GEOLOGY OF THE WESTERN BEATTY WASH AREA,
NEVADA

by
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A thesis submitted to the Faculty and the Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geology).

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ABSTRACT

The purpose of this thesis is to describe and document the stratigraphy and structure of the western Beatty Wash area and to relate local tectonic features to the regional tectonic framework of southwestern Nevada. The northern two-thirds of the Beatty Mountain 1:24,000 topographic quadrangle is underlain by nine widely distributed ash-flow tuffs erupted from the southwest Nevada Volcanic Field, which are from oldest to youngest, 1) Lithic Ridge Tuff; 2) Tram Tuff; 3) Bullfrog Tuff; 4) Topopah Spring Tuff; 5) Tiva Canyon Tuff; 6) Rainier Mesa Tuff; 7) Ammonia Tanks Tuff; 8) Tuff of Buttonhook Wash; 9) and Spearhead member of the Stonewall Flat Tuff. Additional, local units are the tuffs and lavas of Western Beatty Wash, basalts, monolithologic breccia, the debris flows of Owl Canyon, interbedded gravels and tuffs, and the Sober-Up Gulch gravels.

Low-angle normal, high-angle normal and right-lateral strike-slip (transform) faults cut local strata. The low-angle normal Fluorspar Canyon Fault, exposed south of the study area, separates overlying Cenozoic rocks from subjacent late Proterozoic and Paleozoic rocks. Northwest-dipping listric faults branch upward from the detachment fault cutting Tertiary strata into elongate structural blocks. Tuffs and lavas of western Beatty Wash and underlying debris flows lap onto the west end of one tilt block, forming a buttress unconformity that indicates syn-extensional volcanism. Northwest-
striking, right-lateral transform faults cut the Tertiary strata at the west end of Yucca Mountain in the Silicon Mine Fault Zone. On the east side of the transform fault, the curvilinear Thompson fault drops strata down to the southeast forming a breakaway fault for the Crater Flat structural low. Radiometric ages, crosscutting fault relationships, and fault-controlled dike orientations indicate that the extension direction in the area rotated from east-west to northwest-southeast about at 13.4 Ma.

The tuffs and lavas of the Beatty Wash area accumulated in the extensional Oasis Valley structural basin and were themselves subsequently broken and tilted during continued extension. Mudflow deposits containing clasts of Paleozoic limestones and quartzite interfinger with the tuffs and lavas of western Beatty Wash indicating early Sober-Up Gulch Gravels were deposited on the flanks of Bare Mountain at least as early as 11.7 Ma. The finer grained muds and sands at the northern end of the study area probably formed as a playa ponded at the lowest part of the Oasis Valley basin. Minor deformation of the Spearhead member of the Stonewall Flat Tuff and local gravels suggest extension continued to later than 7.6 Ma.

The complex Cenozoic deformation in the study area is similar to that of the central Walker Lane Belt (Hardyman and Oldow, 1991, their domain III). Both areas contain right-lateral strike-slip, high-angle normal, and low-angle normal detachment faults. The extension direction rotated from east-west to northwest-southeast in both areas. If the transform faults extend into the basement, these similarities may indicate that the Fluorspar Canyon Fault is a
thin-skinned tectonic feature associated with strike-slip faulting rather than related to large scale crustal extension.
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INTRODUCTION

Location
The western Beatty Wash area is located within the Great Basin in southwestern Nevada (figure 1) about 50 km east of Death Valley, California and about 160 km northwest of Las Vegas, Nevada. The study area covers nearly 105 square km encompassing the northern two-thirds of the Beatty Mountain 1:24,000 topographic quadrangle (figure 2, Plate I).

Purpose
The southern part of Oasis Valley basin occupies most of the study area. The origin of the Oasis Valley basin is controversial; some contend the basin formed from caldera collapse while others attribute basin formation to extension of the upper crust along a low-angle normal fault.

The debate is significant because the study area is 20 kilometers northwest of the proposed site for a repository of high-level nuclear waste at Yucca Mountain, Nevada. Documentation of the geology of the western Beatty Wash area will be used to help evaluate the present and future tectonic stability of the region surrounding the repository and help in designing regional groundwater models for the area. The purpose of this paper is to describe the stratigraphy and structure of the study area and to relate local tectonic features to the regional tectonic framework.
Figure 1 - Physiographic provinces, Inyo-Mono physiographic subprovince (after Carr, 1984), and select faults of the region. (Modified from Fox and Carr, 1989).
Figure 2 - Location map of the study area. Stippled areas are exposed bedrock.
Methods

The study area was mapped in detail at a scale of 1:24,000 on a topographic base map (Plate I). Descriptions of the stratigraphy and measurements of the structure were recorded in notebooks; site localities were recorded on color aerial photographs and were later transferred to the base map. Site visits were made to type localities of regional ash-flow sheets of the southwest Nevada Volcanic Field and to selected areas adjacent to the study area to become familiar with the regional stratigraphy. Previous mapping of adjacent areas was helpful in extending the regional stratigraphy into the study area. Previous published and unpublished (P. P. Orkild, written communication, 1992) maps of the Bare Mountain 15’ quadrangle at 1:62,500 scale were helpful in becoming familiar with the area.

Geologists working in the region use field and microscopic characteristics to identify ash-flow tuffs (e.g., Byers and others, 1976, Carr and others, 1986). For this study, detailed descriptions were written while in the field to identify the regional units, which are intensely deformed and altered in the study area, and to document the criteria (e.g., degree of welding of glass shards and pumice; composition of lithic fragments; phenocryst shape, composition, and abundance) by which the identification was made (Table 1). In addition, several thin sections were used, primarily to confirm the presence of accessory phenocrysts that distinguish between similar and successively deposited tuffs. Nine sections were measured of the volcanic and sedimentary units to establish thickness of stratigraphic units around the periphery of Oasis
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<td>Unknown</td>
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<td></td>
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1Thermal Remnant Magnetization
2Byers and others, 1989
3David Sawyer, written communication, 1993
4Lipman and others, 1966
5Minor and others, 1993
6Monsen and others, 1993

TSA = Thickness in study area; hv = highly variable
Valley and to document variations in the stratigraphy.

All structural measurements in the study area were made during field mapping. Fault plane and striae orientations were recorded and transferred to the base map. A cross-section was drawn across the northern part of the geologic map of Bare Mountain (Monsen and others, 1992) and used to project down-plunge beneath the study area using the methods of Mackin (1950). From this projection and the gravity models of the area (Snyder and Carr, 1984) two cross sections A-A' (Plate II) and B-B' (Plate III) were compiled. A tectonic map of the entire 7 1/2' Beatty Mountain topographic quadrangle (Plate V) was synthesized by combining observations of this study with tectonic elements of the geologic map of Bare Mountain (Monsen and others, 1992) adjacent to the study area on the south.

Physiography

Vegetation is sparse throughout the study area. Bare Mountain, adjacent to the study area on the south, was named for its "almost total lack of verdure" (Ball, 1907, p.153).

Bare Mountain has an arrowhead shape (figure 2) with the apex to the south and a conspicuous reentrant on the north. On the east and on the west of this reentrant, ridges descend abruptly northward to low lying hills and mesas. The low lying hills extend from Bare Mountain northward to Beatty Wash and span from the town of Beatty, Nevada on the west to Perlite Canyon on the east (figure 2). A series of mesas trend north from the eastern side of the reentrant bordering the western edge of Yucca Mountain. A thick sequence of sediments
extends across most of the northern and western parts of the study area (plate I). Intermittent streams have eroded the sediments forming gullies that empty into Beatty Wash. The hills and mesas mark the southern extent of Oasis Valley, a basin that widens to about 20 km further to the north (Christiansen and others 1977). Beatty Wash enters the northeast border of the study area, follows the northern edge of Yucca Mountain and crosses southwest to join the Amargosa River. The Amargosa River flows south through the western margin of Oasis Valley. Revert Springs, Ute Springs, Hot Springs, and Goss Springs add water to the Amargosa River along the western side of the study area (figure 2).

**Geologic History**

This geologic history refers to the southwestern Nevada region surrounding the western Beatty Wash area. Local geology indicates that depositional, structural, and tectonic events have formed the present geology of the western Beatty Wash area from late Proterozoic through the Cenozoic.

**Late Proterozoic and Paleozoic**

Tertiary volcanic and sedimentary units in the western Beatty Wash area are underlain by late Proterozoic and Paleozoic basement rocks of regional extent. Thinning, rifting, and continental separation formed a stable continental platform on the western edge of the late Proterozoic North American craton (Stewart, 1972). Thick sequences of clastic and carbonate rocks were deposited on the continental margin to form a westward thickening wedge of miogeoclinal sediments (Stewart and
Poole, 1974). Overlying, late Devonian and Mississippian deposits of shale, siliceous siltstone, quartzite, conglomerate and limestone of the Eleana Formation (Fox and others, 1990) are flysch deposits shed, possibly as submarine fan deposits (Poole and Sandberg, 1991), from the Antler orogenic highland eastward into the foreland trough.

Upper Proterozoic and lower Cambrian siliceous clastic rocks compose the lower part of the miogeoclinal wedge and thin from 4 km in the Funeral Mountains (figure 3) to 3 km in the Spring Mountains (figure 1) (Fox and others, 1990). Conformable shelf carbonate strata form the upper part of the miogeoclinal wedge and are similar in thickness to the underlying clastic sequence (Stewart and Poole, 1974). Argillite, siltite, quartzite, and sparse dolomite beds compose the lower part and shelf carbonates, deposited between middle Cambrian and Devonian time, represent the upper part of the miogeoclinal sequence at Bare Mountain (Monsen and others, 1992). Argillite and quartzite strata form the flysch deposits of the Antler orogeny at Bare Mountain (Monsen and others, 1992).

**Mesozoic Deformation**

Mesozoic orogenic compression broke late Proterozoic and Paleozoic strata in the region along thrust faults. Remnants of the thrust faults extend from southeast of the study area in the Spring Mountains (Burchfiel and others, 1974) to the Grapevine Mountains (figure 3) (Reynolds, 1974) on the west.

The oldest deformation near the western Beatty Wash area is recorded in the upper Proterozoic and Paleozoic rocks of Bare Mountain. These rocks were folded and thrust during Mesozoic orogenesis, then extended during
Figure 3 - Fluorspar Canyon detachment fault system. Heavy stipple is Cenozoic rocks. Light stipple is Paleozoic and late Proterozoic strata (from Maldonado, 1990).
the Tertiary (Monsen and others, 1992). Mesozoic orogenesis stacked the rocks at Meiklejohn Peak and Tungsten Canyon along thrust faults and deformed the miogeoclinal strata into both large-scale folds throughout the massif (Monsen and others, 1992) and small-scale folds with northwest axial trends at the north end of Bare Mountain (Greybeck and Wallace, 1991).

Thermal events accompanying Mesozoic deformation of Bare Mountain metamorphosed rocks to low amphibolite facies on the northwest and to greenschist facies on the south and east (Monsen and others, 1992). Late Cretaceous granite intruded the northern strata of Bare Mountain, but postdated metamorphism.

**Cenozoic**

Sedimentation may have been the dominant geologic process in the region between intrusion of late Cretaceous granites and the earliest Tertiary volcanic events. Scattered exposures of Oligocene and early to middle Miocene fluvial and lacustrine sediments border mountain ranges in the region (e.g., Titus Canyon Formation of Stock and Bode, 1935 in the Grapevine Mountains) and most likely underlie Miocene volcanic and sedimentary units in intervening basins (Fox and others, 1990). Correlative Oligocene sediments are not present at Bare Mountain where the only Oligocene rocks are 26 Ma east-northeast-striking diorite dikes (Monsen and others, 1992). The earliest Tertiary sedimentation at Bare Mountain was deposition of early Miocene lacustrine sediments and crystal tuffs.

During the middle Miocene, explosive volcanism within the southwest
Nevada Volcanic field (SNVF) (figure 4) spread nuee ardantes over the region. These eruptions were accompanied by local extrusion of basaltic and rhyolitic lavas. Between 15.25 (± 50 ka) Ma (Sawyer and others, 1994) and 6.3 Ma (Weiss and Noble, 1989) six major eruptive episodes spanning 100,000 to 300,000 year intervals (Sawyer and others, 1994) extruded silicic ash-flows over a 13,000 km² area (Fox and others, 1990). The tuffs erupted from vents, ring dikes, or vent complexes (Fox and others, 1990) and led to caldera collapse. Most of these violent eruptions deposited chemically similar rhyolitic tuff layers (Fox and others, 1990), each zoned from high-silica rhyolite near its base to low-silica rhyolite near its top (Lipman and others, 1966).

The most prominent collapse feature of SNVF, Timber Mountain Caldera (figure 4), was recognized first by R. L. Smith based on the areal topography (Byers and others, 1976, p. 56). This caldera collapsed after eruption of the Timber Mountain Group of tuffs between 11.6 Ma and 11.45 Ma (Sawyer and others, 1994). The formation of the Timber Mountain caldera partly obliterated the Oasis Valley and Claim Canyon calderas (Fox and others, 1990) that possibly were created by eruption, between 12.7 and 12.8 Ma, of the Paintbrush Group of tuffs (Christiansen and others, 1977). The Crater Flat Group of tuffs most likely erupted from the Silent Canyon Caldera Complex at about 13 Ma (Byers and others, 1989). Sources of older tuffs in the region are uncertain. Source vents for tuffs younger than the Timber Mountain Group are at volcanic centers to the northwest (figure 4) (at Black Mountain and the Stonewall Mountain volcanic center, Sawyer and others, 1994).

Eruptions within the SNVF were coeval with Cenozoic extension. The
Figure 4 - Southwest Nevada Volcanic Field (modified from Minor and others, 1993).
western Beatty Wash area lies within a transition zone between the Basin and Range on the northeast, where mountain ranges trend north, and the Inyo-Mono structural-physiographic subprovince (Carr, 1984) (figure 1) on the southwest where ranges trend northwest. The transition zone forms the Walker Lane Belt (Carr, 1984) (figure 1), which is dominated by horizontal rather than vertical tectonics. Deformation orientation changes across the transition zone from dominantly northwest-trending right-lateral shear and low-angle extensional faulting in the Inyo-Mono region to tilting of fault blocks along high- and low-angle normal faults in the Basin and Range region. Components of both types of deformation are present at Yucca Mountain (figure 3) (Fox and others, 1990).

At Bare Mountain, movement along low-angle faults dragged underlying rocks into small-scale folds with northeast axial trends during Tertiary extension (Greybeck and Wallace, 1991). Cenozoic east-dipping high-angle normal faults cut across the backbone of Bare Mountain and along its east front, dropping strata down to the east. West-dipping high-angle normal faults on the northern front of Bare Mountain dropped strata down to the west (Monsen and others, 1992). Low-angle normal faults displaced the Paleozoic sediments toward the southeast near Wildcat Peak, Black Marble Hill, Chuckwalla Canyon, Joshua Hollow and Meiklejohn Peak, and younger Tertiary strata toward the northwest at Fluorspar Canyon.

Several dikes of unknown age strike northeast at the northern end of Bare Mountain. North-trending, 13.9 Ma dikes cut east-dipping high-angle normal faults in the central part of Bare Mountain and along its eastern front
(Monsen and others, 1992). However, in places, these faults cut the dikes and offset latest Pleistocene or Holocene deposits along the eastern front of Bare Mountain (Reheis, 1986).

Tertiary extension fractured Miocene volcanic units exposed on the north front of Bare Mountain in a complex anastomosing pattern. West-dipping high-angle normal faults cut and rotated the strata to moderate or steep dips and locally to vertical dips (Monsen and others, 1992). Southwest-dipping high-angle faults truncate the west-dipping high-angle faults and may be transform faults (the accommodation faults of Greybeck and Wallace, 1991).

Southeast-dipping low-angle normal faults truncate (post-date) some of the east-dipping high-angle faults (Monsen and others, 1992). These low-angle faults displaced Paleozoic rocks toward the southeast near Wildcat Peak, Black Marble Hill, and Chuckwalla Canyon (Monsen and others, 1992).

The Fluorspar Canyon Fault (figure 3, plates II and III), dips north about 25°, and separates an upper plate composed of generally east-dipping Tertiary volcanic rocks from an underlying lower plate composed of upper Proterozoic and Paleozoic rocks (Monsen and others, 1992). Many mappers in this region concur that the Fluorspar Canyon Fault is part of a regional detachment fault system that extends west through the Bullfrog Hills to the Grapevine Mountains in California (Carr and Monsen, 1988, Monsen and others, 1992, Hamilton, 1988, Scott, 1990, and Maldonado, 1990). Geologists disagree on the trend of the Fluorspar Canyon detachment fault surface east of the intersection of Fluorspar Canyon and Tates Wash. Some contend the fault continues east-southeast on the south side of Meiklejohn Peak (Monsen and others, 1992)
while others suggest it may be offset by a north-dipping high-angle fault along Tates Wash (Greybeck and Wallace, 1991). Geologists working in this area have noted left-lateral motion along the fault at Fluorspar Canyon (Greybeck and Wallace, 1991, Friedrich, 1992) and dip-slip motion at Meiklejohn Peak (Monsen and others, 1992).

The Fluorspar Canyon Fault projects northward beneath the western Beatty Wash area. Assuming that the fault forms the contact between Tertiary and Paleozoic rocks below the western Beatty Wash area, gravity data (figure 5) (Snyder and Carr, 1984) indicate that it slopes northward from Fluorspar Canyon, reaching a depth of approximately 0.5 km at the south edge of the study area, and perhaps 3 km at the north edge.

**Previous work**

The rocks and structure at and near Bare Mountain are mentioned in regional reconnaissance studies of Ball (1907) and Ransome and others (1910). Cornwall and Kleinhampl (1961) were the first to map the geology in the study area as part of the Bare Mountain 15' quadrangle at 1:62,500 scale. More recent investigations of the area encompass studies of the metamorphism and structure of northwestern Bare Mountain (Monsen, 1983), surficial deposits of the Bare Mountain 15' quadrangle (Swadley and Parrish, 1988), generalized geologic map of Bare Mountain and Tertiary volcanics to the north in a fieldtrip guidebook (Carr and Monsen, 1988), and a geologic map of Bare Mountain (Monsen and others, 1992).
Figure 5 - Gravity map of study area. Stippled areas are exposed volcanic bedrock. Gray lines are gravity contours; contour interval is 2 mGal (from Snyder and Carr, 1984).
STRATIGRAPHY

Introduction

Stratigraphic relationships in the western Beatty Wash area are summerized in Plate IV. Regional Oligocene and early Miocene sediments are not exposed within the study area but probably comprise subjacent strata in Oasis Valley (Fox and others, 1990, Monsen and others, 1992). Within the study area, Nine regional ash-flow tuffs, ranging from 14.0 to 7.6 Ma in age (Table 1), erupted from the Southwest Nevada Volcanic Field and form most of the Tertiary strata in the study area. Local, informally named units, the lavas of Tram Ridge, basalt, and the lavas and tuffs of western Beatty Wash, comprise the remaining late Tertiary volcanic units. Monolithologic breccias, the debris flows of Owl Canyon, interbedded gravels and tuffs, and Sober-up Gulch Gravels comprise the sedimentary strata in the study area. To be consistent with terminology used by other workers in the region (e.g., Byers and others, 1976, Carr and others, 1986, Maldonado, 1990) the term phenocryst is used rather than crystal lapilli to indicate crystals present in the pyroclastic units. The terms resorbed and "wormy" are also used by geologists to describe crystals of quartz visible in hand sample that are anhedral, perhaps interstitial or skeletal.
**Titus Canyon Formation - (Oligocene and late Miocene(?))**

The Titus Canyon Formation is composed of coarse clastic and finer grained sediments, sedimentary breccia, and volcanic tuffs that overlie late Proterozoic and Paleozoic basement rocks in the Grapevine Mountains to the west of the study area (Stock and Bode, 1935). Although this unit is not present at the surface within the study area, regional relationships indicate it may be present in the subsurface.

**Rocks of Joshua Hollow - (middle and early (?) Miocene)**

The Rocks of Joshua Hollow are composed of conglomerate, sandstone, siltstone, and crystal tuffs that overlie basement rocks along the northeast flank of Bare Mountain (Monsen and Carr, 1992). Although this unit is not present at the surface within the study area, regional relationships indicate it may be present in the subsurface.

**Lavas of Tram Ridge - (Miocene)**

The lavas of Tram Ridge are is greenish-gray weathering to greenish-white. This rhyolitic lava contains reddish-brown veinlets and dark brown devitrified nodules up to several centimeters in size that are, in places, aligned in discontinuous layers. Also present are phenocrysts of quartz, biotite, sanidine and titanite. The unit has a vitric luster and is commonly flow-banded. The basal contact of this lava is not exposed within the study area, but in the adjacent area to the north it conformably overlies the Tunnel Formation (Minor and others, 1993). The minimum exposed thickness for the
lavas of Tram Ridge is 9 m.

Distinctive attributes of this unit includes the titanite, glassy appearance with flow banding, and plagioclase to alkali feldspar ratio commonly of 2:1 (Carr and others, 1986). Weathering processes have created devitrified rinds on individual blocks of the fractured lava and hydrothermal alteration has converted much of the glass to green and white clays. This unit was first described as an un-named lava that is petrographically similar to the overlying Lithic Ridge Tuff (Carr and others, 1986) and was later named by Minor and others (1993).

**Lithic Ridge Tuff - (Miocene)**

The Lithic Ridge Tuff is composed of bedded tuffs overlain by ash-flow tuffs. The unit is altered. The bedded tuffs contain layers of varying thickness and are composed primarily of ash. Abundant lithic clasts, presumably entrained during deposition are distinctive in the ash-flow tuff.

**Bedded Tuffs**

Near the base, the bedded tuffs (not mapped separately) is mottled light maroon and green with dark banding (baked zone?); up section, the unit is yellowish-green altered to yellow. These bedded tuffs contain abundant white small pumice lapilli up to 1 cm in size, small pink lithic lapilli commonly less than 0.5 cm in size, and phenocrysts of biotite, sanidine, and sparse partly resorbed to nearly euohedral quartz. Beds, separated by partings, range from 1 to 70 cm and are commonly 10 to 30 cm in thickness. The thinner beds, 1 to
10 cm thick, are pinkish ash and are overlain by thicker, massive beds (10 to 70 cm thick) of white ash that commonly have anastomosing sheared tops 3 cm thick.

The basal contact is sharp, wavy, and conformable to the underlying lava. The entire sequence is hydrothermally altered to yellowish-brown and dark reddish brown patches. Adjacent to Beatty Wash the unit is 15.1 m thick.

**Lithic Ridge Ash-Flow Tuff**

The Lithic Ridge ash-flow tuff is light gray weathering to dark orangebrown. This unit contains phenocrysts of black biotite, quartz, sanidine, plagioclase, and titanite. Also present is white chalky pumice lapilli that are commonly 0.5 to 1 cm and rarely 4 cm in size. Abundant lithic clasts make up about 30% of the rock. The lithic clasts are angular to subrounded and range from a few cm to 30 cm in size. The lithic clasts include conglomerate, welded tuff, and stoney rhyolitic lava. Abundant, thin green alteration rinds line cavities left by plucked clasts. The unit is massive. The basal contact is sharp and uneven. Adjacent to Beatty Wash the unit is 15.25 m thick.

**Crater Flat Group (Miocene)**

The Crater Flat Group includes the Tram Tuff Formation and the overlying Bullfrog Tuff Formation (Sawyer and others, 1994). The Crater Flat was originally defined by Byers and others (1976) to include the Bullfrog Member and overlying Prow Pass Member, was redefined by Carr and others (1986) to include the Tram Member, and elevated to Group by Sawyer and
others (1994).

**Tram Tuff**

The Tram Tuff is light purplish-brown weathering to a dark brown. This ash-flow tuff contains phenocrysts of plagioclase, sanidine, sparse biotite, sparse hornblende, and small euhedral quartz. Also present are abundant white pumice lapilli (about 25% of rock), and rhyolitic clasts (more abundant higher in the flow). A moderately well-developed compaction foliation is defined by moderately flattened pumice lapilli. Fracture partings (about 1 cm thick near the top of the exposed section) are subparallel to the compaction foliation. Welding increases upward from a nonwelded base to a densely welded top. The basal contact is sharp and hummocky (1 m relief) and unconformable (figure 6) with the underlying Lithic Ridge Tuff. The flow top has been eroded in the study area leaving a residual thickness estimated to be 250 m. The basal part of the unit is distinguished by altered to yellowish-brown and reddish-orange alteration along numerous sets of fractures, and contains abundant white pumice lenticles, abundant quartz, and rare titanite. This unit was named by Carr and others (1986) who defined the type locality along the north side of Tram Ridge (Plate 1). Erosion along joints has produced abundant linear features readily apparent in aerial photographs.

**Bullfrog Tuff**

Three subunits make up the Bullfrog Tuff that was measured at lat 36°67'21"N., long 116°37'48.8"W, on the south side of Thompson Ridge. The
Figure 6 - Tram Tuff (upper half of photo) unconformably overlying Lithic Ridge Tuff. Contact is uneven and hummocky. Trough to crest on right of photo is 1 m. Outcrop is adjacent to and 3 km down Beatty Wash from intersection of Beatty Wash and northeast corner of study area.
lower two subunits are bedded, nonwelded ash-flow tuffs. The uppermost subunit is welded ash-flow tuff.

**Subunit 1 - Bedded Tuff**

These tuff beds are greenish-yellow where fresh and yellowish-brown, white, and light yellowish brown where weathered. The bedded tuff contains phenocrysts of sanidine, small quartz, and abundant biotite. Also present are yellow and pink pumice lapilli, commonly 0.5 cm in size, and lithic clasts of rhyolite 6 to 9 cm, small black lithic clasts less than 0.5 cm and gray and yellow lithic clasts commonly 2 cm in size. The unit is thinly to thickly bedded with beds ranging from 20 cm to about 15 m thick. The beds include fine-grained, moderately well-sorted, thinly bedded tuffs and poorly-sorted, lithic-rich ash-flow tuffs. Near the top of the unit are lithic-rich beds that may be debris flows. On the south side of Thompson Ridge the minimum thickness of this unit is 41 m. Remnants, patches, and ribs of monolithologic breccia composed of Bullfrog welded ash-flow tuff are scattered on these bedded tuffs along much of the south facing lower slope of Thompson Ridge.

**Subunit 2 - Massive Nonwelded Tuff**

This unit is red-orange that weathers to dark pink. This unit contains phenocrysts of quartz, sanidine, and abundant biotite. Also present are small pinkish-white pumice lapilli up to 1 cm in size that increase in abundance upsection, maroon lithic fragments and sparse small red-brown lithic clasts, in addition to thin, flattened cavities about 1 cm in size. The unit is massive and
is prismatically fractured creating prismatic pebbles that litter the ground surface. This unit is 30.5 m thick on the south side of Thompson Ridge.

Subunit 3 - Welded Ash-Flow Tuff

At Thompson Ridge, the welded ash-flow tuff consists of eight recognizable zones that document variations in welding, phenocryst abundance, and alteration. The lowermost zone is brown-white that weathers to white. This zone contains phenocrysts of sanidine, abundant biotite, and smoky resorbed quartz. Also present are reddish-white and white pumice that are commonly 0.5 cm in size and sparse oval lithophysal cavities commonly 2 cm in diameter. This zone is 12.2 m thick on the south side of Thompson Ridge. This zone is hydrothermally altered with characteristic and ubiquitous lisagang rings on every individual block face where yellow oval centers are surrounded by a bleached white ring that is surrounded in turn by a maroon outer ring.

The second zone is similar to the underlying zone except that it has flattened maroon pumice and small flattened lithophysae commonly 3 cm x 4 mm in size. This zone is 4.6 m thick on the south side of Thompson Ridge.

The third zone contains components similar to those of the underlying units, but forms crude columnar joints. The lisagang rings have migrated far enough outward in each block that the yellowish interiors cover most of each rock face. The rock weathers to a grus. This zone is 5.2 m thick and is overlain by a covered interval of grus pebbles about 9.1 m thick on the south side of Thompson Ridge.
The fourth zone is white that weathers to a mottled yellowish-brown. The zone contains phenocrysts of sanidine, biotite, and rare euhedral to common resorbed smoky quartz. Also present are flattened gray pumice commonly 1 cm x 2 mm in size and common flattened lithophysae 2 cm in size. This zone is 18.3 m thick on the south side of Thompson Ridge. This zone has moderately well-developed columnar joints. The columns are completely yellow from outward migration of the lisagang ring centers and maroon rings are restricted to thin bands along fractures between columns. The zone is well foliated with some long "stringers" often tens of centimeters long that may be flattened pumice.

The fifth zone is similar to the underlying zone, however, the columnar joints are well-developed. The phenocrysts include the same components as in the underlying zone but have increased in abundance to about 30% of the rock. The zone is well-foliated with common flattened pumice 3 cm in size and ubiquitous "stringers". In the middle of the zone are small orange clay spherules. This zone is 35 m thick on the south side of Thompson Ridge. This zone, exposed farther east, creates a "stair step" outcrop.

The sixth zone is light brown-red that weathers to brown-red. The zone contains phenocrysts of sanidine, biotite and small sparse quartz. Also present are abundant yellowish pumice that are commonly 2 cm in size giving the zone a "measles" appearance. This zone is 13.6 m thick on the south side of Thompson Ridge and is less resistant than the underlying columnar jointed zones.

The seventh zone is pink with mottled orange that has been
hydrothermally altered to a distinctive, brilliant reddish-orange. This zone contains phenocrysts of quartz, biotite, sanidine, and plagioclase. Also included are pumice that create the mottled orange appearance in the groundmass. This zone contains caverns commonly 5 cm in diameter. The zone is 8.2 m thick on the south side of Thompson Ridge.

The eighth zone is grayish-white that weathers to brown. The zone contains phenocrysts of quartz, sanidine, and large biotite. Also present are small white pumice lapilli, some have been devitrified to spherules, that are commonly 0.5 cm in size. This zone is 9.1 m thick on the south side of Thompson Ridge. This zone and the underlying brilliant reddish-orange zone are readily identified on aerial photographs.

**Paintbrush Group - (Miocene)**

The Paintbrush Group includes two welded ash-flow tuffs, the Topopah Spring Tuff and overlying Tiva Canyon Tuff. The Paintbrush was originally defined as a Formation by Orkild (1965, p.49) and redefined by Byers and others (1976) to include the Topopah Spring, Pah Canyon, Yucca Mountain, and Tiva Canyon Members. The Topopah Spring and Tiva Canyon were originally defined by Hinrichs and Orkild (1961). Neither the Pah Canyon nor the Yucca Mountain Members are present within the study area. The Paintbrush was redefined and elevated to Group status, and the Topopah Spring, Pah Canyon, Yucca Mountain, and Tiva Canyon were elevated to Formations by Sawyer and others (in press).
Topopah Spring Tuff - (Miocene)

The Topopah Spring Tuff is reddish-brown, grayish-red, and white, weathering to dark brown. This tuff contains pumice fragments and phenocrysts of sanidine, plagioclase, and sparse biotite. Moderately flattened, sparse pumice fragments in the vitrophyre define a poorly to moderately well-developed compaction foliation. This tuff is partially to densely welded and displays partings 0.5 to 1 cm thick. The unit contains abundant cavities with jagged, blocky linings up to about 10 cm in size. The basal part of the unit consists of 13.7 meters of massive nonwelded tuff. Its basal contact is sharp and conformable with the underlying Crater Flat Tuff. The basal nonwelded zone is overlain by a pair of vitrophyres that mark the lower part of the welded Topopah Spring tuff. Although the Topopah Spring is highly fractured, the thickness of the entire formation is estimated to be at least 125m.

In this area, this unit is distinguished by a high degree of alteration. The tuff is commonly bleached white; and locally is oxidized to reddish-orange. The oxidized rock has a siliceous matrix, and abundant fracture sets that break the rock to pebble and cobble sized fragments. This member was studied in detail by Lipman and others (1966), who described zones based on variations in lithophysal cavity abundance and composition.

Tiva Canyon Tuff - (Miocene)

The Tiva Canyon Tuff is reddish-gray, light brown, and brown, weathering to dark brown and yellowish-brown. This tuff contains phenocrysts
of abundant sanidine, plagioclase, biotite, and sparse titanite. The biotite
crystals in the lower part of the tuff are small and sparse, but a 35 m thick zone
in the upper-middle part of the tuff and in the crystal rich caprock, biotite
crystals are large and bronzed (about 3% of the rock). This uppermost crystal-
rich part of the unit (about 9 m thick) contains rare lithic clasts up to 8 cm in
size.

The unit contains white, gray, and red-brown pumice fragments. The
white pumice are abundant throughout the tuff and are usually 0.5 to 2 cm in
size, but may rarely reach 7 x 1 cm in size. Gray pumice fragments are also
abundant throughout the unit. The gray pumice range from 1 cm to 20 x 5 cm
in size. The top part of the unit contains red-brown pumice fragments 1 to 2
cm in size.

The Tiva Canyon Tuff also contains zones of lithophysal cavities. A
zone about 8 m thick near the base of the unit contains abundant lithophysae
2 cm in size. This lowermost lithophysal zone is capped by a 3 m
nonlithophysal zone, which is in turn overlain by a second, 16 m thick,
lithophysal zone. The lithophysae in the second zone are often 2 to 8 cm in
size, but rare cavities reach 14 x 6 cm in size. The upper 49 m of the unit is a
nonlithophysal zone.

Fiamme, often 5 cm x 3 mm in size, form a compaction foliation in this
tuff. The fiamme reach 40 cm in size near the middle of the unit. Near this
center, a zone of gray (1.5 cm thick) and red (3 cm thick) bands exhibit flow
foliation around sparse, angular clasts 3 to 5 cm in size.

The Tiva Canyon tuff is partially to densely welded and has a poorly
exposed vitrophyre near the base. The basal contact is sharp and
conformable with the Topopah Springs tuff, though poorly exposed. The
minimum thickness of this unit is 75.7 m. This member is distinguished from
overlying tuffs by lack of quartz and from overlying and underlying tuffs by the
presence of titanite. Aerial photographs reveal that many exposures of this tuff
are oval mounds with abundant gullies radiating from their center. In outcrop,
these mounds consist entirely of disaggregated plates of tuff a few centimeters
thick.

**Interbedded debris flows and bedded tuffs of Owl Canyon**

The Owl Canyon debris flows and bedded tuffs (measured at lat
36°56'52.4"N., long 116°39'11.2"W., near cross section B-B', Plate III) (figures
7 and 8) include five subunits, which are from oldest to youngest, 1) lower
debris flows; 2) lower bedded tuffs; 3) covered interval; 4) upper debris
flows; and 5) upper bedded tuffs. The Owl Canyon deposits are banked
against a buttress unconformity of subjacent, faulted Topopah Spring Tuff.

**Subunit 1 - Lower Debris flows**

The lower debris flows contain gray, white, and brown clasts that
weather to dark gray and brown. The matrix is similar in color but also has
dark maroon layers. This unit is poorly sorted with clasts ranging from silt- and
mud-size to boulders, rarely up to 1.5 m in size. Beds commonly are 30 to 60
cm thick with coarse boulder lags that grade up to finer grained maroon
layers. The lags contain clasts commonly 6 to 10 cm, less commonly to 20 cm,
Figure 7 - Owl Canyon debris flows (lower right) and bedded tuffs (left). The bedded tuffs have same dip as debris flows (about 40° towards the northwest) at contact, but dip of the tuffs decreases upsection. View is to the northeast. Photo taken 0.5 km east of SE1/4 SE1/4 sec. 25, T.11S., R.47E.
Figure 8 - Owl Canyon debris flows. Clasts are primarily Paintbrush Group tuffs with less abundant Bullfrog Tuff. Debris flows dip northwest (right side of photo). Hammer is 32 cm. Photo taken 0.5 km east of SE1/4 SE1/4 sec. 25, T.11S., R.47E.
and rarely to 1.5 m in size. The contacts between beds are gradational and, although poorly defined, are recognized by an abrupt change in clast size and the common maroon color of the thin muddy layers.

In the lower part of the unit, clasts include both gray and light brownish red varieties. The gray clasts contain flattened pumice fragments and sparse resorbed phenocrysts of quartz, whereas the light brownish red clasts are nearly devoid of pumice and phenocrysts. The light brownish red clasts have chonchoidal to blocky fracture. The matrix is white, brown, or dark maroon and consists of crystals, sand, silt and mud. The alteration of the maroon layers include white clasts less than 0.5 cm in size. In places, the matrix is partly silicified. About 10 to 15 m above the base, there is a zone of fractures having little offset. Fracture traces are planar to anastomosing and cut many of the larger clasts. Above this zone of fracturing the components of the matrix include ash and clasts include bedded tuff fragments. This unit is 25.9 m thick.

**Subunit 2 - Lower bedded tuffs**

The bedded tuffs are white weathering to dark gray. Beds range from 6 to 40 cm in thickness. The lowermost beds are conformable with the underlying debris flows (strike and dip of 030/40 NW). Dip diminishes upsection (to strike and dip of 050/25 NW). The lowermost unit contains sparse resorbed quartz and sanidine, abundant silky pumice up to 1 cm in size, and sparse lithic fragments. Intervening beds are ash-fall and ash-flow beds; some are hydrothermally altered to a nearly porcelain sheen. Some of these beds have mullions oriented down dip. Successive beds thin toward
the debris flow, onlapping and cutting off underlying beds. The exposed thickness of this unit is 1.3 m.

**Subunit 3 - Covered interval**

This interval is not exposed laterally. It is covered with colluvium on both sides of the wash, where the section was measured, and covered with bouldery alluvium along the wash bed. Large blocks of the debris flows protrude from the colluvium on the northwestern end of the wash, but are not in place. The covered interval is 38.1 m thick.

**Subunit 4 - Upper debris flows**

The upper debris flows contain clasts that are gray, white, and brown and that weather to dark gray and brown. The matrix is dark reddish-orange and maroon that weathers to darker orange and shades of red. The basal part of the unit is dark gray to light brown weathering to reddish-brown. It contains clasts of densely welded tuff with wormy quartz, and flattened pumice. The basal part is silicified, faulted (015/44E/74S rake, 015/60W), and contains breccia 1 cm thick. The deformation continues into the better exposed debris flows as anastomosing fracture traces. Upsection, the unit contains beds of poorly sorted clasts that range from mud-size to boulders 2 m in size. Some angular clasts contain flattened pumice fragments and sparse crystals of feldspar and wormy quartz while others are nearly devoid of pumice and phenocrysts. The matrix is coarse sand- to mud-size that is commonly dark maroon. The beds contain lags of boulders as large as 50 cm in size at the
base of the section, and are smaller upsection. The fining-up sequences are commonly 60 to 80 cm thick with gradational contacts over a few to several centimeters. Sparse beds 10 to 20 cm thick contain pebble lags with ashy matrices.

About 3 m upsection from the base of this unit is a zone about 1.5 m thick of boulders of Topopah Spring ash-flow tuff 1.5 to 2 m in size. Other large blocks contain phenocrysts of plagioclase, sanidine, and resorbed quartz that may be Bullfrog Tuff. Also present are white, altered, flattened pumice 5 cm long to 20 cm x 2 cm in size, and thin fiamme. Some of the boulders in this zone are fractured. About 26 m upsection from the base of this unit, clasts are commonly light brown and contain sparse phenocrysts of feldspar that may be Tiva Canyon Tuff. The upper part of the unit consists of some layers with 10 to 30 cm-diameter boulders and other layers with smaller pebble lags 20 to 150 cm thick. These layers are capped by 3 to 25 cm thick layers of finer grained materials. The unit is resistant and is 16.8 m thick.

Subunit 5 - Upper bedded tuffs

These bedded tuffs are white and brown that weather to brown, gray and dark brown. This unit is exposed as scattered outcrops. The lowermost beds are conformable with the underlying debris flows (strike and dip 036/42 W) whereas overlying beds decrease in dip (strike and dip 063/18 NW). The lowermost beds contain 10 cm-long pumice, sparse lithics up to 2 cm in size, phenocrysts of feldspar and quartz, and is altered to dark gray. Upsection is a 60 cm thick bed that is silicified with prismatic fracture and small dark lithic
fragments (about 3% of rock) and white oval clasts of tuff. An overlying poorly-sorted ash-flow tuff contains pumice to 1 cm in length and greenish gray and brown glassy clasts up to 2 cm in size (about 10% of rock). Some of the beds are contorted and contacts between beds are well-to poorly-exposed. The uppermost part of this unit consists of a series of 1 cm to 20 cm thick beds. Some of the beds are oxidized, some are silicified, and some contain abundant lithic clasts. The capping bed is a debris flow with blocks of Tiva Canyon Tuff up to 40 cm in size in a silicified matrix. The thickness is unmeasurable, but is at least tens of meters.

**Tuffs and lavas of western Beatty Wash (Miocene)**

The tuffs and lavas of western Beatty Wash consist of five informally defined members 1) undivided tuffs, 2) well-indurated bedded tuffs, 3) poorly indurated bedded tuffs containing clasts of perlite, 4) undivided rhyolitic lava, and 5) glassy rhyolitic lava. The lavas intertongue locally with the tuff units. The lavas and tuffs thin and thicken and pinch out locally. The rhyolitic lavas form a series of prominent exposures along a northerly trend in the east-central part of the study area. Below, descriptions of undivided tuffs and rhyolitic lavas are followed by descriptions of two measured sections, one on the east and the other on the west of the north-trending exposures of the rhyolitic lava. These measured sections represent the variety of components within the in stratigraphic sequence of this unit. The rhyolitic lavas were first described by Cornwall and Kleinhampel (1961). The lavas and underlying bedded tuffs were described for the adjacent area to the south by Monsen and

**Undivided rhyolitic lava member**

The member is dark to light gray, reddish-white, brown, green, and white that weathers to gray, brown, and white. This unit is composed of glassy to devitrified rhyolitic lava, blocky lava, and rhyolitic ash. The lava contains phenocrysts of ubiquitous quartz and sanidine, sparse plagioclase, and rare biotite. The lava contains abundant lithophysal cavities that are commonly round to oval and range in size from about 0.5 cm to 1 m. The smaller spherules agglutinate appearing as a lava froth. Locally, the lava is an intrusion breccia with clasts up to 20 cm in a fine matrix. Also present locally are blocks of glassy lava up to 2 m in an ashy matrix. The stoney facies is highly indurated and is altered to various shades of red and green. This unit is distinguished by its phenocrysts of quartz and feldspar, glassy or stoney character, abundant gas cavities, and flow foliation.

**Rhyolitic lava member**

The rhyolitic lava is light gray, dark gray, and brown weathering to greenish white and white. The lava contains phenocrysts of quartz and sanidine, sparse plagioclase, and rare biotite. The rhyolitic lava is locally glass with perlitic fracture. It has a well-developed flow foliation with vertical to folded (open to isoclinal) inclinations. This unit is highly fractured and broken into angular blocks. The rhyolitic lava is conformable on underlying units.
**Undivided tuff member**

This member is white, gray, and dark gray weathering to light brown, brown, and reddish brown. The unit consists of pumice-fall, ash-fall, bedded, and ash-flow tuffs and surge deposits. Each of these subunits contains phenocrysts of quartz, feldspar, and biotite in varying abundance and proportions. Pumice-fall tuffs, bedded tuffs, and the bases of ash-flows contain lithic fragments in varying abundance. The subunits range from massive to bedded with beds ranging from less than 1 cm to several meters in thickness. The pumice-fall tuffs and ash-fall layers are moderately- to well-sorted, while the ash-flows and surge deposits are poorly sorted. Partings between beds of the surge deposits are planar, while the partings between bedded tuffs are wavy to planar. Locally, the ash-flow tuff is pink, most likely baked and oxidized by overlying rhyolitic lava. In the east-central part of the study area, this unit is mapped as two units, each a thick sequence of bedded tuffs described below in the eastern section. The unit locally also includes two beds located in the southeast part of the study area, both about 0.5 m thick, underlain by a thin mafic unit. The two beds and underlying mafic unit may correlate with the Homes Road Tuff, a phreatomagmatic deposit in the adjacent area north of the study area (Minor and others, 1993). In the southeast part of the study area, part of the western Beatty Wash unit was injected as flame structures and as vertical dikes (figure 9) into the base of an overlying local tuff that is capped by monolithologic breccia composed of clasts of the Rainier Mesa Member. The base, where exposed, is sharp and conformable. The thickness of this unit varies over the study area.
Figure 9 - Intrusion dike of reworked tuff into ash-flow tuff. Both are parts of the tuffs and lavas of western Beatty Wash. Pole is 1.52 m. Photo taken 0.2 km east of SE1/4 NE1/4 sec. 1, T.12E., R.47E.
**Eastern Section**

The eastern section measured at lat 36°56'36.6"N., long 116°39'51.8"W. includes three units that belong to the lavas and tuffs of western Beatty Wash. The units measured strike 060 and dip 4 SE near the base of the section. The lowest unit exposed is gray, blocky perlitic lava. The middle unit is a series of resistant bedded tuffs. The upper unit is a less indurated series of oxidized bedded tuffs that contains distinctive clasts of gray and dark brown perlite clasts. This sequence of units is overlain by the Rainier Mesa welded Tuff.

**Lowermost unit - Perlite**

This lowermost unit is a greenish to grayish white perlitic rhyolitic lava that weathers to grayish-brown. This perlite contains phenocrysts of euhedral quartz, sanidine and sparse biotite. The partly vitric groundmass is streaky with flow foliation that curves around crystals and spindley, oval vesicles. The unit is massive, fractured, and blocky. The basal contact is not exposed, however, the exposed outcrop is about 4 m thick.

**Middle unit - well-indurated bedded tuffs**

The color of the middle unit varies upsection. The lower part of the middle unit is white weathering to a white-brown. About 15 m upsection, the matrix is a pinkish-white weathering to mottled brown and white-brown, and about 21 m upsection there is a sharp change in color to whitish-pink.
weathering to a dark orange-pink. This unit contains sparse and small phenocrysts of quartz, biotite and feldspar. The quartz phenocrysts become pink, larger, and euhedral near the top of the unit. The unit also contains white, green, yellow and orange pumice fragments that weather to pink and orange. In the upper part of the unit the pumice fragments are pink and white. The size of the pumice fragments is commonly 0.5 cm throughout the unit, but a few pumice fragments are 1.5 cm in the lower part of the unit and 3 to 4 cm in the upper part. In addition, this unit contains abundant, angular, small (less than 0.5 cm in size) red-brown lithic fragments. The unit also contains sparse gray, green, and red, angular to subangular stoney clasts that range from 1 to 4 cm in size. Near the base of the unit are thin discontinuous layers containing pebbles up to 3 cm. Sparse, dark brown, subrounded rhyolitic clasts 20 cm in size lie in a parting about 8 m above the base of the unit.

Unique to this unit are irregular-width light brown rinds that surround blocks of this tuff. The rinds also enclose pumice fragments, pink ashy clasts and lithic fragments, giving the tuff a mottled appearance throughout much of the unit. The pink ashy clasts range from 9 to 14 cm, whereas lithic clasts and pumice fragments range from 3 to 4 cm in size. These components commonly have light brown rinds about 1 cm thick, but the rinds increase in width and merge locally.

Beds range in thickness from about 3 m near the base to a few cm near the top of this unit. Weak striations ornament the anastamosing and sharply scalloped to planar partings between beds. Near the top of the unit beds cut and fill and thick and thin. Fractures create pebbly to weakly prismatic
surfaces. The matrix in the upper part is less shandy and more indurated than in the lower part. Below the sharp color change about 21 m above the base is a white 3 cm thick layer in which green pumice fragments have been smeared into three hummocky thin layers. The basal contact of this unit is covered with talus over about 20 cm, but relationships indicate the base must be sharp and hummocky. The thickness of this unit is about 26.5 m.

040/5 SE Strike and Dip Near Top of this Unit

**Upper Unit - poorly-indurated bedded tuffs**

This upper unit is pink that weathers to dark pink, orange, and mottled brown. The upper unit contains phenocrysts of quartz, sanidine, and sparse biotite. It also contains white and pinkish-white pumice fragments up to 0.5 cm in size near the base of the unit and gray-brown pumice fragments 2 cm in size with white thin rims near the top of the unit. The pumice fragments become larger and more abundant upsection. Throughout the unit are sparse to abundant clasts of angular, tabular, and tear-drop shaped, gray perlite and dark brown and brown-banded glassy clasts. These glassy clasts are commonly 2 to 3 cm and rarely up to 5 to 7 cm in size. While these glassy clasts are common throughout the unit, the interval from 35 to 53 m above the base of the unit contains channel lags and 0.5 m-thick zones in which glassy clasts are abundant, and most frequently composed of gray perlite. The groundmass is ashy and predominantly vitric throughout the unit. Beds range in thickness from 1 m to a few cm. Partings between individual beds are indistinct to well-defined and are planar and uneven. The beds are commonly
friable, not well indurated, form slopes, and erode to caverns with a "popcorn" texture, however some beds are more resistant and ledgy. The top 1 m of the unit contains distinctive dark gray, silty patches and a capping layer that may be a soil. The basal contact is sharp and uneven, but is recognized by the presence of glassy clasts and decreased induration. The unit is 27.2 m thick.

Western Section

This section (measured at lat 36°56'13.5"N., long 116°41'6.3"W.) includes four subunits. The four subunits, from lower to upper, include 1) a sequence of pumice-fall beds; 2) a sequence of thin planar beds of sand, silt, and mud; 3) a sequence of debris and mud flows with common scour and fill channels that locally cut through both of the lower two units; and 4) a sequence of ash-flow and pumice-fall deposits capped by gray perlitic lava breccia.

Subunit 1 - Pumice-Fall Deposits

These deposits are white weathering to brown-white. This unit is composed primarily of pumice fragments 3 to 4 cm in size, but also contains phenocrysts of quartz, sanidine, and biotite. Also present are abundant lithics commonly up to 2 cm in size that are primarily composed of gray, glassy perlite. Faint partings separate the upper part of the unit into beds 1 to 30 cm thick. Some of these beds are composed of pumice fragments 2 to 5 mm in size, while others are 1 cm thick beds of lithic clasts or pumice fragments. The beds are poorly to moderately well-sorted. The basal contact of the unit is not
exposed, but just east of this section pumice-fall beds overlie rhyolitic lava. At the measured section locality, the exposed thickness of this unit is 1 m, however, just to the east, the unit is at least 20 m thick.

Subunit 2 - Planar beds of sand, silt, mud
These beds are light and dark gray weathering to brown-gray. The unit is composed of fine sand, silt, and mud with very sparse white pumice fragments near the top of the unit. The unit is thinly bedded with beds commonly 7 mm in thickness, but ranging from 1 mm to 1.2 cm in thickness. The unit is moderately well-sorted. Beds are planar and even. The basal contact is gradational over 2 cm with the underlying unit.

Subunit 3 - Debris and Mud Flows
These debris and mud flows are gray and brown weathering to dark gray and grayish brown. This unit contains clasts of rhyolitic volcanic rocks, quartzite, and limestone, and yellowish varved mud rip-up clasts to 10 cm in size. The matrix consists of sand, silt, and mud. The unit is poorly sorted with clasts ranging from mud-size to 0.5 m diameter boulders. Scour and fill channel deposits range from 2 to 25 cm in thickness near the base of the unit, but increase to 1.5 m in thickness over most of the unit. These channels contain cobble and boulder lag deposits that range from a few centimeters to 0.5 m thick, and that grade up to cobble, pebble and sand deposits. Some beds, up to 1.3 m thick, are mud-rich with sparse to common cobble, pebble, and boulder clasts. The larger clasts are commonly angular to rarely
subangular. The basal contact is sharp but uneven over 1.2 m deep scour channels. The unit locally cuts entirely through the subjacent units to the pumice layers below (figure 10). Imbrication of clasts indicates origin was from the southwest. This unit is about 9 m thick.

**Subunit 4 - Ash-flow and Pumice-Fall Sequence**

This unit consists of pumice-fall deposits, lithic-rich ash-flows, ash-flow tuffs, and a capping glassy perlitic lava breccia. Six subunits were recognized. The lowermost subunit is a light gray-brown ash-flow tuff that weathered to brown. This subunit contains phenocrysts of quartz and biotite and possibly monazite. Also present are white pumice fragments up to 1 cm in size, and abundant lithic clasts of coarse sand to larger dark gray fragments and glassy perlite clasts. The subunit is massive with common weathered caverns. The base is gradational with the underlying subunit and includes a dark gray sand that varies from a few cm to 0.5 m thick. This subunit is 2.4 m thick.

The second subunit consists of white pumice-fall beds that weather to grayish-white. The beds range from 1 to 5 cm in thickness and are separated by sharp partings. Near the base of the subunit the beds contain moderately- to well-sorted, angular pumice that are commonly 1 to 3 mm in size. The pumice fragments increase gradually to 1 to 5 mm in size. The character of the beds changes abruptly to alternating ash layers and pumice layers. This sequence is capped by 4 cm of laminated ash. The contact with the underlying subunit is sharp and planar. This subunit is 28 cm thick.
Figure 10 - Lower part of Sober-Up Gulch gravels. Gravel and sand scour and fill structures cut into planar beds (light gray) and pumice-fall (white-gray) deposits. Exposed part of pole is 1 m. Photo taken in NW1/4 SE1/4 sec. 35, T.11S., R.47E.
The third subunit is a white ash-flow tuff that weathers to gray. This subunit contains phenocrysts of quartz, sanidine, and large, bronzed biotite. Also present are white and brown pumice fragments up to 1 cm in size, and abundant lithic fragments. The weathered surface has a coarse sandy texture. This subunit is overlain by a brown ash-flow with similar constituents. These ash-flow tuffs are 0.92 m thick.

The fourth subunit is gray ash-flow tuff weathering to dark brown. This tuff contains quartz, sanidine and sparse biotite. Also present are abundant white and brown pumice fragments up to 1 cm in size, and abundant gray and dark gray perlitic clasts. This subunit is a poorly exposed slope former. The basal contact is marked by a coarse gravel lag about 30 cm thick and is gradational. This subunit is 3.3 m thick.

The fifth subunit is white ash-flow tuff that weathers to a pinkish-white. The subunit contains quartz, sanidine, and sparse biotite. Also present are white pumice fragments up to 1 cm in size, and gray perlitic clasts up to 0.5 cm in size with other lithic fragments ranging up to 2 cm in size. The subunit is massive with a sharp planar base. This subunit is about 6.6 m thick.

The uppermost subunit is breccia composed of abundant clasts of gray perlite, with clasts commonly 20-40 cm in size. The breccia overlies the eroded top of the subjacent ash-flow. This top section is estimated to be 7.6 m in thickness. It is overlain by erosional remnants of the Sober-Up Gulch Gravels.
**Monolithologic breccia of Beatty Wash - (Miocene?)**

Where fresh, the monolithologic breccia of Beatty Wash is purplish to reddish brown, reddish to bluish gray, and orange-pink the color of the units from which the breccia was derived. Angular to subangular clasts of welded ash-flow tuff, non-welded tuff, and rhyolitic lava compose the breccia. The clasts range in size from blocks several meters across to coarse sand. Smaller clasts commonly make up a monolithologic, indurated matrix that is sparse to locally abundant. The monolithologic breccia forms tabular or irregular shaped masses composed of blocks commonly 3 to 4 meters across that, in places, are themselves composed of clasts varying in size from boulder to sand. Clasts of differing lithology are rarely mixed; welding zone boundaries present within the parental ash-flow tuffs can still be discerned as layers of monolithologic breccia. The inclination of primary foliations of individual clasts indicate that some have been rotated to random orientations and that some have been rotated very little. The basal contact is rarely exposed. However, at the base of one tabular slab of ash-flow tuff breccia, comprised of layers of welded and nonwelded tuff, flame structures and dikes of the underlying bedded tuff penetrate as much as 2 meters upward into the nonwelded tuff. The monolithologic breccia is distinguished by its lithologic homogeneity and breached nature, wide range of clast size, common lack of fine-grained matrix, areal extent, and stratigraphic position. Where this unit is hydrothermally altered it is white, light gray, and brown and weathers to dark brown and black.
Timber Mountain Group (Miocene)

The Timber Mountain Group consists of two formations, the Rainier Mesa Tuff and the Ammonia Tanks Tuff, and one informal unit, the Tuff of Buttonhook Wash, in the study area. These tuffs were originally considered members of the Timber Mountain Tuff, first defined by Orkild (1965) and redefined by Byers and others (1976) to include ash-flow tuffs and air-fall tuffs having abundant quartz phenocrysts, an age of about 11 m. y., and Timber Mountain caldera as a source. The Rainier Mesa Member was originally defined as a member by Hinrichs and Orkild (1961) and the Ammonia Tanks was first defined by Orkild (1965) and redefined by Byers and others (1976). The Tuff of Buttonhook Wash was first described by Carr and Quinlivan (1966) and included as part of the Timber Mountain Tuff by Byers and others (1976). Minor and others (1993) elevated the Timber Mountain to Group, and the Rainier Mesa and Ammonia Tanks to Formation status. In addition, Minor and others (1993) have determined limits on the age of eruptions of this tuff to be between 11.6 and 11.45 Ma.

Rainier Mesa Tuff

The Rainier Mesa Tuff can be distinguished by the characteristic orange-pink nonwelded base with centimeter sized pumice fragments and large, abundant, and euhedral phenocrysts of quartz. The measured section (SE1/4 SE1/4 sec. 36, T.11S., R.47E.) (figures 11 and 12) is divided into 5 zones. These include, from lowest to highest, 1) lowestmost non-welded; 2) partially welded; 3) densely welded; 4) densely welded and crystal-rich; and
Figure 11 - Measured stratigraphic section of the Rainier Mesa Tuff (SE1/4 SE1/4 sec. 36, T.11S., R.47E.). Filled irregular shapes are glass, open shapes are lithophysal cavities, and ovals in wedge at bottom of section are perlite clasts.
Figure 12 - Photo of measured section of the Rainier Mesa Tuff. View is to the north. Photo taken in SE1/4 SE1/4 sec. 36, T.11S., R.47E.
5) partially welded.

**Zone 1 - Nonwelded ash-flow tuff**

The lowermost part of the non-welded zone is grayish white that weathers to brown and changes abruptly to gradationally over about 1 m to pink and reddish-orange that weathers to brown. Zone 1 contains sparse phenocrysts (about 1% of rock) of euhedral, pink quartz, biotite, and chatoyant sanidine. Quartz crystals commonly lie within the pumice fragments or along the boundaries of pumice. The lower part of the zone contains sparse white pumice fragments commonly 2 cm in size, whereas the upper part of the zone contains equant brown pumice fragments that range from 3 to 6 cm in size. Some of the lithic fragments form lags and discontinuous layers of boulders and blocks of gray and grayish brown perlite up to 60 cm in size. Others are rare clasts of Tiva Canyon tuff up to 10 cm in size, rip-up clasts from the underlying unit 14 to 30 cm in size, and smaller brown glassy and gray vitric clasts less than 1 cm in size. These fragments decrease in abundance and size upsection. This lower part of the zone is massive and erodes to large caverns with pumice fragments and lithic clasts protruding from the ashy matrix. The basal contact is sharp and uneven to planar. Locally the contact cuts 1.5 m into the underlying ash-flows. This part is 4.6 m thick.

The upper part of this zone is red-orange ash-flow tuff that weathers to brown and brown-pink and is more indurated than the lower part. This part contains phenocrysts that increase in abundance (to about 5 % of rock) from the lower part, and include sanidine, biotite and abundant, euhedral pink
quartz. Also present are brown pumice fragments commonly 2 mm to 2.5 cm in size that have interiors of wavy black and red-brown glassy spindles. In addition, this part of the zone contains sparse, small stoney, red glassy, black glassy, and red-brown earthy lithics commonly less than 1 cm in size. This part has sparse, rounded to semi-flattened lithophysae 3 to 4 cm and rarely 10 cm in diameter, as well as cavities left from the erosion of pumice fragments. The top of the zone is weakly columnar jointed and contains pumice fragments that are slightly flattened and aligned to form a weak foliation. This part is 2.13 m thick.

**Zone 2 - Partially welded ash-flow tuff**

This zone includes a lower part that weathers to pink-brown to brown and that grades to an upper part that weathers bluish-gray to purple-gray. The lower part has a vitric groundmass that contains phenocrysts of quartz, sanidine and biotite. Also present are brown, slightly flattened pumice that are commonly 8 cm x 2 cm and 7 cm x 4 cm and rarely up to 9 cm in size. In addition, the unit contains black glassy globules that are aligned to form a weak foliation. The upper part of this zone has a devitrified groundmass that contains the same phenocrysts as the lower part, pumice 3 to 4 cm in size that are ubiquitously replaced by small spherules, black fiamme commonly 3 to 5 cm in length, and abundant semi-flattened lithophysae with blue-gray coatings, combining to form a moderately well-developed foliation. This unit is 9.15 m thick.
Zone 3 - Densely Welded Ash-flow Tuff

The lowermost part of this zone is purple-brown weathering to brown. This lower part contains phenocrysts of sanidine, biotite, and euhedral quartz (about 15% of the rock) and has well-developed, nearly horizontal foliation defined by flattened pumice fragments and aligned lithophysal cavities. These cavities vary in abundance throughout the zone. The lowermost 1.5 m of this lower zone is free of lithophysal cavities, the overlying 1.5 m has sparse lithophysal cavities, and the capping 6.7 m has abundant lithophysal cavities that are commonly 2 to 3 cm and rarely 7 to 9 cm in size. The lower zone also contains sparse lithic clasts including at least one 10 cm diameter clast of Tiva Canyon Tuff. The weathering surface of this unit is pitted where the zone contains lithophysal cavities and smoother where the zone is free of lithophysae. Surfaces of columnar joints are planar and smooth. This zone is 9.75 m thick.

A parting that is most likely a cooling break separates the lower part of the zone from the upper part of the zone. The proportion of phenocrysts increases (to about 20% of rock) in the upper part of the zone. Also present is a second set of columnar joints.

Erosion of the top and bottom of the upper part of the densely welded tuff has created a rounded profile for the columnar joints. Within this upper part, the lithophysae are sparse in the lowermost 1.5 m, moderately abundant and increasing in size to 10 cm x 2 cm (some having crystalline spherules lining the cavities) in the overlying 0.6 m, and sparse and 10 to 12 cm in size in the capping 10.7 m. The top 6.7 m has very sparse lithophysae with black
coatings on the interiors. Overlying this part is a poorly exposed, slope forming interval with exfoliated surfaces about 3.05 m in thickness.

**Zone 4 - Densely Welded and Crystal-rich Ash-flow Tuff**

The lower part of this zone is reddish-brown weathering to dark brown. The upper part of the zone is black and brown weathering to black near the top. Abundance of phenocrysts increases abruptly within this zone (about 50% of rock). They include quartz, sanidine, plagioclase, and biotite. However, the quartz phenocrysts are small and decrease in abundance through this zone, whereas the sanidine, plagioclase, and biotite become both larger and more abundant. The lowest 1.5 m of this zone is free of lithophysae, whereas the overlying 4.6 m contains sparse large lithophysae that are 10 to 28 cm in size. Capping this interval is an upper part that has sparse, small lithophysae with black coatings on the interiors. The top of this zone is moderately well-foliated.

Locally, this zone forms a massive talus about 5 m thick of dark, monolithologic clasts in a light colored matrix. The matrix is light gray to white and has large euhedral phenocrysts of pink quartz, bronzed biotite, and sanidine. The matrix is ashy with some pumice fragments, and commonly is silicified. The clasts are dark brown and gray, angular to subrounded, and up to 1.5 m in size. These clasts contain flattened and recrystallized pumice fragments and phenocrysts of plagioclase (large), sanidine, and bronzed biotite. The base is uneven and planar. Stratigraphic relations and composition indicate that the talus is formed from part of zone 4.
Zone 5 - Partially welded ash-flow tuff

This zone is light grayish-brown and weathering to light and dark brown. This zone contains phenocrysts of bronzed biotite, sanidine, plagioclase, and large, euhedral pink quartz. Also present are oval to elongate shaped light brown or gray pumice fragments commonly containing spherules of recrystallization that range from a few mm to 4 cm, but are commonly 2 cm in size. This zone has sparse small black-gray lithic fragments (about 5% of the rock) that range from coarse sand to 10 cm in size.

This zone has a faint compaction foliation. This zone is poorly exposed and often forms a rubbly slope. The unit is about 6 m thick.

Scattered, local outcrops of boulder rubble cap zone 5. The boulder rubble is dark chocolate brown weathering to dark brown and black. The boulders are highly vitric and contain phenocrysts of quartz, sanidine, and sparse biotite. Also present are streaky gray and white and silky white pumice fragments 2 cm in size. This part has dark-gray fiamme that form a streaky, moderately well-developed foliation.

Ammonia Tanks Tuff

The Ammonia Tanks Formation is bluish-gray to pinkish-gray weathering to bluish-brown and brown. The Ammonia Tanks is an ash-flow tuff that contains common white pumice fragments up to 5 cm and abundant red-brown, earthy lithic fragments up to 3 cm, as well as, common lithophysal cavities and phenocrysts of abundant, euhedral quartz and chatoyant
sanidine, and sparse plagioclase, biotite and titanite. This unit has a well-developed compaction foliation defined by flattened pumice fragments and aligned lithophysal cavities. This member is densely welded at all exposures within the study area. The basal contact of this unit is not well exposed within the study area, but in adjacent areas south and west is said to be conformable with the underlying Rainier Mesa Member (Monsen and others, 1993, Maldonado, 1990). A complete section of this unit is not exposed within the study area, but the minimum thickness is estimated to be about 100 m. This unit is distinguished by the presence of phenocrysts of abundant, euhedral quartz and sparse titanite. Along the southwestern border of the study area the unit is cut by basaltic dikes. The dikes are highly weathered, about 2 to 3 m across, and have reddish baked zones. The basalt is greenish-black, and studded with reddish iddingsite crystals.

**Tuff of Buttonhook Wash**

The Tuff of Buttonhook Wash is bluish-gray to reddish-brown weathering to gray and brown. It is an ash-flow tuff that contains common light brown and brown pumice fragments up to 4 cm containing spherules. Also present are phenocrysts of common quartz and sanidine and sparse plagioclase, biotite, and titanite. The unit is nonwelded to partially welded. The basal contact is not exposed within the study area, but in adjacent areas to the north, is conformable with and separated from the underlying Ammonia Tanks Member by a cooling break (Minor and others, 1993). This unit is poorly exposed, with thickness of about 6 m. This tuff is distinguished by
presence of titanite, large pumice, and nearly complete alteration of the upper part to clays. The tuff was likely erupted during the waning stages of the Ammonia Tanks eruptions (Byers and others, 1976). In the study area this unit is present only at a single small exposure along a wash just north of Beatty Wash in s. 24, T.11S., R.47E.

**Basaltic Lavas (Miocene)**

The basalts are dark gray weathering to black. They are basaltic flows that contain small red crystals of iddingsite and abundant white amygdules filled with calcite. This unit is dense and massive in the interior to vesicular and rubbly at the margins of individual flows. The basal contact appears to be sharp and conformable on the underlying Ammonia Tanks Member and tuff breccia (unit p of Monsen and others, 1993). This unit is about 75 m thick. This unit is distinguished by its dark color, vesication, dense character, white amygdules, and an age of 10.7 Ma (Monsen and others, 1993). These basalts were first described in detail by Cornwall and Kleinhampel (1961) and redefined by Monsen and others (1993). This unit occurs as scattered exposures along the Amargosa River and as several large exposures along the southwestern border of the study area.

This study follows the nomenclature of Monsen and others (1992) in breaking out the subunits Tb1, Tb2, Tb3, and p along the mutual southern border of the study area. Tb1, Tb2, and Tb3 are basalt flows. Tb1 overlies the Ammonia Tanks Tuff and is dated at 10.7 Ma (Monsen and others, 1992). The subunit p is a poorly exposed orange-pink tuff with abundant biotite, quartz,
and possible sanidine that separates Tb3 and Tb2. Locally, feeder dikes of basalt cut the Ammonia Tanks Tuff along faults.

**Spearhead Member of Stonewall Flat Tuff-(Miocene)**

This ash-flow tuff (measured at lat 36°57'29"N., long 116°41'1.9"W.) (figure 13) consists of 2 subunits; a lower shard tuff subunit and an upper partially welded tuff subunit. The lower subunit is nonwelded, shardy and friable and contain abundant load casts (figure 14). The upper subunit is partially-welded and well-indurated forming the larger portion of the tuff. The Spearhead is restricted to the western part of the study area and appears to fill areas of low paleo-topography such as a paleo-channel along the southern bank of lower Beatty Wash. Along this bank the subunits intertongue with gravels. This sequence is mapped as interbedded gravels and tuffs (unit Tgsi). The Spearhead Member was defined by Weiss and Noble (1989) while working on the Stonewall Mountain Volcanic Center.

**Subunit 1 - Shard Tuff**

This tuff is gray to light brown-gray weathering to a dark gray and light-brown. This unit contains phenocrysts of sparse sanidine and plagioclase. Also present are moderately abundant blue-gray and brown vitric pumice fragments that are commonly 1 cm in size, as well as, sparse reddish-gray and mottled red and white lithics that are up to 1 cm in size and gray, perlitic lithics less than 0.5 cm in size. The groundmass consists of abundant unflattened black and light brown glass shards that give the unit a "salt and pepper"
Figure 13 - Spearhead member of the Stonewall Flat Tuff. Pole is 1.52 m. Photo taken in NW1/4 NE1/4 sec. 26, T.11S., R.47E.
Figure 14 - Load structures in the lower part of the Spearhead member. Hammer is 31 cm. Photo taken in NW1/4 NE1/4 sec. 26, T.11S., R.47E.
appearance in hand sample. The unit is nonwelded and friable. A hummocky parting separates the lower 5 to 12 cm, that is cracked from load structures, from the rest of the subunit. The basal contact is not exposed, however the exposed interval is 1.0 m thick.

**Subunit 2 - Partly Welded Ash-flow Tuff**

This subunit is light purplish-gray weathering to dark purplish-gray. This subunit contains bluish-gray flattened pumice fragments about 1 cm in size, green-yellow clay and brown stoney lithic clasts up to 0.5 cm in size, and sparse phenocrysts of small quartz and large sanidine. The unit also contains flattened, randomly oriented cavities up to 5 cm x 0.5 cm in size. The upper part is less indurated. Coloration is darker along the fractures and lightens towards block interiors resulting in blocks with patchy light brown interiors and darker rims. The top is broken by anastomosing partings. The basal contact is planar and sharp. This unit is about 3 m thick.

**Interbedded gravels and tuffs (Pliocene and Late Miocene(?))**

These interbedded gravels and tuffs are gray, blue-gray, reddish-brown, and brown weathering to brown, light brown, and gray. The unit contains debris flows, bouldery mud flows, beds of gravels and sands, and beds of reworked ash and pumice fragments. The unit is massive to moderately well bedded. The unit overlies monolithic breccia. This unit has not been mapped prior to this study.
Measured section of interbedded gravels and tuffs

Five units were recognized in this section (figure 15 and 16) measured at NW1/4 SW1/4 sec.35, T.11S., R. 47E., from oldest to youngest: 1) monolithic breccia of perlitic lava; 2) monolithic breccia of Rainier Mesa ash-flow tuff; 3) cut and fill channels of debris flows and mudflows—the base of the subunit has an abundant sandy component that grades to coarser clasts upsection; 4) debris flows, gravelly mud flows, and reworked ash and pumice fragments; 5) debris flows, gravelly mud flows, and reworked ash and pumice fragments. The upper two units are of similar stratigraphic composition and sequence of beds, however, the uppermost subunit has thicker debris flows and larger clasts.

Unit 1 - Monolithic breccia of perlitic lava

This monolithic breccia is white. Blocks weather to dark gray and the matrix to white. The blocks composing the breccia are angular and glassy and commonly 0.5 m in size. These blocks contain sparse phenocrysts of quartz, sanidine and biotite. The base of the subunit is not exposed. The thickness of this subunit is about 2 m.

Unit 2 - Monolithic breccia of Rainier Mesa Tuff

This unit contains clasts derived from different zones of welding within the Rainier Mesa Tuff. Clasts of this breccia range in size from sand to boulders 2 m in diameter. The clasts of variably welded tuff form layers within the breccia whose sequence is inverted from normal stratigraphic order. The
Figure 15 - Measured stratigraphic section (NW1/4 SW1/4 sec.35, T.11S., R. 47E.) of interlayered reworked tuffs, debris flows, and mud flows overlying layers of monolithologic breccia.
Figure 16 - Base of Sober-Up Gulch gravels. Contact between sandy gravels and overlying monolithologic breccia of Rainier Mesa Tuff (white unit on lower left). Hammer is 32 cm. Photo taken NW1/4 SW1/4 sec.35, T.11S., R. 47E.
matrix consists of smaller clasts similar in lithology to the breccia blocks. The basal contact is sharp but uneven over about 0.5 m. The thickness of the unit is about 6 m but is thicker elsewhere in the study area.

**Unit 3- Debris flows with abundant sandy component**

The lower part of these flows is dark gray weathering to light gray. The debris flows contain volcanic, limestone, and quartzite clasts that range in size from silt to boulders 80 cm in diameter. Also present are sparse clasts up to 10 cm composed of yellowish-green silty mud. Beds 30 cm thick of pebbly sands and sandy gravels have been cut by channels up to 1 m deep. These channels are filled with thin cross-bedded sands with gravel lags. Clasts in the gravel lags range from 5 to 20 cm in size. The clasts are angular to subangular. The unit is poorly sorted and beds are defined by the scours and fills. The beds range from a few cm to 30 cm thick.

The upper part of this sequence of debris flows is light brown that weathers to dark brown. The debris flows in this upper part are poorly sorted with clasts ranging in size from sand and silt to boulders 70 cm in diameter. The clasts are angular to subangular. The beds in this part are commonly 30 to 70 cm thick, thicker than the lower part. The beds range from clast-rich with sparse muddy matrix to pebbly, cobbly, bouldery muds. Contacts between beds are well- to poorly-defined as channel scours with course gravel lags. The basal contact is sharp and scalloped into the underlying breccia. This unit is about 6.5 m thick.
**Unit 4 - Lower sequence**

This sequence consists of a lowermost reworked tuff overlain by a massive lithic-rich, resistant debris flow that is capped by a series of thinner debris flows. The reworked tuff is grayish-brown weathering to brown. The reworked tuff contains white pumice fragments commonly 2 cm in size, gray vitric clasts commonly 0.5 cm in size, small brown stony lithic clasts, and sparse phenocrysts of quartz, biotite, and sanidine. The reworked tuff is massive, about 1 m thick, and contains erosional caverns and irregular shaped protrusions.

The massive debris flow with sparse matrix overlies the reworked tuff and contains clasts that are commonly 3 to 5 cm and rarely 20 cm in size. This unit is poorly sorted, contains angular to subangular clasts, and forms a resistant ledge about 1 m thick.

Overlying the massive debris flow is a series of thinner debris flows that are poorly- to well-defined and contain abundant scour and fill structures. The beds vary from clast-rich to matrix-rich with lenses of pebbles and cobbles. The beds range in thickness from 20 to 60 cm and are poorly sorted. The clasts vary from angular to subrounded and range from silt to boulders 75 cm in diameter. These thinner debris flows contain sparse clasts of limestone breccia. This unit is about 6 m thick.

**Unit 5 - Upper sequence**

This sequence consists of a lowermost reworked tuff overlain by a massive lithic-rich, resistant debris flow that is capped by a series of thinner
debris flows, similar to unit 4. The composition and form of the reworked tuff and massive debris flow is similar to that of subunit 2, however, the series of debris flows at the top of the subunit is thicker than its counterpart in unit 4 and contains clasts of the Rainier Mesa ash-flow tuff up to 80 cm in size near the top of the subunit. Unit 5 is about 12 m thick and is capped by an erosional surface of gravels.

**Gravels of Sober-up Gulch (Pliocene and Late Miocene(?))**

This unit is gray, reddish brown, brown, black, varicolored weathering to light brown and dark brown. The unit is composed of siliciclastic, carbonate, rhyolitic, and basaltic gravel and sand and is typically highly eroded. The clasts are subangular to rounded, poorly sorted to moderately well-sorted and range from fine sand to boulders 3 m in longest dimension. The unit is massive to moderately bedded, commonly as discontinuous layers. The unit contains beds of sand and pebbly sand and are poorly to well-cemented with carbonate and silica that form resistant ledges. The basal contact is conformable on various lithologies: 1) monolithologic breccias of Rainier Mesa in the southern part of the study area; 2) monolithologic breccia of Tram Tuff in the Northeast part of the study area; and 3) Spearhead on the western part of the study area. The unit has a minimum thickness of 180 m (Swadley and Parrish, 1988).

This unit was first described by Cornwall and Kleinhampel (1961). The largest clasts lie predominantly between the southern border of the study area and Beatty Wash. This area also contains the only siliciclastic and carbonate
clasts. Clast size generally decreases from the southern and western parts of
the study area towards the central and northern part.

**Interbedded sandstone and mudstone (Miocene(?))**

The sandstone and mudstone is light green, white, red and gray
weathering to brown, gray, and brownish red. The sandstone and mudstone
contain pebble-sized pumice fragments that are sparse to abundant and, in
places, form discontinuous layers. The sandstone is thin- to medium-bedded,
fine- to coarse-grained, moderately well-sorted, and moderately- to well-
cemented, while the mudstone is massively bedded, very fine-grained,
moderately well-sorted, and poorly cemented. Sands are cliff-forming units
generally overlying slope-forming mudstone. The distinguishing features of
this unit from the Sober-up Gulch gravels are its sorting, grain size, and
presence of sparse pumice fragments. This unit was first described by
Swadley and Parrish (1988) as a lens-shape body within the gravels in the
northern and central parts of the study area.

**Undivided Terrace deposits (Quaternary(?))**

The undivided terrace deposits in the western part of the study area are
grayish brown weathering to dark gray. The deposits are poorly sorted with
clasts ranging from boulder- to sand-size. The terraces capping the deposits
commonly have desert pavement surfaces, but locally, are eroded.
Commonly, the terrace deposits contain calcrete that is concentrated in zones
1 to 3 m below the terraces. An upper and lower terrace are distinguished
along Beatty Wash (plate 1).

**Upper terrace deposits**

This upper terrace deposits (figure 17) measured at lat 36°56'19.5"N., long 116°41'30.9"W. is dark gray brown that weathers to light gray. The deposit is poorly sorted gravel containing subangular to rounded volcanic clasts that range in size from mud to boulders 75 cm in diameter. The unit is moderately well-bedded with beds that range in thickness from 60 cm to a few cm. Beds 10 to 25 cm thick consist of lags of boulders that are commonly 13 to 17 cm and rarely up to 75 cm in size. These beds alternate with thinner beds of boulder, cobble and pebble sand. Some of the sandy beds are 1 cm thick and planar, while others form weak foresets or are cross bedded. Overlying beds commonly fill scours a few cm deep, filled with coarser grained lags that grade up to finer grained materials. The top half of the section contains common pebbly sand, mud and silt layers, generally finer grained than the lower half of the section. Beds are fining up sequences. Basal contacts of the beds are gradational over 0.5 to several cm. The base of the deposit is not exposed, however, the deposit is at least 25 m thick. Imbrication of clasts indicate deposition from currents flowing southwest. A resistant calcrete bed a few cm thick is exposed near the top of the unit. The top of the unit is an eroded depositional terrace exposed along the northern side of lower Beatty Wash.
Figure 17 - Lower part of the upper terrace deposits adjacent to Beatty Wash. Hammer is 32 cm. Photo taken in NE1/4 SW1/4 sec.35, T.11S., R. 47E.
**Lower terrace deposits**

The lower terrace deposits are brown, weathering to a dark brown. The deposits form a thin veneer capping the Spearhead Tuff. The surface of the terrace consists of poorly sorted pebbles over silt forming a desert pavement. Clasts range in size from silt to boulders, but are commonly pebbles a few cm in diameter. The clasts are angular to subangular. This terrace is absent along part of Beatty Wash.

**Alluvium, colluvium, and slope wash (Quaternary)**

This unit lines the modern stream channels and gullies of the gravels. The unit is gray and brown, weathering to a light gray. The unit is poorly sorted and contains chiefly welded tuff, basalt, limestone, and siliciclastic clasts that range in size from mud to boulders. The unit ranges from poorly cemented to loose clasts. The clasts are angular to rounded. Locally, accumulations of sand (eolian?) cover the alluvium. Slope wash does not appear to have moved recently. The base of the unit is not exposed but is probably conformable on underlying units.
STRUCTURE

Introduction

The low-angle north-dipping normal Fluorspar Canyon Fault truncates several of the east-dipping, high-angle normal faults cutting central Bare Mountain (Monsen and others, 1992). Deformed Cenozoic volcanic and sedimentary strata form the upper plate of the Fluorspar Canyon Fault. Exposures of moderately to intensely deformed volcanic units lie in the southeastern 1/3 and the northwestern corner of the study area (Plate I). The Spearhead member of the Stonewall Mountain Tuff, Miocene (?) sediments, and Quaternary deposits within the study area are only slightly deformed. The more intensely deformed rocks have been cut by high- and low-angle normal faults, right-lateral transform faults and have been broken into syn- or post-deformation monolithologic breccia.

Northwest-dipping faults cut the older volcanic rocks of the upper plate in the hills just north of Fluorspar Canyon and south of the study area tilting these rocks to the southeast (Monsen and others, 1992). Removing the northward structural plunge at the north end of Bare Mountain rotates local south-dipping transform faults to nearly vertical indicating northward projection must be from north of the vertical transform fault. A cross-section constructed just north of the transform fault, creates a framework with which to project the Fluorspar Canyon Fault surface and upper plate structure beneath the study
area.

The northwest-dipping high-angle normal faults cut strata as young as the basalts. The faults probably merge at depth with the Fluorspar Canyon fault.

The east-west cross-section through the study area (Plate II) cannot be balanced because motion of upper plate structural blocks is not within the plane of the section. Several of the blocks moved obliquely to the plane of the section. In cross-section A-A' (plate II), seemingly impossible faulting at the Tiva Canyon/lavas and tuffs of Western Beatty Wash contact require movement of blocks in directions oblique to the section. The faulted Timber Mountain Group and basalts are overlain by nearly horizontal and little deformed Spearhead Member of the Stonewall Mountain Tuff and also by nearly flat-lying gravel and sand deposits.

High-angle northwest-dipping normal faults slice the Crater Flat Group and overlying Paintbrush Group into elongate blocks and tilt these strata to the southeast. Unconformably overlying tuffs and lavas of western Beatty Wash, monolithologic breccia, Timber Mountain Group, and basalts have also been faulted and tilted to the southeast. The faults continue to the northeast cutting through the Crater Flat and Paintbrush sequence of tuffs south of Owl Canyon to intersect the Silicon Mine Fault Zone (Plates I and V).

**Yucca Mountain**

The western end of Yucca Mountain (figure 2) forms a prominent massif that is about 4 km long by 2.4 km wide and reaches 1460 m elevation at Brick
(figure 2). This massif trends southwest from the northeastern border of the study area. Two ridges form the massif, Tram Ridge on the north and Thompson Ridge on the south. Thompson Ridge extends about 1.6 km farther southwest than Tram ridge.

**Tram Ridge**

The north side of Tram Ridge (Plate V) is composed chiefly of Tram Tuff that unconformably overlies an east-dipping sequence of older rocks. Lithic Ridge Tuff, associated bedded tuffs and the underlying lavas and dikes of Tram Ridge, the oldest units within the study area, crop out about 3 km down Beatty Wash from the eastern border of the study area (Plate I). Monolithologic breccia composed of clasts of Tram and Tiva Canyon Tuffs lie on the highly fractured Tram Tuff east of the Lithic Ridge section. Tertiary gravels unconformably overlie all of these rocks on the north side of Beatty Wash and themselves dip about 11° to the northwest.

A sequence of lavas of Tram Ridge and overlying Lithic Ridge tuff and associated bedded tuffs dips about 36° to the east in small outcrops about 3 km down Beatty Wash from the east border of the study area. Tram tuff unconformably overlies this sequence.

The Tram Tuff covers most of the northern slope of Tram Ridge and forms a broad, gentle north-trending syncline (Plates I and V). The west limb of the syncline dips about 25° to 30° to the northeast and the east limb, near the east border of the study area, dips 10° to 15° to the northwest. Several sets of northeast-trending joints intensely fracture the Tram tuff. Erosion at the fracture
intersections created broad arcuate lineaments that open to the north and northeast. Concentrations of desert flora along the eroded joints are visible in aerial photographs. The Tram Tuff is highly eroded and monolithologic breccia derived from the Tram Tuff forms scattered outcrops that scab the north slope.

The Tram Tuff is highly fractured, jumbled, and hydrothermally altered along the northern slope of Tram Ridge. Fault scarps dip moderately to the south and southwest. Minor faults show little offset and commonly contain gouge several centimeters thick.

Beatty Wash enters the study area at the northeastern border and flows along the north side of Tram Ridge. Monolithologic breccias (unit Trx on Plate I) crop out along a 1 km stretch of the northern bank of Beatty Wash about 1.2 km from the northeastern border of the map. A hill of monolithologic breccia derived from the Tiva Canyon tuff overlies broken and shattered blocks of the Tram tuff. Clasts of Tiva Canyon monolithologic breccia form distinct layers that retain the normal stratigraphic order of welding zones present within intact Tiva Canyon tuff. East of and adjacent to this exposure, a nearly 60 m thick layer of monolithologic breccia composed of clasts of the Tram tuff overlies a 2 m-thick layer of monolithologic breccia composed of clasts of the Tiva Canyon tuff (figure 18). At the eastern end of this exposure, monolithologic breccia of the Tiva Canyon is juxtaposed against monolithologic breccia of the Tram tuff along a nearly vertical contact. Clasts of the Tiva Canyon tuff and Tram tuff are not mixed.

Tertiary gravels dip about 11° to the northwest and onlap the bedrock exposures on the north side of Beatty Wash. An inferred northeast-trending
Figure 18 - Monolithologic breccia of Tram Tuff overlying monolithologic breccia of Tiva Canyon Tuff. Person is 2 m. Outcrop is adjacent to and 1.5 km down Beatty Wash from intersection of Beatty Wash and northeast corner of study area.
fault cuts these gravels just north of the onlap. While there is no exposure of the fault, the linear trend is easily seen on aerial photographs and follows or corresponds with a low linear valley in the gravels.

**Thompson Ridge**

A conformable sequence of Bullfrog, Topopah and Tiva Canyon Tuffs form the southeast slope of Thompson Ridge. The units are highly fractured and disaggregated, commonly covering slopes with prismatic pebbles. The Tiva Canyon Tuff at the top of the section has been broken into plates commonly a few cm thick that cover the hill. The units have been hydrothermally altered.

Thompson Ridge (Plate V) contains east-trending, southeast-dipping and north-trending, east-dipping faults. The curvilinear Thompson fault cuts the southeast shoulder of Thompson Ridge. The north-trending faults merge with the Thompson Fault at their northern ends. While these are the longest fault traces, the strata are cut by many faults and fractures with shorter traces. Commonly these fault traces are arcuate, concave towards the southeast. Slide blocks, ribs and irregular shaped masses of monolithologic breccia (unit Trx on Plate I) composed of clasts of Bullfrog Tuff cover much of the lower southeast face of Thompson ridge. Bullfrog monolithologic breccia contains clasts 10 to 30 cm but range up to 1 m in size.

The arcuate, southeast-dipping, low-angle normal Thompson fault (Plates I and V) cuts older Miocene tuffs placing Tiva Canyon tuff on the southeast side of the fault against Tram tuff on the northwest. The fault plane
dips from 45° to 57° toward the southeast. Striations along the southwest end of this fault rake 75° to 86° to the east and those near the northeast end of the fault rake 57° to 65° to the east. The northeast end of the fault appears to merge with an east-dipping normal fault that drops Tiva Canyon tuff on the east against Tram tuff on the west. The east end of the Thompson fault contains about 0.5 m of silicified stretched pebble conglomerate. The southwest end of the Thompson fault is truncated by a normal fault of the Silicon Mine Fault Zone that dips about 85° to the southwest. Strata within the hanging wall block of the Thompson Fault (southeast of trace of the fault) dip 27° toward the northwest, nosing into the fault surface. The Thompson fault was interpreted to be a caldera margin fault by Carr and others (1987).

Two faults trend northeast, subparallel to the Thompson fault along the southeast face of Thompson Ridge (Plate I). The southernmost fault plane dips 77° northwest, has striations with rakes of 75° southwest, and separates bedded tuffs on the northwest side of this fault from deformed Bullfrog tuff on the southeast. The west end of this fault is truncated by a fault that dips 63° to the west, part of the Silicon Mine Fault Zone. On the north side of the north-dipping fault, the dip of a small listric fault shallows from 17° to 44° to the west and cuts a massive nonwelded tuff. Below this listric fault are gray angular blocks of tuff in a reddish tuff matrix of similar composition. On the south side of the north dipping fault is a zone of disrupted upper Bullfrog Tuff with a possible fault dipping 24° east.

Two north-trending faults merge with the northeast end of the Thompson fault. The easternmost of these two faults can be traced for a short distance
from the Thompson Fault to the southeast. The plane of this north-trending fault dips 45° east-southeast and drops the Tiva Canyon tuff down to the southeast. The westernmost of the two north-trending faults arcs to the northeast as it approaches the Thompson fault. This north-trending fault offsets units from the Paintbrush group, Crater Flat group, and monolithic breccias of the Bullfrog tuff. The fault plane dips 46° east-southeast and striations on this plane have rakes of 63° southwest.

The western end of Thompson Ridge (Plate V) is chiefly a southeast-dipping tilted block of Bullfrog, Topopah Spring, and Tiva Canyon tuffs. These strata dip about 20° southeast. The northwest-trending Silicon Mine Fault Zone borders the tilted block on the east and a low bench of intensely faulted and hydrothermally altered strata form the west end of the block. On the southeast lower slope are subparallel elongate ridges of monolithic breccia of Tiva Canyon and Rainier Mesa tuffs.

Three identifiable faults and one inferred fault cut rocks across the southwestern slope of West Thompson Ridge. A northeast-trending, southeast-dipping, high-angle normal fault cuts strata across the northwest shoulder of Thompson Ridge. Two fault planes, separated by a few meters, form this fault on the southwestern end of the ridge. The fault plane on the southeast dips 67° to the northwest and the fault plane on the northwest dips 57° southeast, with striations indicating nearly pure dip-slip motion.

A northeast-trending fault that dips 87° northwest and has striations that rake 30° northeast, cuts rocks about mid-slope. The strike-slip component of this oblique slip fault is unique compared to the more common dip-slip
components recorded on many fault planes in the area. South of this oblique-slip fault is an inferred, down to the south normal fault that drops Tiva Canyon tuff on the south against highly fractured Topopah Spring tuff on the north. This fault appears to cut units across the entire length of a bench on the lower south side of the southeast slope.

A fault trends from the southwest towards the top of the ridge, has a 55° dip southeast and 70° rake to the southwest, and splays at its southwest end into two faults. The south splay dips 60° southeast and a rake of 65° northeast.

Many intersecting, short faults cut Bullfrog, Topopah Spring, and Tiva Canyon tuffs on a low bench on the western end of Thompson Ridge. Prominent scarps dip about 70° to the south. One such scarp contains a centimeter wide groove with a rake of 55° east created presumably by a pebble sheared off at one end of the groove. On the sheared face of the pebble are two sets of slickensides, one set with rakes of 55° east and the other 89° east.

A large elliptical mass of fractured and broken Tiva Canyon tuff caps the southeast-dipping tilt block of west Thompson Ridge. Blocks within this mass dip from 23° to 55°, generally southeastward. The irregular shaped mass of Tiva Canyon is underlain by severely fractured and hydrothermally altered Topopah Spring tuff. Erosion of the fractures cover the area with prismatic blocks, cobbles, and pebbles of Topopah Spring tuff. Erosion of the prismatic fragments creates many subparallel northwest-trending gullies and intervening ridges along the northwest and southwest slopes of Thompson Ridge easily seen in aerial photographs. Lower on the southeast slope are two subparallel ridges. The northern ridge consists entirely of monolithologic breccia
composed of Tiva Canyon Tuff while monolithologic breccia composed of Rainier Mesa Tuff forms the southern ridge

**Silicon Mine Fault Zone**

A northwest-trending fault zone (Plates I and V) is exposed from just southeast of the Thompson Mine to northwest of the Silicon Mine. This zone is about 160 m wide and is broken by numerous faults and fractures. This fault zone drops Topopah Spring Tuff on the southwest against Bullfrog Tuff (figure 19) on the northeast. The zone consists of intersecting fractures, some that are separated by a few cm. Many of the fractures contain thick or thin bands of fault gouge. An alignment of small outcrops of boxwork silica cap the fault zone. The head of a small dogleg wash exposes the intersection of the Silicon Mine Fault Zone with a northeast-trending fault and displays a complex array of several fault splays. Oblique-slip and dip-slip faults that have short surface traces break the strata in this area into thin slivers and highly broken blocks.

**Monolithologic Breccias**

Monolithologic breccia extends across nearly the entire length of the lower southern slopes of West Thompson Ridge (Plate V). A 1.6 km long irregularly shaped mass of monolithologic breccia composed of mostly Tiva Canyon covers the southwest part of the ridge. An elongate mass of monolithologic breccia composed of the Rainier Mesa Tuff and a very small exposure of breccia of the Tiva Canyon tuff lies just south of and subparallel to the elongate mass of Tiva Canyon monolithologic breccia. The clasts forming
Figure 19 - Bullfrog monolithic breccia. Pole is 1.52 m. Photo taken at the east side of the Silicon Mine Fault Zone, 0.5 km northwest of the Thompson Mine.
the elongate mass of Rainier Mesa monolithologic breccia are partially to
densely welded, light gray tuff and indurated. Farther south, large broken
clasts derived from the upper part of the Rainier Mesa tuff form a small isolated
outcrop. Gravels lie adjacent to these large broken boulders on the east, and
cover deformed, pink non-welded Rainier Mesa tuff.

**Western border of Yucca Mountain**

The western ends of Thompson Ridge and Tram Ridge form the western
border of Yucca Mountain (figure 2, Plate V). Thompson Ridge on the south
extends about 1.5 km farther to the southwest than Tram ridge on the north.
The ridges are separated by a topographic re-entrant eroded by a dogleg wash
that empties into Beatty Wash. Three zones of differing geologic character, the
southern zone, the re-entrant zone and the northern zone form the western
boundary of Yucca Mountain.

**Southern zone**

Thin, indurated breccias comprised of clasts of the older, underlying
units commonly form planar layers that dip about 30° toward the west and
separate the younger and older tuffs. Lavas and tuffs of western Beatty Wash
and overlying Rainier Mesa Tuff form a large mesa and unconformably overlie
Bullfrog, Topopah Spring, and Tiva Canyon tuffs of West Thompson Ridge.
The older tuffs are faulted, highly fractured, and hydrothermally altered. The
younger tuffs are less intensely fractured and lack hydrothermal alteration. The
younger units dip about 11° to 14° to the northwest on the southeast side of the
mesa and dip about 5° southeast on the northwest side of the mesa.

**Re-entrant Zone**

This zone is underlain by the southeast-dipping tilt-block sequence of West Thompson Ridge. Many sets of fractures cut Topopah Spring Tuff forming a steep northwest-facing slope. These fractures are separated by a few centimeters to a few meters. The underlying Bullfrog Tuff is poorly exposed and the overlying Tiva Canyon tuff is stripped from the western top of the ridge, except for a small outcrop caught between two ridge-cutting antithetic faults. The rocks forming the entire slope are hydrothermally altered; the rocks of the lower slope are commonly bleached white (silicified) while rocks of the upper slope are commonly hydrothermally altered to brilliant orange (oxidized). The Topopah Spring Tuff and overlying interbedded debris flows and tuffs of western Beatty Wash form a buttress unconformity. The layers of debris flows dip about 40° to the northwest. The tuffs are intercalated with the upper part of the debris flows and are conformable on their northwestern face. Successive, younger tuff beds, with decreasing dips, onlap and truncate underlying beds. Upsection, thin, rare layers of debris flows are interbedded with the tuff beds and decrease in thickness and abundance upsection. The debris flows pinch out. Some faults cut the bedded tuffs and continue into the older rocks below while other faults cut the younger tuffs, but do not continue into the underlying older units. Exposures of the debris flows are discontinuous along strike. Locally (lat 36°56'52.4"N., long 116°39'11.2W.), the debris flows form U-shaped exposures where they have filled paleochannels cut into underlying
Topopah Springs Tuff. Farther west along strike, the debris flows are planar where they banked against Topopah Springs Tuff on the lower northwest slope of West Thompson Ridge. Small exposures of fractured and broken bedded tuffs, breccias of the upper part of the Bullfrog tuff, fractured Bullfrog tuff, and a small hill of highly broken Tiva Canyon tuff form the east end of the northwest slope of West Thompson Ridge.

**Northern Zone**

A curvilinear fault cuts northeast across the southeast-dipping tilt block of West Thompson Ridge. This fault crosses the dogleg wash and forms a gully that runs along the western end of Tram Ridge and empties into Beatty Wash. Along the east side of the gully at the western end of Tram Ridge the tuff and lava of western Beatty Wash have been hydrothermally altered and minutely shattered. The breccias thus formed have been eroded into many parallel ribs, a few centimeters wide, separated by nearly parallel fracture planes. These planes dip about 40° to the west. Monolithologic breccias derived from the Tiva Canyon Tuff overlie thinner exposures of monolithologic breccias derived from the Bullfrog Tuff at the head of this gully. At the mouth of the gully hydrothermally altered massive units of the Bullfrog monolithologic breccia overlie debris flows.

Adjacent to Beatty Wash, Rainier Mesa tuff caps a sequence of debris flows, massive monolithologic breccia of Bullfrog tuff, monolithologic breccia of Tiva Canyon tuff, and tuffs of Western Beatty Wash (figures 20, 21, and 22). Bedding plane faults in the lower part of the Rainier Mesa Tuff strike northwest
Figure 20 - Rainier Mesa Tuff (resistant outcrops in lower left and upper right) overlying breccia with clasts of Bullfrog Tuff and Tiva Canyon Tuff (light colored slope in middle of photo). Lower right is Beatty Wash. View is to the southwest. Photo taken in the northern zone, 0.2 km east of SE1/4 SE1/4 sec. 24, T.11S., R.47E.
Figure 21 - Breccia composed of clasts of Bullfrog Tuff and Tiva Canyon Tuff overlain by Rainier Mesa Tuff (not in photo). Hammer is 32 cm. Photo taken in the northern zone, 0.2 km east of SE1/4 SE1/4 sec. 24, T.11S., R.47E.
Figure 22 - Northern zone sequence that includes Rainier Mesa Tuff with bedding plane slip at base of columnar joints, overlying thinned western Beatty Wash tuffs, and breccia with clasts of Tiva Canyon Tuff and Bullfrog Tuff (light slope on right). Truck is in Beatty Wash. View is to the northeast. Photo taken in the northern zone, 0.2 km east of SE1/4 SE1/4 sec. 24, T.11S., R.47E.
with a consistent dip of 25° southwest and rake of 23° northwest. A northwest-trending listric fault thins western Beatty Wash tuffs, decreases dip from 64° to 35° southwest, and rakes 30° to the southeast. This sequence of breccias and tuffs widens and continues north along the fault. Exposures of the north zone end at a triangular mass of Tiva Canyon monolithologic breccia where it has been covered by gravels.

**Oasis Valley**

A series of mesas capped by Rainier Mesa Tuff lie between Yucca Mountain on the east and lavas and tuffs of western Beatty Wash on the west in the east-central part of the study area. The large mesa at the west end of Thompson Ridge is cut by a northeast-trending northwest-dipping fault. On the southwest end of the mesa a northwest-trending listric fault dips 35° to 54° to the southwest. The southeast end is highly fractured. Northwest axial trends mark synclines and anticlines within the lower Beatty Wash tuffs on the northwest end of the mesa. East limbs strike 160° and dip about 20° to the east while west limbs strike 105° and dip about 20° to the west. The tuffs decrease in dip from 52° to 12° upsection, west of the folds.

The southernmost mesa is partly capped by monolithologic breccia composed of clasts of Rainier Mesa Tuff (figure 23). Tuffs of western Beatty Wash underlie the breccia and contain flame structures and a dike that is 17 cm wide at the base and pinches out 117 cm above the base (figure 9).

West of Tram Ridge, Beatty Wash separates an arcuate ridge from a mesa, both of which are capped by Rainier Mesa Tuff. The ridge is cut by both
Figure 23 - Monolithologic breccia of Rainier Mesa Tuff overlying tuffs of western Beatty Wash. Pole is 1.52 m. Photo taken in NE1/4 SE1/4 sec. 1, T.12S., R. 47E.
northwest-trending and northeast-trending faults, which drop strata down to the west. The Rainier Mesa conformably overlies the lavas and tuffs of western Beatty Wash and thickens on the northern end of the ridge. A single growth-fault cuts northwest through the mesa across Beatty Wash from the arcuate ridge.

Broken and disrupted Rainier Mesa tuff crosses the middle of the western boundary of s.24 T.11S. R.47E. and continues to the southeast. This highly broken ridge is most likely a slide block. A loose rubble of boulders up to 4 m across cover the northern slope of this elongate ridge.

A fault cutting the Spearhead Tuff is exposed in a wash that trends subparallel to and lies north of Beatty Wash. At this exposure, the more indurated Spearhead is highly fractured, with fault gouge to 3 cm wide and veinlets of silica up to 1 cm wide that anastomose through rock. A northeast-trending fault cuts the rock, dips 75° to the west, and rakes 82° to the north. This fault contains about 10 cm of fault gouge and offsets the tuff 2.3 m. On the east side of fault is about a 4 m wide shear zone along which pieces of the underlying lowest parts of the tuff abut the overlying more indurated parts.

North- and northeast-trending faults cut the gravels. Although the faults with longer traces have poorly exposed fault planes, a fault with a short trace is exposed along the south bank of Beatty Wash. This fault plane trends due north and dips 74° to the west.

Several small exposures of monolithologic breccia composed of clasts of stoney rhyolite or of glassy rhyolite overlain by Rainier Mesa Tuff are scattered along the banks of Beatty Wash and along gullies that empty into
Beatty Wash. In one exposure along Beatty Wash monolithic breccia of Rainier Mesa overlies monolithic breccia of glassy rhyolite. Layers of breccia retain the stratigraphic order of and are substantially thinner than their parent rocks. Some of these scattered exposures contain trains of boulders several meters across of indurated monolithic breccia, commonly composed of clasts of the Rainier Mesa tuff.

**Northwest corner of the study area**

The Amargosa river flows south between outcrops of volcanic rocks on the northwest corner of the study area. The volcanic rocks are faulted and hydrothermally altered. Sober-Up Gulch gravels overlie the volcanic rocks.

**East of Amargosa River**

A ridge of younger ash-flow tuffs extends into the study area from the north. These tuffs dip about 30° to 40° to the east and southeast. A single northwest-dipping fault offsets these tuffs dropping them down to the northwest.

South of this ridge, near Bailey's Hot Springs, is an oval area, elongate to the north, of Timber Mountain Group. Several intersecting, but short, faults appear to have cut these tuffs and breccias, though no attitudes were determined. Silicified monolithic breccias of Rainier Mesa tuff cover the surface.
West of Amargosa River

West of the Amargosa River is a second oval area of Rainier Mesa Tuff similar in form to that on the east side of the river. Ammonia Tanks Tuff exposed at the south end of the oval area of tuff dips about 45° to the southeast. Several small faults with northeast trends cut this block. These faults appear to be cut by a pair of inferred faults with northerly trends that extend into the large oval of Rainier Mesa tuff.

Farther north in the northwest corner of the study area, is a disorderly group of slide blocks and silicified monolithologic breccia and polythologic breccia of Bullfrog, Tiva Canyon and Rainier Mesa Tuffs. Individual slide blocks of Tiva Canyon and Bullfrog tuff dip about 47° to 70° to the east. A west-dipping low-angle fault dips 22° to 38° northwest and is overlain by blocks of limestone about 1 m thick that are overlain by blocks of Bullfrog tuff. The limestone breccia also lies in scattered exposures along the northwest border of the study area.

Quaternary Faulting

Large and polished fault scarps on west Thompson Ridge suggest possible Quaternary movement along local faults (Kenneth F. Fox, Jr., oral communication, 1994). The presence of numerous springs along the Amargosa River indicates possible Quaternary movement along local normal faults (Plates I, II, and III).
DISCUSSION AND CONCLUSIONS

Previous Work

Origin of Oasis Valley

Geologists have developed both volcanic and tectonic models to explain the origin of Oasis Valley. The volcanic model explains the topographic depression underlying Oasis Valley as a caldera collapse feature. The tectonic model derives the local topography by regional tectonic extension.

Volcanic Models

The Oasis Valley caldera segment (OVCS), first proposed by D. C. Noble in 1967 (Byers and others, 1976) and Timber Mountain caldera form the Timber Mountain-Oasis Valley caldera complex (figure 24) (Christiansen and others, 1977). Most workers in the SNVF have agreed that collapse of the Timber Mountain caldera, northeast of the study area, was related to eruption of the Timber Mountain Group. But there is disagreement over which eruption(s) led to collapse of the partially preserved OVCS. Geologists have debated the extent, timing, and even the existence of the OVCS. Key exposures lie east of, in the Transvaal Hills, and west of, at Oasis Mountain, Oasis Valley (figure 24). Distribution, structural and depositional relationships, and physical properties of volcanic units within and near the OVCS were
Figure 24 - Oasis Valley Caldera Segment and Timber Mountain Caldera. Stippled pattern outlines topographic uplands (modified from Byers and others, 1976).
similar to those within other calderas in SNVF, which suggests that a caldera underlies Oasis Valley.

Byers and others (1976, p. 56-59) presented evidence that the OVCS collapsed due to eruption of the Rainier Mesa Tuff, Ammonia Tanks Tuff, or both. Debris flows intertonguing with the upper Rainier Mesa Tuff in the Transvaal Hills (figure 24), debris flows containing blocks of Rainier Mesa and Tiva Canyon Tuffs at Oasis Mountain, and the proximity of rhyolitic lavas of western Beatty Wash to OVCS are analogous to similar relationships within the Timber Mountain caldera and elsewhere in the SNVF. D. L. Healey (1969) conveyed to Byers and others (1976, p.58) that a steep gravity gradient east of Oasis Mountain coincides with Oasis Valley and likely deepest cauldron subsidence. 450 m of Rainier Mesa tuff in the Transvaal Hills with granophyric texture (typical of thick, possibly intracaldera, ash-flows) and dipping 25° to the west, outward from the Timber Mountain caldera wall, suggests that eruption of Rainier Mesa Tuff led to collapse of the OVCS (Byers and others, 1976).

The Ammonia Tanks Tuff is 450 m thick at Oasis Mountain and dips easterly 35° in the lower and middle part and 75° in the upper part. This tuff thins to 150 m over the Transvaal Hills where a 10° angular unconformity separates the west-dipping Ammonia Tanks Tuff from the underlying Rainier Mesa Tuff (Byers and others, 1976). These relationships suggest that eruption of the Ammonia Tanks Tuff may also have led to collapse, or further collapse of the OVCS.

Christiansen and others (1977) also inferred that the Oasis Valley caldera segment exists; however, the authors did not agree among themselves
(Christiansen and others, 1977, p. 949) on when the segment collapsed. Some of the authors agreed with earlier views (Byers and others, 1976) that the OVCS was created as a result of eruption of the Rainier Mesa and Ammonia Tanks Tuffs. Others argued that the younger, Rainier Mesa and Ammonia Tanks Tuffs simply collected in an Oasis Valley basin formed during an earlier collapse, related to eruption of tuffs from the Paintbrush Group (Christiansen and others, 1977, p.949 and p.952-953). Christiansen and others (1977) note that although Paintbrush Tuffs are found in upland exposures south, west, and north of Oasis Valley, they are not exposed within Oasis Valley. Christiansen and others (1977) also note that near Oasis Valley, the Timber Mountain Group is sharply unconformable with the underlying Paintbrush Group, yet these groups are conformable elsewhere in the region. In addition, tuffs of the Timber Mountain Group are "plastered against steep inward-facing slopes" (Christiansen and others, 1977, p. 953) surrounding the Oasis Valley basin and the lower part of the group (Rainier Mesa Tuff) ponded to its greatest thickness of 300 m in Oasis Valley. Finally, the Rainier Mesa Tuff in the Transvaal Hills is interpreted as being within the Timber Mountain Caldera rather than the OVCS because the Rainier Mesa Tuff is only partially welded and is thicker in earlier erupted parts rather than later erupted parts, as commonly seen in tuffs erupted in other areas. Christiansen and others (1977) conclude that collapse of the OVCS may be related to either the eruption of the Timber Mountain Group or to the eruption of the Paintbrush Group; an unequivocal determination is not possible.

Noble and others (1991) presented a model having no Oasis Valley
caldera segment. They suggested that instead, nested calderas at Timber Mountain were the sources for the Rainier Mesa and Ammonia Tanks Tuffs.

**Tectonic Models**

The region surrounding the western Beatty Wash area lies within the Walker Lane Belt. The Walker Lane Belt lies between the Basin and Range on the northeast, where north-trending normal faults bound horsts and grabens, and the Inyo-Mono subprovince (Carr, 1984) on the southwest, with northwest-trending ranges. The complex types and styles of deformation within the Walker Lane Belt during the Cenozoic have led geologists to develop models that invoke extensional and strike-slip fault tectonics. In these models, the crust is extended as much as 100% (Hamilton and Myers, 1966) to 250% (Maldonado, 1990) along low-angle normal (detachment) faults that separate upper plate strata from subjacent lower plate rocks. South of the study area, the Fluorspar Canyon Fault is viewed as a low-angle normal fault, a segment of a regional detachment fault system that extends west through the Bullfrog Hills to the Grapevine Mountains (Carr and Monsen, 1988, Monsen and others, 1992, Hamilton, 1988, Scott, 1990, and Maldonado, 1990).

Complex Cenozoic deformation caused faulting throughout the central Walker Lane Belt (figure 1) (Keller and others, 1987, Hardyman, 1984). Hardyman and Oldow (1991) define, in the central Walker Lane Belt, three domains of differing structural deformation: 1) domain I, where north-south striking normal faults cut and strongly tilted Tertiary and pre-Tertiary basement rocks; 2) domain II, bordering the east and west sides of the Walker Lane Belt,
where Tertiary rocks are not significantly deformed; and 3) domain III, where through-going right-lateral strike-slip faults are kinematically related to thin-skinned, low-angle detachment faults. In their domain III, the detachment forms a basal decollement of transtensional "nappes" in the overlying Tertiary strata driven by strike-slip faults cutting the basement (figure 25). Hardyman and Oldow (1991) note a rotation from east-west directed extension (17 to 11 Ma) to northwest-southeast directed extension (10 to 8 Ma). Extension accompanied volcanism (Keller and others, 1987) in the central Walker Lane Belt. Pre-existing zones of weakness enhanced shallow emplacement of magmas promoting development of hydrothermal systems (Hardyman and Oldow, 1991).

The Oasis Valley area overlies the Fluorspar Canyon Fault, dipping 25° northward from Bare Mountain, and is part of an allochthonous upper plate of regional extent (Carr and Monsen, 1988). Extension has been primarily along this single fault (Hamilton, 1988), or along two subparallel detachment faults (Maldonado, 1990), or along tiers or stacks of detachment faults ranging in position from the middle, ductile crust to the surface (Scott, 1990).

Hamilton (1988) contends the Fluorspar Canyon Fault is a segment of a regional, undulatory low-angle fault that originally sliced through the entire crust at moderate angle. In his view, the moderately-dipping fault rose isostatically following tectonic denudation and rotated progressively from east to west to low-angle at a westward-moving hinge. That rotation stranded allochthonous blocks over the low-angle part of the fault. The fault is now inactive in the study area; the tilting of Cenozoic rocks above the Fluorspar
Figure 25 - Transtensional model of central Walker Lane. A indicates movement away from observer and T indicates movement towards observer. Kinematically related strike-slip, detachment and associated listric normal faults (from Hardyman and Oldow, 1991).
Canyon Fault represents the final movement along the fault in the area. Hamilton (1988) views Bare Mountain as a great domiform detachment surface where metamorphosed rocks of the lower plate rose from middle crust depths of 10 - 20 km. The fault extends east below Yucca Mountain (Hamilton, 1988).

Carr and Monsen (1988) agree with this view. However they suggest that the fault breaks to the surface on the northeast end of Bare Mountain and does not continue to the east. The deformation of the Crater Flat area is attributed to a separate and older tectonic regime (Carr and Monsen, 1988). In their view, the Fluorspar Canyon Fault separates Cenozoic rocks from the late Proterozoic and Paleozoic basement, but may split, with the lower splay cutting basement rocks south of Meiklejohn Peak (Monsen and Carr, 1992).

Maldonado (1990) mapped two detachment faults, an upper fault that separates upper plate Miocene volcanic rocks from slices of an underlying middle plate composed of unmetamorphosed basement rocks. A lower fault separates the middle plate from underlying metamorphosed basement strata.

Scott (1990, p.278) contends the breakaway and detachment of Carr and Monsen (1988) is the youngest extension event in the region. Scott (1990) also suggests the part of the Fluorspar Canyon Fault, east of the breakaway, may extend east to Yucca Mountain.

The upper plate rocks overlying the detachment faults are cut by listric normal faults that branch upwards from the low-angle normal faults and slice the upper plate into elongate structural blocks (Fox and others, 1990). Movement on the detachment faults is transferred to the normal faults through rotation of the blocks, thereby attenuating and extending the upper brittle crust.
(Fox and others, 1990, p. 56-12). Zones of closely spaced faults adjacent to block bounding faults are termed imbricate fault zones (Scott, 1990) or broken zones (Spengler and Fox, 1989) that result from block separation and rotation adjacent to listric faults. In addition to low- and high-angle normal faults, the upper plate is cut by northeast-striking left-lateral and northwest-striking right-lateral faults (Fox and others, 1990, Scott, 1990).

Hamilton (1988) contends that extension ceased in the Bare Mountain area after 11.2 Ma and continues only to the west in the Death Valley area. Fox and others (1990), however, pointing to widespread evidence of Quaternary movement on the faults, contend that the deformation climaxed in the late Miocene and resumed in the Pliocene and Holocene, albeit at lower rates than those that prevailed in the late Miocene.

**Results of This Study**

**Upper Plate Deformation**

The northward structural plunge from Bare Mountain as documented by the mapping of Monsen and others (1992), and mapping undertaken as part of this study indicates that the Fluorspar Canyon Fault extends northward beneath the surface of the study area and separates upper plate, low density tuffs and sedimentary rocks from higher density carbonate and siliciclastic late Proterozoic and Paleozoic basement rocks (Plates II and III). The projected depth to the Fluorspar Canyon Fault ranges from approximately 0.5 km at the south edge of the study area to perhaps 3 km at the north edge. Northwest-
dipping, high-angle normal faults cut the strata into discrete, elongate structural blocks and likely merge listrically with the low-angle normal Fluorspar Canyon Fault (Plates II and III). The structural blocks—made up of units composing the stratigraphic section from Titus Canyon Formation (?) through Sober-Up Gulch Gravels—were rotated on northeast-trending axes, tilting these strata to the southeast. Northwest-striking, right-lateral transform faults cut the volcanic units south of the study area and at the Silicon Mine Fault Zone on Yucca Mountain (Plate V).

The Lithic Ridge Tuff and lavas of Tram Ridge strike due north and dip west in the northeast part of the study area, adjacent to Beatty Wash. This orientation coupled with the presence of an unconformity below the overlying Tram Tuff suggests that westward-directed extension tilted the older rocks between 14.0 and 13.4 Ma (Table 2). North-striking, 13.9 Ma dikes cutting the Paleozoic rocks of Bare Mountain, south of Meiklejohn Peak (Monsen and others, 1992) also indicate east-west extension in the area. The Tram Tuff probably filled a structural down warp to the east of the tilted Lithic Ridge section and may have been slightly deformed into a broad syncline (Plate V).

In the northeastern part of the study area, the Yucca Mountain massif is cut by the Silicon Mine Fault Zone (Plate I), a northwest-trending right-lateral fault. The Silicon Mine Fault Zone separates two domains with differing degrees of extension and strikes parallel to the extension direction which, coupled with local right step of offset features and opposing stratal tilts, indicates that it is a right-lateral fault. This transform fault coincides with a gravity high indicated by the contoured gravity model for the area (Snyder and
<table>
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<tr>
<th>TIME PERIOD</th>
<th>EVENT</th>
<th>EVIDENCE</th>
</tr>
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<tbody>
<tr>
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<td>Regional stratigraphy (Stewart and Poole, 1974)</td>
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<tr>
<td>Mesozoic</td>
<td>Orogenesis, thrust faulting</td>
<td>Regional structure (Burchfiel and others, 1974, Reynolds, 1974)</td>
</tr>
<tr>
<td>Oligocene</td>
<td>Deposition of sediments</td>
<td>Regional stratigraphy (Fox and others, 1990)</td>
</tr>
<tr>
<td>Early Miocene</td>
<td>Deposition of sediments</td>
<td>Bare Mountain stratigraphy (Monsen and others, 1993)</td>
</tr>
<tr>
<td>Middle Miocene - 14.0 - 13.4 Ma</td>
<td>East-West directed extension</td>
<td>North-trending, dikes (Monsen and others, 1993) East-dipping Lithic Ridge Tuff overlain unconformably by Tram Tuff</td>
</tr>
<tr>
<td>Post 12.7 Ma</td>
<td>Syn-volcanic extension</td>
<td>Buttress unconformity, tuffs and lavas of western Beatty Wash deposited against debris flows deposited against upthrown fault block of Topopah Spring</td>
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<tr>
<td>Pre 11.6 Ma</td>
<td>Deposition of early Sober-up Gulch Gravels</td>
<td>Tuffs of western Beatty Wash interbedded with gravels</td>
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<tr>
<td>11.6 Ma</td>
<td>Syn-volcanic extension</td>
<td>Abrupt change in thickness in Rainier Mesa Tuff across fault, about twice as thick on downthrown block</td>
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<tr>
<td>Post 11.6 Ma</td>
<td>Northwest-trending, right-lateral transform faults</td>
<td>Offset Rainier Mesa Tuff along Silicon Mine Fault. Zone and south of study area (Monsen and others, 1992)</td>
</tr>
<tr>
<td>Post 11.6 Ma</td>
<td>Monolithologic breccia</td>
<td>Monolithologic breccia composed of Rainier Mesa and older tuffs</td>
</tr>
<tr>
<td>13.4 Ma to 10.7 Ma</td>
<td>Change in extension style and direction</td>
<td>Northwest-striking, right-lateral transform faults, northwest dipping block bounding faults, northeast-striking basalt dikes</td>
</tr>
<tr>
<td>7.5 Ma</td>
<td>Deposition of Spearhead Member of Stonewall Mtn Tuff within gravels</td>
<td>Exposures in study area</td>
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<tr>
<td>Post 7.5 Ma</td>
<td>Waning deformation</td>
<td>Minor offset of Spearhead and overlying gravels</td>
</tr>
</tbody>
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Heavy shading - information from other studies
Light shading - information from this study and other studies
No shading - information from this study
Carr, 1984, figure 5). The gravity high is probably due to the presence at depth of a basement high, either a paleoridge or a structurally high fault block. This basement block or paleoridge, possibly composed of Paleozoic strata, apparently influenced upper plate deformation as extension proceeded. The Silicon Mine Fault Zone separates west-dipping, high-angle normal faults above the Fluorspar Canyon detachment fault from east-dipping, high-angle normal faults above the Bare Mountain Fault (Plates II and III). On the east side of the transform fault, the curvilinear Thompson fault drops strata down to the southeast indicating that it is a breakaway fault for the Crater Flat structural low. The transform fault cuts units possibly as young as Rainier Mesa Tuff (Plate I). A subparallel northwest-striking right-lateral--and presumably transform--fault cuts units as young as the Rainier Mesa Tuff south of the study area (Monsen and others, 1992). The presence of northwest-striking transform faults, northeast-striking basalt dikes, and northwest-dipping high-angle normal faults indicate northwest directed extension of the upper plate (Table 2).

**Growth faults**

Between the transform faults, an elongate tilt block extends from the intersection of Perlithe and Fluorspar Canyons to the western end of Yucca Mountain. Exposures at Owl Canyon indicate that the debris flows of Owl Canyon and intertonging tuffs of Western Beatty Wash lap against the northwest side of the tilt block forming a buttress unconformity.

A large mesa, west of the Owl Canyon exposures, is cut by a high-angle normal fault. Rainier Mesa Tuff is draped across the fault with an abrupt
change in thickness; the Rainier Mesa Tuff is about twice as thick on the
downthrown block as on the up-thrown block. The buttress unconformity and
the varying thickness across the fault indicate that the block bounding fault is a
growth fault with syn-volcanic movement. The Topopah Spring Tuff of the
footwall block is broken intensely by many minor faults and may be a broken
zone (Spengler and Fox, 1989) suggesting that the growth fault is listric to a
low-angle fault at depth (Fox and others, 1990).

**Monolithologic Breccias**

Monolithologic breccias formed through gravity slides are common
occurrences in the Great Basin (Grose, 1959, Burchfiel, 1974, Kreiger, 1977,
Topping, 1993, Maldonado, 1993, Minor and Fleck, 1994, Simonds and
Fridrich, in review). The presence of monolithologic breccias composed of
Tram, Bullfrog, and Tiva Canyon Tuffs on the flanks of Thompson and Tram
Ridges indicates that faulting, uplift, and stratal tilting created slides after 12.7
Ma. Monolithologic breccias composed of clasts of Rainier Mesa Tuff indicate
that extension and deformation continued past 11.6 Ma.

Several disconnected mesas capped by Rainier Mesa Tuff, in the east-
central part of the study area, lie along the south, re-entrant, and northern
zones west of Yucca Mountain (figure 5). Two of these mesas straddle Beatty
Wash (Plate I) and may have moved as slide masses in a manner similar to
those described in the Spring Mountains (Burchfiel and others, 1974).
Burchfiel and others (1974) note that, in a spectrum of size and amount of
disruption of slide masses, the largest gravity slides are brecciated at the base,
yet remain coherent near the top of the mass.

In the re-entrant and northern zones, Rainier Mesa Tuff overlies the tuffs and lavas of western Beatty Wash, which in turn overlies breccias composed of Tiva Canyon and Bullfrog Tuffs. In other exposures in the re-entrant zone, Rainier Mesa Tuff and lavas and tuffs of western Beatty Wash overlie debris flows whose clasts consist of Tiva Canyon and the Bullfrog Tuffs indicating the breccias may be derived from the debris flows. Mesas composed of this--debris flows, lava and tuff of western Beatty Wash, Rainier Mesa Tuff--stratigraphy may have moved as slide masses "cushioned" at some localities by the tuffs of western Beatty Wash. In Beatty Wash (Plate I) movement along listric faults has placed Rainier Mesa Tuff on (or against) the breccias cutting out the tuffs of western Beatty Wash. This relationship may be similar to that described by Hardyman (1975, p.1100) in the central Walker Lane where local detachment faults cut the Tertiary strata "typically localized in incompetent nonwelded tuff zones between competent volcanic units". Hardyman (1975) also notes these intra-volcanic detachments remove intervening units.

South of the mesas that straddle Beatty Wash, other mesa exposures of capping Rainier Mesa Tuff and underlying units, do not display similar faulting and cut out of units. Still other mesa exposures in the northern zone (Plate V), north of those straddling Beatty Wash, have been thoroughly disrupted including the capping Rainier Mesa Tuff. This pattern of increasing disruption upward through the slide masses, from south to north, indicates a south to north increase of deformation from the re-entrant zone to the northern zone on the west end of Yucca Mountain (Plate V).
Normal faulting of the upper plate rocks above the Fluorspar Canyon detachment fault left oversteepened slopes at topographic high areas surrounding the periphery of Oasis Valley. Mass movements of debris flows and gravity slide masses may have moved in response to the oversteepened slopes. Reversed stratigraphic order of some layers of monolithologic breccia to their parent rocks suggest the units "peeled" away along stratigraphic contacts.

**Sober-Up Gulch Gravels**

The sedimentary gravels deposited within the Oasis Valley basin are composed chiefly of detritus of Paleozoic basement rock. The lithologies of the clasts and their coarse size suggest that Bare Mountain may have been the source for the gravels along its northern flank. The pod of finer grained muds and sands at the northern end of the study area probably formed as a playa ponded at the lowest part of the Oasis Valley basin. Mudflow deposits containing clasts of Paleozoic limestones and quartzite interfinger with the tuffs and lavas of western Beatty Wash. This relationship indicates that the gravels on the northern flank of Bare Mountain were deposited at least as early as 11.7 Ma. Gravels also overlie the Spearhead Tuff, indicating that their deposition continued after 7.5 Ma.

**Conclusions**

Middle Miocene eruptions of the Southwest Nevada Volcanic field draped the region with lava and ash-flow tuffs. These volcanic units were
deformed by Tertiary extension and overlain by Middle Miocene (?) Gravels of Sober-Up Gulch. Deformation is primarily by north-dipping low-angle normal, northwest-dipping high-angle normal, and right-lateral strike-slip faulting.

The Oasis Valley area, rather than being a concealed caldera as postulated by Byers and others (1976), is a structural basin (Plates II and III) formed above and in conjunction with the Fluorspar Canyon detachment fault system. The northeast-trending segment of the Amargosa River and a northeast-trending linear drainage are superimposed on the axis of the basin. Northwest-dipping faults drop strata down to the northwest in a series of tilt blocks within the basin. This structural basin and the volcanic and sedimentary rocks that cover the study area formed above the Fluorspar Canyon detachment fault north of Bare Mountain.

The east-tilted block of Lithic Ridge Tuff (14 Ma) overlain unconformably by Tram Tuff (13.4 Ma) as well as north-trending, 13.9 Ma dikes at Bare Mountain suggest basin and range style faulting continued until 13.4 Ma. This style of deformation was replaced by that of the Inyo-Mono subprovince, where northwest-trending right-lateral transform faults and northwest-dipping listric faults cut the Tertiary volcanic and sedimentary rocks of the upper plate between 13.4 and 7.5 Ma. The sparse deformation of the Spearhead Tuff and the overlying Sober-up Gulch Gravels indicate deformation had slowed after 7.5 Ma. Deformation may have resumed during the Quaternary forming the large, polished fault scarps along west Thompson Ridge and fault conduits giving rise to springs along the Amargosa River.

Debris flows intertonguing with the upper part of the Rainier Mesa Tuff
and the Ammonia Tanks Tuff interpreted as intracaldera debris flows (Byers and others, 1976) were not found within the study area. The debris flows of Owl Canyon, composed of clasts of Tiva Canyon Tuff and Bullfrog Tuff, are stratigraphically lower than the debris flows described by Byers and others (1976) and could not have been deposited during formation of a caldera after eruption of the Rainier Mesa Tuff or Ammonia Tanks Tuff.

The buttress unconformity, formed where debris flows and the tuffs of western Beatty Wash onlapped the offset Topopah Spring Tuff indicates that the area was probably undergoing extensional faulting and stratal tilting at the time the tuffs of Western Beatty Wash were erupted. Magmas forming the tuffs and lavas of Western Beatty Wash, rather than erupting from ring fractures within a caldera (Byers and others, 1976), probably migrated from deep magma chambers along pre-existing zones of weakness formed by faulting and erupted locally. These magmas may have supplied heat to drive hydrothermal systems. The collapse feature related to eruption of the tuffs and lavas of Western Beatty Wash may be Timber Mountain Caldera rather than the Oasis Valley Caldera Segment. Such separation of vent from collapse feature (and magma chamber) have been documented at Katmai, Alaska (Hildreth, 1987, 1991, Wallmann and others, 1990).

Western Beatty Wash tuffs and lavas accumulated within the Oasis Valley structural basin and subsequently were themselves broken and tilted during continued extension. The Rainier Mesa Tuff later filled the Oasis Valley structural basin. Remnants of the Rainier Mesa form a series of disconnected mesas that may have moved as gravity slide masses with fragmentation within
the slide masses increasing south to north on the west side of Yucca Mountain. Elsewhere in the study area, fragmentation within gravity slide masses is pervasive. The Ammonia Tanks Tuff, basalts, and Spearhead Tuff lie along the axis of the Oasis Valley structural basin suggesting continued development of the structural basin and local extension later than 7.6 Ma.

The complex Cenozoic deformation in the study area is similar to that of the central Walker Lane Belt (Hardyman and Oldow, 1991, their domain III). Both areas contain right-lateral strike-slip, high-angle normal, and low-angle normal detachment faults. The extension direction rotated from east-west to northwest-southeast in both areas. These similarities may indicate that the Fluorspar Canyon Fault is a thin-skinned tectonic feature associated with strike-slip faulting rather than related to large scale crustal extension.
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