon Tuff**--Widespread calc-alkaline welded ash-flow tuff sheet erupted at 12.7 Ma from Claim Canyon caldera. Compositionally zoned from lower crystal-poor rhyolite (common sanidine, sparse hornblende, and abundant sphene) to upper trachyte (common sanidine and plagioclase, sparse biotite and clinopyroxene, rare hornblende, and sparse sphene). Distinguished by dominance of sanidine among felsic phenocrysts, presence of sphene, and reversed magnetic polarity; lower part commonly is conspicuously platy. Locally hydrothermally altered and brecciated in Bullfrog Hills. Exposures consist entirely of outflow in quadrangle, and unit is widely distributed throughout central part of map area with maximum exposed thickness about 110 m

Tpm **Middle Paintbrush Group rhyolites**--Lava flows and related nonwelded tuff present at Pahute Mesa that were erupted between deposition of major Paintbrush ash-flow tuff units (Tpt and Tpc). Lavas contain common sanidine, common to rare plagioclase and biotite, and rare quartz. The lowest unit, the rhyolite of Silent Canyon, has the highest plagioclase content, common biotite as the only mafic mineral, and lacks sphene; overlying rhyolite of Echo Peak is characterized by sparse to common biotite, rare clinopyroxene, and abundant sphene; uppermost crystal-poor rhyolite of Delirium Canyon has sparse plagioclase, rare hornblende and biotite, and abundant sphene. Distinguished by stratigraphic position and by reversed magnetic polarity of lava flows. Maximum thickness for individual flow units ranges from 140 to 390 m

Tpt **Topopah Spring Tuff**--Widespread calc-alkaline welded ash-flow tuff sheet erupted at 12.8 Ma from as yet uncertain caldera source located in general vicinity of Timber Mountain caldera complex. Compositionally zoned from lower crystal-poor rhyolite (sparse plagioclase and rare sanidine, biotite, and quartz) to upper trachyte (common sanidine and plagioclase, sparse biotite and clinopyroxene, and local rare quartz). Local overlying bedded tuff is zoned in similar fashion. Unit distinguished by high sanidine content but lower sanidine/plagioclase ratio than that of Tiva Canyon Tuff (Tpc), negligible quartz content, absence of sphene, and normal magnetic polarity. Consists entirely of outflow in quadrangle; tuff widely distributed in southeastern part of map area where it has a maximum exposed thickness of about 140 m

Tac **Calico Hills Formation (Miocene)**--Sequence of calc-alkaline rhyolite lavas and related tuff erupted from vents in Calico Hills area south of quadrangle and in Area 20 caldera in subsurface of Pahute Mesa (Sawyer and Sargent, 1989) at 12.9 Ma. Lavas represent post-collapse eruptions related to Crater Flat Group magmatism. Lava sequence is compositionally zoned from lower rhyolite (contains common quartz, plagioclase, and sanidine and sparse biotite) to upper crystal-poor rhyolite (contains sparse quartz and sanidine, and rare plagioclase and biotite). Also includes crystal-rich rhyolites of Pool (sparse biotite and hornblende) and Inlet (common biotite and sparse hornblende) in subsurface of Pahute Mesa. On the west side of Yucca Flat, in Rainier Mesa/southern Belted Range area, and north of Silent Canyon the map unit may include undivided bedded tuff associated with the Bullfrog Tuff (unit Tcb), the Wahmonie Formation (not mapped separately in quadrangle, but important to the south), the Paintbrush Group (units Tpt, Tpm, and Tpc), and (or) pre-Rainier Mesa rhyolites (unit Tmrl). Normal magnetic polarity, high relative quartz content, Fe-rich mafic mineral chemistry, common bedded tuff character, and local zeolitization are distinctive. Maximum exposed thickness 120 m; ponded to more than 2200 m within Area 20 caldera

Crater Flat Group (Miocene)--Calc-alkaline assemblage of ash-flow sheets, lavas, and related nonwelded tuff erupted from Area 20 caldera and possibly from the vicinity of the proposed Prospector Pass caldera (south of quadrangle; Carr and others, 1986) between about 13.5 and 13.1 Ma. The Bullfrog Tuff (unit Tcb), the only major Crater Flat unit present in the quadrangle, erupted from Area 20 caldera where it is ponded to a thickness of more than 600 m in the subsurface of Pahute Mesa; a larger part of caldera may have been obliterated by younger Timber Mountain caldera complex. Crater Flat assemblage is distinguished by high relative quartz contents among the felsic minerals and Fe-rich mafic mineralogy. Subdivided into:

Tcg **Latite of Grimy Gulch**--Local intermediate-composition, mainly crystal-poor lava flows erupted on flank of Silent Canyon caldera complex at south end of Kawich Valley. Contains common plagioclase and olivine, sparse clinopyroxene, and rare sanidine and quartz (both with reaction rims). Normal magnetic polarity. Maximum thickness 76 m

Tcb **Bullfrog Tuff**--Widespread calc-alkaline, variably welded, rhyolite ash-flow tuff sheet. Regional variations in lithic content from lithic-poor welded tuff south of quadrangle at Yucca Mountain to thick, compositionally zoned, lithic-rich nonwelded tuff in central part of map area in the buried Area 20 caldera. Outflow Stockade Wash lobe east of caldera, previously called Stockade Wash Tuff, has common sanidine, quartz, plagioclase, and biotite, rare hornblende, and maximum thickness of 120 m. Intracaldera facies in Area 20 caldera is compositionally zoned, from lower rhyolite (common sanidine and quartz, sparse plagioclase, and rare biotite) to upper rhyolite (common sanidine, plagioclase and quartz, sparse biotite, and rare hornblende); it has a high lithic content, is intercalated with landslide breccia deposits, and has maximum thickness of about 680 m. Tuff is hydrothermally altered and locally brecciated in Bullfrog Hills. Distinguished by high relative quartz content among the felsics, sparse to rare biotite and hornblende, Fe-rich mafic minerals, general absence of sphene, and normal magnetic polarity. About 13.2 Ma in age. Includes local subunit (tuff of Rickey) in subsurface of Pahute Mesa; on west side of Yucca Flat, and in Rainier Mesa/southern Belted Range area may include undivided bedded tuff of Deadhorse Flat Formation (unit Tbd), Wahmonie Formation, Calico Hills Formation (unit Tac), the Paintbrush Group (units Tpt, Tpm, and Tpc), and (or) pre-Rainier Mesa rhyolites (unit Tmrl)

Belted Range Group (Miocene)--Peralkaline assemblage of ash-flow sheets, lavas, and related nonwelded tuff erupted from the older Grouse Canyon caldera of the Silent Canyon caldera complex between 13.85 and 13.5 Ma. Grouse Canyon Tuff (unit Tbg), the major caldera-forming unit, has a strong petrologic affinity with the pre-caldera Comendite of Split Ridge (unit Tbgs). Following eruption of Grouse Canyon Tuff and its ponding within caldera, further caldera collapse occurred, and a thick sequence of post-caldera peralkaline lavas and related tuff, the Deadhorse Flat Formation (unit Tbd), accumulated within Grouse Canyon caldera in the subsurface of Pahute Mesa and overflowed it to the north into the Saucer Mesa area. Belted Range Group is distinguished by its peralkaline mineralogy and chemistry; petrographically, it is characterized by high alkali feldspar and low plagioclase contents, absence of biotite and hornblende, and presence of Fe-rich clinopyroxene and fayalitic olivine; quartz is common to sparse in some units, and absent in others; chemically, Belted Range Group is distinguished by high iron and low aluminum in rhyolitic compositions, and anomalous, high concentrations of zirconium and rare-earth elements. Subdivided into:

Tbd **Deadhorse Flat Formation**--Post-caldera lavas and related tuff erupted and ponded within Grouse Canyon caldera between 13.7 and 13.5 Ma. Mineralogy is variable among the different stratigraphic subunits of formation, which range from crystal-rich comendite (peralkaline rhyolite) and trachyte to crystal-poor and aphyric comendite. Common alkali feldpsar (sodic sanidine) is the dominant felsic phenocryst phase, whereas clinopyroxene and fayalitic olivine are the only mafic phenocryst minerals. Unit includes comendite of Lambs Canyon (with common quartz), aphyric comendite of Kaw Station, comendite and low-silica comendite of Saucer Mesa, comendite of Chartreuse (with sparse quartz and rare plagioclase), and trachyte of Muenster (with abundant alkali feldpspar and rare plagioclase). Formation distinguished by phenocryst mineralogy (general absence of biotite, hornblende, and plagioclase) and distinctive geochemistry. Comendite of Lambs Canyon has reversed magnetic polarity and comendite of Saucer Mesa has normal polarity. Maximum thickness about 1600 m in subsurface of Pahute Mesa; maximum exposed thickness about 150 m. Locally includes:

Tbdb **Comendite of Basket Valley**--Comendite lava and welded to nonwelded tuff present stratigraphically between overlying comendite of Saucer Mesa and underlying comendite of Chartreuse in the subsurface. Separated from rest of Deadhorse Flat Formation only northeast of Grouse Canyon caldera where it forms a distinct mappable unit at base of formation. Distinguished by petrography (abundant alkali feldspar and rare quartz, clinopyroxene, and fayalitic olivine), strong light rare-earth element enrichment, and rheomorphic character of lava. Includes a low-silica comendite lava north of Apache Tear Canyon. Normal magnetic polarity. Maximum exposed thickness about 150 m

Tbg **Grouse Canyon Tuff**--Widespread peralkaline welded ash-flow tuff sheet erupted at 13.7 Ma from Grouse Canyon caldera of Silent Canyon caldera complex. Compositionally zoned from lower aphyric comendite to upper moderately crystal rich comendite (common alkali feldspar and rare quartz, plagioclase, clinopyroxene, and fayalitic olivine). Groundmass arfvedsonite is common in devitrified, welded upper part. Basal aphyric comendite bedded tuff is more widely distributed to east and southeast than ash-flow tuff, and consists of multiple normally graded, 3-15 m thick beds each containing basal pyroclastic shards and pumice grading upward to fine ash. Unit distinguished by high alkali feldspar content relative to other felsic phases, absence of biotite, strong zonation in geochemistry, conspicuous greenish- to bluish-gray color of lower welded tuff and bedded tuff, and anomalous normal magnetic polarity. Maximum intracaldera thickness about 575 m in subsurface of Pahute Mesa; outflow is widely distributed to northeast (in Belted Range) and west of caldera complex; distribution to south poorly constrained because of younger calderas and outflow tuff sheets; maximum exposed outflow thickness about 110 m; maximum thickness of bedded tuff 150 m

Tbgs **Comendite of Split Ridge**--Pre-caldera aphyric comendite lava flows and related tuff erupted at 13.85 Ma. Exposed at Split Ridge southeast of Silent Canyon caldera complex. Normal magnetic polarity. Maximum thickness about 380 m

Tob **Older basalt (Miocene)**--Local basalt and (or) basaltic andesite lava flows exposed near base of Miocene volcanic sequence at north end of Yucca Flat, beneath Grouse Canyon Tuff (unit Tbg) in area west of Black Mountain, and beneath Bullfrog Tuff (unit Tcb) in Bullfrog Hills. Locally very crystal rich, containing common olivine and clinopyroxene, and common to rare plagioclase. Basalt microporphyritic near Yucca Flat; contains very abundant olivine below Grouse Canyon Tuff; hydrothermally altered in Bullfrog Hills. Distinguished from other basalt units by lower stratigraphic position. Basalt near Yucca Flat has normal magnetic polarity. Maximum exposed thickness exceeds 50 m

Ti **Tertiary intrusion (Miocene)**--Andesitic, hydrothermally altered, hypabyssal intrusion poorly exposed in Bullfrog Hills. Contains common plagioclase and clinopyroxene phenocrysts. Intrudes Proterozoic and Paleozoic basement rocks and predates or is coeval with overlying older basalt unit (Tob)

Trl **Lithic Ridge Tuff (Miocene)**--Regional, partly welded to welded calc-alkaline ash-flow tuff erupted at 13.85 Ma from unknown caldera source possibly in vicinity of Crater Flat south of quadrangle. Contains common plagioclase and sanidine, and sparse quartz, biotite, and sphene. Distinguished by high plagioclase content relative to other felsic phases and anomalous reversed magnetic polarity. Maximum exposed thickness in quadrangle 30 m

Trc **Lavas and dikes of Tram Ridge (Miocene)**--Widespread calc-alkaline, crystal-rich dacite lava flows, intrusive feeders, and local related tuff erupted at 14.0 Ma. Contains abundant plagioclase and biotite, sparse sanidine, hornblende, and sphene, and rare quartz. Distinguished by abundant plagioclase and biotite, and reversed magnetic polarity. Partly equivalent to units in subsurface of Yucca Mountain south of quadrangle (andesites and dacites in drill holes G-1 and G-2, and tuff of Units B and C). Correlative with calc-alkaline tephra in bed 4JK (Carroll, 1989, fig. 2) of unit Tn. Maximum exposed thickness about 450 m

Tn **Tunnel Formation (Miocene)**--Diverse sequence of dominantly red and white bedded and nonwelded rhyolite tuff; possibly includes subordinate, reworked, epiclastic tuff. Mappable unit where ponded in local paleobasins mainly in eastern part of quadrangle, most notably at Rainier Mesa, but also on west side and in subsurface of Yucca Flat. Upper beds (4JK) [see Carroll (1989, fig. 2) for stratigraphic context of number/letter-designated subunits of formation] consist of interfingering calc-alkaline and peralkaline tephra; peralkaline, aphyric comendite tuff is apparently related to comendite of Quartet Dome (unit Tuq), whereas calc-alkaline tuff is associated with lava of Tram Ridge (unit Trc) or slightly older calc-alkaline sources (bed 4GH). Non-peralkaline middle beds (3D, 4A-F) contain common sanidine and sparse quartz and plagioclase, and are very mafic-poor (rare clinopyroxene and biotite); crystal content of middle beds increases slightly down section. Bed 3D includes rare hornblende. Lower beds consist of crystal-poor tuff (sparse plagioclase and rare sanidine, quartz, and biotite [bed 3BC]) underlain by crystal-rich tuff (common plagioclase, sanidine, quartz, and biotite, and rare hornblende [bed 3A]). Top of unit is defined as base of Grouse Canyon Tuff (unit Tbg) or Lithic Ridge Tuff (unit Trl); base of formation is top of Tub Spring Tuff (unit Tub). Formation distinguished by its significant local thickness (as much as 200 m), typical zeolitic alteration, and internal variations in petrography and chemistry

Toq **Rhyolite of Quartz Mountain (Miocene)**--Calc-alkaline rhyolite to dacite lava flows, plugs, and related tephra envelopes stratigraphically above and below tuff of Tolicha Peak (unit Tot); exposed in western part of quadrangle. Three types of modes recognized in rhyolite lavas above tuff of Tolicha Peak: (1) common sanidine and plagioclase, sparse biotite, rare clinopyroxene, and abundant sphene, (2) common sanidine, plagioclase, and quartz, and sparse hornblende, and (3) very abundant to abundant plagioclase and biotite, common to sparse alkali feldspar and hornblende, rare quartz, and very abundant to sparse sphene; lavas of the latter type are possibly correlative with lavas of Tram Ridge (unit Trc). Dacite lava flows and intrusive masses below tuff of Tolicha Peak exposed in Mt Helen area are crystal rich with abundant plagioclase, biotite, and hornblende, and common large (more than 1 cm), conspicuous quartz. Two types of modes identified in pre-Tolicha Peak rhyolite lavas in Tolicha Peak area: (1) common quartz, plagioclase, sanidine, and biotite, rare hornblende, and sparse sphene, and (2) sparse alkali feldspar and biotite. Post-Tolicha Peak flows have reversed magnetic polarity. Maximum exposed thickness more than 250 m. Intercalated with and related to bedded tuff of Quartz Mountain (unit Toqb)

Toqb **Bedded tuff of Quartz Mountain (Miocene)**--Bedded and nonwelded, crystal- and lithic-rich, rhyolite tuff and tuff breccia associated with and compositionally similar to intercalated rhyolite of Quartz Mountain lavas (unit Toq); in Mt Helen area includes bedded, fluvial to lacustrine, locally tuffaceous sedimentary rocks that may be partly related to tuff of Tolicha Peak (unit Tot). Lithic fragments typically composed of Quartz Mountain lava. Locally zeolitized. Maximum exposed thickness more than 300 m. Includes tuff above, below, and, locally, equivalent(?) to Tolicha Peak; may also locally include tuff of Sleeping Butte (unit Tos)

Tos **Tuff of Sleeping Butte (Miocene)**--Sequence of two calc-alkaline rhyolite ash-flow tuffs and associated bedded tephra exposed in Sleeping Butte area about 12 km north of Oasis Valley; tuffs probably erupted from caldera source in this area. Distal facies of unit may be present further north in areas mapped as bedded tuff of Quartz Mountain (unit Toqb). Upper tuff is partly welded, massive, lithic rich, and crystal poor, with sparse alkali feldspar and rare biotite. Underlying, more densely welded tuff is strongly zoned from lower mafic-poor rhyolite with common sanidine and quartz, sparse plagioclase, and rare pseudomorphs of clinopyroxene and (or) hornblende, to upper crystal-rich rhyolite with abundant sanidine and plagioclase, sparse pseudomorphs of hornblende and (or) clinopyroxene and biotite, and rare quartz. Upper tuff apparently laps onto lower densely welded tuff east of Sleeping Butte. Lower welded tuff distinguished by high sanidine content, locally abundant granitoid inclusions, stratigraphic position, and normal magnetic polarity. Maximum exposed cumulative thickness about 400 m. Unit may include tuff related to lavas and dikes of Tram Ridge (unit Trc), and possibly correlative with beds 4GH of Tunnel Formation (unit Tn)

Tuq **Comendite of Quartet Dome (Miocene)**--Peralkaline crystal-rich comendite lava domes and related tephra mainly exposed around south margin of Kawich Valley. Contains abundant sanidine, common quartz, sparse fayalitic olivine, and rare clinopyroxene. Distinguished by peralkaline mineralogy (absence of plagioclase and biotite), high relative quartz content, and normal magnetic polarity. Maximum exposed thickness 250 m. May be in part correlative with bed 4J of Tunnel Formation (unit Tn) and therefore closer in age to Grouse Canyon Tuff (unit Tbg) than petrographically similar Tub Spring Tuff (unit Tub)

Tot **Tuff of Tolicha Peak (Miocene)**--Distinctive calc-alkaline, very crystal poor, welded rhyolite ash-flow tuff exposed in western part of quadrangle and erupted from unknown source. Contains rare plagioclase, sanidine, and quartz, and no mafics (except local rare biotite). Conspicuous platy to hackly, orangish- to pinkish-brown appearance in outcrop; poorly exposed. Normal magnetic polarity. Maximum exposed thickness exceeds 300 m. Correlative with beds 3BC of Tunnel Formation (unit Tn)

Tub **Tub Spring Tuff (Miocene)**--Widespread peralkaline welded ash-flow tuff present in Belted Range and northeast side of Yucca Flat; erupted at 14.9

Ma from a buried and poorly constrained caldera possibly in eastern Pahute Mesa or southern Kawich Valley. Compositionally zoned from lower crystal-poor comendite containing common sanidine and quartz, and rare plagioclase and biotite, to upper crystal-rich comendite containing abundant sanidine, common quartz, and sparse clinopyroxene and fayalitic olivine. Distinguished from peralkaline Grouse Canyon Tuff (unit Tbg) and younger units by high relative quartz content. Normal magnetic polarity. Maximum exposed outflow thickness 90 m

Tout **Older undivided tuff (Miocene)**--Three or more, probably unrelated, rhyolitic welded ash-flow tuff sheets exposed in Gold Flat area and southern Belted Range. Contain variable phenocryst abundances of plagioclase, alkali feldspar, quartz, biotite, hornblende, clinopyroxene, and sphene. Includes tuff of Wilsons Camp, tuff of Gold Flat, and, near south end of Kawich Valley, aphyric ash-flow tuff of Cache Cave Draw. Latter tuff has reversed magnetic polarity

Tour **Older undivided rhyolite lavas (Miocene)**--Calc-alkaline lava flows and related tephra exposed chiefly in Belted Range but also in Gold Flat. Contains variable phenocryst abundances of quartz, alkali feldspar, plagioclase, biotite, and hornblende. Variable magnetic polarity; includes rhyolites of Belted Peak (normal polarity), Johnnies Water (reversed polarity), O'Briens Knob (reversed polarity), and Gold Flat. Maximum exposed composite thickness about 600 m

Ton **Older tunnel beds (Miocene)**--Lower sequence of zeolitized, dominantly white, bedded and nonwelded rhyolite tuff and reworked epiclastic tuff. Limited exposures around north end of Yucca Flat and southern Kawich Valley; extensive in subsurface of Rainier Mesa and Yucca Flat. Distinguished from overlying Tunnel Formation (unit Tn) by stratigraphically intervening Tub Spring Tuff (unit Tub). Maximum exposed thickness about 10 m. Includes tunnel beds 1 and 2 of Carroll (1989, fig. 2), and may locally include nonwelded tuff equivalent to units Toy, Tor, and Tof, and tuff of Whiterock Spring

Tuk **Trachytes and comendites of Kawich Valley (Miocene)**--Peralkaline lava flows, feeder dikes and associated intrusive bodies, and related tephra interpreted to predate Tub Spring Tuff (unit Tub). Trachyte lavas, locally exposed along western margin of Kawich Valley and Saucer Mesa, contain common sanidine, olivine, and clinopyroxene. Comendite lava flows comprise moderately crystal poor rocks present at Ocher Ridge and crystal-rich varieties in the Wheelbarrow Peak area of the Belted Range; comendite lavas contain abundant to common sanidine and quartz, and rare clinopyroxene. Maximum exposed thicknesses 110 m and 375 m, respectively. Comendite of Ocher Ridge has normal magnetic polarity

Tod **Older dacitic lavas (Miocene)**--Crystal-rich lava flows containing abundant plagioclase and common biotite and hornblende. Some flows contain quartz, clinopyroxene, and hornblende and lack biotite. Distinguished from older undivided rhyolite lavas (unit Tour) by lack of alkali feldspar. Present along margin of Kawich Valley and in Gold Flat; maximum exposed thickness about 250 m. Flows near Kawich Valley have normal magnetic polarity

Toy **Tuff of Yucca Flat (Miocene)**--Subregional, nonwelded to partly welded, calc-alkaline rhyolite ash-flow sheet erupted at 15.05 Ma from unknown source. Present in subsurface and along margins of Yucca Flat. Contains common plagioclase, sanidine, and biotite, and sparse quartz and hornblende; typically zeolitized. Reversed magnetic polarity. Maximum thickness 80 m

Tor **Redrock Valley Tuff (Miocene)**--Subregional, welded, calc-alkaline, crystal-rich rhyolite ash-flow sheet erupted at 15.1 Ma from unknown source near Timber Mountain; exposed along west and north margins of Yucca Flat. Contains common plagioclase, sanidine, and biotite, rare quartz and hornblende, and sparse sphene; some samples contain common hornblende in excess of biotite. Distinguished by high relative plagioclase and low relative quartz contents, reversed magnetic polarity, common dense welding (atypical in lower tuff units), and red color where altered. Maximum exposed thickness about 125 m

Tof **Fraction Tuff (Miocene)**-- Crystal-rich rhyolite ash-flow tuff containing common plagioclase, sanidine, quartz, and biotite, sparse hornblende, rare clinopyroxene, and very abundant sphene. Magnetic polarity reversed. Source unknown; exposed along northern margin of Yucca Flat; maximum exposed thickness 475 m. Includes tuff of Whiterock Spring

Tep **Pahranagat Lakes Tuff (Miocene)**--Calc-alkaline, crystal-rich, rhyolite ash-flow tuff sheet erupted at 22.65 Ma from probable caldera source in Kawich Range in central Nevada caldera complex. Contains abundant quartz, common sanidine, plagioclase, and biotite, rare hornblende, and common sphene. Reversed magnetic polarity. Exposed near northeastern corner of quadrangle; maximum exposed thickness about 250 m. Equivalent to tuff of White Blotch Spring

Tes **Shingle Pass Tuff (Oligocene)**--Widespread calc-alkaline rhyolite ash-flow tuff sheet erupted at 26.7 Ma probably from caldera source in Quinn Canyon Range in central Nevada caldera complex. Contains common sanidine, plagioclase, and pyroxene, sparse quartz and biotite, and rare hornblende and fayalitic olivine. Normal magnetic polarity, indicating that only lower Shingle Pass cooling unit is present in quadrangle.

Exposed in Belted Range and Rhyolite Hills in northeastern part of quadrangle; maximum exposed thickness about 250 m

Tea **Tuff of Antelope Springs (Oligocene)**--Generally crystal-rich welded ash-flow tuff erupted from an unknown source possibly near the Cactus Range north of quadrangle. Zoned from dacite to rhyolite. Contains common quartz, sanidine, and plagioclase, and local sparse biotite and psuedomorphs of hornblende and (or) clinopyroxene. Locally includes basal bedded tuff. Reversed magnetic polarity. Exposed in northwestern part of quadrangle; maximum exposed thickness about 100 m

Tem **Monotony Tuff (Oligocene)**--Widespread calc-alkaline, very crystal-rich dacite welded ash-flow tuff sheet erupted at 27.31 Ma from caldera source in southern Pancake and northern Reveille Ranges in central Nevada caldera complex. Contains very abundant plagioclase and biotite, abundant hornblende, and common quartz, sanidine, and clinopyroxene. Extremely crystal-rich nature, anomalous normal magnetic polarity, and brownish, hummocky outcrop appearance are distinctive. Exposed in Belted Range and Rhyolite Hills in northeastern part of quadrangle; maximum exposed thickness about 210 m

Tec **Clastic sedimentary rocks (Oligocene?)**--Weakly cemented, poorly bedded and poorly exposed fanglomerate containing poorly sorted, angular to subrounded pebbles, cobbles, and boulders composed of quartzite and subordinate sedimentary rocks of Paleozoic and (or) late Proterozoic age. Lack of Tertiary volcanic clasts is diagnostic, and, in conjunction with depositional lower and upper contacts with probable Wood Canyon Formation (unit ƐZw) and tuff of Antelope Spring (unit Tea), respectively, indicates an Oligocene or older age. Exposed in limited area west of Mt Helen where unit has a maximum thickness of more than 100 m. Equivalent to fanglomerate unit of Ekren and others (1971) and possibly lateral equivalent of rocks of Pavits Spring of Hinrichs (1968) and (or) Horse Spring Formation

Kg **Granitic rocks (Cretaceous)**--Equigranular and porphyritic intrusive rocks that range in composition between biotite granodiorite and biotite monzogranite; rocks exposed in 3 separate localities. Includes the Climax stock (101 Ma; Naeser and Maldonado, 1981) at northern end of Yucca Flat, in which an older, equigranular hornblende-biotite granodiorite phase is intruded by porphyritic biotite monzogranite (Houser and Poole, 1960). Homogeneous biotite monzogranite comprises the Gold Meadows stock (93.6 Ma; Naeser and Maldonado, 1981) north of Rainier Mesa. A small mass of muscovite-bearing perthite granite is exposed east of Saucer Mesa in the Kawich Range

PPbs **Bird Spring Formation (Lower Permian and Pennsylvanian)**--Limestone, calcareous mudstone, and minor chert-pebble conglomerate and sandy limestone; well-bedded, ledgy, medium-gray unit in outcrop; echinoderm, bryozoan, brachiopod, and other fossils common throughout; fusilinids are distinctive and abundant in the middle and upper parts of the unit. Base is an indistinct paraconformity above the MDe unit. Unit only preserved in southeastern part of quadrangle in the core of a synclinal fold at Syncline Ridge, where it is equivalent to the Tippipah Limestone. Maximum thickness 1250 m (Miller, 1989)

MDe **Eleana Formation (Mississippian and Upper Devonian)**--Chert-rich sandstone and pebble conglomerate, and siliceous siltstone and minor bioclastic limestone; laterally variable unit containing thick-bedded lenticular red-brown sandstone-conglomerate turbidite beds, laminated green-brown siltstone, and discrete ocher-weathering carbonate turbidite beds; coarser clastic layers generally form rounded hills in the Eleana Range whereas siltstone is largely covered by alluvium. Informally described as 10 subunits by Poole and others (1961) that consist of thin limestone conglomerate (about 35 m) above a channeled, unconformable base, a thick middle section of siliciclastic turbidite deposits (more than 2000 m), bioclastic limestone with common crinoid and brachiopod fossils (about 150 m), and a thick upper unit of siltstone and local, thin quartzarenite beds (more than 1200 m). Exposed in eastern part of quadrangle west and north of Yucca Flat. Recent work by Cashman and Trexler (1991) suggests the possibility that the latter thick siltstone section near Syncline Ridge and northern Mine Mountain ("unit J" of Poole and others, 1961) may be an eastern shallow-water facies that is coeval with all of the siliciclastic section in the Eleana Range to the west

Ds **Simonson Dolomite (Middle Devonian)**--Dolomite and local sandy dolomite; medium- to dark-gray, conspicuously bedded, ledge-forming unit that includes a distinctive yellow, silty, cherty dolomite at the base; distinguished by uniform bedding, alternating dark and light layers, and by common dolomitized relics of brachiopods, tubular corals, and stromatoporoids. Unit exposed in southeastern part of quadrangle; section in Carbonate Wash has an anomalously high limestone/dolomite ratio, contains limestone conglomerate, and may reflect a deeper-water western facies of the Simonson; unit is variably brecciated south of Syncline Ridge in Mine Mountain area. Maximum thickness in quadrangle about 300 m

DOd **Dolomite (Lower Devonian, Silurian, and Upper Ordovician)**--Medium- to dark-gray, thick-bedded to indistinctly bedded, sparsely fossiliferous dolomite and minor sandy dolomite; rocks are intensely brecciated south of Syncline Ridge in Mine Mountain area. Unit exposed in eastern part of quadrangle. Includes rocks equivalent to the Sevy Dolomite, dolomite of the Spotted Range, and Ely Springs Dolomite. Maximum thickness in quadrangle about 550 m

Oe **Eureka Quartzite (uppermost Middle Ordovician)**--Orthoquartzite; conspicuous white to pale-orange unit that appears massive in outcrop but is internally laminated and locally cross bedded; fine-grained, well-sorted quartz sand with variable silica cement. Thickness about 110 m. Mapped in eastern part of quadrangle north of Yucca Flat

Op **Pogonip Group (Middle Ordovician and uppermost Lower Ordovician)**--Silty limestone, dolomite, and subordinate chert and siltstone; well-bedded, ledge- and cliff-forming unit that is marked by medium- to dark-gray carbonate beds and brown-orange silty or cherty zones; fossil content is variable, but brachiopods, oncolites, and corals are locally conspicuous. Unit consists of thin-bedded silty Goodwin Limestone at the base (about 350 m) and overlying Antelope Valley Limestone (about 550 m) that contains numerous sandy beds near the top (A. Harris, written comm., 1992). Isolated outcrop north of Quartz Mountain is lowermost Pogonip Group (earliest Ordovician; A. Harris, written comm., 1992); all other exposures in eastern part of quadrangle

Ꞓnb **Nopah and Bonanza King Formations (Upper and Middle Cambrian)**--Limestone, dolomite, and subordinate chert, shale, and siltstone; well-bedded, thick unit that consists of light- to dark-gray, massive-weathering carbonate beds, yellow to brown, fissile silty carbonate, and red-brown calcareous shale. The Bonanza King Formation (1300 m total) consists of dark-gray limestone at the base (about 320 m), thick-bedded light-gray dolomite (about 300 m), conspicuously banded light- and dark-gray dolomite (about 540 m), and light-gray limestone at the top (about 150 m); the overlying Nopah Formation (630 m total) consists of the Dunderberg Shale Member at the base (about 100 m), thin-bedded cherty limestone in the middle (about 320 m), and thick-bedded dark-gray limestone (about 200 m) at the top (Barnes and Christiansen, 1967). Macrofossils are sparse, but trilobite debris is common in the Dunderberg and phosphatic brachiopods are found higher in the Nopah section. Exposed in easternmost part of quadrangle east and north of Yucca Flat

Ꞓc **Carrara Formation (Middle and Lower Cambrian)**--Limestone, siltstone, and shale mapped in two areas of quadrangle. In Belted Range, unit consists of interlayered dark-gray limestone, red-brown silty limestone, and olive shale; about 500 m thick. In Bullfrog Hills, limestone is lighter gray, less silty, and locally brecciated; preserved thickness about 100 m (Maldonado and Hausback, 1990). Sparse fossils consist of trilobite debris and phosphatic brachiopods

Ꞓz **Zabriskie Quartzite (Lower Cambrian)**--Orthoquartzite exposed in Bullfrog Hills in southwestern part of quadrangle; consists of massive-weathering, white to pink, laminated and cross-bedded, densely cemented orthoquartzite with conspicuous tubular trace fossils (worm burrows); intensely brecciated. Maximum thickness about 200 m (Maldonado and Hausback, 1990)

ꞒZw **Wood Canyon Formation (Lower Cambrian and Late Proterozoic)**--Orthoquartzite, quartzite, siltstone, and subordinate limestone and shale. In Belted Range and at northern end of Yucca Flat, unit consists of interlayered olive-brown micaceous shale, micaceous quartzite, and local beds of quartzite-granule conglomerate; about 1100 m thick (Ekren and others, 1967). In Bullfrog Hills, partly exposed section consists of interstratified dark olive brown micaceous shale and siltstone and minor bedded gray limestone; maximum exposed thickness about 220 m (Maldonado and Hausback, 1990)

Zs **Stirling Quartzite (Late Proterozoic)**--Quartzite, siltstone, and orthoquartzite. At northern end of Yucca Flat, unit consists of thin-bedded, flaggy, pink to red-brown, densely cemented, well-sorted orthoquartzite; locally micaceous; maximum exposed thickness about 890 m (Barnes and Christiansen, 1967). In Kawich Range, unit consists of pink quartzite, micaceous siltstone, and medium-gray limestone and dolomite; maximum exposed thickness about 1600 m (Rogers and others, 1967)

Xm **Metamorphic rocks (Early? Proterozoic)**--Biotite schist and biotite-epidote schist, intruded by gneissic monzogranite with compositional foliation defined by abundant biotite and sparse muscovite; quartz strained. Schist and monzogranite are intruded by aplite and pegmatite dikes that show no planar fabric; absolute age of dikes unknown. Unit poorly exposed in Trappman Hills along northern border of quadrangle. Schist yielded reset K-Ar muscovite age of 14.0 Ma (McKee, 1983), indicating that Proterozoic basement in the Trappman Hills was uplifted in the middle Miocene, probably due to regional crustal extension

GEOLOGIC HISTORY SUMMARY

The region of the Pahute Mesa quadrangle, located near the west margin of the Proterozoic craton, was the depositional site of thick platform-carbonate and clastic sequences during the Late Proterozoic and Paleozoic. The alternating clastic and carbonate rocks that resulted from this early deposition are presently exposed only in the westernmost and easternmost parts of the quadrangle. The clastic and carbonate sedimentary rocks were recognized and described by Winograd and Thordarson (1975) as aquitard and aquifer hydrogeologic units, respectively. In Late Proterozoic through Middle Cambrian time a lower clastic sequence (Sterling Quartzite through Carrara Formation) was laid down, followed in Middle Cambrian to Middle Devonian time by deposition of a lower carbonate sequence (Bonanza King Formation through Simonson Dolomite). An upper clastic sedimentary sequence of the Eleana Formation was deposited during the latest Devonian and Mississippian as the stable platform was disrupted by the Antler orogeny northwest of the map area. Carbonate sedimentation resumed with deposition of the Bird Spring Formation in Pennsylvanian and Early Permian time.

The region experienced significant crustal shortening during the Mesozoic Sevier orogeny, which is expressed in the map region by mainly east-vergent fold and thrust deformation involving the pre-Mesozoic sedimentary basement rocks; the only unequivocal thrust fault *exposed* in the map area is located in the Eleana Range northwest of Syncline Ridge. In Cretaceous time, following the Sevier event, the granitic Climax and Gold Meadows stocks and smaller intrusive masses were emplaced in the northeastern part of the map area.

The map region experienced a prolonged period of nondeposition and erosion from Cretaceous through Oligocene and, locally, Miocene time as suggested by the lack of early Tertiary rocks in the quadrangle and a relatively high-relief unconformity at the base of the Tertiary section exposed in the Eleana Range. This unconformity likely results, in part, from regional crustal uplift that occurred during late Paleogene and (or) early Neogene time. The earliest known Tertiary deposition in the quadrangle area was recorded by the Oligocene(?) clastic sedimentary rocks, exposed in the northwestern part of the map area, which lack Tertiary volcanic clasts (Ekren and others, 1971). In late Oligocene and early Miocene time the first of several major episodes of volcanism occurred with the emplacement of calc-alkaline ash-flow tuff sheets from sources north and east of the map area; the Monotony, Shingle Pass, and Pahranagat Lakes Tuffs were erupted from the central Nevada caldera complex to the east (Best and others, 1989; Scott and others, in press) whereas the tuff of Antelope Springs probably erupted from a caldera to the north (Ekren and others, 1971).

Volcanism associated with the SWNVF, which encompasses the entire Pahute Mesa map area and whose rocks underlie most of the quadrangle's ranges and mesas, occurred episodically in Miocene time over a period of about 6 m.y. between about 15 and 9 Ma (Byers and others, 1976a; Sawyer and others, in press). Eruption of 17 extensive, discrete, calc-alkaline and peralkaline ash-flow-tuff sheets during this time resulted in the collapse of 6 known calderas, 5 of which overlapped or were nested to form the Timber Mountain and Silent Canyon caldera complexes and the Claim Canyon caldera; the sources of the 6 oldest and 2 intermediate-aged ash-flow sheets remain uncertain, as they most likely are buried by younger calderas. Volumetrically subordinate, but related, mainly silicic lava and pyroclastic flows were erupted from the calderas and from isolated smaller vents. The greatest eruptive activity in the SWNVF occurred between about 14.0 and 12.7 Ma during which time volcanic rocks of the Belted Range (13.85-13.5 Ma), Crater Flat (13.2 Ma), and Paintbrush (12.8-12.7 Ma) Groups were erupted to form the Grouse Canyon and Area 20 calderas (Silent Canyon caldera complex) and the Claim Canyon caldera, respectively (Sawyer and others, in press). Volumetrically, activity peaked twice with eruption of the major Paintbrush ash-flow tuffs (Topopah Spring and Tiva Canyon Tuffs) and, following a 0.75 m.y. hiatus, with eruption of the main Timber Mountain Group ash-flow sheets (Rainier Mesa and Ammonia Tanks Tuffs) between 11.6 and 11.45 Ma. Eruption of these widespread tuff sheets resulted in collapse of the Rainier Mesa and partly nested Ammonia Tanks calderas and formation of the Timber Mountain caldera complex. The youngest caldera-forming eruptions associated with the SWNVF occurred between 9.4 and 9.15 Ma with emplacement of the relatively small-volume Thirsty Canyon Group ash-flow tuffs (Rocket Wash, Pahute Mesa, Trail Ridge, and Gold Flat Tuffs); collapse of the isolated Black Mountain caldera, which was the source of these tuffs, occurred during the eruption of one or more of the units. Numerous basalt lava flows erupted just before, during, and soon after emplacement of the Thirsty Canyon tuffs south and west of the Black Mountain caldera, resulting in a local bimodal late Miocene volcanic stratigraphy. Other than eruption of these basalt flows and extrusion of basaltic lavas at Dome Mountain in the moat of the Timber Mountain caldera complex roughly 1 m.y. before, mafic volcanism was volumetrically minor compared with the silicic volcanism that characterized the SWNVF.

Between 7.45 and 7.5 Ma, nearly 2 m.y. after eruption of the tuffs of the Thirsty Canyon Group, two ash-flow tuffs (Spearhead and Civet Cat Canyon Members of the Stonewall Flat Tuff) were emplaced in the northwestern part of the map area (Hausback and others, 1990); their eruptions resulted in caldera collapse and formation of the Stonewall Mountain volcanic center (Hausback and Frizzell, 1986; Weiss and Noble, 1989), which overlaps the northwest corner of the quadrangle. Although these tuffs and spatially and temporally associated rhyolite lava flows vented within the SWNVF, they are probably related to a volcanic province younger than 10 Ma centered northwest of the quadrangle (Sawyer and others, in press).

Evidence of early- and pre-SWNVF extensional deformation exists in several areas of the quadrangle, although generally the timing of the deformation is not well constrained. Near the northeastern corner of the map area, gravity-driven low-angle sliding and brecciation of blocks of early Paleozoic sedimentary rock likely occurred prior to deposition of the Monotony Tuff at 27.3 Ma (Ekren and others, 1971). Extension occurred along the northern border of the quadrangle in the southern Kawich and northern Belted Ranges between about 17 and 26 Ma as evidenced by normal faults striking within 45^{o} of east-west that only displace pre-SWNVF rocks (Ekren and others, 1968; 1971). Normal and oblique faulting and resultant west- to southwest-directed extension occurred along the western margin of Yucca Flat most likely before deposition of the Redrock Valley Tuff at 15.1 Ma (Cole and others, 1989); this faulting was accompanied by stratal tilting and high-level block sliding and brecciation along presently low-angle faults that were previously thought to be thrust faults. Similar, although more intense, deformation involving early Miocene and older rocks occurred in the Trappman Hills area just north of map area (Ekren and others, 1971). This deformation may have occurred in the upper plate of a detachment fault as structurally lower Proterozoic metamorphic "core" rocks of the Trappman Hills were uplifted and cooled at 14 Ma (McKee, 1983). High-angle normal faulting and minor associated northwest-southeast extension occurred at the north end of Yucca Flat during and soon after emplacement of the Redrock Valley Tuff (Minor, 1989; 1990).

Between about 14 and 10.5 Ma a pulse of extensional deformation migrated from the Tolicha Peak area southward to the Bullfrog Hills as indicated by a time-transgressive angular unconformity exposed intermittently along the west escarpment of Pahute Mesa (Minor and others, 1991). This deformation was characterized by moderate northwest- (northern area) and southeast-directed (southern area) tilting of fault blocks and accompanying rotation of bounding northeast-striking normal faults to moderate dips. Half-graben extensional basins that developed syntectonically received coarse, locally derived erosional debris and brecciated slide blocks (mapped as proximal sedimentary rocks). In the Bullfrog Hills large fault blocks locally detached along low-angle failure surfaces and were variably brecciated during tectonic transport and as they slid towards basins. Deformation during this time period in the Bullfrog Hills and extensional faulting along more northerly trends that overprinted it soon thereafter were likely related to inferred north-northwest movement on the Bullfrog Hills detachment system which is locally exposed just south of the southern map boundary (Maldonado and Hausback, 1990; Maldonado, 1990).

Neogene extension spatially and temporally overlapped caldera collapse structures of the SWNVF. Generally down-to-west normal faulting and accompanying gentle eastward stratal tilting occurred repeatedly in the eastern Pahute Mesa area between formation of the Grouse Canyon caldera at 13.7 Ma and emplacement of the Rainier Mesa Tuff at 11.6 Ma (Warren and others, 1985). This growth faulting, and similar synvolcanic faulting documented and described along the western margin of Yucca Flat (Minor, 1989; 1990) and south of the quadrangle in the Yucca Mountain area (Christiansen and others, 1977; Carr, 1984; Scott and Bonk, 1984; Scott, 1990) may have been caused in large part by the recurring episodes of caldera formation that occurred nearby during the faulting (Christiansen and others, 1977; Carr, 1984; Warren and others, 1985). Alternatively this earlier faulting may have been related to the 14-10.5 Ma deformational pulse that occurred in the western part of the quadrangle.

Most faults cutting Tertiary rock units shown on the map formed after about 11 Ma following development of the Timber Mountain caldera complex. These faults, which largely controlled development of the major physiographic basins in the map area (e.g., Yucca Flat), chiefly formed along north-northwest to north-northeast strike directions in late Miocene time during a clockwise rotation of the regional stress field of as much as 80^{o} (Carr, 1974; Minor, 1989; 1990). The faults formed mainly with high-angle dips and experienced dominantly normal components of slip. Strike-slip faulting was rare throughout most of the Neogene in the map region and was mainly confined to local, discontinuous zones that experienced only minor cumulative displacement (Minor, 1990; 1991; Hudson and others, in press). This observation, and paleomagnetic data that indicates negligible vertical-axis rotation for volcanic rocks of the SWNVF in most of the map area (Hudson and others, in press), strongly suggests that dextral strike-slip faults of the Walker Lane did not extend into the central and eastern parts of the volcanic field during the Neogene, contradicting the proposal of Carr (1984).

Sedimentary and volcanic basin-fill deposits accumulated in the young extensional basins during late Neogene and Quaternary time. The gravels of Oasis Valley were deposited over at least a 3 m.y. period in latest Miocene and Pliocene time within several basins in the western part of the quadrangle. During this time basalt flows were erupted in the Timber Mountain caldera complex at Buckboard Mesa and at Thirsty Mountain north of Oasis Valley where they formed a broad shield volcano. The latter area was the site of further basaltic eruptions in late Quaternary time that resulted in two cinder cones that possibly vented along preexisting faults. Detritus shed from the local ranges and uplands was deposited along with subordinate amounts of eolian and lacustrine sediment in the major physiographic basins of the quadrangle during latest Neogene and Quaternary time. Minor normal fault activity occurred throughout the map area in Quaternary time; north- to north-northeast-striking faults developed mainly in the major basins at this time, the most notable being the Yucca Fault that transects Yucca Flat. Several faults in Yucca Flat and Pahute Mesa have recently been reactivated as a result of underground nuclear testing.

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