UNITED STATES DEPARTMENT OF THE INTERIOR

GEOLOGICAL SURVEY

GEOLOGY OF THE RAINIER MESA-AQUEDUCT MESA TUNNEL AREAS--
U12n TUNNEL

By

D.L. Hoover and J.E. Magner

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CONTENTS

CONTENTS--Continued

Illustrations

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ABSTRACT

The U12n tunnel area is located beneath Rainier Mesa on the Nevada Test Site, Nye County, Nevada. Stratigraphic units in the U12n area include Precambrian and Cambrian quartzite, Ordovician to Devonian dolomite and limestone, Cretaceous quartz monzonite, 25 Miocene and Pliocene volcanic rock units, and Quaternary colluvium and alluvium. Volcanic rocks in drill holes are classified into two chemical groups: calc-alkaline and peralkaline; four depositional processes: ash-fall tuff, reworked ash-fall tuff, tuffaceous sandstone, and ash-flow tuff; and four alteration types: vitric, zeolitized, argillized, and silicified. Alteration of the volcanic rocks to predominantly zeolites, clay minerals, or silica is related to both stratigraphy and structure.

Pre-volcanic structures are the CP thrust fault, a right-lateral fault zone that can be projected into the U12n area, and the Gold Meadows stock; Tertiary structures are depositional folds and predominantly normal faults. The right-lateral fault zone may have provided pre-existing planes of weakness during Tertiary deformation that resulted in west-northwest to northwest normal faults in the U12n area in contrast to north-south to north-northeast faults north and south of the U12n area. Normal faults at tunnel level have displacements that range from less than 3 to 125 ft or more. The Tertiary volcanic rocks were deposited on a pre-Tertiary, steep-sided drainage system and formed depositional folds. The Rainier Mesa depositional syncline is the major structure in the U12n area in addition to the normal faults. Drill-hole data indicate that the axis of syncline in the volcanic rocks parallels the contact between quartzite in the upper plate and dolomite and limestone in the lower plate of the CP thrust fault.

INTRODUCTION

Rainier and Aqueduct Mesas have been the location of most of the underground nuclear tests in tunnels at the Nevada Test Site (NTS), Nye County, Nevada. The area is about 75 miles[1] west-northwest of Las Vegas and about 35 miles north-northwest of Mercury, Nevada (fig. 1). The first underground nuclear test was conducted in the U12b tunnel on Rainier Mesa in 1957. Between 1970 and 1985, nuclear testing has been conducted in three tunnels, U12e, U12n, and U12t (fig. 2).

Between 1957 and 1981, the U.S. Geological Survey conducted most of the geological and geophysical investigations in the tunnels on Rainier and Aqueduct Mesas. Much of the data from these investigations was reported in administrative reports and memoranda to the National Laboratories and the Department of Defense, who were conducting the underground nuclear testing in the tunnels.

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[1]Numerical data from source documents and maps used to compile this report were all measured in the English system. The English system has been retained in this report to eliminate the task of conversion to the metric system and to prevent errors that might be caused by conversion.
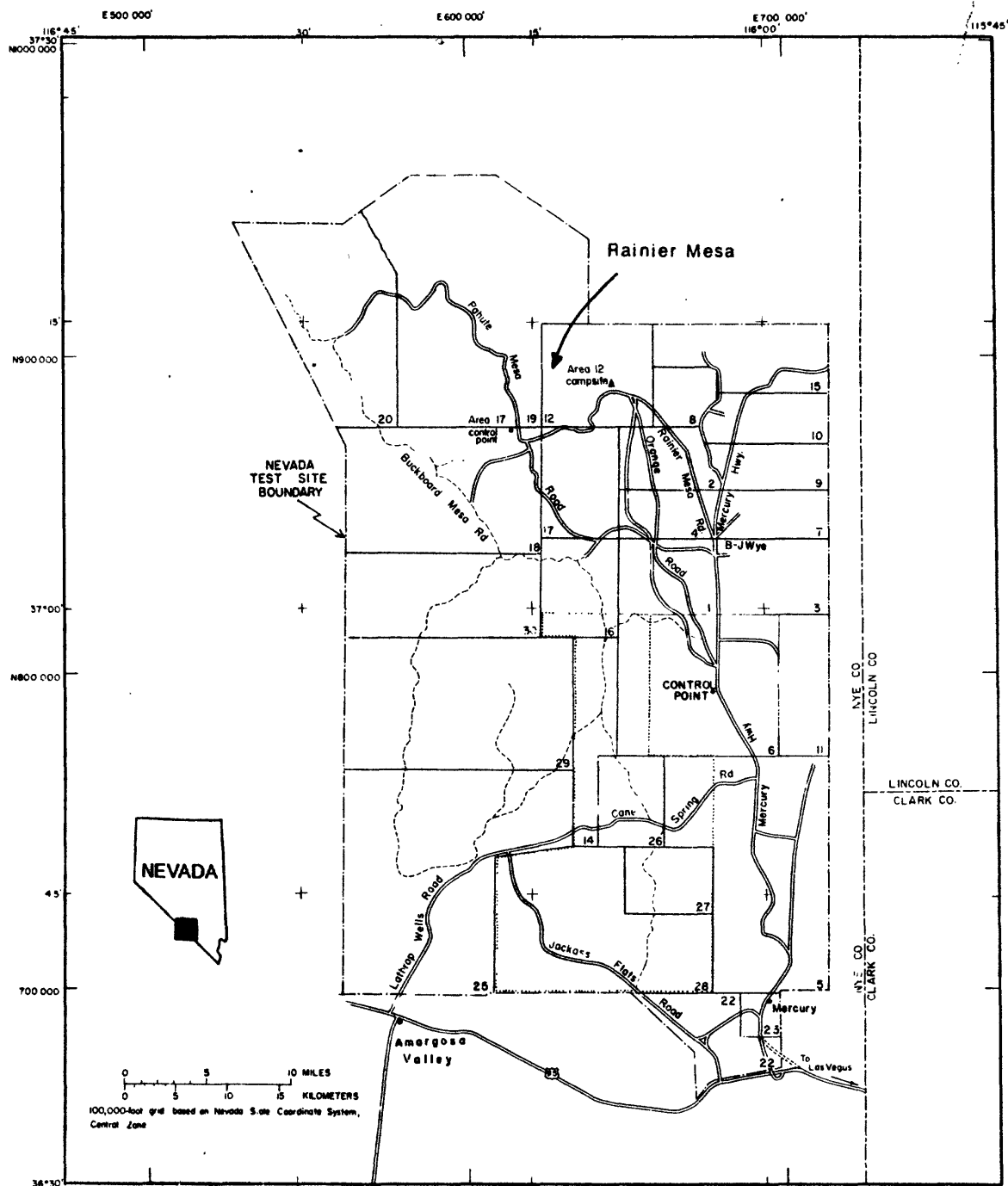
Figure 1.--Index map of the Nevada Test Site.
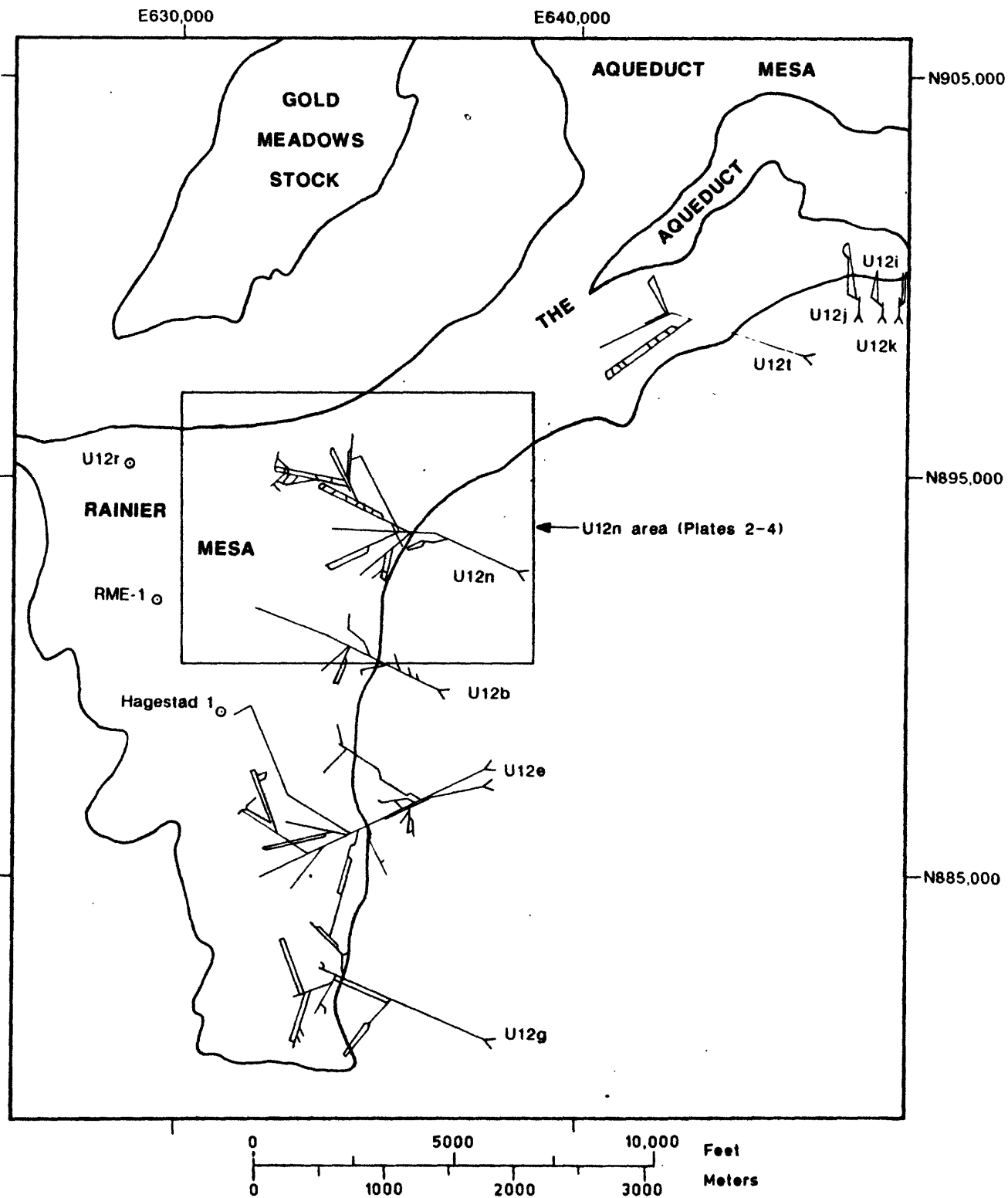
Figure 2.--Index map of Rainier Mesa and vicinity.

The purpose of this report is to summarize and interpret the geology of the U12n tunnel area from published reports and data in the files of the U.S. Geological Survey. Some data are derived from unpublished reports by geologists of Fenix & Scisson of Nevada on drifts and drill holes constructed between 1981 and 1985 that were transmitted to the U.S. Geological Survey for the purpose of containment evaluation. Stratigraphic contacts in cores were checked or revised where strip logs of lithologies in drill holes indicated contacts might be in error. The report emphasizes stratigraphy and structure. Alteration of the volcanic rocks to zeolites and clay are discussed in the context of stratigraphy and structure, but their effects on tunnel construction, containment of nuclear tests, and physical and dynamic properties of the rocks are not discussed because of insufficient data in the files of the U.S. Geological Survey.

The U12n tunnel portal is located on the east side of Rainier Mesa at an elevation of 6,023 ft at Nevada State coordinates N. 892,667 ft and E. 638,645 ft (fig. 2). The access adit and main drifts for nuclear experiments have a total length of more than 30,000 ft. Drifts parallel to the main drifts, cross cuts, and side drifts total more than 16,000 ft. Horizontal and vertical exploratory drill holes that were entirely cored total more than 42,000 ft. Additional, short horizontal and angled drill holes for geophysical and geological data and vertical holes for instrumentation total more than 16,000 ft.

The U12n drifts have been driven into bedded tuffs of Tertiary age beneath Rainier Mesa. The mesa is steep-sided, roughly trapezoidal, and capped by densely welded tuff. The top of the mesa above the U12n tunnel ranges in elevation from about 7030 ft to 7500 ft or 1007 ft to 1477 ft above the tunnel portal. Above the U12n area, surface drainage is to the northeast along the axis of a depositional syncline in densely welded tuff.

In the U12n area, older volcanic rocks were deposited in a southwest-draining valley and its tributaries and form a depositional syncline. Ash-flow tuffs at the surface were deposited in a valley that drains northeast. At the south end of Rainier Mesa, the western flank of the syncline may have been removed by erosion. Northeast of the U12n area, the Aqueduct and Aqueduct Mesa are also depositional synclines (Gibbons and others, 1963).

Structures adjacent to Rainier Mesa that may have influenced the depositional and structural history of the mesa include:
1. The complex graben that forms Yucca Flat about 3 mi east of Rainier Mesa.
2. The Timber Mountain caldera, the walls of which are about 1 mi southwest of the southwestern corner of the mesa.
3. The Silent Canyon caldera, the walls of which are 1-3 mi west of the mesa.
4. The Gold Meadows stock that intrudes Precambrian and Cambrian quartzite at the north edge of the mesa.
The two calderas were sources for most of the volcanic rocks beneath Rainier and Aqueduct Mesas.

Previous Investigations

The U.S. Geological Survey began investigations of the Nevada Test Site in 1951. Stratigraphic nomenclature of the Rainier Mesa area has been developed as investigations of other NTS areas added to the knowledge of the volcanic stratigraphy. Development of the present volcanic stratigraphy (table 1) is only outlined in this report.

Johnson and Hibbard (1957) mapped the volcanic rocks of NTS, including Rainier Mesa, as the Oak Spring Formation. Hansen and Lemke (1958) mapped parts of Rainier Mesa south and east of the U12n tunnel area and divided the Oak Spring Formation into eight members. On Rainier Mesa, volcanic rocks below the lower part of the Grouse Canyon were divided into tunnel beds 1-4. Hinrichs and Orkild (1961) placed the tunnel beds in the lower member of the Oak Spring Formation and identified the Tub Spring Member as a separate stratigraphic unit. Poole and McKeown (1962) raised the Oak Spring Formation to the rank of group and divided it into the Piapi Canyon and the Indian Trail Formations. The Piapi Canyon Formation included all units above the Grouse Canyon Member. The Indian Trail Formation included the Grouse Canyon Member, the Tub Spring Member, and an informal unit, the lower member (Gibbons and others, 1963). The lower member included tunnel beds 1-4 and other informal units.

Recognition of the similarity in chemistry and source of the peralkaline ash-flow tuffs of the Grouse Canyon and the Tub Spring resulted in the redefinition of these members as the Belted Range Tuff (Sargent and others, 1965). The ash-fall tuffs of the lower member of the Grouse Canyon were included as informal units of the Belted Range Tuff. In the Rainier Mesa area, these ash-fall tuffs have been mapped as tunnel bed 5 since the definition of the Belted Range Tuff. At the same time, the Piapi Canyon Formation was redefined as the Paintbrush Tuff and the Ammonia Tanks and Rainier Mesa Members of the Timber Mountain Tuff (Orkild, 1965). Dixon and others (1976) abandoned the name, Indian Trail Formation, defined the Crater Flat Tuff, Redrock Valley Tuff, and Fraction Tuff, and relegated all other volcanic rocks below the Grouse Canyon Range Tuff except these tuffs and the Tub Spring Member to informal units that include tunnel beds 1-5 in the Rainier Mesa area. The ash-flow tuff formerly identified as the Crater Flat Tuff in the Rainier Mesa area has been demonstrated to differ petrographically from the Crater Flat Tuff at its type locality. This tuff has been informally named the tuff of Yucca Flat in the Rainier Mesa-Yucca Flat area (Carr and others, 1984). Stratigraphic units in vertical drill holes are summarized by Maldonado and others (1979).

Depositional folds and the northwest trend of faults in the U12n area are apparent on the Rainier Mesa geologic map (Gibbons and others, 1963). Carr (1974) noted the northwest-trending right-lateral fault zone that projects through the U12n area and related this and other fault zones to the Walker Lane and regional stress patterns. The structural geology of the U12n.02, U12n.03, and U12n.10 drifts was described in separate reports (Eye, Danilchik, and Feazel, 1980; Eye, Carroll, and others, 1980; U.S. Geological Survey, 1979). Healey and Miller (1963) defined the configuration of the Gold Meadows stock on the basis of gravity data. Snyder (1977) mapped the Gold Meadows stock in detail. The CP thrust fault beneath the U12n area is named for an outlier of the upper plate in the CP Hills south of Rainier Mesa (Barnes and Poole, 1968).

Table 1.--Development of stratigraphic nomenclature of volcanic rocks in the Rainier Mesa area

Present Stratigraphy[1]	Johnson and Hibbard, 1958	Hansen and Lemke 1958	Hinrichs and Orkild 1961[1]	Poole and McKeown 1962	Orkild, 1965[1] Sargent and others, 1965	Dixon and others, 1976[1]	Maldonado and others 1979[1]
Timber Mtn. Tuff — Bedded tuff of the Ammonia Tanks Member; Rainier Mesa Mbr.	Oak Spring Fm.	Oak Spring Fm. — Tos 8	Oak Spring Fm. — Rainier Mesa Mbr.	Rainier Mesa Mbr.	Timber Mtn. Tuff — Ammonia Tanks Mbr.; Rainier Mesa Mbr.	Timber Mtn. Tuff — Ammonia Tanks Mbr.; Rainier Mesa Mbr.	Timber Mtn. Tuff — Ammonia Tanks Mbr.; Rainier Mesa Mbr.
Paint-brush Tuff — Bedded tuffs		Tos 7	Survey Butte Mbr.	Survey Butte Mbr.	Bedded tuffs	Paint-brush Tuff — Bedded tuffs	Paint-Brush Tuff — Bedded tuffs
Stockade Wash Tuff			Stockade Wash Mbr.	Stockade Wash Mbr.	Stockade Wash Mbr.	Stockade Wash Mbr.	Stockade Wash Mbr.
Tuffs of Area 20 and Dead Horse Flat							Tuffs of Area 20 and Dead Horse Flat
Belted Range Tuff — Grouse Canyon Mbr.		Tes 6	Grouse Canyon Mbr. / Upper part, Lower part	Indian Trail Fm. — Grouse Canyon Mbr.	Grouse Canyon Mbr.	Belted Range Tuff — Grouse Canyon Mbr.	Belted Range Tuff — Grouse Canyon Mbr.
Tunnel bed 5		Tos 5	Tunnel bed 4	Lower part — Tunnel bed 4	Indian Trail Fm. — Tunnel bed 5	Tunnel bed 5	Tunnel bed 5
Tunnel bed 4		Tos 4	Tunnel bed 4	Lower Mbr. — Tunnel bed 4	Tunnel bed 4	Tunnel bed 4	Tunnel bed 4
Tunnel bed 3		Tos 3	Tunnel bed 3	Tunnel bed 3	Tunnel bed 3	Tunnel bed 3	Tunnel bed 3
Belted Range Tuff — Tub Spring Mbr.			Tub Spring Mbr.	Tub Spring Mbr.	Belted Range Tuff — Tub Spring Mbr.	Belted Range Tuff — Tub Spring Mbr.	Belted Range Tuff — Tub Spring Mbr.
Tunnel bed 2		Tos 2	Tunnel bed 2	Indian Trail — Tunnel bed 2	Tunnel bed 2	Tunnel bed 2	Tunnel bed 2
Tuff of Yucca Flat		Tos 1	Tos 1	Tunnel bed 1	Tunnel bed 1	Crater Flat Tuff	Crater Flat Tuff
Tunnel bed 1						Tunnel bed 1	Tunnel bed 1
Redrock Valley Tuff						Redrock Valley Tuff	Redrock Valley tuff
Older bedded tuffs / Fraction Tuff						Older bedded tuffs / Fraction Tuff	Older bedded tuffs / Fraction Tuff
						Older bedded tuffs	Older bedded tuffs
Paleocolluvium							Paleocolluvium

1 Subunits of tunnel beds 1-4 omitted for clarity.

Investigations have been related of zeolites, clay minerals, and silica mostly to mineral or ground-water chemistry in administrative reports and on drill-hole strip logs. The occurrence of abundant clay in the U12n.03 drift was related to faults and the axis of the Rainier Mesa syncline (Ege, Carroll, and others, 1980). The relationship of zeolites and other alteration products to stratigraphy and lithology was part of an investigation of the genesis of zeolites in the NTS area (Hoover, 1968).

STRATIGRAPHY

Rocks within the U12n tunnel area include Precambrian to Cambrian quartzite and schist, Ordovician to Devonian dolomite and limestone, Cretaceous quartz monzonite, Miocene and Pliocene ash-flow tuffs, ash-fall tuffs, and tuffaceous sediments, and Quaternary alluvium and colluvium (table 2). The Precambrian and Paleozoic sedimentary rocks were highly deformed prior to intrusion of the Cretaceous Gold Meadows stock of quartz monzonite. Erosion of the sedimentary rocks and the quartz monzonite stock left a surface of high relief on which the volcanic rocks were deposited. Stratigraphic units in the basal part of the volcanic rocks are deeply eroded, but younger volcanic rocks contain only local unconformities in the U12n area.

Pre-volcanic Rocks

Stirling Quartzite and Wood Canyon Formation

The Stirling Quartzite of Precambrian age and the Wood Canyon Formation of Precambrian(?) and Cambrian age crop out north of the U12n area. The outcrops are on the south and east sides of the Gold Meadows stock which intrudes these formations (Gibbons and others, 1963). Quartzite, schist, and micaceous siltstone of the two formations have been penetrated in the UE12n#2, #3, #8, #9, and #10 drill holes (pl. 1), the Rainier Mesa Exploratory #1 (RME-1) (fig. 2) drill hole, the Hagestad #1 drill hole, and drill holes in tunnels around the U12n.10 working point (WP) (pl. 1). All drill holes referred to are in the U12n area (fig. 2, pl. 3) unless otherwise noted.

Both formations are named for locations in the Spring Mountains (Nolan, 1929). Although the two formations differ in the content of micaceous rocks and color, parts of each formation resemble the other. The Stirling Quartzite is mostly dark-reddish-purple and dark-brown to pale-red and pinkish-gray micaceous quartzite in the lower part, grayish-red micaceous siltstone and pinkish-gray quartzite in the middle part and micaceous siltstone grading upward to light-gray quartzite in the upper part. The Wood Canyon Formation consists of yellowish-gray and grayish-orange micaceous siltstone and shale with interbedded quartzite in the lower part, grayish-red quartzite in the middle part and light-gray quartzite and dusky-yellow to light-olive very micaceous siltstone and quartzite in the upper part (Harley Barnes and others, written commun., 1963). This similarity and alteration of the rocks near the Gold Meadows stock led to mapping of the two formations as one unit just north of Rainier Mesa (Gibbons and others, 1963).

Era	System	Series	Stratigraphic unit	Map symbol	Age[1] (m.y.)
	Quaternary		Alluvium and colluvium	Qac	
	Tertiary	Pliocene	Timber Mountain Tuff		
			Bedded tuffs of the Ammonia Tanks Member	Tmrab	
			Rainier Mesa Member	Tmr	11.1
		Miocene	Paintbrush Tuff		
			Bedded tuffs	Tpb	
			Stockade Wash Tuff	Tsw	13.2
			Tuffs of Area 20 and Dead Horse Flat	Trdb	
			Belted Range Tuff		
			Grouse Canyon Member	Tbg	13.6-13.8
			Tunnel bed 5	Tt5	
			Tunnel bed 4		
			Subunit 4K	Tt4K	
			Subunit 4J	Tt4J	
CENOZOIC			Subunit 4H	Tt4H	
			Subunit 4G	Tt4G	
			Subunit 4F	Tt4F	
			Subunit 4E	Tt4E	
			Subunit 4A-D	Tt4A-D	
			Tunnel bed 3		
			Subunit 3D	Tt3D	
			Subunit 3BC	Tt3BC	
			Subunit 3A	Tt3A	
			Belted Range Tuff		
			Tub Spring Member	Tbt	
			Tunnel bed 2	Tt2	
			Tuff of Yucca Flat	Tyf	14.8-15.7
			Tunnel bed 1	Tt1	
			Redrock Valley Tuff	Trv	15.7
			Older tuffs		
			Fraction Tuff	Tf	16-18
			Bedded tuffs	Tot	
		Miocene(?)	Paleocolluvium	Tc	
MESOZOIC	Cretaceous		Gold Meadows stock	Kqm	93.6
PALEOZOIC	Devonian Silurian Ordovician		Dolomite and limestone	DSOl	
	Cambrian		Wood Canyon Formation	€p€ws	
PRECAMBRIAN			Stirling Quartzite		

[1]Sources of age dates are listed in text.

Sections of the Stirling Quartzite and the Wood Canyon Formation penetrated in drill holes in the U12n area are too short to identify the stratigraphic unit. The distribution of quartzite and micaceous schist in drill holes in the northern part of the U12n area (fig. 3) indicates that identification of either formation is uncertain in short drill hole penetrations. Quartzite in the U12n area commonly lacks the reddish to brownish color typical of the Stirling Quartzite. Proximity of the Gold Meadows stock, presence of quartz monzonite in the UE12n#10 and RME-1 drill holes, and presence of garnet, pyrite, and magnetite in these holes indicate that the color of the Stirling Quartzite may be bleached by contact metamorphism. Presence of schist, rather than micaceous siltstone found in other areas, may also indicate contact metamorphism. Because distinction of the two formations is uncertain in the limited sections in drill holes, these rocks are referred to in this report as undifferentiated Stirling Quartzite and Wood Canyon Formation.

Ordovician to Devonian Dolomite and Limestone

Ordovician to Devonian dolomite crops out just east of Rainier Mesa. The northernmost outcrop is about 2000 ft east of the U12n tunnel portal (Gibbons, and others, 1963). The dolomite in outcrops is light to dark gray with some mottled grayish-red beds, finely crystalline, and very thin bedded to massive (Gibbons and others, 1963). In the U12n area, the U12b.07-2 drill hole penetrated 295 ft of dolomite that underlies the volcanic rocks. The dolomite in this drill hole is light to dark gray, fine to medium crystalline, and indistinctly bedded. Dolomite and limestone have been penetrated only in holes southeast and east of synclinal axis in the U12n area and areas to the north. Subcrops of dolomite and limestone beneath volcanic rocks have been found only in drill holes in the southern part of the U12n area and further south.

Lack of fossils makes the age of the dolomite uncertain. In the Ranger Mountains southeast of NTS, dolomite that was correlated by lithology to the Rainier Mesa outcrops contains Middle Ordovician to Silurian fossils. Dolomite of the Nevada Formation of Middle Devonian age is present as fault blocks in Rainier Mesa outcrops (Harley Barnes and others, U.S. Geological Survey, written commun., 1963).

Gold Meadows Stock

A quartz monzonite stock of Cretaceous age crops out in Gold Meadows about 2500 ft north of the edge of Rainier Mesa (fig. 2). The quartz monzonite intrudes the Stirling Quartzite and Wood Canyon Formation that dip 22° to 65° into the quartz monzonite outcrop (Gibbons and others, 1963). The UE12n#10 drill hole penetrated 27 ft of quartz monzonite beneath the volcanic rocks (Maldonado and others, 1979), and 62 ft of the Stirling Quartzite and Wood Canyon Formation beneath the quartz monzonite. Pre-volcanic rocks were not penetrated in the UE12n#11 drill hole, but paleocolluvium at the bottom, which overlies pre-volcanic rocks in nearby drill holes, contains both quartz monzonite and quartzite clasts. In the RME-1 drill hole about 66 ft of quartz monzonite overlie 121 ft of quartzite in the bottom of the hole. The quartzite contains pyrite and is intruded by pegmatite, aplite, and granite at 3,722, 3,762, and approximately 3,765 ft, respectively (V.C. Cole, written commun., 1990). About 1,400 ft west of the U12n area and about 3,000 ft north-northwest of the RME-1 drill hole, the U12r drill hole penetrated 540 ft of quartz monzonite beneath the volcanic rocks.
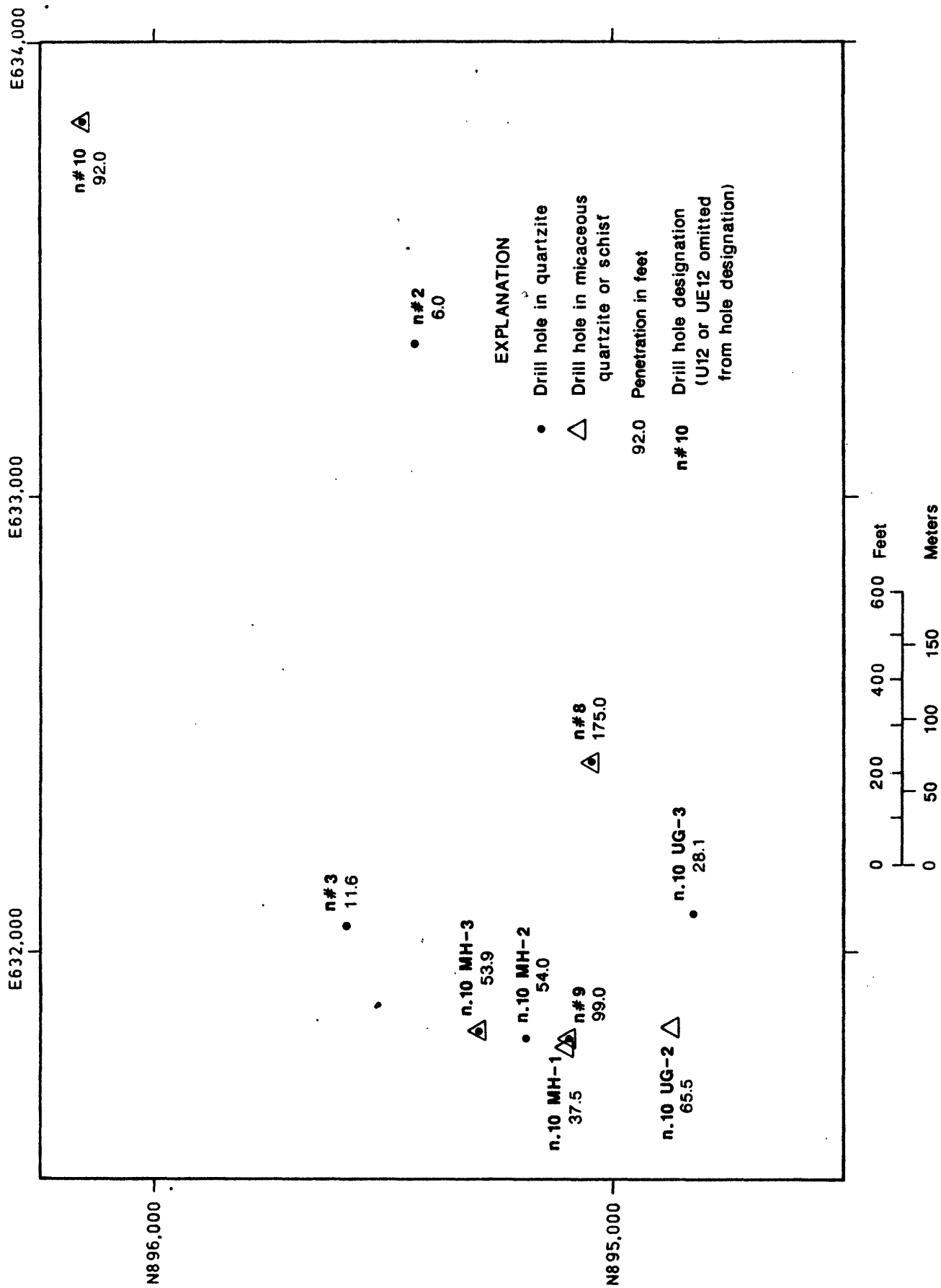
Figure 3.—Distribution of quartzite and micaceous schist in drill holes in the U12n area.

The quartz monzonite contains quartz (18.2-32.8 percent), alkali feldspar (19.5-47.8 percent), plagioclase (15.5-50.5 percent), biotite (0.8-6.6 percent), and accessory apatite, sphene, and opaque minerals (Snyder, 1977). Biotite from the quartz monzonite is 93.6 m.y. old (Naeser and Maldonado, 1981).

Gravity data indicate a steep slope on the quartz monzonite beneath the northern edge of Rainier Mesa (Healey and Miller, 1963). Pegmatite dikes in quartzite and schist that were penetrated in the UE12n.10 drill hole indicate that the quartz monzonite is north of the mesa edge at tunnel level (pl. 3) in the U12n area.

Volcanic Rocks

Volcanic rocks in the Rainier Mesa area include ash-flow and ash-fall tuffs, reworked ash-fall tuffs, and tuffaceous sandstones. Most of the volcanic rocks originated in the Timber Mountain and Silent Canyon volcanic centers, but the origin of some tuffs has not been identified. Reworked ash-fall tuffs and tuffaceous sandstones have been derived locally from ash-fall tuffs.

The volcanic rocks are divided into two petrologic groups: calc-alkaline and peralkaline. Different classification systems have been used to emphasize differences in calc-alkaline rocks and to denote the uniqueness of peralkaline rocks (Byers and others, 1976). Calc-alkaline ash-flow tuffs older than the Paintbrush Tuff are normal calc-alkalic rhyolites; ash-flow tuffs of the Paintbrush Tuff and younger rocks are alkali-calcic and range from quartz latite to rhyolite. Peralkaline rocks are comenditic ash-flow and ash-fall tuffs in the Rainier Mesa area.

The volcanic rocks in the U12n area were deposited in a southwest-trending valley eroded into the pre-volcanic rocks. The paleovalley has a slope of about $14°$ on the northwest side and about $7°$ on the southeast side. These paleoslopes are reflected in the dips of the volcanic rocks.

The stratigraphic units in the U12n area are listed in table 2. Below tunnel bed 2, some stratigraphic units are not present everywhere because of erosion or nondeposition. Tunnel bed 2 and younger ash-fall tuffs and tuffaceous sediments are continuous in the U12n area, but the ash-flow tuffs of the Tub Spring and Grouse Canyon Members of the Belted Range Tuff are limited to areas on Rainier Mesa that were topographically low during their deposition.

Lithologic Terminology

With few exceptions, the texture and lithology of individual beds are repeated in two or more stratigraphic units. Similarity of petrology and of depositional processes and a lack of significant erosion of most of the volcanic rocks have resulted in visual similarities that are repeated throughout the bedded tuffs. Only ash-flow tuffs can be stratigraphically identified with certainty in hand specimen.

11

The need for positive stratigraphic identification has led to lithologic descriptions that are based on visual characteristics. Petrographic investigations and chemical analyses elsewhere on the NTS coincide with similarities or differences in visual characteristics, but stratigraphic identification in the bedded tuffs of Rainier mesa is based mostly on characteristics of a sequence of beds rather than specific characteristics of one bed or one interval.

To identify stratigraphic units, individual beds are mapped or logged first on the basis of two chemical types--calc-alkaline and peralkaline; and second, on the basis of depositional process--ash-flow tuff, ash-fall tuff, reworked ash-fall tuff, and tuffaceous sandstone. The type of alteration (or its absence) is noted as vitric, zeolitized, argillized, or silicified. The visual characteristics used to identify the chemical types, depositional process, and type of alteration are described below.

Color alone can not be used to identify volcanic stratigraphic units, but color may reduce the number of possibilities. Vitric and zeolitized rocks of the same tunnel bed subunit usually differ greatly in color. Zeolitized peralkaline rocks are usually some shade of yellow, but may also be shades of pink, white, or red. Argillized rocks are often a dark shade of red, but also may be brown, yellow or white to light shades of gray. Stratigraphic units may also differ in color from one part of Rainier Mesa to another even though the clay or zeolite content does not change significantly. Paleo-weathering zones may be lighter or darker in color than the unweathered subunit. In short, color may be useful as a guide within individual tunnel areas, but other characteristics are usually needed to identify a stratigraphic unit.

Bedded tuffs

Subunits of the tunnel beds contain varying amounts of ash-fall tuff, reworked ash-fall tuff, and tuffaceous sandstones that are collectively referred to as bedded tuffs. Although bedded tuffs, as defined here, do not include ash-flow tuffs, some massive ash-fall tuffs of the tunnel beds may be nonwelded ash-flow tuffs. The relatively uniform character and lack of bedding in subunits 3A, 3D, and 4J suggest that these stratigraphic units may be nonwelded ash-flow tuffs. Welding of these subunits has not been seen in the U12n tunnel area, but has been reported in the U12t tunnel area (D.R. Townsend, Fenix & Scisson of Nevada, oral commun., 1986).

Calc-alkaline rocks

Calc-alkaline bedded tuffs vary in color--white, very pale gray, and pale orangish yellow, or brownish gray. Moderate- to dark-reddish or brownish hues are common, but shades of yellow are less common and green is uncommon. Pinkish hues are usually present only in very fine grained rocks. Pumice usually comprises less than 10 percent of ash-fall and reworked ash-fall tuffs, but in a few beds, pumice may be as much as 40 percent. Phenocryst content may range from less than 1 percent to commonly 5 to 10 percent. Lithic fragments usually comprise much less than 5 percent, are usually scattered throughout a bed, and are usually less than 2 inches in diameter. Only subunit 4E contains more or larger lithic fragments. The volume of reworked ash-fall tuffs and tuffaceous sandstones may equal or exceed ash-fall tuffs in some stratigraphic units. Tuffaceous sandstones are usually less than 10 in thick and occur in tunnel beds 1-4 and the bedded tuff of the Paintbrush Tuff.

12

Peralkaline rocks

Altered peralkaline rocks range from pale yellowish gray and pale orange pink to mostly grayish yellow, greenish yellow, and yellowish green. Reddish or brownish hues are scarce except in ash-flow tuffs. Vitric peralkaline tuffs are medium to dark gray in contrast to vitric calc-alkaline tuffs that are mostly white to light gray or pale brown. Pumice usually comprises a major part of the ash-fall and reworked ash-fall tuffs. Phenocrysts usually comprise less than 2 percent of individual beds and generally are smaller than in calc-alkaline tuffs. Lithic fragments commonly comprise 5 to 10 percent of individual beds, are sometimes concentrated at or near the base of a section of mostly peralkaline tuff, and are often 1-4 inches in diameter in ash-fall tuffs. The volume of ash-fall tuffs is much greater than that of reworked ash-fall tuff and tuffaceous sandstones. Tuffaceous sandstones are usually less than 4 in thick and usually occur only in the uppermost subunit of tunnel bed 4 and in tunnel bed 5.

Ash-flow tuffs

Partly to densely welded tuffs can be recognized by flattened pumice and finely crystalline quartz and feldspar that was formed by devitrification during cooling. Slightly welded to nonwelded tuffs that remained vitric after cooling and were later altered to zeolites, clay, or silica can be mistaken for ash-fall tuff where such ash-flow tuffs are less than 10 feet thick. Uniformity of texture, mineralogy, and distribution of lithic fragments throughout a bed, coupled with the approximate stratigraphic position, usually serve to distinguish ash-flow from ash-fall tuffs.

Ash-fall tuffs

Ash-fall tuffs are poorly sorted, but are usually uniform in texture. Color sometimes varies from light to dark or dark to light between the bottom and top of a bed. Pumice is usually elongated with a ratio of thickness to length of 1:2 or more. Pumice may have slightly rounded ends, but well-rounded pumice is rare. Pumice and lithic fragments commonly have a maximum dimension greater than 1 in. and are frequently greater than 2 in. Pumice and lithic fragments are usually scattered throughout a bed.

In some intervals of peralkaline ash-fall tuffs, basal beds may have a greater amount of lithic fragments at or near the bottom of the bed. Pumice is often argillized in a zeolitized matrix and may be a contrasting color. Reddish or brownish hues are more common in ash-fall tuffs than in reworked ash-fall tuffs or tuffaceous sandstones.

Reworked ash-fall tuffs

Reworked ash-fall tuffs are derived from ash-fall tuffs by local sheetwash, or wind transportation. They may be gradational upward from ash-fall tuffs, or where they have been transported for a sufficient distance, may be bounded by bedding planes. Reworked ash-fall tuffs are poorly to moderately sorted, but the size range of pumice and lithic fragments is usually smaller than in ash-fall tuffs. Pumice may be either argillized or zeolitized in a zeolitized matrix. Reworked ash-fall tuffs often have a "dirty" appearance that becomes recognizable only after comparison of reworked ash-fall tuffs with their ash-fall tuff equivalents. The "dirty" appearance may be caused by incorporation of organic matter, soil, or eolian dust.

Tuffaceous sandstones

Tuffaceous sandstones are the result of wind or water transportation far enough to reduce the range of particle size to mostly or all sand sizes or smaller. Tuffaceous sandstones range from well-sorted sandstones comprised entirely of glass shards or altered shards to sandstones that may contain as much as 10 percent pumice or lithic fragments. Some "sandstones" may actually be ash-fall tuffs because alteration usually destroys macroscopic evidence of well-sorted, fine-grained ash-fall tuffs. Most sandstones are pale shades of gray, pink, or orange. Pumice in sandstones is usually white or a lighter shade than the matrix. Many sandstones are silicified. Tuffaceous sandstones are rarely more than 15 in thick and are usually less than 10 in thick.

Vitric rocks

Vitric rocks preserve the original glass of shards and pumice, but lenses and individual beds within a vitric interval may be completely altered to zeolites. Conversely, a few zeolitized beds may contain vitric pumice or patches of vitric shards. Vitric rocks usually lack the coherence of zeolitized rocks, but some nonwelded ash-flow tuffs may be slightly indurated. Most vitric rocks are white, light to medium gray, or pale brown.

Zeolitized rocks

Zeolitized rocks are the result of alteration of vitric rocks by ground water (Hoover, 1968). Zeolite content usually ranges from 10 to 60 percent. Silica, as cristobalite or quartz, clay minerals, and feldspar are formed with the zeolites. Zeolitized rocks typically have a chalky appearance. Color ranges from pale shades of gray to moderate red or brown hues in calcalkaline rocks to shades of yellow or green in peralkaline rocks. These rocks are easily broken by a hammer and can be deeply scratched by a knife under pressure. Zeolite crystals are microcrystalline except for sparse occurrences in openings along faults and fractures and occasionally in pumice.

On Rainier Mesa, complete alteration of volcanic rocks to zeolites or clay minerals roughly parallels the bedding, but the alteration may cross stratigraphic boundaries (Hoover, 1968). A transition zone between completely altered rocks and vitric rocks ranges from less than 3 ft to more than 50 ft thick. Both calc-alkaline and peralkaline nonwelded ash-flow tuffs, ash-fall tuffs, reworked ash-fall tuffs, and tuffaceous sandstones may be zeolitized.

Argillized rocks

Volcanic rocks that contain visibly recognizable clay minerals are termed argillized rocks. Nearly all zeolitized rocks and some vitric rocks contain small amounts clay, but some beds contain enough clay to produce slaking. The clay content ranges from enough to cause slaking after a core is dried in air to complete disintegration when a core is immersed in water. Argillized rocks are easily carved with a knife. Argillized beds are less common in peralkaline than calc-alkaline rocks. Dark-hued rocks are often argillized, but the more abundant light-colored rocks may contain equal or greater amounts of argillization. In some ash-fall tuffs, pumice is argillized in a zeolitized matrix.

14

Silicified rocks

Silicified beds, usually less than 15 in thick, are scattered throughout zeolitized and argillized volcanic rocks and are more common in calc-alkaline than in peralkaline rocks. Silicified beds are usually light-colored tuffaceous sandstones and very fine grained ash-fall tuffs, but thin ash-fall tuffs and reworked ash-fall tuffs are occasionally silicified. The silicification of individual beds, particularly throughout a tunnel complex or larger area, indicates that most of the silicification is probably part of the ground-water alteration of the volcanic rocks. At a few locations, darker-hued ash-fall tuffs are silicified at the top. The silicification has caused lightening of the color or a change from red or brown to light gray that has an irregular lower boundary. This alteration of ash-fall tuffs is not continuous and may be the result of weathering while the ash-fall tuffs were exposed at the surface. Silicified beds are difficult to break with a hammer. A knife produces only faint marks in silicified rocks.

Paleocolluvium

Quartzite, schist, and quartz monzonite clasts occur at the base of the volcanic rocks in a matrix that contains variable amounts of clay minerals and tuff. Volcanic clasts are sparse in the paleocolluvium. The clasts range in size from pebbles to large boulders, but most of the clasts are less than 8 inches in diameter. The matrix consists of clay minerals that were probably produced by weathered pre-volcanic rocks and disintegrated tuff. In the UE12n#10 drill hole, the matrix is almost entirely reworked ash-fall tuff and tuffaceous sandstone. Typically, the paleocolluvium is moderate reddish brown to reddish brown. Where tuff comprises most of the matrix, the color may be moderate reddish orange to pale reddish brown. Bedding in the paleocolluvium in the U12n area is sparse to absent. Thickness of the paleocolluvium in the U12n area ranges from 2 ft in the UE12n#3 drill hole to more than 180 ft in the UE12n#11 drill hole where the base of the paleocolluvium was not reached. The top of the paleocolluvium is defined by the upward disappearance of clasts of pre-Tertiary rocks larger than 2 inches in diameter. Paleocolluvium may also be indicated by smaller clasts combined with a lack of bedding and volcaniclastic textures and an abundance of clay for more than 10 ft.

Paleocolluvium is not present in the U12b.07-2 drill hole, but is present in other drill holes in the U12n area. On the north side of the Rainier Mesa syncline, paleocolluvium is thicker to the east in the UE12n#2, n#10, and n#11 drill holes (8 to more than 180 ft) than to the west in the UE12n#3, n#8, and n#9 drill holes (2-21 ft). West of the U12n area, the paleocolluvium is 66 ft thick in the RME-1 drill hole and 50 ft thick in the U12r drill hole. Differences may be caused by local paleotopography or by post-colluvium erosion.

Older Tuffs

Lithologic logs (D.R. Miller, U.S. Geological Survey, written commun., 1970; Maldonado and others, 1979) have included part or all of the volcanic rocks below tunnel bed 2 in older tuffs. Older tuffs in some drill holes have included, in ascending order, bedded tuff, the Fraction Tuff, bedded tuff, the Redrock Valley Tuff, tunnel bed 1, and the tuff of Yucca Flat. The ash-flow tuffs (Fraction and Redrock Valley Tuffs and the tuff of Yucca Flat) vary greatly in thickness and are not present in some drill holes.

Older bedded tuffs contain more clay and red colors than tunnel bed 2, but the older bedded tuffs cannot be differentiated in the absence of the ash-flow tuffs that separate them. In contrast to the older tuffs, tunnel bed 2 and younger stratigraphic units have a relatively uniform variation in thickness and are present throughout the U12n area. In the UE12n#3 drill hole, older tuffs are not present and tunnel bed 2 rests on paleocolluvium. Erosion over a paleotopographic high of pre-Tertiary rocks may be the cause of thin or absent older tuffs in the area of UE12n#2, n#3, n#8, and n#9 drill holes.

Fraction Tuff

The Fraction Tuff, as originally described (Ekren and others, 1971) contains 20-54 percent phenocrysts. In contrast, the Redrock Valley Tuff and the tuff of Yucca Flat contain less than 20 percent phenocrysts. The Fraction Tuff also contains more quartz, 18-40 percent (table 3) of the phenocrysts, in contrast to 0-6 percent in the Redrock Valley Tuff (Byers and others, 1976) and 9-24 percent in the tuff of Yucca Flat (Carr and others, 1984). Although biotite as a percentage of phenocrysts is similar in the three ash-flow tuffs, the biotite content of the Fraction Tuff is much greater because of the higher content of phenocrysts. Biotite and hornblende in the Fraction Tuff range from 0 to 9 percent of the phenocrysts (Ekren and others, 1971).

North of Rainier Mesa in the Nellis Bombing and Gunnery Range, the Fraction Tuff is pinkish gray, pale brown, and light red, and contains several cooling units and intercalated ash-fall tuffs. The maximum thickness is about 7,200 ft. In Test Well 8 (TW8), southwest of Rainier Mesa, the Fraction Tuff is 1,150 ft thick. The tuff is present just west of the U12n area in the RME-1 drill hole (3,391-3,528 ft). Ash-flow tuffs of the Fraction Tuff have not been identified in the U12n area, but may be present in the UE12n#8 drill hole. In UE12n#8, the ash-flow tuff between 1,563 and 1,583 ft that may be the Fraction Tuff is grayish orange to grayish orange pink, contains abundant biotite and other phenocrysts and some ash-fall tuffs, and overlies paleocolluvium.

The age of the Fraction Tuff is between 16 and 18 m.y. In the Nellis Bombing and Gunnery Range, ages of 15.7+0.5 and 16.4+0.5 m.y. were determined from sanidine (Marvin and others, 1970) and 17.8+0.48 m.y. from biotite (Ekren and others, 1971). An age of 15.0+0.55 m.y. for biotite from TW8 (Ekren and others, 1971) is probably too young because of alteration or heating at the edge of the Timber Mountain and Silent Canyon calderas.

Older bedded tuffs

Bedded tuffs that underlie tunnel bed 2 have been identified as older bedded tuffs and the overlying tunnel bed 1 or as older bedded tuffs only (Maldonado and others, 1979). Older bedded tuffs can only be distinguished from tunnel bed 1 if the Redrock Valley Tuff is present beneath tunnel bed 1. Older bedded tuffs can be identified in the U12n area only in the UE12n#8 drill hole where these tuffs are intercalated with ash-flow tuffs that may be the Fraction Tuff.

The older bedded tuffs in other parts of Rainier and Aqueduct Mesas resemble tunnel bed 1 and the lower part of tunnel bed 2 in color and lithology. Colors range from shades of gray, orange, and pink, to reds and reddish browns. Shades of green are not present in the older bedded tuffs in contrast to their presence in tunnel bed 2. Moderate to dark hues of reddish brown and red may be more abundant in the older bedded tuffs than in tunnel beds 1 and 2, but the amount of older bedded tuffs penetrated in drill holes is too small to be certain of this. The older bedded tuffs do not contain peralkaline tuffs, but this lack is also characteristic of tunnel bed 1 and the lower part of tunnel bed 2. Zeolitized, silicified, or argillized beds in the older bedded tuffs of other areas appear to resemble tunnel beds 1 and 2.

Where the Redrock Valley Tuff is absent, older bedded tuffs and tunnel bed 1 should be combined. Where the tuff of Yucca Flat is also absent, then older bedded tuffs, tunnel bed 1, and the lower part of tunnel bed 2 that lacks peralkaline tuffs should be combined because lithologic differences cannot be distinguished where these ash-flow tuffs are not present.

Redrock Valley Tuff

The Redrock Valley Tuff is a single ash-flow cooling unit named for Redrock Valley just south of Rainier Mesa (Byers and others, 1976). In the U12n area, this tuff was penetrated in the UE12n#2, n#8, and U12b.U7-2 drill holes (D.R. Miller, U.S. Geological Survey, written commun., 1970; Maldonado and others, 1979). Thicknesses in these drill holes are 26, 19, and 113 ft, respectively. The Redrock Valley Tuff is apparently not present in the UE12n#3, n#9, n#10, and n#11 drill holes. In the RME-1 drill hole, the thickness is 592 ft. Southwest of Rainier Mesa, the Redrock Valley Tuff has a maximum thickness of 1,370 ft in TW8. In the U12n area and elsewhere beneath Rainier Mesa, the thickness of the Redrock Valley Tuff is apparently affected by paleotopography and post-depositional erosion.

In the U12n area, the Redrock Valley Tuff is grayish orange pink, very pale orange, and moderate reddish orange, devitrified, and nonwelded to partly welded. In the RME-1 drill hole, just west of the U12n area, the tuff contains intervals that are brown to moderate-reddish-brown color, densely welded, and mostly devitrified to zeolitized. Quartz phenocrysts are absent to very sparse and rarely can be seen with a hand lens. The tuff contains pumice lenticles 0.4-0.8 in long. The pumice contains abundant biotite and hornblende phenocrysts that are 0.04 in or less in length. Sparse quartz phenocrysts, presence of biotite and hornblende in the pumice, and less than 20 percent phenocrysts are the major characteristics that distinguish the Redrock Valley Tuff from the Fraction Tuff and the tuff of Yucca Flat (table 3).

The age of the Redrock Valley Tuff, determined on sanidine from the type locality, is 15.7±0.6 m.y. (Marvin and others, 1970).

Table 3.--Mineralogical differences of the Fraction Tuff, Redrock Valley Tuff, and the tuff of Yucca Flat

Stratigraphic unit	Phenocrysts (percent of rock)	Quartz (percent of phenocrysts)	Biotite and hornblende (percent of phenocrysts)	Distinguishing characteristics
Fraction Tuff[1]	20-54 (mostly 25-40)	18-40 (mostly 20-30)	0-9 (mostly 2-6)	Abundant phenocrysts; abundant biotite; lithic fragments common.
Redrock Valley Tuff[2]	6-18	0-6	1-20	Quartz and biotite phenocrysts not prominent; biotite and hornblende common in sparse pumice; lithic fragments sparse.
Tuff of Yucca Flat[3]	9-13	9-24	4-16	Quartz phenocrysts prominent; biotite phenocrysts not prominent; lithic fragments mostly rhyolitic and variable in content.

Data from:
[1]Ekren and others, 1971
[2]Byers and others, 1976
[3]Carr and others, 1984

18

Tunnel Beds

Bedded tuffs were initially mapped as four informal stratigraphic units on the east side of Rainier Mesa (Gibbons and others, 1963): tunnel beds 1-4. In the underground mapping of the tunnels and in vertical drill holes on Rainier Mesa, this nomenclature has been continued. The definition of the Belted Range Tuff and its two members, the Tub Spring and Grouse Canyon, deleted the peralkaline ash-fall tuffs beneath the Grouse Canyon Member as the lower part of that member (Sargent and others, 1965). These ash-fall tuffs have since been informally called tunnel bed 5.

Ash-flow tuffs of the tuff of Yucca Flat and the Tub Spring Member of the Belted Range Tuff are intercalated between tunnel beds 1 and 2 and between tunnel beds 2 and 3, respectively. Although these ash-flow tuffs are not part of the tunnel beds as originally defined, they are included in this report under tunnel beds so that they may be described in stratigraphic sequence.

When underground mapping of the tunnel beds began, each tunnel bed was informally subdivided into mapping subunits designated by letters. Lack of exposure underground, sparse data in drill holes, variable thickness, and the lack of distinctive beds have led to the discarding of letter subunits in tunnel beds 1 and 2. In tunnel beds 3 and 4, some letter subunits have been combined because distinctive beds or contacts are not everywhere present.

Tunnel bed 1

Tunnel bed 1 is defined as the bedded tuffs that occur between the Redrock Valley Tuff and the tuff of Yucca Flat. The only location in the U12n area where bedded tuffs occur between these two ash-flow tuffs is in the UE12n#2 drill hole. Bedded tuffs identified as tunnel bed 1 in the UE12n#10 drill hole (Maldonado and others, 1979) are probably the lower part of tunnel bed 2. The addition of these beds to those identified as tunnel bed 2 would make the total thickness 146 ft, similar to thicknesses of 153.5-187 ft of tunnel bed 2 in six holes in the U12n area (D.R. Miller, U.S. Geological Survey, written commun., 1970; Maldonado and others, 1979). In the UE12n#11 drill hole, bedded tuffs identified as tunnel bed 1(?) are mostly shades of reddish brown and may be older tuffs. Near the working point (WP) of the U12n.10 tunnel, tunnel bed 1 is absent or cannot be distinguished from tunnel bed 2 because the tuff of Yucca Flat is not present.

Tunnel bed 1 consists of yellowish-gray, grayish-orange-pink, moderate-reddish-brown, and small amounts of pale-red and dark-reddish-brown, reworked ash-fall tuff, ash-fall tuff, and tuffaceous sandstone. Peralkaline tuffs are not present. Most of tunnel bed 1 is zeolitized, but thin silicified beds are present throughout the unit. Tunnel bed 1 resembles the lower part of tunnel bed 2 in lithology and color and may not be distinguishable from tunnel bed 2 in the absence of the tuff of Yucca Flat. Tunnel bed 1 is 27 ft thick in the UE12n#2 drill hole, but it is as much as 147 ft thick elsewhere beneath Rainier Mesa.

Tuff of Yucca Flat

The tuff of Yucca Flat, formerly called the tuff of Crater Flat in the Rainier Mesa area (Carr and others, 1984), is present in the UE12n#2, n#6, n#8, and U12b.07-2 drill holes (D.R. Miller, U.S. Geological Survey, written commun., 1970; Maldonado and others, 1979). The ash-flow tuff in UE12n#11 between 1,611- and 1,661-ft depth, identified as an older Tertiary tuff (Maldonado and others, 1979), is probably the tuff of Yucca Flat. The tuff of Yucca Flat is not present in the UE12n#3, n#9, and n#10 drill holes.

The tuff of Yucca Flat is a simple cooling unit of nonwelded to partially welded ash-flow tuff. Colors range from yellowish gray, grayish pink, and moderate orange pink to pale red and pale to moderate reddish brown. Quartz phenocrysts are relatively abundant and comprise 9 to 24 percent of the phenocrysts (table 3). Thickness varies from 16 ft in UE12n#2 to greater than 195 ft in UE12n#6. In the RME-1 and U12b.07-2 drill holes, the thicknesses are 164 and 245 ft respectively. The tuff of Yucca Flat is younger than the Redrock Valley Tuff and older than the rhyolite lava of Kawich Valley. These units limit the age of the tuff of Yucca Flat to between 15.7 and 14.8 m.y. (Carr and others, 1984).

Tunnel bed 2

Tunnel bed 2 is the oldest stratigraphic unit that is continuous throughout the Rainier Mesa area. Tunnel bed 2 is defined as the bedded tuffs that lie between the tuff of Yucca Flat below and the Tub Spring Member of the Belted Range Tuff above. Peralkaline bedded tuffs that have been included with the Tub Spring Member in some drill-hole logs (Maldonado and others, 1979) are included in tunnel bed 2 in this report because the Tub Spring Member is defined as an ash-flow tuff (Sargent and others, 1965).

The colors of tunnel bed 2 are predominantly light shades of gray, pale orange, orange pink, and yellow orange. Peralkaline rocks, present only in the upper part, range in color from greenish yellow to pale olive. Light to moderate shades of red, reddish brown, and brown are present throughout tunnel bed 2. The lithology is predominantly calc-alkaline rocks and a majority of the rocks are reworked ash-fall tuff and tuffaceous sandstones. Most of tunnel bed 2 is zeolitized. Silicified beds are mostly calc-alkaline.

Tunnel bed 2 contains the oldest peralkaline bedded tuffs in the U12n area. These peralkaline tuffs are thought to be correlative to the rhyolite lava of Kawich Valley (Carr and others, 1984), the oldest known stratigraphic unit of the Silent Canyon caldera that is dated at 14.8+0.6 m.y. (Marvin and others, 1970).

The base of tunnel bed 2 is located at the top of the tuff of Yucca Flat. Because the top of the tuff of Yucca Flat lies below the rhyolite lava of Kawich Valley, the oldest known peralkaline unit of the Silent Canyon caldera, the base of tunnel bed 2 lies below the lowest peralkaline bedded tuffs in the tunnel beds. The upper contact of tunnel bed 2 is at the base of the Tub Spring Member or, where this ash-flow tuff is not present, at the base of the massive calc-alkaline ash-fall tuffs of tunnel bed 3A. A pisolitic bed, present in the upper 100 ft of tunnel bed 2, varies from pale red to moderate orange pink in color. Lighter and darker shades are present in gradational bands and within individual pisolites. The pisolites range from 2-4 inches in diameter and commonly are broken. The pisolite bed varies from 4-12 inches in thickness.

20

The thickness of tunnel bed 2 ranges from 153.5-187 ft in six vertical drill holes (D.R. Miller, written commun., 1970; Maldonado and others, 1979). In the UE12n#10 drill hole, the thickness was logged as 53 ft, but the tuff of Yucca Flat is not present. If bedded tuffs identified as tunnel bed 1 and ash-fall tuffs included in the Tub Spring Member are added to tunnel bed 2, then the actual thickness of tunnel bed 2 in UE12n#10 is 146 ft.

Tub Spring Member of the Belted Range Tuff

The Tub Spring Member is a peralkaline, ash-flow tuff (Sargent and others, 1964). In the UE12n#1 drill hole, this tuff is pale reddish brown to light brown, partially to densely welded, and devitrified. In the U12n.10 drifts, the tuff is thin, pale to moderate greenish yellow to grayish yellow and reddish orange, nonwelded, and zeolitized. Phenocrysts, that include abundant quartz, may comprise 20-25 percent of the tuff. Thickness of the Tub Spring Member ranges from 2-65 ft in nine vertical drill holes. The maximum thickness, northeast of Rainier Mesa, is about 300 ft (Sargent and others, 1965). The age of the Tub Spring Member has not been determined, but the tuff overlies the rhyolite of Kawich Valley about 5 miles northwest of Rainier Mesa and is therefore less than 14.8 m.y. old.

The Tub Spring Member was deposited over most or all of the U12n area, but thins toward structural highs and may be absent in other parts of Rainier Mesa. Erosion is not evident at the top of the Tub Spring Member and the thinning or absence of this tuff is probably depositional.

Tunnel bed 3

Tunnel bed 3 contains three subunits, 3A, 3BC, and 3D, that are continuous in the U12n area. The lower and upper subunits are almost entirely massive ash-fall tuffs. The middle subunit is a sequence of thin-bedded ash-fall tuff, reworked ash-fall tuffs, and tuffaceous sandstones. Total thickness of tunnel bed 3 in the U12n area ranges from 89-251 ft (D.R. Miller, U.S. Geological Survey, written commun., 1970; Maldonado and others, 1979); data from vertical drill holes indicate that thicknesses less than 150 ft are probably the result of section omitted by faults.

Subunit 3A.--The subunit is almost entirely moderate-reddish-brown to moderate-reddish-orange, massive ash-fall tuff. Less than 1 percent consists of pale-reddish-brown, grayish-orange-pink, and moderate-orange-pink, thin bedded, calc-alkaline reworked ash-fall tuffs and tuffaceous sandstone and thin beds of pale-yellowish-brown peralkaline ash-fall tuff. Lithic fragments and pumice are not prominent in subunit 3A. Most of the subunit is zeolitized. Most of the argillized and silicified beds are calc-alkaline ash-fall tuff. Thickness of subunit 3A varies from 15-46 ft in eight vertical drill holes (D.R. Miller, U.S. Geological Survey, written commun., 1970; Maldonado and others, 1979). The massive, red to brown ash-fall tuff of subunit 3A and its location overlying the Tub Spring Member make this subunit a prominent marker bed throughout the Rainier Mesa area.

Subunit 3BC.--Originally mapped as two separate subunits, subunits 3B and 3C have been combined because their contact could not be identified everywhere with certainty in the Rainier Mesa area. Subunit 3BC contains mostly calc-alkaline rocks that are about half ash-fall tuff and half reworked ash-fall tuff and tuffaceous sandstone. The calc-alkaline rocks are grayish orange pink, moderate reddish brown to orange, moderate to light red, and moderate orange pink and are thin to thick bedded. Peralkaline rocks occur as thin to thick beds throughout the subunit. Peralkaline rocks are grayish yellow, pale yellow brown, and very pale orange, and consist of almost equal amounts of ash-fall tuff and reworked ash-fall tuff. Lithic fragments comprise 5-15 percent of some peralkaline ash-fall tuffs. Individual beds may be argillized or silicified, but most of subunit 3BC is zeolitized. Argillized and silicified beds are mostly calc-alkaline rocks. The thickness of subunit 3BC in seven vertical drill holes ranges from 61-105 ft.

The base of subunit 3BC is defined by the massive character and reddish-brown color of subunit 3A; the top of 3BC by the similar appearance of subunit 3D.

Subunit 3D.--The subunit is almost entirely calc-alkaline, massive ash-fall tuff. Colors are mostly moderate to dark reddish brown, moderate reddish orange, and grayish orange pink. At some locations, the uppermost 3-10 ft appear to be bleached to grayish orange to pale reddish brown in color. The contact of the bleached colors with the darker colors below is irregular. The bleached rocks are silicified at some locations. The calc-alkaline rocks contain small amounts of reworked ash-fall tuff and tuffaceous sandstone that are usually lighter shades of the adjacent ash-fall tuffs. In the lower one-third of subunit 3D, a single bed of peralkaline ash-fall tuff occurs at some locations. The bed is less than 3 ft thick and may grade into calc-alkaline ash-fall tuff above. The color of the peralkaline bed is pale yellowish brown to grayish orange. Pumice ranges from 1-1 $\frac{1}{2}$ in long. Pumice colors are lighter than the matrix, and range from almost white to pale orange pink to pale yellowish gray. Lithic fragments are not prominent in subunit 3D. Thickness of subunit 3D ranges from 29-57 ft in seven vertical drill holes. Subunit 3D closely resembles subunit 3A, but 3D has larger and more abundant pumice. The massive ash-fall tuff and its position between thin-bedded subunits make the subunit a marker horizon throughout Rainier Mesa.

Tunnel bed 4

Tunnel bed 4 contains seven stratigraphic subunits. Subunits 4A-D and 4F contain less ash-fall tuff than the other subunits. Subunit 4G is predominantly peralkaline tuff; other subunits are mostly calc-alkaline tuff. Total thickness of tunnel bed 4 varies from 338-465 ft in eight vertical drill holes, but drill hole data indicate that thicknesses less than 375 ft may be caused by beds omitted by faults.

Subunit 4A-D.--Subunit 4A-D combines four subunits that cannot be recognized throughout the Rainier Mesa area. The subunit is mostly grayish yellow to yellowish gray and grayish orange pink with sparse, thin beds of pale to moderate reddish brown, moderate reddish orange, dusky yellow, and pale yellowish brown. The base of the subunit is commonly a peralkaline ash-fall tuff less than 3 ft thick that contains 5-10 percent lithic fragments as large as 4 inches in diameter. The color of this basal bed is grayish yellow

to dusky yellow. Where this bed is not present, the base is recognized by the underlying massive calc-alkaline ash-fall tuffs of subunit 3D. Beds in subunit 4A-D range from 1$\frac{1}{2}$ in to 3 ft in thickness. Most beds are less than 1-ft thick. The subunit is mostly calc-alkaline tuff. More than half of the subunit is ash-fall tuff. Argillized and silicified beds are mostly calc-alkaline rocks. The top of subunit 4A-D is commonly a peralkaline ash-fall tuff similar to the basal bed. In the absence of subunit 4E, the top of subunit 4A-D may not be distinguishable from subunit 4F. Thickness of subunit 4A-D ranges from 41-96 ft in six vertical drill holes.

Subunit 4E.--The subunit is mostly massive, calc-alkaline, ash-fall tuffs that commonly contain large lithic fragments. Subunit 4E is moderate-reddish-brown to reddish-orange ash-fall tuffs with lesser amounts of reworked ash-fall tuffs, tuffaceous sediments, and peralkaline ash-fall tuffs that are grayish orange pink, grayish yellow, moderate orange pink and pale yellowish brown. Subunit 4E contains 5-15 percent volcanic lithic fragments that are commonly larger than 2 in and may be as large as 10 inches in diameter. The largest lithic fragments are in the basal 3-6 ft. The lithic fragments are black to very dark reddish brown and commonly have a rind that is moderate to dark reddish brown and 0.2-1 in thick. Most of the subunit is zeolitized. Thickness of subunit 4E ranges from 19-42 ft in five vertical drill holes.

Subunit 4E is recognized by the presence of massive ash-fall tuff, large lithic fragments, more shades of red than other subunits in tunnel bed 4, and the general lack of peralkaline ash-fall tuff. Where these characteristics are not well developed or not present, the lack of distinctive beds in the top of subunit 4A-D and the base of subunit 4F make the recognition of subunit 4E difficult. In the UE12n#1 drill hole, subunit 4E lacks some of these characteristics and the contact with subunit 4F is uncertain. In the UE12n#3 drill hole, subunit 4E was not recognized and may not be present or may be included in subunit 4F.

Subunit 4F.--The unit is a heterogeneous mixture of mostly calc-alkaline ash-fall tuff, reworked ash-fall tuff, and tuffaceous sandstone and small amounts of peralkaline bedded tuffs. The tuffs are mostly yellowish gray to grayish yellow and grayish orange pink to moderate orange pink with sparse beds that are reddish to moderate reddish brown. Beds are mostly less than 1 ft thick and none is more than 3 ft thick. Most of the subunit is zeolitized. Thickness of subunit 4F ranges from 39-103 ft in six vertical drill holes.

The predominant characteristics of subunit 4F are the lithologic heterogeneity and thin beds. Absence of subunit 4E makes location of the lower contact of 4F difficult to identify. Peralkaline ash-fall tuffs that are commonly present at the top of subunit 4A-D have an aggregate thickness much greater than 3 ft. In subunit 4F, peralkaline ash-fall tuffs are present only as individual beds less than 3 ft thick that are present throughout the subunit. The top of subunit 4F is at the top of a silicified tuffaceous sandstone. The sandstone varies from pale pink to grayish orange pink to moderate pink or orange pink. Thickness of the sandstone ranges from 2-12 inches. The sandstone is always present except in sparse, shallow channels that are 5-25 ft wide that were eroded in the top of subunit 4F prior to deposition of subunit 4G. The sandstone is underlain by a calc-alkaline ash-fall tuff that is pale yellowish brown to pale red to light brownish gray, and

contains abundant grayish yellow to pale yellowish orange pumice that is 1-2 inches in diameter.

Subunit 4G.--The subunit is a sequence of predominantly peralkaline ash-fall tuffs. The tuffs are mostly very pale orange, grayish yellow, and grayish orange pink. Calc-alkaline reworked ash-fall tuff and tuffaceous sandstone are interbedded with peralkaline ash-fall tuff in the basal 3-6 ft of the subunit, and grade upward into peralkaline ash-fall tuff that contains few, if any, thin beds of calc-alkaline bedded tuffs. Lithic fragments are present throughout the subunit and are rarely more than 2 inches in diameter. Most of the subunit is zeolitized. Thickness of the subunit ranges from 14-28 ft in nine vertical drill holes.

Subunit 4G is characterized by the predominance of peralkaline ash-fall tuff, a lack of shades of red, and small lithic fragments throughout the subunit. The top of subunit 4G is at the base of the first bed with red colors. The red colors in subunit 4H may be light-pink coloration of the matrix around very pale orange pumice, or pink to light-red color in a bed, or splotches of light to moderate red. The red colors are in a single bed. Ash-fall tuffs in the base of subunit 4H may resemble beds in the upper part of subunit 4G.

Subunit 4H.--The subunit is mostly calc-alkaline bedded tuffs. Color ranges from yellowish gray to grayish yellow and yellowish brown to brownish gray and moderate brown. A few thin red beds occur in the lower half of the subunit. Moderate-reddish-brown, very pale orange to grayish-orange-pink, and pale- to moderate-greenish-yellow beds are present throughout the subunit. Subunit 4H is mostly calc-alkaline tuff. Thickness of subunit 4H ranges from 30-45 ft in nine vertical drill holes.

Subunit 4H has no distinguishing characteristics by itself, but differs from both subunit 4G and 4J. The presence of brown and moderate-red colors and sparse lithic fragments distinguish subunit 4H from subunit 4G. Thin beds and lesser amounts of brown or red colors distinguish subunit 4H from the thick to massive beds and predominantly brown to red colors of subunit 4J.

Subunit 4J.--The subunit is predominantly calc-alkaline ash-fall tuffs. Colors are mostly browns or reds that range from moderate red brown to pale yellow brown and yellow brown to pale brown and moderate brown. A few grayish-yellow to yellowish-gray and moderate- to dusky-yellow beds are present in the lower and upper 10-15 ft of subunit 4J. Argillization is more common in subunit 4J than in older subunits, but argillization of 4J in the U12n area may be related to its position in the Rainier Mesa syncline and faulting. Silicified rocks have not been found in subunit 4J. Thickness of subunit 4J ranges from 25-59 ft in eight vertical drill holes.

The distinguishing characteristics of subunit 4J are the thick to massive beds and the brown to red colors. Subunit 4K lacks the darker brown and red colors of subunit 4J and contains thicker sequences of peralkaline ash-fall tuff.

Subunit 4K.--The subunit is mostly calc-alkaline bedded tuffs, but grades from mostly calc-alkaline in the lower half to almost completely peralkaline in the upper 30-60 ft. Colors of zeolitized beds range from yellowish gray to grayish yellow and pale to moderate yellowish brown in the lower half to dusky yellow and olive gray to greenish yellow in the upper 60 ft. Vitric beds in subunit 4K are light to moderate gray and greenish gray. Argillization in subunit 4K is as common as in subunit 4J, probably for the same reasons. Thickness of subunit 4K ranges from 82-185 ft in five vertical drill holes, but thicknesses greater than 110 ft may include part of tunnel bed 5.

The scarcity of brown and red colors except for scattered beds in the lower half and the presence of peralkaline tuffs more than 3 ft thick distinguish subunit 4K from subunit 4J. The upper part of subunit 4K and all of tunnel bed 5 are entirely peralkaline tuffs. The top of subunit 4K is at the top of the uppermost tuffaceous sandstone in these peralkaline tuffs. This sandstone ranges from 2-12 inches in thickness.

Tunnel bed 5

Tunnel bed 5, formerly the lower part of the Grouse Canyon Member, is comprised entirely of peralkaline ash-fall tuff. Calc-alkaline ash-fall tuff, peralkaline tuffaceous sandstone, and possibly peralkaline reworked ash-fall tuff, noted as tunnel bed 5 in some drill holes, are probably part of subunit 4K. Where tunnel bed 5 is zeolitized, the color ranges from pale to dark greenish yellow to dusky yellow. Where the stratigraphic unit is vitric, colors range from light to dark gray to greenish gray. Argillized rocks have not been found in tunnel bed 5. Thickness of tunnel bed 5 ranges from 83-165 ft in eight vertical drill holes.

Tunnel bed 5 closely resembles the upper part of subunit 4K, but the absence of calc-alkaline bedded tuffs, reworked ash-fall tuffs, and tuffaceous sandstones in tunnel bed 5 distinguish it from subunit 4K. Where the Grouse Canyon Member is not present above tunnel bed 5, a change to calc-alkaline bedded tuffs and the presence of reworked ash-fall tuffs and tuffaceous sandstones identify the tuffs of Area 20 and of Dead Horse Flat or the bedded tuffs of the Paintbrush Tuff.

Grouse Canyon Member of the Belted Range Tuff

The Grouse Canyon Member is a compound cooling unit of peralkaline ash-flow tuff (Sargent and others, 1965). It is present in the U12n area only in the UE12n#1, n#5, and n#6 drill holes. The tuff is light to moderate brown, moderate red brown, moderate to dusky red, and moderate yellowish brown, devitrified, and slightly to mostly densely welded. Total phenocryst and lithic fragment content are less than 5 percent in the U12n area. A tuffaceous conglomerate that underlies the Grouse Canyon Member in the UE12n#1 drill hole is included in the member. The conglomerate contains abundant lithic fragment as large as 8 inches in diameter. The conglomerate may be a mud flow related to the Grouse Canyon Member, or it may be local ash-fall tuff of tunnel bed 5. It is included in the Grouse Canyon Member because the probable mud-flow origin is more likely to be related to the Grouse Canyon Member than to tunnel bed 5.

In the Rainier Mesa area, the Grouse Canyon Member was deposited only in topographic lows (Gibbons and others, 1963). Near the axis of the Rainier Mesa syncline, tunnel bed 5 is 91 and 82 ft thick in the UE12n#1 and n#6 drill holes, respectively. On the north flank of the syncline, tunnel bed 5 ranges from 93-148 ft thick in five drill holes. The thinning of tunnel bed 5 at the base of the Grouse Canyon Member is the first evidence of major erosion above the base of tunnel bed 2. The limitation of the Grouse Canyon Member to topographic lows indicates that deposition was probably limited to these areas.

Tuffs of Area 20 and of Dead Horse Flat

The tuffs of Area 20 and of Dead Horse Flat are two informal units that were defined in drill holes on Pahute Mesa. These units are thickest within the Silent Canyon caldera west of Rainier Mesa (Orkild and others, 1969), but the maximum thickness outside the caldera is 300 ft (Byers and others, 1976). In the U12n area, they have been identified only in the UE12n#1 and n#6 drill holes (Maldonado and others, 1979). The tuff of Area 20 is calc-alkaline and contains more lithic fragments than the Paintbrush Tuff. The tuff of Area 20 overlies the predominantly peralkaline tuff of Dead Horse Flat. The two tuffs have not been separated in the Rainier Mesa area, but both tuffs are probably present because both calc-alkaline, lithic-rich and peralkaline bedded tuffs have been logged in drill holes on Rainier Mesa.

The tuffs of Area 20 and of Dead Horse Flat in the U12n area are pale to dark yellowish brown, very pale orange, dark yellow orange, and very light gray. These tuffs are mostly calc-alkaline ash-fall and reworked ash-fall tuffs. In the UE12n#1 drill hole, the tuffs are vitric and 202 ft thick; in UE12n#6, they are zeolitized and 269 ft thick.

The presence of both calc-alkaline and peralkaline tuffs distinguishes the tuffs of Area 20 and of Dead Horse Flat from the peralkaline tuffs of tunnel bed 5. Lithic fragments as large as 4 inches in diameter are common in the tuffs of Area 20 and Dead Horse Flat, but lithic fragments are small and sparse in the overlying bedded tuffs of the Paintbrush Tuff. Zeolitization may be more common in the tuffs of Area 20 and of Dead Horse Flat than in the Paintbrush, but the lower part of the bedded tuffs of the Paintbrush Tuff is zeolitized elsewhere on Rainier Mesa. Vitric tuffs of Area 20 and of Dead Horse Flat may be included as part of the Paintbrush Tuff in other drill holes of the U12n area, but identification only in the two drill holes nearest the synclinal axis suggests that the thickest section of the tuffs of Area 20 and of Dead Horse Flat may have been deposited only in the bottom of the syncline or may have been removed by erosion on the flanks of the syncline.

Stockade Wash Tuff

The Stockade Wash Tuff (Byers and others, 1976) has been found only in the UE12n#1, n#6, and the RME-1 drill holes near the synclinal axis. The tuff is a white to light-gray and very light gray, nonwelded, vitric to zeolitized, calc-alkaline ash-flow tuff. In outcrop, the Stockade Wash Tuff is pale yellowish gray to light yellowish brown with orange pumice. In the subsurface, the pumice is somewhat darker than the color of the groundmass. Biotite is present throughout the tuff. Lithic fragments are usually less than 2 inches in diameter and range from very sparse to less than 5 percent.

Thickness of the Stockade Wash Tuff is 10 ft in UE12n#1; 47 ft in UE12n#6; and more than 119 ft in RME-1. The maximum thickness is about 375 ft on the west and south sides of Rainier Mesa.

In Yucca Flat, the Stockade Wash Tuff intertongues with the tuffs of Area 20 and of Dead Horse Flat. These tuffs have not been recognized above the Stockade Wash Tuff on Rainier Mesa, but the lower part of the bedded tuffs of the Paintbrush may include these tuffs in some drill holes.

Bedded Tuffs of the Paintbrush Tuff

The bedded tuffs of the Paintbrush Tuff (Byers and others, 1976) are various shades of light to medium gray with a few beds that are pale yellowish brown, very pale orange, and grayish orange pink. The tuffs are comprised of calc-alkaline ash-fall and reworked ash-fall tuffs and tuffaceous sandstone that are mostly vitric. A few beds may be slightly to mostly argillized or silicified. The lower one-quarter to one-third may contain zeolitized rocks. Pumice ranges from sparse to very abundant. Lithic fragments are usually less than 2 inches in diameter and are usually sparse, but a few beds may contain 5-10 percent. Thickness ranges from 442-652 ft in eight vertical drill holes.

The bedded tuffs of the Paintbrush Tuff can be differentiated from tunnel bed 5 by the lack of peralkaline beds and, in some beds, by sparse, small lithic fragments and sparse pumice. Peralkaline beds are not present in the bedded tuffs of the Paintbrush Tuff, in contrast to the tuffs of Area 20 and of Dead Horse Flat. Lithic fragments are less abundant and smaller in the Paintbrush Tuff than in the tuffs of Area 20 and of Dead Horse Flat. Massive bedding and pumice of contrasting color distinguish the Stockade Wash Tuff from the Paintbrush Tuff. Pale-pink or orange colors grading up to reddish colors and lack of bedding distinguish the basal nonwelded part of the overlying Rainier Mesa Member of the Timber Mountain Tuff from the Paintbrush Tuff.

Timber Mountain Tuff

Rainier Mesa Member

The Rainier Mesa Member (Byers and others, 1976) is a compound cooling unit of calc-alkaline ash-flow tuff that caps Rainier Mesa. The basal 30-75 ft ranges from orange pink to pale pink to pale red, and is nonwelded to partially welded. The upper part ranges from reddish gray to purplish gray, and is partially welded to mostly densely welded. The upper 60 ft may contain a densely welded black vitrophyre at some locations on Rainier Mesa. Thickness of the Rainier Mesa Member ranges from 131-150 ft in six drill holes near the northern edge of Rainier Mesa. Near the synclinal axis, the tuff is 306 ft thick in UE12n#1 and 412 ft thick in UE12n#6. The age of the Rainier Mesa Member is 11.1 m.y. (Marvin and others, 1970).

Bedded tuffs of the Ammonia Tanks Member

The bedded tuffs of the Ammonia Tanks Member crop out in an area 1,150 ft long and 350 ft wide about 300 ft east-northeast of the UE12n#6 drill hole. The tuffs are light shades of gray and brownish gray, vitric, thin-bedded, and

resemble the bedded tuffs of the Paintbrush Tuff. Maximum thickness is less than 15 ft. The welded tuff of the Ammonia Tanks Member is not present in the U12n area.

Colluvium and Alluvium

Colluvium is present on the steep sides of Rainier Mesa and as isolated patches on top of the mesa. The colluvium consists of mostly pebble- to boulder-sized fragments with space between the fragments partly to completely filled by sand- to clay-sized material. On the sides of Rainier Mesa, most of the colluvium is gravity controlled. On the top of the mesa, colluvium is mostly debris and wash controlled. Thickness of the colluvium ranges from 0 to 30 ft, but most deposits are less than 15 ft thick.

Alluvium covers the bottom of the wash along the axes of the Rainier Mesa and Aqueduct synclines. The range in fragment sizes is similar to colluvium, but boulders are smaller and the alluvium contains more sand- and clay-sized material.· Thickness ranges from 0 to 15 ft. The age of the colluvium and alluvium is not known, but it is probably Quaternary.

DISTRIBUTION OF LITHOLOGIES AND ROCK ALTERATION

Lithologic and alteration data recorded on colored strip logs from core in horizontal and vertical drill holes were compiled for each stratigraphic unit (tables 4-6)[2]. Graphic data of these compilations show the relationships of lithologies and rock alteration to stratigraphic units (figs. 4, 5).

Except for subunit 4G and tunnel bed 5, bedded tuffs in all stratigraphic units contain at least 70 percent calc-alkaline rocks (table 4, fig. 4A). Only a few feet of tunnel bed 1 have been cored, but this unit is apparently all calc-alkaline. The distribution of calc-alkaline ash-fall tuff roughly parallels the distribution of calc-alkaline rocks (table 4, fig. 4A). Total ash-fall tuff decreases irregularly from about 97 percent in tunnel bed 5 to about 60 percent in subunit 4A-D, but has no systematic change, is irregularly distributed in tunnel beds 2 and 3, and reaches a minimum of about 39 percent in tunnel bed 2 (table 4, fig. 4A). The distribution of tuffaceous sandstone has a roughly inverse relationship to the distribution of ash-fall tuff (table 4, fig. 4B). This inverse relationship is an indication of reworking and erosion.

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[2]Lithologic and alteration data for horizontal and vertical drill holes were compiled separately and then combined. Percentages within a stratigraphic unit should be the same regardless of the orientation of drill holes, provided that the samples are from the same general area and that samples are large enough. A few differences between horizontal and vertical holes were found to be related to location and are discussed in the text. Except for tunnel bed 2, the total thickness corrected for dip of stratigraphic units penetrated in drill holes ranges from 4 to 10 times the true stratigraphic thickness of each stratigraphic unit.

Table 4.--Lithology of tunnel beds 2-5 in drill holes, U12n area[1]

Tunnel bed	2	3A	3BC	3D	4A-D	4E	4F	4G	4H	4J	4K	5
Total feet of core	1450	911	2490	4045	3611	1275	5527	846	2292	2435	5029	688
Percent of total footage												
Calc-alkaline rocks	73.9	99.6	87.8	99.5	78.6	98.0	86.7	24.5	74.8	87.5	72.6	0.1
Ash-fall tuff	21.7	98.7	45.4	91.6	51.4	70.3	51.3	16.2	54.7	85.2	58.2	0.1
Reworked ash-fall tuff	41.7	0.8	33.9	7.8	20.4	22.3	26.5	7.3	16.4	2.2	12.9	0.0
Tuffaceous sandstone	10.6	0.1	8.5	<0.1	6.7	5.4	8.8	0.9	3.7	0.1	1.5	0.0
Peralkaline rocks	26.1	0.4	12.2	0.5	21.4	2.0	13.3	75.5	25.2	12.5	27.4	99.9
Ash-fall tuff	17.7	0.4	6.4	0.5	8.4	2.0	9.6	68.2	19.1	12.0	23.8	96.7
Reworked ash-fall tuff	8.4	0.0	5.8	0.0	12.2	0.0	3.3	6.7	5.9	0.5	3.5	2.5
Tuffaceous sandstone	0.0	0.0	0.0	0.0	0.8	0.0	0.5	0.6	0.2	0.0	0.2	0.5
Total ash-fall tuff	39.4	99.1	51.8	92.1	59.9	72.3	60.9	84.4	73.8	97.1	81.9	96.8
Total reworked ash-fall tuff	50.1	0.8	38.7	7.8	32.6	22.3	29.8	14.1	22.3	2.8	16.4	2.5
Total tuffaceous sandstone	10.6	0.1	8.5	<0.1	7.5	5.4	9.3	1.5	3.9	0.1	1.7	0.7

[1]From lithologic data recorded on strip logs of drill holes.

29

Table 5.--Argillization in tunnel beds 2-5 in drill holes, Ul2n area[1]

Tunnel bed	2	3A	3BC	3D	4A-D	4E	4F	4G	4H	4J	4K	5
Total feet of core	1450	841	2216	3231	2864	1275	5066	690	1944	1968	3762	688
					Percent of total footage							
Calc-alkaline rocks	1.9	2.1	4.1	6.0	1.2	2.6	4.4	3.3	7.8	10.1	8.5	0.0
Ash-fall tuff	0.7	1.9	2.2	5.9	0.2	2.2	3.1	2.2	6.5	10.1	6.0	0.0
Reworked ash-fall tuff	1.0	0.2	1.7	<0.1	0.9	0.4	1.0	1.0	1.2	0.0	2.5	0.0
Tuffaceous sandstone	0.3	0.0	0.2	0.0	0.1	0.0	0.3	0.1	0.1	0.0	<0.1	0.0
Peralkaline rocks	1.0	0.0	0.0	0.0	0.1	<0.1	0.9	3.6	0.8	<0.1	1.8	0.0
Ash-fall tuff	0.6	0.0	0.0	0.0	0.1	<0.1	0.8	2.5	0.4	<0.1	1.8	0.0
Reworked ash-fall tuff	0.5	0.0	0.0	0.0	0.0	0.0	<0.1	1.2	0.4	0.0	0.0	0.0
Tuffaceous sandstone	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total ash-fall tuff	1.2	1.9	2.2	5.9	0.4	2.3	3.9	4.6	6.9	10.2	7.7	0.0
Total reworked ash-fall tuff	1.4	0.2	1.7	<0.1	0.9	0.4	1.1	2.2	1.6	0.0	2.5	0.0
Total tuffaceous sandstone	0.3	0.0	0.2	0.0	0.1	0.0	0.3	0.1	0.1	0.0	<0.1	0.0
Total argillized rocks	3.0	2.1	4.1	6.0	1.3	2.7	5.3	7.0	8.6	10.2	10.3	0.0
Argillized ash-fall tuff as percent of total argillized rocks	41.9	88.9	53.3	99.5	28.9	85.3	73.2	66.7	80.2	100	75.1	0.0
Argillized calc-alkaline ash-fall tuff as percent of total argillized rocks	23.3	88.9	53.3	99.5	15.8	82.4	57.6	31.2	75.5	99.5	58.0	0.0

[1]From lithologic data recorded on strip logs of drill holes.

30

Table 6.—Silicification in tunnel beds 2-5 in drill holes, U12n area[1]

Tunnel bed	2	3A	3BC	3D	4A-D	4E	4F	4G	4H	4J	4K	5
Total feet of core	1450	841	2216	3231	2864	1275	5066	690	1944	1968	3762	688
					Percent of total footage							
Calc-alkaline rocks	5.4	0.8	2.8	1.3	5.1	2.8	3.3	0.1	0.5	0.0	1.8	0.0
Ash-fall tuff	1.7	0.8	1.1	1.2	1.8	0.3	1.2	0.0	0.3	0.0	0.7	0.0
Reworked ash-fall tuff	1.7	0.0	1.2	<0.1	1.9	0.8	0.3	0.1	0.2	0.0	0.6	0.0
Tuffaceous sandstone	2.1	0.0	0.6	0.0	1.4	1.7	1.7	0.0	0.0	0.0	0.5	0.0
Peralkaline rocks	1.0	0.0	0.6	0.3	2.0	0.5	<0.1	0.0	0.5	0.0	0.5	0.9
Ash-fall tuff	0.1	0.0	0.1	0.3	1.3	0.5	<0.1	0.0	0.3	0.0	0.5	0.3
Reworked ash-fall tuff	0.9	0.0	0.5	0.0	0.8	0.0	<0.1	0.0	0.2	0.0	0.0	0.6
Tuffaceous sandstone	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Total ash-fall tuff	1.9	0.8	1.2	1.5	3.1	0.9	1.3	0.0	0.5	0.0	1.2	0.3
Total reworked ash-fall tuff	2.6	0.0	1.7	<0.1	2.7	0.8	0.4	0.1	0.4	0.0	0.6	0.6
Total tuffaceous sandstone	2.1	0.0	0.6	0.0	1.4	1.7	1.7	0.0	0.0	0.0	0.5	0.0
Total silicified rocks	6.5	0.8	3.5	1.6	7.1	3.4	3.4	0.1	0.9	0.0	2.3	0.9
Silicified tuffaceous sandstone as percent of total silicified rocks	31.9	0.0	16.9	0.0	19.6	51.2	51.5	0.0	0.0	0.0	19.8	0.0

[1]From lithologic data recorded on strip logs of drill holes.

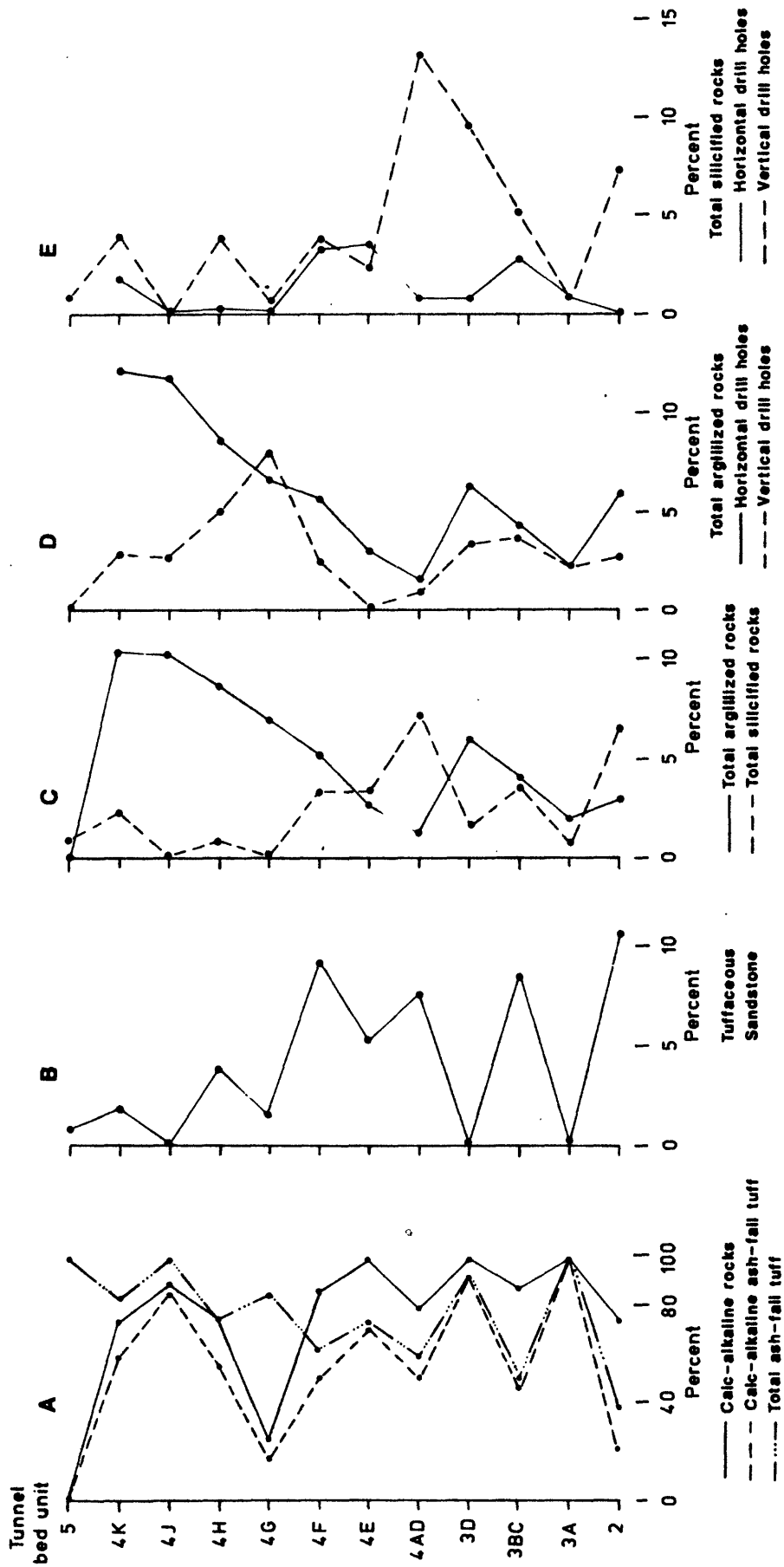Figure 4.--Stratigraphic distribution of lithologies and rock alteration in tunnel beds 2-5 from horizontal and vertical drill holes, U12n area.
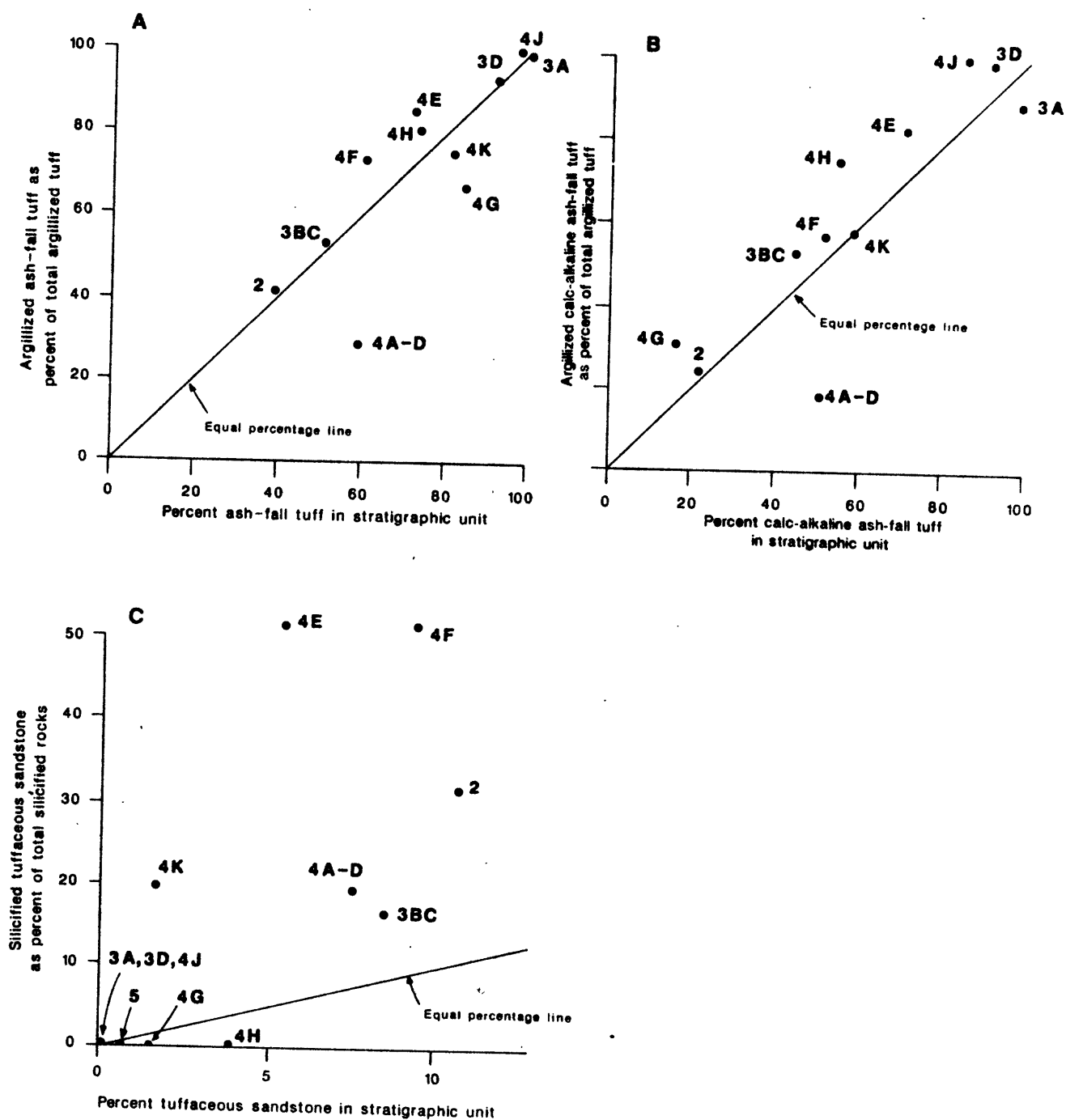
Figure 5.--Stratigraphic distribution of argillized ash-fall tuff, argillized calc-alkaline ash-fall tuff, and silicified tuffaceous sandstone compared to distribution of ash-fall tuff, calc-alkaline ash-fall tuff, and tuffaceous sandstone, respectively.

33

Weathering and migration of water have altered most of the formerly vitric bedded tuffs of tunnel beds 1-5 and older volcanic rocks to zeolites, clay minerals, silica minerals, and probably feldspar (Hoover, 1968). An understanding of the distribution of the alteration products is needed for prediction of physical properties of volcanic rocks in unexplored areas.

Zeolitization

Zeolites are a significant alteration product in most subunits of tunnel bed 4 and all of the older rocks. The top of continuous zeolitization, below which vitric rocks are not present in bedded tuffs, varies in elevation in the U12n area, but the top is generally in subunit 4K or tunnel bed 5 (table 7). In the UE12n#6 and RME-1 drill holes, the top is in the Stockade Wash Tuff and the tuffs of Area 20 and Dead Horse Flat, respectively. Where the relationship between the top of zeolitization and faults can be observed or reliably inferred, faults displace the top of zeolitization and are, therefore, younger than the zeolitization.

The apparent top of zeolitization, where zeolites are first encountered, is 15-695 ft above the top of continuous zeolitization in the U12n area. Variations in permeability may be the cause of irregular zeolitization above the top of continuous zeolitization (Hoover, 1968). Density log excursions appear to be related to zeolitization in many holes (R.D. Carroll, U.S. Geological Survey, written commun., 1985), but are 19-209 ft below the top of continuous zeolitization (table 7). Although the density log excursions occur near the top of continuous zeolitization, the excursions are found over a larger stratigraphic range (table 7).

Table 7.--Elevation of the top of zeolitization in the U12n area
[Leaders, ---, indicate no data]

Drill hole	Apparent top of zeolitization		Top of continuous zeolitization		Density log excursion[1]		Remarks
	Elevation (ft)	Stratigraphic unit	Elevation (ft)	Stratigraphic unit	Elevation (ft)	Stratigraphic unit	(Elevation of U12n tunnel approximately 1850 m)
UE12n#1	6477	Tdrb	6289±	Tbg	6102	4K	
UE12n#2	6649±	5	6634±	5	6542	5	
UE12n#3	6840±	Tpb	6520±	4H	6545	4H	Apparent and continuous zeolitization tops not clear on strip log
UE12n#4	6850	Tpb	6679	5	6660	5	Apparent top not clear on strip log
UE12n#6	7030±	Tmr	6335±	Tdrb	---	---	Not definable on density log
UE12n#8	7194±	Tpb	6520	4K	6381	4H	Irregular zeolitization indicated by density log between 6381 and 6532 ft
UE12n#9	7003	Tpb	6418±	4K	6375	4G	Irregular zeolitization indicated by density log between 6375 and 6568 ft
UE12n#10	6624±	5	6544±	4K	6335	4H	Irregular zeolitization indicated by density log between 6335 and 6535 ft
UE12n#11	6784±	Tpb	6363	4K	6362	4K	Apparent and continuous zeolitization tops not clear on strip log
RME-1	---	---	6259-6357	Tpb-Trdb	---	---	No core in interval; vitric Tpb above, zeolitized Trdb below interval; density log not available

[1]Data from R. D. Carroll, U.S. Geological Survey, written commun., 1985.

Argillization

Argillized rocks, as defined by visible evidence in core, range from 1.3 to 10.3 percent of the stratigraphic units in tunnel beds 2-4 (table 5). Argillization was not observed in tunnel bed 5. The stratigraphic relationship of increasing amounts of argillized rocks to the synclinal axis is apparent when data from vertical drill holes (samples are mostly on the northern slope of the syncline) are compared to samples from horizontal holes (samples are mostly near center of syncline) (fig. 4C). When the data are separated into data from vertical holes (samples are mostly on the northern slope of the syncline) and data from horizontal holes (samples from younger units are closer to synclinal axis), the stratigraphic relationship of increasing amounts of argillized rocks to the synclinal axis is apparent (fig. 4D). Data from horizontal holes are from a limited stratigraphic interval. In horizontal holes, argillization of successively younger stratigraphic units is representative of argillization in a cross section from the flank to the axis of the syncline. Intense argillization of subunits 4J and 4K in the U12n.03 and n.05 drill holes may somewhat exaggerate the relationship of argillization and the syncline, but this relationship is clearly expressed in subunits 4A-D through 4H also (fig. 4D).

In addition to proximity to the synclinal axis, argillization is also related to lithology. Argillization of ash-fall tuffs is slightly higher than can be accounted for by the ash-fall content of most stratigraphic subunits (fig. 5A). Similarly, argillization of calc-alkaline ash-fall tuff is higher than can be accounted for by the calc-alkaline ash-fall tuffs of nearly all stratigraphic units (fig. 5B). These differences may be caused by differences in permeability or chemistry.

Argillization in the U12n.03 drift (Ege and others, 1980) indicates a relationship to faults, the synclinal axis, and lithology. The U12n.03 drift crosses the synclinal axis at tunnel construction station (C.S.) 13+00 (pl. 2). Subunits 4J and 4K are present between C.S. 7+17 and 18+69 on either side of the axis. North- to north-northwest-trending faults are subparallel to the drift between C.S. 0+00 and 17+00. Argillization, defined by resistivities less than 20 ohm-meters (Ege and others, 1980), is present in subunits 4J and 4K between C.S. 11+00 and 18+00. During construction, heaving ground that was caused by the weak, intensely argillized rock was encountered between C.S. 12+00 and 17+00. Although faults are as frequent and ash-fall tuff is nearly as abundant in subunits 4G and 4H as in units 4J and 4K, intense argillization is present only in a few thin beds between C.S. 0+00 and 11+00 in subunits 4G and 4H. The coincidence of the synclinal axis, faults, and abundant ash-fall tuff appears to control the location of intense argillization in the U12n.03 drift.

Argillization of subunits 4J and 4K in the U12n.05 main drift also indicates that the synclinal axis, abundant ash-fall tuffs, and faults control location of intense argillization (J.R. Ege and D.L. Hoover, U.S. Geological Survey, written commun., 1971). The U12n.05 drift crosses the synclinal axis at C.S. 16+40 (fig. 6). Subunits 4J and 4K are present between C.S. 9+97 and 22+35 on either side of the axis. Intense argillization is present in subunits 4J and 4K and in subunit 4H. Heaving ground that was caused by the weak, intensely argillized rock occurred between C.S. 9+00 and C.S. 21+00. Extensometer data, survey data, and drill hole data indicated that the
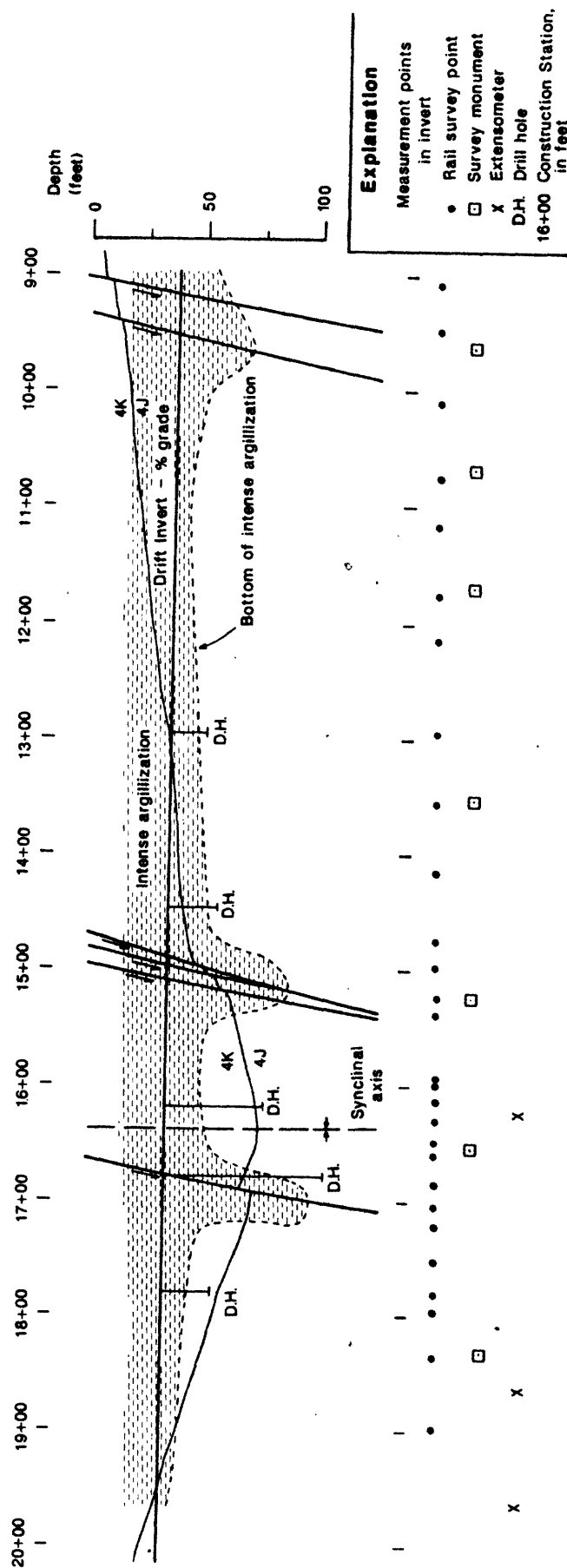
Figure 6.—Cross section along centerline of U12n.05 main drift showing intense argillization near faults and synclinal axis in tunnel bed subunits 4J and 4K. Data from J.R. Eye, Walter Danilchik, and D.L. Hoover, U.S. Geological Survey, written communs., 1971-76. Vertical exaggeration = 2X.

37

argillized rock failed at depths of 10 to 40 ft around the drift (J.K. Eye, and D.L. Hoover, U.S. Geological Survey, written commun., 1971). Intense argillization was thickest near fault zones (fig. 6). X-ray analyses of samples from elsewhere in the syncline indicate that intensely argillized rocks, such as those in the U12n.03 and n.05 drifts, may contain more than 50 percent montmorillonite (R.D. Carroll, U.S. Geological Survey, written commun., 1986).

Silicification

Silicified rocks comprise 0 to 7.1 percent of the rocks in the U12n area (table 6). Although the stratigraphic distribution of all silicified rocks suggests an inverse relationship to the distribution of argillized rocks (fig. 4C), stratigraphic distribution of silicified rocks in vertical and horizontal holes indicates that this relationship does not exist (fig. 4D, E). With a few exceptions, tuffaceous sandstones are much more susceptible to silicification than other rocks (table 6, fig. 5C).

MAP COMPILATION

The U12n area has been mapped at tunnel level by numerous geologists of the U.S. Geological Survey and Fenix & Scisson of Nevada from 1961 to 1985. As each drift or drill hole was completed, fault and stratigraphic contact strikes from adjacent drifts and drill holes were adjusted to fit the new data. The tunnel-level map (pl. 2) has been revised to provide consistency of map and drill-hole data throughout the U12n area. The revisions are based on data in the U.S. Geological Survey files as of May 1985. These data include unpublished and published reports and maps by Survey geologists and maps compiled by Fenix & Scisson of Nevada, geologists for containment evaluation of drifts excavated since 1981.

The tunnel-level map (pl. 2) is drawn on a slightly undulating plane that tilts gently to the east. Undulations are present because drifts were constructed at grades of 0.5 to 1.0 percent and were driven at various angles to the main drift and each other. The average grade between the portal (elevation 1835.8 m) and the U12n.10 WP (elevation 1850.7 m), the WP furthest removed from the portal, is 0.72 percent. Only faults that cross two or more drifts or horizontal drill holes, have displacements greater than 1 ft, or are significant to tunnel construction are shown on plate 2. Geologic mapping is at an elevation of 5 ft above the floor of the tunnel.

The map on top of the pre-volcanic rocks (pl. 3) shows structure contours, axes of paleotopography, and the major faults. The map was constructed from drill-hole data and from fault data projected from tunnel level. Construction of the map was begun in fault blocks where elevations of the pre-volcanic rocks were known from drill holes. Faults were projected from tunnel level position and dip. Fault traces on the top of the pre-volcanic rocks were constructed from intersections of contours on the pre-volcanic rocks and contours on the fault planes. In fault blocks where only one drill-hole elevation was available or where elevations were not available, contours were constructed by the use of fault displacements and dips at tunnel level.

Only faults that cross the axis of the Rainier Mesa and Aqueduct Mesa synclines and that have a displacement of 10 ft or more at one or more locations were projected to the pre-volcanic surface. Splays of the easternmost fault were projected because they are a part of the same fault in the area of the synclinal axis. The northeast-trending fault near the U12n.10 WP was included because gravity data indicated a significant displacement at the top of the pre-volcanic rocks (U.S. Geological Survey, 1979). Where fault dips were not available in drifts, dips were assumed. The assumed dip was based on dips measured elsewhere on the same fault. In a few locations, assumed dips were based on dips of faults with a similar displacement and orientation. Variable dips, strike changes, and high relief of the pre-volcanic surface cause the irregular traces of faults on the pre-volcanic surface.

Contours are shown as smooth and mostly conformable with the stratigraphic contacts at tunnel level. In outcrop, this smoothness and conformity are not always present in areas where the pre-volcanic rocks have high relief. Actual elevations more than 1,000 ft away from drill holes may vary 75-300 ft from elevations interpreted from the contours.

The surface map (pl. 4) shows contacts, faults, and inferred faults on top of Rainier Mesa and on part of the eastern slope. Most of the U12n surface area was remapped at a scale of 1:12,000 (F.M. Byers, Jr., and R.P. Snyder, U.S. Geological Survey, written commun., 1973).

STRUCTURE

Pre-volcanic structures in the U12n area include Mesozoic folds and faults in Paleozoic rocks and the Gold Meadows stock. Structures in the volcanic rocks are normal faults and depositional folds that have been influenced by the pre-volcanic structures.

Pre-volcanic Structures

During Mesozoic time, Paleozoic eugeosynclinal and miogeosynclinal rocks were subjected to regional compressional deformation. In the U12n area, this deformation is expressed as the CP thrust fault (Barnes and Poole, 1968) and as a west- to northwest-trending right-lateral fault zone that can be extrapolated from east of the U12n area.

CP Thrust Fault

The CP thrust fault places the Stirling Quartzite and the Wood Canyon Formation of Precambrian and Cambrian age over dolomite of Ordovician to Devonian age. The location of the edge of the thrust fault is inferred to be parallel to and near the synclinal axis in the tunnel beds and older volcanic rocks (pl. 1). On the north side of the syncline, several drill holes have penetrated quartzite or paleocolluvium that contains quartzite from the upper plate of the thrust fault. On the south side of the syncline, the U12b.07-2 drill hole penetrated dolomite in the lower plate at the base of the volcanic rocks.

Right-lateral Fault Zone

Compressional deformation that caused the CP thrust fault also caused west- to northwest-trending right-lateral faults. These lateral faults have been found at several locations in the NTS area (Carr, 1974). Several lateral faults have also been noted in the Syncline Ridge area (Hoover and Morrison, 1980). The presence of a lateral fault beneath the U12n area cannot be demonstrated, but can be inferred from two lines of evidence: (1) projection of a right-lateral fault zone east and southeast of Rainier Mesa, and (2) orientation of faults in volcanic rocks in the U12n area.

The right-lateral fault zone is expressed by offset of pre-Tertiary contacts and structure. From east to west, these offset features are (pl. 3):
1. CP thrust fault in the Oak Spring quadrangle (Barnes and others, 1963).
2. Contact between subunits G and H of the Eleana Formation.
3. Easternmost contact of overturned beds in the Eleana Formation.
4. Subunit E of the Eleana Formation within overturned beds.
5. Thrust fault of Ordovician to Devonian dolomitic limestone over the Eleana Formation.
6. Contact between subunits B and C of Devonian dolomite on the east side of Rainier Mesa.

The right-lateral offset of the CP thrust fault (1, pl. 3) in the Oak Spring quadrangle was interpreted from drill-hole and gravity data (U.S. Geological Survey, 1974). The south side of the fault zone was interpreted to have 500 ft of displacement down to the south at the base of the volcanic rocks. This fault was inferred between the area of investigation and the southernmost west-northwest-trending fault with lateral offset at the north end of the Eleana Range. On the north side of the fault zone, the contact between subunits G and H is offset across the northernmost fault (2, pl. 3). Although the contact is not exposed on the north side of the fault, the contact on the south side of the fault is exposed and leaves little doubt as to the right lateral movement (Barnes and others, 1963).

A zone of overturned beds in the Eleana Formation is present in the Eleana Range and in outcrops north of the main wash that drains Rainier Mesa. The easternmost contact of these overturned beds is terminated at the south and north edges of the right lateral fault zone by west-northwest-trending faults (3, pl. 3). Similarly, subunit E within the overturned beds is terminated (4, pl. 3). Within the fault zone, outcrops indicate that several lateral faults differentially offset the overturned beds and unit E, but individual faults within the zone are concealed (Gibbons and others, 1963). Just west of the overturned beds, Ordovician to Devonian dolomitic limestone is thrust over the Eleana Formation south of the lateral fault zone (5, pl. 3). Within the lateral fault zone, the thrust fault is concealed by alluvium, but crops out north of the zone (5, pl. 3). The northern outcrop and outcrops of Devonian limestone within the lateral fault zone leave little doubt as to the right-lateral offset within the zone. Two outcrops of the Antelope Valley Formation at the northwest corner of the Eleana Range (pl. 3) indicate at least 2,000 ft of offset between the thrust fault south of the lateral fault zone and the southern side of the zone.

The contact between units B and C of Devonian dolomite is also offset at least 2,000 ft laterally (6, pl. 3). The fault is concealed beneath alluvium in the wash that begins just south of the U12n portal. North of the wash and the concealed fault, the contact of units B and C lies east of the outcrop of unit C (6, pl. 3). The right-lateral offset is therefore at least 1,300 ft. About 2,500 ft east of this outcrop of unit C, another outcrop of unit C indicates the possibility of another right-lateral offset of 3,000 ft or more (6, pl. 3).

Faults in volcanic rocks north and south of the U12n area have mostly N. $10°$ W. to N. $20°$ E. trends in contrast to mostly N. $20°$-$40°$ W. trends of faults in the U12n area. The N. $10°$ W. to N. $20°$ E. trend is common in most volcanic rocks throughout the NTS area. Where Mesozoic right-lateral faults that have E-W to N. $25°$ W. trends are present, faults in volcanic rocks may parallel the older fault trends. In the Syncline Ridge area, about 7 miles southeast of Rainier Mesa, Mesozoic right-lateral faults with west-northwest trends were reactivated during Tertiary time along part of their length and offset the volcanic rocks north of Syncline Ridge and between Syncline Ridge and Mine Mountain (Hoover and Morrison, 1980). Presence of the right-lateral fault zone just east of the U12n area and the contrast between normal fault trends in volcanic rocks and fault trends in the U12n area strongly suggest the presence of a Mesozoic right-lateral fault zone beneath the U12n area. During late Tertiary time when the NTS area was subjected to N. $50°$ W. extension (Carr, 1974), the right-lateral fault zone would have provided preexisting planes of weakness. Vertical movement along these planes could account for the different orientation of faults in the U12n area.

Gold Meadows Stock

Intrusion of the quartz monzonite stock of Cretaceous age in Gold Meadows into the upper plate of the CP thrust may have deformed the upper plate along the north edge of Rainier Mesa and along the west side of Aqueduct Mesa. This deformation may have influenced the location of the paleovalleys beneath the Rainier Mesa and Aqueduct synclines and the location of the divide between the paleovalleys of the two synclines (pl. 1).

The effects of deformation by the intrusion on the possible right-lateral fault zone beneath the U12n area are uncertain. Faults with the greatest displacement in the volcanic rocks change strike from N. $25°$-$30°$ W. south of the synclinal axis to N. $10°$-$15°$ W. north of the syncline. The change in strike may be caused by Mesozoic deformation of the lateral fault zone, by location of the upper plate on the north side of the syncline, by local stress changes caused by the intrusion, or some combination of these factors.

Age of CP Thrust Fault and the Right-Lateral Fault Zone

About 7 miles southeast of Rainier Mesa, the Tippipah Limestone of Pennsylvanian to Permian age has been deformed by folding, thrust faults, and right-lateral faults that are contemporaneous with the CP thrust and the lateral fault zone of the U12n area. Therefore, the age of the CP thrust and the lateral fault zone are post-Tippipah Limestone. Intrusion of the upper plate of the CP thrust fault by the Gold Meadows quartz monzonite in the RME-1 drill hole and around the edge of the Gold Meadows stock establishes the age

of the thrust fault as older than the Gold Meadows stock of Cretaceous age. Although the thrust faults and lateral fault zones in the Rainier Mesa and Syncline Ridge areas could be as old as Permian, Carr (1974) associates the right-lateral faults in the NTS area with the Walker Lane Belt shear zone. In the Walker Lane Belt, displacement of Jurassic plutons and depositional characteristics of Jurassic sediments indicate that movement may have begun after Middle Jurassic time (Carr, 1974).

Structures in Volcanic Rocks

Prior to deposition of the volcanic rocks, Precambrian through Mesozoic rocks were deeply eroded by two drainage systems in the U12n area. Deposition of volcanic rocks in the paleovalleys and their interfluves produced depositional folds. The volcanic rocks were deformed by normal faults, probably in two or more episodes of faulting after deposition of tunnel bed 4.

Depositional Folds

Deposition in paleodrainaye systems in the pre-volcanic rocks has produced depositional folds in the volcanic rocks. The major folds in the U12n area are the Rainier Mesa and Aqueduct synclines. Source directions, faults, and possibly deformation related to the Timber Mountain or Silent Canyon calderas have affected the location of the synclinal axes within the volcanic rocks. Dips of the volcanic rocks decrease upward in the section. Thickness of stratigraphic units in the lower and upper parts of the volcanic rocks vary and may be dependent on erosion and position within the syncline or the direction and distance from depositional sources.

Fold axes

On top of the pre-volcanic rocks and at tunnel level, the Rainier Mesa and Aqueduct synclines are approximately coincidental. The two synclines are separated by a divide just east of construction station (C.S.) 13+00 in the U12n.03 drift. The Rainier Mesa syncline plunges southwest and the Aqueduct syncline plunges northeast. At the surface, a single syncline plunges northeast roughly parallel to the subsurface axes of the two synclines, but offset 300-400 ft to the south (pl. 2-4). The offset between the axial traces may be caused by greater deposition of the Paintbrush Tuff on the north side of the syncline, erosional migration of the paleovalley prior to the deposition of the Rainier Mesa Member, or by uplift of the northern side of the syncline. West of the U12n drifts and drill holes, detailed mapping (pl. 4) indicates that the surface trace shown on the Rainier Mesa quadrangle (Gibbons and others, 1963) actually passes just south of the RME drill hole. Reconnaissance investigations by the senior author indicates that the surface trace of the axis probably exits the west side of Rainier Mesa at approximately Nevada State coordinate N. 886,000.

West of the U12n area, the location of the synclinal axis is uncertain at the top of the pre-volcanic rocks. The axis is inferred to follow the trace of the CP thrust fault. This inference is based on the presence of the Stirling Quartzite and Wood Canyon Formation of the upper plate in drill holes on the north side of the syncline and dolomite in the U12b.07-2 drill south of the axis. A similar relationship on Aqueduct Mesa is present in drill holes on either side of the axis of the Aqueduct syncline. Dips between the UE12n#6 and RME-1 drill holes, approximately normal to the inferred axis, below tunnel bed 5 (table 8) also suggest that the axis is near the RME-1 drill hole.

Table 8.--Elevation of stratigraphic units in the UE12n#6
and RME-1 drill holes, U12n area

Stratigraphic Unit	Elevation of top of stratigraphic unit (feet)		Difference in elevation UE12n#6 minus RME-1 (feet)
	UE12n#6	RME-1	
Rainier Mesa Member (surface)	7420	7367	53
Grouse Canyon Member	6200	6263[1]	-63
Tunnel bed 5	6093	6179[2]	-86
Tunnel bed 4	6010	5973-6062[3]	37 to -52
Tunnel bed 3	5699	5667	32
Tub Spring Member	5498	5416	82
Tuff of Yucca Flat	5298	4732	566

[1]Top of unit in uncored interval between 6260 and 6327 ft. Contact picked at excursion on gamma ray log.
[2]Top of unit in uncored interval between 6122 and 6250 ft. Contact picked at excursion on gamma ray log.
[3]Top of unit in uncored interval.

Elevations of stratigraphic units in the UE12n#6 and the RME-1 drill holes (table 8) indicate that the subsurface axial trace of the synclinal axis in tunnel bed 4 and older units is near the RME-1 drill hole, but that the axial trace is near UE12n#6 in tunnel bed 5 and the Grouse Canyon Member. Units below tunnel bed 4 and the Rainier Mesa Member slope toward the RME-1 drill hole, but the top of tunnel bed 5 and the Grouse Canyon Member slope toward UE12n#6. The slope of the younger units may indicate a depositional, rather than an erosional, migration of the synclinal axis toward UE12n#6. The source of tunnel bed 5 and the Grouse Canyon Member, the Silent Canyon caldera, is a few miles west and northwest of RME-1. Decrease in thickness of tunnel bed 5, an ash-fall tuff, away from the caldera may have been large enough that deposition caused southward migration of the synclinal axis.

Penetration of the lower plate of the CP thrust fault and the thick section of volcanic rocks in the RME-1 drill hole also suggest that the subsurface axis of the Rainier Mesa syncline is just south of the drill hole. The RME-1 drill hole penetrated altered dolomite beneath quartz monzonite and quartzite intruded by pegmatite dikes. The presence of dolomite, rather than limestone that is present in the Stirling Quartzite and the Wood Canyon Formation, indicates that the lower plate of the CP thrust fault was penetrated. The CP fault was not seen because of poor core recovery, but both the quartzite and dolomite were brecciated near the inferred fault. Volcanic rocks in the RME-1 drill hole are the thickest section in northern Rainier Mesa. Quartz monzonite in the U12r drill hole about 3,300 ft north of RME-1, is about 1,750 ft higher than in RME-1. This elevation makes it unlikely that a major north-south paleovalley passes through RME-1.

West of the U12n drifts, the location of the synclinal axis at tunnel level is uncertain, but several lines of evidence suggest that the subsurface traces approximate the surface trace. The axis of the syncline was not encountered in the U12n extension drift (pl. 2) and therefore must be north of that drift (D.R. Townsend, Fenix & Scisson of Nevada, oral commun., 1985). In the U12n area, drill-hole data indicate that the axial traces at tunnel level and on top of the pre-volcanic rocks approximate the trace of the CP thrust fault on top of the pre-volcanic rocks.

Dips and thickness of volcanic rocks

The northern paleovalley slope of the Rainier Mesa syncline averages 14° and relief is about 2,400 ft from the closest peak of the Gold Meadows stock to the bottom of the Rainier Mesa paleovalley. Average paleovalley slopes from the northern edge of Rainier Mesa range from 25° to 29° between UE12n#2, n#3, n#8, and n#9 drill holes and the paleovalley axis. The average slope from UE12n#10 is about $19^\circ30'$, and from UE12n#11, less than $9^\circ30'$ to the paleovalley axis. The lower slopes and greater thickness of paleocolluvium in the last two holes and the location of these drill holes just west of and on the downthrown side of a large fault strongly suggest the presence of a tributary to the Rainier Mesa synclinal valley along the fault trace. The convexity of the northern paleovalley slope in the U12n.10 area toward the synclinal axis suggests that intrusion of the Gold Meadows stock may have deformed the upper plate of the CP thrust. Sparse elevations at the base of the volcanic rocks indicate that paleovalley slopes range from 4°-$12^\circ30'$ on the south side of the Rainier Mesa syncline.

Depositional folds in the U12b tunnel area at the south edge of the U12n area indicate that fold axes of tributaries on the south side of the Rainier Mesa syncline are subparallel to the axis. Depositional folds between the U12n portal and C.S. 25+00 indicate that tributaries are subparallel to the Aqueduct paleovalley. The axis of a syncline just east of the U12n portal can be traced for at least two miles parallel to the Aqueduct syncline (Gibbons and others, 1963).

Stratigraphic units of the volcanic rocks might be expected to be greater in thickness and the amount of reworked ash-fall tuff and tuffaceous sandstone in the center of the syncline than on the flanks because of greater deposition in the center and greater erosion on the flanks. Comparison of unfaulted stratigraphic units in UE12n#1, near the synclinal axis, and UE12n#3, highest on the north flanks of the syncline, does not indicate a consistent thickening or greater amount of reworked ash-fall tuff and tuffaceous sandstone within individual stratigraphic subunits of the tunnel beds but aggregate thickness and amount of reworked ash-fall tuff and tuffaceous sandstone is greater in the center of the syncline (table 9).

Part or all of the difference in tunnel beds 3-5 could be ascribed to different sources at various distances, but the thicknesses of the Paintbrush Tuff and the Rainier Mesa Member of the Timber Mountain Tuff (table 9) indicate that deposition was greater in the center. Data on units between the Tub Spring Member of the Belted Range Tuff and the pre-volcanic rocks are sparse, but 190 ft of section below tunnel bed 3 in UE12n#3, as compared to 1,646 ft in the RME-1 drill hole near the center of the syncline and the absence of some of the older ash-flow tuffs on the synclinal flanks, also indicate erosion on the flanks and greater deposition in the center of the syncline.

Depositional folds have been maintained during deposition of the volcanic rocks, but dips are generally less in younger stratigraphic units, particularly on the flanks of the Rainier Mesa syncline (table 10). Most of the change in dip occurs between tunnel bed 1 and younger units.

At tunnel level where control points are dense, contacts of stratigraphic units in tunnel beds 2-4 are relatively smooth and thicknesses change gradually. Structure contours on the paleovalley slopes (pl. 3) reflect the smoothness of contacts at tunnel level, but control points are sparse and the paleovalley slopes may have relief not indicated by the contours. Thicknesses of units below tunnel bed 2 range from 2 ft in UE12n#2 on the west to 276.5 ft in UE12n#11 on the east (Maldonado and others, 1979). The variation in thickness, approximately along the structure contours, suggests more relief than the contours indicate, but data on the elevation of the paleovalley slopes is too sparse to indicate such relief.

Faults

At tunnel level, several faults extend across the U12n area and have displacements of 6-125 ft down to the west (pl. 2). Between these longer faults, shorter faults with displacements of 2-25 ft join the longer faults at acute angles. Most of the shorter faults are displaced down to the west. Dips on the longer faults mostly range from 65° to 85°, but locally dips are 55° to 65°. Dips on the shorter faults mostly range from 60° to 80°, but a few faults have dips as low as 40° and as large as 85°.

45

Table 9.--Comparison of total thickness and percent of reworked ash-fall tuff and tuffaceous sandstone in stratigraphic subunits, UE12n#1 and UE12n#3.

	UE12n#1		UE12n#3	
Stratigraphic subunit	Thickness (m)	Reworked ash-fall tuff and tuffaceous sandstone (percent)	Thickness (m)	Reworked ash-fall tuff and tuffaceous sandstone (percent)
3A	7.9	0.0	5.2	0.0
3BC	41.1	33.3	23.2	34.2
4G	6.7	9.1	4.9	18.8
4H	10.7	14.3	14.3	23.4
4J	22.6	8.1	14.6	2.1
4K-5[1]	61.6	22.3	69.8	12.2
All tunnel beds	150.6	20.9	132.0	15.9
Tpb[2]	245.5		199.0	
Tmr	93.3		41.5	

[1]Subunits combined because contact may be erroneous in UE12n#3.
[2]Includes tuffs of Area 20 and of Dead Horse Flat and Stockade Wash Tuff.

Table 10.—Average dips in volcanic rocks, U12n area

Stratigraphic Unit	North flank of syncline UE12n#2, #3, #8, #9, #10, #11			Near axis of syncline RME-1, UE12n#1			South flank of syncline U12.b07-2, UE12n#4, #6		
	Average dip	Median dip	Range dip (No. of samples)	Average dip	Median dip	Range dip (No. of samples)	Average dip	Median dip	Range dip (No. of samples)
Paintbrush Tuff, tuffs of Area 20 and Dead Horse Flat	13°34' (14)	13°30'	9°-20°	4°00' (5)	2°00'	2°-10°	9°40' (3)	10°00'	4°-15°
Tunnel beds 4 and 5	13°22' (41)	13°00'	2°-25°	8°12' (24)	8°00'	2°-17°	8°53' (9)	9°00'	6°-12°
Tunnel bed 3	14°05' (12)	14°30'	8°-21°	3°30' (6)	3°30'	2°-5°	10°24' (5)	9°00'	9°-15°
Average tunnel bed 3 and younger units	13°32' (67)	13°00'	2°-25°	6°48' (35)	7°00'	2°-17°	9°28' (17)	9°00'	4-15
Tunnel bed 2	17°00' (20)	15°30'	5°-29°	8°46' (13)	8°00'	1°-18°	9°38' (11)	9°00'	3°-17°
Tunnel bed 1 and older tuffs	24°47' (9)	24°00'	18°-32°	11°48' (10)	11°00'	3°-26°	30°52' (8)	32°30'	14°-43°

The orientation of the longer faults ranges from N. 13° W. to N. 52° W., but most of the faults have a N. 15°-30° W. strike. The north-northwest strike in the U12n area and in volcanic rocks at the surface around the U12n portal contrast with north-south to north-northeast strikes in areas south and northeast of the U12n area. A scarp in pre-volcanic rocks with 100-250 ft of offset was interpreted from gravity and drill hole data in the U12n.10 area (U.S. Geological Survey, 1979). This fault scarp, buried by volcanic rocks, has a northeast trend subparallel to faults at tunnel level. The northwest strikes in the U12n area may be caused by reactivation during Tertiary time of the pre-volcanic right-lateral fault zone. The northwest-southeast direction of extension that began about 10 m.y. ago should not produce vertical movement on northwest-trending faults (Carr, 1974), but local stress variations may have caused reactivation of this fault zone.

Orientation of the shorter faults ranges from N. 50° W. to N. 45° E., but most faults have strikes between N. 10° W. and N. 40° W. Some of the shorter faults appear to be subparallel splays of the longer faults, but most join the longer faults at large acute angles or are isolated from the longer faults. Most of the shorter faults may be the result of failure within blocks between longer faults, and thus, may be only indirectly related to reactivation of faults in the pre-volcanic fault zone. Northeast-trending faults near the end of the U12n.10 drift may be caused by Tertiary reactivation of faults in pre-volcanic rocks with similar strikes.

Exposures of fault planes in the U12n drifts have slickensides that indicate the last movement on these faults was downdip or at a small angle to the dip. Most faults contain less than half an inch of gouge. Faults with displacements greater than 15 ft may have fractures or small faults subparallel to the main fault in a zone that is rarely more than 3 ft wide. Fault breccia usually occurs only in the strongest rocks, such as well-sorted, zeolitized reworked ash-fall tuff or silicified, tuffaceous sandstones. Cavities in fault breccias usually have a maximum dimension less than 1 ft. Cavities along fractures in silicified tuffaceous sandstones have been found next to faults. The cavities are irregular and usually have a maximum dimension less than 0.4 ft. Near the end of the U12n.06 drift, cavities in a tuffaceous sandstone next to the large fault at C.S. 20+45 contained viscous silica gel. The silica gel in the cavities suggests that these cavities may be caused by dissolution of silica in the tuffaceous sandstone.

Some of the longer faults at tunnel level extend to the surface (pls. 2, 4, 5). The trace of the surface faults across steep slopes along the Aqueduct surface drainage indicates that the faults are very near vertical at the surface. The surface traces are northeast of the traces at tunnel level. The near vertical dips and the offset location at the surface requires an increase in dip between the tunnel level and surface. The increase may be gradual because of changes in stress with depth, the increase may occur at discontinuities of physical properties such as near the base of the Rainier Mesa Member and at the top of the zeolitized tuffs, or more probably, the dips may increase for both reasons.

Shorter faults may be lacking at the surface for two reasons:
1. They intersect the longer faults below the surface.
2. Smaller displacements are absorbed by the weak, vitric bedded tuff of
    the Paintbrush Tuff.
A third reason may be that the small displacements of the shorter faults are
concealed at the surface, but detailed mapping (F.M. Byers, and R.P. Snyder,
U.S. Geological Survey, written commun., 1976) and large exposures of bedrock
indicate this reason is unlikely. On Rainier Mesa and Pahute Mesa, fewer
faults are present in vitric bedded tuffs than in more competent rocks
adjacent to them.

Compaction faults, caused by overburden weight, in vitric bedded tuffs of
the Paintbrush Tuff exposed on Rainier and Pahute Mesas have displacements of
6 in to 3 ft that die out within 15-30 ft of the maximum displacement. This
die-out of compaction faults suggests a similar termination of the shorter
faults that occur in the tunnel beds.

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