Geology of the USGS and Rainier Tunnel areas, Nevada Test Site

By Wallace R. Hansen and Richard W. Lemke

Trace Elements Investigations Report 716

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By Wallace R. Hansen and Richard W. Lemke

ABSTRACT

The USGS And Rainier Tunnel areas are in the northwest part of the Nevada Test Site. These tunnels were used for the underground detonation of large high-explosive charges and a relatively low-yield (1.7 kt) nuclear device. The Rainier Tunnel area is on the east margins and slope of Rainier Mesa, which is an outlier of the Belted Range. The USGS Tunnel area is at the foot of a ridgelike salient about 1½ to 2½ miles east of Rainier Mesa.

Rocks exposed in the Rainier Tunnel area include limestones of the Nevada formation (Devonian), volcanic tuffs, welded tuffs and tuffaceous sandstones of the Oak Spring formation (Tertiary), and alluvium (Quaternary). The USGS Tunnel area is underlain by the Oak Spring formation. In the Rainier Tunnel area the Oak Spring formation is divided into 8 map units, nearly all of which are rhyolitic or quartz latitic; only 3 of these units crop out in the USGS Tunnel area, but higher and lower units of the formation occur nearby.

The Nevada Test Site lies within a region that has been subjected to two and possibly three or more periods of structural deformation. Folding and faulting both preceded and followed deposition of the Oak Spring formation, and occurred intermittently during its deposition. Over most of its outcrop area the Oak Spring formation is gently folded. The axes of several small northeast-trending folds pass through the Rainier Tunnel area. Within the USGS area the structure is generally homoclinal, and the beds dip mostly 5° to 15° east or northeast.

Small normal faults are abundant in the USGS Tunnel area. Most of the faults fall within two well-defined sets--one set trends northeast, dips northwest and is upthrown on the southeast; the other set trends northwest, dips northeast, and is upthrown on the southwest. The pattern of two mutually opposed sets of normal faults suggests a west to east tensional condition in the earth's crust at the time of faulting.

Faults are less abundant at the Rainier Tunnel area than at the USGS Tunnel area, but their relations are similar and their origin probably is the same.

Joints are abundant at the USGS Tunnel area and form a well-defined pattern subparallel to the faults. Joints are relatively fewer at the Rainier Tunnel area except in the welded tuffs where they are very abundant.

On February 21, 1957, 10 tons of 60 percent dynamite was exploded in the USGS Tunnel. Rough estimates indicate that about 54,000 tons of rock was involved in the lifting, breakage, or fracturing that accompanied the blast. The quantity of closely broken rock, however, was much smaller. Most of the surface breakage followed pre-existing faults, joints, or bedding planes. An instant after the shot was detonated, a horizontally directed blast of gas, dust and rock emerged at high velocity from the portal of the tunnel; the escape of energy from the tunnel was due to partial destruction of one wall of the shot chamber.

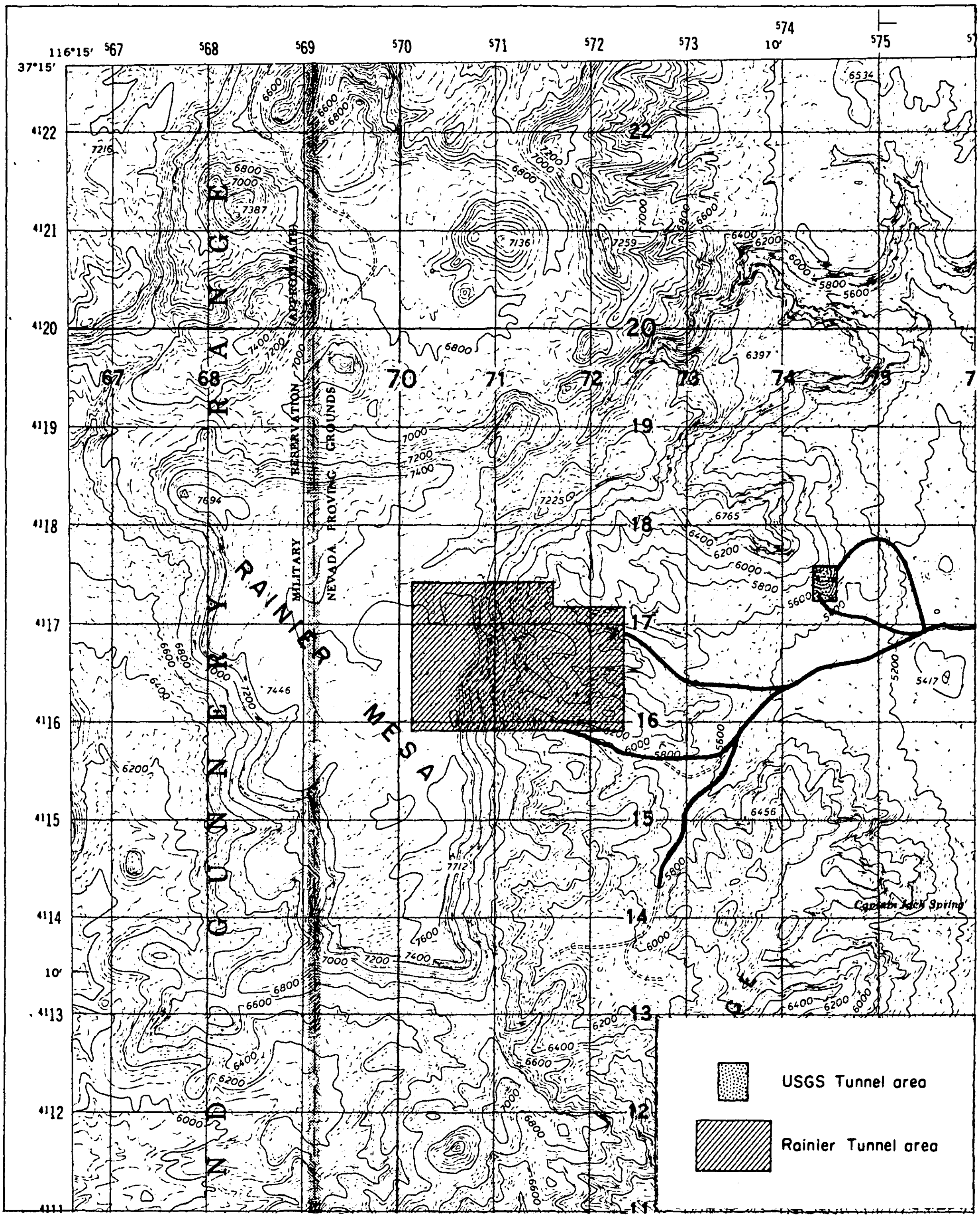
On April 5, 1957, 50 tons of dynamite was exploded in the USGS Tunnel. The energy of this shot was better contained than that of the 10-ton shot, and the rock breakage and fracturing were correspondingly greater. About 1¼ million tons of rock was lifted and fractured by the explosion. The quantity of closely broken rock, however, was much less. Again, most of the strongest displacements were along pre-existing fractures, but many fractures were formed within previously sound rock. Within 200 feet of ground zero the fracture pattern was radial. Beyond that distance, most of the breakage followed pre-existing faults, joints, or bedding planes. The disturbed area is roughly triangular in outline, being bounded on two sides of steep faults and on the third side by the trace of a bedding plane.

In addition to deep fracturing, many boulder-size fragments of rock were spalled from the faces of ledges or low cliffs, apparently owing to rebound as the shock wave was reflected from the ground surface. The largest of these fragments weighed 50 tons or more.

INTRODUCTION

Areas referred to herein as the USGS Tunnel area and the Rainier Tunnel area are in the northwest part of the Nevada Test Site in the Tippipah Spring quadrangle (fig. 1A). The USGS Tunnel area (fig. 1) is within grid units 17-18 N., and 74-75 E.; the Rainier Tunnel area (fig. 2) is mainly within grid units 16-18 N., and 70-73 E. Both sites are reached from Camp Mercury, Nev. over all-weather roads through Frenchman and Yucca Flats, a mean distance of about 40 miles.

The USGS Tunnel was the site of 10- and 50-ton underground dynamite explosions in the winter and spring of 1957. The Rainier Tunnel was the site of the underground atomic explosion of September 19, 1957. The purpose of these tests, in brief, was to determine the feasibility of underground detonation as a standard method of testing atomic devices. These relatively small explosions (the Rainier device had a rated energy yield equivalent to 1.7 kilotons of dynamite) provided a basis for



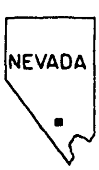


FIGURE IA. LOCATION MAP SHOWING NORTHWEST CORNER OF TIPPIPAH SPRING QUADRANGLE, NEVADA TEST SITE

1 ½ 0 1 2 3 Miles

1000 500 0 1000 2000 3000 4000 Meters

1000 500 0 1000 2000 3000 4000 Yards

predicting the behavior of larger possible tests in similar rock media. The purpose of this report is to outline briefly the geologic background of these areas, and to describe the surface effects of the high-explosive tests. The underground effects of the high-explosive tests are described separately by Cattermole (1958); the geologic effects of the Rainier atomic test, which had not yet been performed at the time the following report was first written, is described separately by Gibbons (1958).

Topography

The USGS Tunnel is on a low south-facing bedrock spur about 300 feet high at the foot of a higher east-trending ridgelike salient of Rainier Mesa which is about 2 miles to the west and is an outlier of the Belted Range. An alluvium-floored re-entrant into Yucca Flat extends westward past the USGS Tunnel area toward the Rainier Tunnel area. The Rainier Tunnel area is on the east margin and slope of Rainier Mesa 1½ to 2½ miles west of the USGS area.

Total relief in the area is about 2,300 feet; altitude ranges from about 5,300 feet at the alluvial flat below the USGS Tunnel to nearly 7,600 feet at the top of Rainier Mesa. The east slope of the mesa, including the tunnel are, is indented by several small canyons or ravines 300 to 400 feet deep.

Natural slopes in this area rarely exceed 30°. Slopes of 25°, however, are common, and most slopes attain 20° or more. In many places the rimrock of the mesa forms sheer cliffs, and slopes just below the rimrock are as steep locally as 40°. Vertical slope breaks of 10 to 20 feet or so are common also along some of the more resistant beds that crop out below the rimrocks.

Field methods

The geology of the USGS Tunnel area was mapped by planetable methods at a scale of 50 feet per inch, using a telescopic alidade and stadia rod. The topographic base for the geologic map was prepared by Holmes and Narver, Atomic Energy Commission contractors, with modifications by the U. S. Geological Survey. The surface fracture pattern of the 10-ton explosion was mapped by planetable and alidade at a scale of 20 feet per inch; the fracture pattern of the 50-ton explosion was sketched on a planetable board at a scale of 50 feet per inch using a Brunton compass, tape, and control previously established by Holmes and Narver and the U. S. Geological Survey.

The geology of the Rainier Tunnel area was plotted in the field on air photographs flown for the Atomic Energy Commission by Hycon Aerial Surveys, Inc. With the same photography, multiplex methods were then used to compile the geology onto a topographic base prepared by Hycon.

In consequence of the successful Rainier test, further underground testing was planned, and the area to the south of the Rainier Tunnel was selected as the site. Additional geologic information, therefore, was requested, and accordingly the area was mapped by Hansen in October 1957 (fig. 2A).

Stratigraphic sections at the USGS area were measured with an Abney level mounted on a 5-foot Jacob staff; intervals of less than 5 feet were measured directly with a steel tape or with a Brunton compass used as a clinometer held against the Jacob staff. Similar methods were used at the Rainier area, supplemented by information taken from logs of drill holes.

Acknowledgments

This report was prepared under the general supervision of Ernest Dobrovolny, who directed the high-explosive test fired in the USGS Tunnel in the winter and spring of 1957. Preliminary geologic studies by him and by E. B. Eckel paved the way for the authors and greatly simplified our field work.

Much credit is due Warren L. Peterson who was instrument man for most of the planetable work in the USGS Tunnel area and who logged part of the cores in the Rainier Tunnel area.

Thin sections of selected rock samples from outcrops and drill holes were examined by Ray E. Wilcox. Much valuable information gained from his studies has been incorporated without further acknowledgment into the logs of drill holes and the narrative descriptions of various rock units.

This work is part of a program that the U. S. Geological Survey is conducting at the Nevada Test Site on behalf of the Albuquerque Operations Office, U. S. Atomic Energy Commission.

STRATIGRAPHY

Rocks exposed in the Nevada Test Site consist of various sedimentary rocks of Paleozoic age, volcanic and sedimentary rocks of Tertiary age, and unconsolidated alluvial and playa deposits of Quaternary age (Johnson and Hibbard, 1957, p. 333-384). In addition, there are intrusive rocks of Cretaceous or Tertiary age and contact-metamorphosed rocks of Paleozoic age, although none of these crop out in the areas shown on the accompanying maps.

Paleozoic rocks

Nevada formation

Paleozoic rocks of the Test Site range in age from Early Cambrian to probably early Permian. According to Johnson and Hibbard (op. cit.) they have a total thickness of about 22,000 feet of which more than 16,000 feet is limestone and dolomite. The remainder is chiefly quartzite, shale, and conglomerate. Paleozoic rocks that crop out in the Rainier Tunnel area are Devonian in age and are shown on Johnson and Hibbard's map (pl. 32) as undifferentiated Devils Gate(?) limestone and Nevada formation. According to the formation descriptions published by Johnson and Hibbard (1957, p. 354), the rocks within the Rainier Tunnel area probably should be assigned to unit C of the Nevada formation. This unit consists of dark-gray to black dense finely crystalline thick-bedded massive limestone that contains a few chert bands and nodules and some interbeds of lighter gray dolomite. Many of the limestone beds contain small rodlike stromatoporoids, and some contain larger concentric reniform masses several inches in diameter.

Unit C of the Nevada formation forms rough irregular outcrops that weather to form ledgy breaks a few feet to a few tens of feet high. It contrasts markedly in color and physiographic expression from the beds of the Oak Spring formation which overlie it unconformably along the eastern base of Rainier Mesa.

Tertiary rocks

Oak Spring formation

The name Oak Spring formation was applied by Johnson and Hibbard (1957, p. 367) to the predominantly tuffaceous rocks that crop out at Oak Spring Butte about 10 miles northeast of Rainier Mesa. The same formation underlies the USGS Tunnel area and most of the Rainier Tunnel area. At the Rainier Tunnel area it has been subdivided into 8 separate map units that can be traced throughout the area and for considerable distances beyond. In ascending order, these are designated Tos_1 to Tos_8 respectively. Only units Tos_2, Tos_3, and Tos_4, in ascending order, crop out in the small USGS Tunnel area, but higher and lower units are recognized nearby. To better bring out the geologic structure at the map scale used for the USGS Tunnel area map (fig. 1), moreover, it was convenient to subdivide units 2, 3, and 4 into smaller map units consisting of several individual beds per unit. The following general descriptions of the Oak Spring formation are based largely on observations made at the Rainier Tunnel area, but they apply equally well to the USGS Tunnel area.

At Rainier Mesa the Oak Spring formation is approximately 1,900 feet thick. In a series of composite surface sections along the face of the mesa a total thickness of about 1,875 feet was measured. A thickness of 1,896 feet was obtained from the Hagestad drill hole, drilled on top of the mesa just southwest of the Rainier Tunnel area. As the top of the formation at Rainier Mesa is a stripped erosion surface, the full thickness of the formation undoubtedly exceeds 1,900 feet. At Oak Spring Butte, Johnson and Hibbard (1957, p. 369) measured about 2,000 feet of section, and they reported even thicker sections west of Frenchman Flat.

Texturally, the tuffs of the Oak Spring formation range widely from exceedingly fine-grained rocks to coarse lapilli tuffs, tuff breccias, and agglomerates. Fragments of tubular pumice and foreign inclusions are common, in fact some beds consist largely of pumice fragments. Where small foreign fragments, such as quartzite, are abundant, the rock is referred to in measured sections and core logs as tuffaceous grit. Hard flintlike rock is referred to as porcellanite. The porcellanites, however, are largely surface or near-surface features. They are cemented by a zeolitic matrix that is very hard on the outcrop but is very soft underground.

Table 1 (see appendix) is a composite stratigraphic section of rocks exposed at the USGS Tunnel area. Table 4 is a similar section of the formation exposed near the Rainier Tunnel. The portal of the USGS Tunnel is collared in bed 20 of table 1. This bed, therefore, has been referred to as the "portal bed." As it is an excellent horizon marker and can be traced from the USGS area to the Rainier area and beyond, its top was selected as the horizon for the structure contouring of the Rainier area, figure 4. (Bed 20 of table 1 is bed 27 of table 4.)

At Rainier Mesa, unit Tos_1 consists of nonwelded bedded tuffs totalling about 210 feet thick. Most beds are purplish red to pinkish red, fine grained, and siliceous. Except for resistant beds at the top and base, most beds are poor ledge formers. Altered pumice, ash shards, subangular quartzite fragments, and blebs of limonite are abundant locally in most beds. Quartz, feldspar, and biotite form abundant phenocrysts in a commonly silicified groundmass. A basal conglomerate, as much as 5 feet thick, locally forms the base of the unit. It consists essentially of subangular fragments of light blue limestone, argillite, and quartz mostly less than one inch long. A prominent ledge-forming tuff 15 feet thick, overlying the conglomerate, weathers to distinctive pale reddish purple aggregates less than a quarter of an inch in diameter.

Unit Tos_2 consists of nonwelded bedded tuffs to tuffaceous sandstone totalling about 120 feet thick. Most beds are light gray to buff, but pink red, and reddish purple beds and stringers are fairly common. The overall color contrasts markedly with that of the units below and above. Individual beds commonly range from 3 feet to 15 feet in thickness, are fine- to coarse-grained, and well laminated to massive. Most beds form fairly distinct ledges. Pumice, ash shards, and quartzite fragments are sparse to moderately abundant. Quartz and feldspar crystals are the most abundant phenocrysts, and biotite and an opaque oxide next most abundant. Several beds contain sufficient detrital quartz to be classed as tuffaceous sandstones; most are thinly laminated and exhibit some crossbedding. The most prominent tuffaceous sandstone is a bed about 35 feet thick that forms the uppermost bed of the unit. It is locally conglomeratic with glassy fragments less than one inch in longest dimension.

Unit Tos_3 consists of nonwelded beds of tuff except for a small lens of welded tuff (denoted as wt on the map) in the extreme northern edge of the mapped area. The thickness of the unit is about 100 feet.

Most of the nonwelded beds in the unit are pink, red, purple, light gray, or buff. Beds range from 12 to 35 feet in thickness.

The basal bed of the unit (bed 14 of the USGS area; bed 24 of the Rainier area) is dark brick red and forms a distinctive blocky outcrop. Most are fairly massive, medium to coarse grained, and are good ledge formers. The uppermost bed (bed 20 of the USGS area), which is about 35 feet thick and pink to red, is known as the portal bed.

Pumice fragments are abundant in most beds and are as much as 2 inches long in the basal part of the portal bed. Ash shards and quartzite fragments are scattered throughout some beds and black obsidian fragments, rimmed with white halos, are common in the portal bed. Phenocrysts of quartz, feldspar, biotite, and an opaque oxide are present in most beds.

The lens of rhyolitic welded tuff in unit Tos_3 has a maximum exposed thickness of approximately 15 feet. It does not occur at the USGS area. It is pale purplish red, dense, and hard, and contains scattered flattened cavities mostly less than half an inch long. It contains many phenocrysts of quartz and alkali feldspar and scattered phenocrysts of biotite and a few red crystals (rusted olivine?). Elongate masses of quartz and feldspar in the tuff appear to be possibly devitrified collapsed pumice. Other masses of brown material look like devitrified glass of possibly andesite composition. The groundmass consists of compacted and devitrified dusty shards.

Unit Tos_4 consists of nonwelded beds of tuff totalling about 285 feet thick. Most beds are light gray to buff; but pink beds or pink mottling is fairly common, whereas a few beds are yellowish green. The beds are commonly 2 to 15 feet thick, fine to medium grained and are well laminated to fairly massive. Yellowish green porcellanitic beds, a few inches to several feet thick, form hard, dense ledges and most other beds crop out conspicuously. Pumice (commonly devitrified) and ash shards are moderately abundant and quartzite and obsidian fragments are locally numerous. Phenocrysts consist chiefly of feldspar, quartz, biotite, and an opaque oxide. Bed 43 of the Rainier area (table 4), which is about 35 feet thick and whose top is about 50 feet below the top of the unit, is a distinctive marker bed. It is pink (mottled with white) to red, soft, lightweight, and contains abundant white pumice fragments commonly half an inch long but as much as 1½ inches in length. It is correlative with Bed 24b of the USGS area.

Unit Tos_5 consists of nonwelded beds of pumiceous tuff ranging from about 100 to 125 feet in total thickness. An unconformity at its top (fig. 3) likely accounts for the range in thickness. The tuffs are fine to coarse grained and well bedded; individual laminations are commonly a few inches to 4 feet thick. The beds are mostly yellowish green, greenish gray, or greenish brown, and they form a distinctive color band on the hillside. They are generally of light weight and are poor to moderately good ledge formers. Tubular pumice fragments are abundant in most beds, and some more resistant bands about 0.5 foot thick contain scattered to numerous fragments of quartzite and volcanic rocks. Obsidian and perlite fragments are common also. Much of the basal bed has a sugary texture probably caused by partial devitrification of the pumice fragments. Phenocrysts are generally small and scattered and consist chiefly of feldspar and quartz and minor biotite. A few black mafic grains are scattered throughout the beds.

Unit Tos_6 is a lenticular body of rhyolitic welded tuff exposed on the east slope of Rainier Mesa. It is exposed along an outcrop length of about 1,300 feet centering at "Cat Hill" (see fig. 2) from which it extends to the south and to the north. Its greatest exposed thickness, about 125 feet, is just north of "Cat Hill." The rock is hard and dense, and stands in nearly vertical ledges. It is mostly olive brown where fresh and is purplish red or pink where oxidized. It contains scattered phenocrysts of quartz and sanidine, spare biotite and clumps of opaque oxide, lenses of collapsed zeolitized pumice, in a groundmass of compacted devitrified shards. Partly filled elongated cavities and dark coarsely devitrified zones 2 to 3 inches long and a quarter to half an inch across give the rock a striking distinctive appearance. Inclusions of foreign material are common. Some of these are several inches across, although most of them are much smaller. They consist chiefly of volcanic rock fragments but include a few fragments of granitic material, quartzite, and other rock types. In most places 2 to 3 feet of dark gray to olive brown perlite or pitchstone occurs at the base. Just north of "Cat Hill" the lower several feet is strongly brecciated and is recemented by milky white opal. A generally present basal conglomerate, locally as much as 5 feet thick, consists chiefly of quartzite and volcanic rock fragments but also contains a few pebbles of granitic material.

Unit Tos_7 consists of highly variable nonwelded light gray and light brown bedded tuffs totalling about 720 feet thick. It appears to be unconformable on units Tos_6 and Tos_5 below. Most beds are very granular and, except for about the basal 180 feet and the upper 50 feet, are very friable. As a result, exposures are few, especially in the middle part of the unit; in some places overburden is as much as 60 feet thick. Most of the granules consist of sand-size quartz and feldspar. Biotite is common and quartzite fragments are common locally. The basal 50 feet and the top 35 feet contain abundant pumice fragments. The upper 35 feet is related genetically to the overlying welded tuff of unit Tos_8 and grade imperceptibly into it through a transition zone about 4 feet thick.

Unit Tos_8, about 270 feet thick, forms the caprock of Rainier Mesa and the high spur just northwest of the USGS Tunnel area. It consists chiefly of welded tuffs in two distinct ash flows emplaced probably in two separate volcanic eruptions. The lower ash flow is chiefly rhyolite; the upper is chiefly quartz latite. At the base the lower welded tuff grades downward through a zone several feet thick into coarse-textured very pumiceous porous nonwelded tuff or pumicite. The upper welded tuff grades upward into porous nonwelded tuff. The two ash flows that comprise the unit are distinguished readily at a distance by a dark-colored band of vitrophyric welded tuff about 10 to 15 feet thick above the base of the upper flow and by differing erosional forms. Viewed at close range, however, the actual contact between flows is difficult to find.

Thin sections of representative core samples of unit Tos_8 were studied by Ray E. Wilcox, and a complete description of these is planned for a future publication. In the most general terms, the sections show a dense groundmass of tightly packed shards and collapsed pumice characterized by irregular spherulitic devitrification. Near the top of the welded tuff there are streaky bands of obsidian containing many opaque microlites. Partly filled elongated cavities are abundant at some levels. In contrast with the welded tuffs of unit Tos_6, those of unit Tos_8 contain abundant phenocrysts and very few large foreign inclusions. Euhedral and fragmental phenocrysts of feldspar and quartz are abundant; biotite, clinopyroxene, and an opaque oxide are sparse. The feldspar ranges from sanidine at the alkali end to oligoclase, andesine, and labradorite. The groundmass of the overlying nonwelded part of the upper ash flow is not compacted, it consists mostly of devitrified shards and pumice, and contains fewer phenocrysts than the underlying welded tuff.

The tuffs at the USGS Tunnel area are all included in units Tos_2, Tos_3, and Tos_4. All are rhyolitic or quartz-latitic except possibly beds 24f and 24h, which on the basis of their phenocrysts may be dacitic. Most beds contain pumice and ash shards, and about half the beds contain obsidian fragments. According to Ray E. Wilcox (personal communication, 1957) the fragments were initially glassy and subsequently have been devitrified or otherwise altered throughout except for the interiors of some of the dense obsidian. A predominating alteration product is a zeolitelike silica-rich heulandite which acts as a cementing material between shards and other fragments and also lines cavities. Of the foreign fragments, subangular to subrounded gray to drak-brown quartzose material predominates; granitic, gneissic, schistose fragments and older volcanic fragments occur in subordinate amounts.

Phenocrysts of quartz and alkali feldspar are sparse to abundant. Wilcox's studies indicate that the alkali feldspar is a soda-sanidine that probably corresponds to the soda-orthoclase of the welded tuffs that cap Rainier Mesa. Phenocrysts of plagioclase (largely oligoclase or oligoclase-andesine) are generally less abundant than quartz or sanidine but are present in all but a few beds. Altered biotite and an opaque oxide (probably magnetite) were noted in over half the beds. Phenocrysts of green hornblende were found in a few of the upper beds and rare crystals of pyroxene were noted in three beds. Sparse crystals of titanite(?) were found in beds 23-1 and 23h.

Semiquantitative spectrographic analyses, rapid rock analyses, and specific gravity determinations were made of samples from beds 19b, 20, 22e, 24f. (See tables 2 and 3 in appendix.) These analyses show that there is only a small range in chemical composition between the beds that were sampled. Of the major oxides, SiO_2 ranges from 65 to 71.5 percent; Al_2O_3 ranges from 11.4 to 13.4 percent; K_2O ranges from 1.5 to 4.4 percent; CaO ranges from 0.63 to 3.7 percent; and Na_2O ranges from 1.4 to 2.1 percent. Oxides of iron, magnesium, titanium, phosphorus, and manganese are minor constituents. Minor amounts of titanium, manganese, barium, berryllium, chromium, copper, gallium, lanthanum, nickel, lead, scandium, strontium, yttrium, ytterbium, and zirconium were detected spectrographically.

Quaternary alluvium

Alluvium derived from the Nevada limestone and the Oak Spring formation has been deposited along a few small tributaries in the mapped area. It is mostly sand-size to cobble-size material although some silt- and boulder-size material is present. It ranges in thickness from a thin veneer to several feet.

GEOLOGIC STRUCTURE

General features

The Frenchman-Yucca Flats area of the Nevada Test Site lies within a region that has been subjected to two and possibly three or more periods of structural deformation. Strongly deformed Paleozoic rocks are overlain unconformably by gently folded Tertiary rocks of the Oak Spring formation. Folding and faulting both preceded and followed deposition of the Oak Spring formation, and occurred intermittently during its deposition. Unconformities occur within the Oak Spring formation at the tops of units Tos_5 and Tos_6, and probably at the base of the uppermost bed of unit Tos_7.

Frenchman and Yucca Flats are interior-drainage basins, or bolsons, typical of the Basin and Range province of Nevada. Both basins are underlain centrally by broad flat blankets of alluvium that rise gently toward the flanks of the enclosing hills where they merge with sloping coalesced alluvial fans. Here and there at the foot of the hills, small piedmont scarps in the alluvium mark recently active basin faults. Several of these faults southeast of Frenchman Flat are visible from the Mercury highway, especially in the late afternoon when the sun is low. In Yucca Flat, a large recently active fault, named the Yucca fault by Johnson and Hibbard (1957, pl. 32), extends north to south across the flat from Oak Spring Butte to Yucca Pass--a distance of more than 20 miles. To the north the Yucca fault joins other major faults that extend north beyond the limits of the Test Site.

The hills bordering Yucca Flat are themselves much faulted; those to the east of the flat are more so than those to the west. The USGS and Rainier Tunnels, at the northwest side of Yucca Flat, are within the less faulted part of the area. Even so, small faults are common and sizeable ones are present.

Structure of the USGS Tunnel area

Rocks exposed in the USGS Tunnel area (fig. 1) are part of the Oak Spring formation. Paleozoic rocks crop out nearby, but within the map area they are concealed by about 300 to 450 feet of nonwelded tuffs of the Oak Spring formation. The Oak Spring formation rests on the upturned edges of the Paleozoic rocks with an angular unconformity that is very pronounced in most places and has considerable local relief. The unconformity is well exposed near the Rainier Tunnel where shallow channels in the top of the Paleozoic limestone are filled with conglomerate in the base of the Oak Spring.

Folds

Over most of its outcrop area the Oak Spring formation is gently folded into shallow anticlines and synclines. In the area surrounding the USGS Tunnel these folds trend generally to the northeast; the axes of several such folds pass through the Rainier Site. Within the USGS area, the structure is generally homoclinal. A short distance to the north the axis of a sizeable anticline trends about east-northeast and plunges gently eastward, and to the east the axis of a minor syncline trends generally south. Between these fold axes, within the USGS site, the beds dip mostly to the east or northeast at angles of 5° to 15°; local departures from this general attitude are common, especially near and along faults (fig. 1).

Faults

Small normal faults, with vertical displacements of a few inches to 50 or 60 feet, are abundant in the USGS Tunnel area. Room A was intentionally located in a highly fractured area near several faults to test the behavior of high explosives in fractured rock. Room B was located in sounder, less fractured rock. Within the area most faults fall within either of two well-defined sets--one that trends northeastward and dips northwest and one that trends northwestward and dips northeast. Faults of the northeast set are upthrown to the southeast and faults of the northwest set are upthrown to the southwest. Exceptions to this rule are rare, and one or two curved faults that change orientation from northwest to northeast also change attitude and throw consistent with the above pattern. The very marked divergence in trends of the two fault sets shown on figure 1 is due partly to the influence of topography on their traces; the actual divergence in strikes is appreciably less. Dips, where measurable, range mostly from 50° to 70°. The pattern of two mutually opposed sets of normal faults suggests a west to east tensional condition in the earth's crust at the time of faulting.

For their relatively small displacements, most of the faults of the area have relatively wide zones between walls. On the other hand, the widths of fault zones vary widely within single faults and in short distances, depending apparently on the behavior of the particular beds through which the faults pass. In general, fracturing in the form of shattering or sheeting is more extensive in the hanging wall than in the footwall, and in places the limits of the fault zone in the hanging wall are vague or indefinite. These generalizations are confirmed by underground as well as surface observations.

Joints

Joints also are abundant in the area, and they also form a well-defined pattern of two sets subparallel to the faults. Generally steeper than the faults, however, their dips range mostly from 70° to vertical.

At any given location, one joint set commonly predominates over the other. Generally speaking, the northeast set is stronger and more persistent than the northwest set, but locally the converse is true. Prior to the tests, joints were stronger and more closely spaced at the surface in the vicinity of Room A than they were in the vicinity of Room B. Prior to the dynamite explosions few joints had been traced much more than 40 feet along any single fracture, but after the explosions, when some joints were opened up by the blasts, it became evident that some of them extended several times that distance as discrete and continuous, although tight, fractures.

Structure of the Rainier Tunnel area

The Rainier Tunnel is located in an area of volcanic rocks on the east flank of Rainier Mesa 1½ to 2½ miles west of the USGS Tunnel. This area, shown on figure 2, is 7,500 feet long west to east and is 5,000 feet wide north to south. The volcanic rocks of the Rainier area are gently folded into a series of apparently shallow-rooted east-trending anticlines and synclines. These folds are superimposed on more complexly deformed Paleozoic rocks, mainly limestones of Devonian age. Three methods of presentation are used to portray the spatial characteristics of these folds and associated geologic structures: (1) a geologic map (fig. 2), (2) geologic sections (fig. 3), and (3) a structure contour map (fig. 4). On the geologic map the folds are indicated by the plotted traces of their axes and by dip and strike symbols that depict the variations in bedding attitudes.

Geologic sections were prepared to show the two-dimensional form of the folds parallel to selected surface profiles. Section A-A' is parallel to and coincides in part with the centerline of the Rainier Tunnel. As the tunnel line and the line of section cross the structural trends at oblique and variable angles, true thicknesses and dips of beds do not appear in section A-A', but instead, components of thickness and dip are shown. Section B-B', on the other hand, is drawn more nearly perpendicular to the structural trends, and hence thicknesses and dips of beds are shown in nearly true scale (fig. 3). Both of the geologic sections and the structure contour map as well, were drawn prior to completion of the Rainier Tunnel. Additional subsurface data, made available since these figures were drawn and since completion of the tunnel, will be incorporated into later versions of the illustrations being prepared for future publication.

The structure contour map (fig. 4) portrays the three-dimensional form of the folds in the volcanic rocks but makes no attempt to show the structure in the underlying limestone. For this map the top of the portal bed, the uppermost bed in unit Tos_3, was selected as the reference horizon upon which the contours were drawn. West of the outcrop of the portal bed the contours are underground and are shown as solid lines. East of the surface outcrop, the contours are projected into space above the ground surface and are shown as broken lines; they indicate the restored position of the portal bed prior to its erosion.

The structure contours are most accurately drawn in the central part of the map area where the portal bed is near to the ground surface and where control data are plentiful. Owing to lack of control west of the face of the mesa, contouring was not extended into that area.

Folds

The general trend of folding in the area is northeastward. For convenience of description the following names, north to south, are applied to the folds in the immediate vicinity of the Rainier Tunnel: the Point Mabel syncline, the Cat Hill anticline, the False Start syncline, and the UCRL anticline. The Point Mabel syncline and the UCRL anticline are segments of sizeable structural features that extend well beyond the limits of the area mapped. The Cat Hill anticline and the False Start syncline, however, are minor structures entirely within the mapped area; they can be envisaged as second-order folds modifying the flanks of the larger Point Mabel and UCRL folds. Their trends--about N. 80° W.--are oblique to the trends of the major structures.

Over most of the area the folds plunge gently westward, and along the face of the mesa nearly all dips have a westerly component. A few thousand feet east of the mesa rim, however, the Point Mabel and UCRl folds reverse and plunge eastward. The UCRL anticline, therefore, is a closed, doubly plunging fold. Its point of culmination approximately underlies the third switchback of the road to the Rainier Tunnel, and its closure is about 75 feet.

A thousand feet or so north of the Point Mabel syncline is a large unnamed anticline. This feature has little expression in units Tos_7 and Tos_8, but it is well developed in the underlying older units of the Oak Spring formation. As it is mostly outside the mapped area, it has not been examined in detail, and would have little effect upon any tests planned for the Rainier Tunnel. A small unnamed syncline just south of the UCRL anticline can be observed between the second and third switchbacks on the road to the tunnel. Its axis is plotted on the geologic map (fig. 2).

Faults

Faults are not abundant in the Rainier Tunnel area, and most of those present are of small size. Most of the faults trend northwestward. They are too few in number to warrant any definite conclusions as to their possible relationships to one another, but they seem to fall into two sets or families. Faults of one set trend mostly N. 15° W. to N. 35° W., are upthrown on the northeast, and probably dip southwestward; faults of the other set trend from about N. 45° W. to about N. 70° W., are upthrown on the southwest and dip northeast. The displacement habits of the two sets of faults and the relationship of one set to the other are the same as those of the faults at the USGS Tunnel area; and chances seem good, therefore, that the faults of the two areas are related and were formed by the same stresses at about the same time.

Joints

In the nonwelded tuffs, joints are less prominent in the Rainier Mesa area, by and large, than in the USGS area; and fewer of them have been mapped. The hard welded tuffs that cap the mesa, however, are very susceptible to jointing; and along the rims of the mesa large near-vertical columnar joints are very conspicuous. The shocks and vibrations of the Rainier Test dislodged numerous large boulders of welded tuff from the cliffs of the rimrock by failure along joint planes.

Numerous lineaments in the cap rock of the mesa can be observed on air photographs and are plotted on the map. Many of these lineaments are inconspicuous or virtually undetectable on the ground, most of them undoubtedly are joints in the welded tuffs, but some may be faults. Fracturing produced in the cap rock of the mesa by the Rainier Test was influenced in its pattern by the orientation of lineaments at the surface, and most individual fractures coincided with pre-existing joints or lineaments.

GEOLOGIC EFFECTS OF THE HIGH-EXPLOSIVE TESTS AT THE USGS TUNNEL SITE

Surface effects of the 10-ton explosion in Room A

On February 21, 1957, at 2:01:01 p.m. 10 tons of 60 percent nitroglycerin gelatin dynamite was exploded in Room A. At the instant of the explosion the entire area above Room A was lifted several feet by the blast--visual estimates range as high as 10 feet. An instant later the surface fell back toward its original position. Precision surveys before and after indicate that a roughly oval area covering about 3,700 square feet was permanently raised a foot or more above its former position, and a subcircular area of nearly 12,000 square feet was lifted half a foot or more. The uplift--both transitory and permanent--was predominantly southwest of ground zero, chiefly because the shortest distance above the chamber to the ground surface is southwest of ground zero. Most of the rock breakage caused by the blast was in the southwest quadrant also. Rough estimates indicate that about 54,000 tons of rock was involved in lifting, breakage, or fracturing. The quantity of closely broken rock, however, was much smaller.

An instant after the shot was detonated, a horizontally directed blast of gas, dust, and rock fragments emerged from the portal of the tunnel. The gas-dust cloud traveled thousands of feet from the portal before it lost momentum and was dispersed into the atmosphere by the wind. The large volume of rock hurled from the tunnel by the blast was deposited in a narrow cone of dispersal fanning outward from the portal. Blocks of rock a foot in diameter were thrown 150 feet from the portal, although most of the material carried that far was smaller; small stones were thrown as far as 400 feet. Like a blast from a giant shot gun, the scatter pattern was narrow, well defined, and remarkably clean cut. Juniper trees partly in the trajectory of the cloud were stripped of leaves, bark, and branches on the side within the path but were left unmarked on the other side. A tree 75 feet from the portal was stripped clean, but a mounted set of fuse boxes less than a foot away was undamaged. The escape of energy from the tunnel was due to partial destruction of one wall of the shot chamber by the explosion, which permitted the gases to by-pass the stemming outside the room; this effect is more fully discussed by Cattermole (1958, p. 12).

Pre-existing planes of weakness exerted a strong influence on the surface pattern of fracturing caused by the blast; most of the breakage, in fact, followed pre-existing fractures; and the area of deformation was largely delimited by pre-existing fractures. The extent and limits of fracturing are shown in figure 5, "Pattern of fractures opened by 10-ton explosion, USGS Tunnel area."

Deformation west of Room A was restricted mostly to the area between ground zero and the northeast-trending fault 10 feet west of ground zero. Some breakage and lifting occurred along bedding planes west of this fault, probably because the fault plane dips westward and the shock wave from the blast was partly transmitted through it; were it to dip eastward, it probably would have dampened the shock more completely.

Southwest of ground zero deformation was largely restricted by the northwest-trending fault that passes up Portal Draw. This fault dips eastward. Again, however, minor fracturing and movement occurred to the west of the fault, mostly along old joints.

On the south, deformation was limited largely by the outcrop of Bed 22a. The base of this bed served as a parting plane above which all overlying rocks were lifted upward by the blast and below which little or no surface deformation took place. That is, downslope from the outcrop of Bed 22a, deformation was negligible. Several higher bedding planes also served as parting planes. Lifting extended eastward along the base of Bed 22a to a point 57 feet southeast of the tunnel centerline where a strong joint plane restricted further movement.

The most distant observed effects of the blast occurred about 310 feet south-southwest of the chamber where the ground opened slightly along the hanging wall of the same northeast fault that passes just west of ground zero.

On the east the limits of deformation were somewhat indefinite, owing probably to a lack of any strong, continuous, or well-defined structural features that might have served to restrict the movement. The greatest surface displacement followed a small pre-existing fault due south of ground zero, and most of the severe fracturing was west of this fault; the west side of the fault was uplifted 10 inches vertically relative to the east side.

North of ground zero surface deformation was negligible, chiefly because the ground surface rises rapidly in that direction, and the amount of cover above the shot chamber increases accordingly.

A small crater caused apparently by escaping gas was formed 150 feet south by west of the shot chamber at the junction of Bed 22a and the fault in Portal Draw. For several hours gas "bubbles" rose through the fine dust that formed the bottom and lips of the crater, and a strong odor of gas remained at the crater 24 hours after the test.

Surface effects of the 50-ton explosion in Room B

On April 5, 1957 at 6:30:31 a.m. 50 tons of 60 percent nitroglycerin gelatin dynamite was exploded in Room B. The area over the chamber was lifted several feet by the blast. High-speed photographs taken at the time indicate that a maximum uplift of 15 feet occurred over ground zero between 0.7 second and 1.2 seconds after the explosive was detonated. Most of the doming was within a radius of about 100 feet of ground zero, but uplift and severe fracturing occurred as distant as 525 feet from ground zero. An instant after the blast the ground surface fell back toward its previous position and the present fracture pattern became fixed. The extent and limits of fracturing are shown in figure 6, "Pattern of fractures opened by the 50-ton explosion, USGS Tunnel area."

From knowledge gained by the blast in Room A, a more effective stemming method was devised for the Room B explosion, and the 50-ton blast was completely contained insofar as the tunnel was concerned. The more effective containment of the 50-ton explosion and, hence, the proportionately increased energy expended into the rock probably account in large part for the many times greater rock deformation by the 50-ton explosion than by the 10-ton explosion, especially in view of sounder pre-blast rock conditions above the 50-ton chamber and a higher calculated containment factor for the 50-ton explosion. Although 50 tons of explosive should yield 5 times the energy of 10 tons, the surface effects to the 50-ton blast extend over about 12 times the area of the 10-ton blast, and the volume of rock involved is estimated to be about 23 times as great. Rough estimates based on surface and underground observation indicate that about 758,000 cubic yards of rock, or about 1¼ million tons, was involved in the lifting, breakage, and fracturing caused by the 50-ton blast. The quantity of closely broken rock was much less. About 32,250 cubic yards, or about 54,000 tons, was involved in the 10-ton shot. A logical conclusion is that a large quantity of the energy of the 10-ton blast was expended out of the tunnel in the gas-dust cloud that accompanied the explosion.

As with the Room A explosion, most of the strongest displacements were along pre-existing fractures in the rocks, but in contrast with the Room A explosion, many strong fractures were formed within previously sound rock. The fracture pattern caused by the blast is mainly radial and focuses at the surface near ground zero, but the pattern is modified by pre-existing fractures along which renewed movement or dilation occurred and by differential cover above Room B owing to topography. Fracturing was relatively light in the northwest quadrant of the blast area because of higher ground and hence greater thickness of cover in that direction. The severest fracturing was eastward from ground zero within a radium of about 100 feet of ground zero.

Pronounced radial fracturing occurred mostly in the area within 200 feet of ground zero where the surface was strongly dilated by the updoming caused by the blast. Beyond 200 feet most of the breakage followed pre-existing planes of weakness in the rocks, such as faults, joints, and bedding planes. Such planes of weakness served to outline the entire disturbed area, except for a relatively few outlying fractures.

In plan the disturbed area is roughly triangular with a base facing east and an apex pointing west. The length of the base is about 600 feet, the distance from base to apex is about 360 feet, and the area within the disturbed triangle is about 12,000 square yards. Again, minor effects and some sizeable fracturing occurred outside the triangle, but the most notable effects are within. The broad base of the triangle, on the east, is formed of a near-continuous fracture or zone of fractures along a pre-existing west-dipping fault; the apex of the triangle is at the intersection of two faults which underwent movement when Room A was detonated and which underwent renewed movement when Room B was detonated. During both explosions these faults largely limited deformation on the west. The southwest side of the triangle is marked by a zone of bedding-plane breaks shown at the ground surface by open fractures along bedding planes or by low scarps in the overburden; the northwest side of the triangle is defined by discontinuous open fractures that dip steeply toward the southeast and trend radially from ground zero.

Relative to the surrounding hillside, the triangular area defined above was lifted upward and pushed southward by the force of the explosion. Differential horizontal displacement is especially pronounced along the fault that bounds the triangle on the east where sets of en echelon tension fractures were produced by horizontally directed couples. Strong differential movement also occurred within the triangular area itself, and outside the immediate intensely fractured vicinity of ground zero the greatest accumulative displacement was along a series of south-trending fractures due south of ground zero. Along each of these fractures, the west side moved up and southward relative to the east side.

In the intensely fractured area near ground zero the present fracture and displacement pattern are the composite result of the movement and breakage that accompanied updoming at the instant of the explosion and the gravitative collapse that immediately followed. The greatest single displacement is along an old north-trending fracture 35 feet east of ground zero. Prior to the explosion this fracture had no appreciable displacement at the ground surface, but underground it may have joined a small slip near station 3+05. As a result of the blast, a surface scarp was formed along this fracture for a distance of about 200 feet, centering due southeast of ground zero where its displacement--upthrown on the east--is about 72 inches. From that point the displacement diminishes gradually northward and southward.

A second large scarp, also upthrown to the east and with a maximum displacement of nearly 3 feet, was formed along an old fault 10 feet west of ground zero. (This fault crosses the main tunnel at station 2+65.) The scarp dies out gradually to the north. To the south, it ends rather abruptly in a maze of fractures in the old fault zone. The wedge-shaped area between the two large scarps, which contains ground zero, is less severely fractured than the area just to the east; but it contains exceptionally large openings--some as much as 4 feet across--and numerous grabenlike collapse features. Gas from the ignition of the dynamite issued from these openings for several days after the blast.

Most of the fractures caused by the 10-ton explosion in Room A were further widened or otherwise modified by the 50-ton explosion in Room B. One large fracture trending south from ground zero of Room A, approximately along coordinate E 646,770, had its relative displacement reversed by the B explosion. The west side of this fracture was uplifted by the A explosion; the east side was uplifted by the B explosion which cancelled out the displacement caused by the first blast. Renewed lifting occurred at the base of Bed 22a in the tunnel portal area. Additional lifting occurred to the southeast, where this bedding plane previously was unaffected, to a point where the bed abuts at the surface against a prominent fault at grid point E 646,910, N 892,630. This is the same fault that surfaces 10 feet west of ground zero and crosses the tunnel at station 2+65. At that point the lifting crossed the fault and extended southeastward along a juxtaposed bedding plane in unit 19. Unit 19 formed the back in Room B prior to the explosion just as Bed 21 had formed the back in Room A. The scarp formed by these lifted bedding planes defines the southwest limit of the disturbed area and is one side of the triangle previously mentioned.

At grid point E 646,930, N 892,460, the lifted bedding plane in unit 19 abuts against the prominent pre-existing west-dipping fault that served as an east and southeast boundary to the fractured area, the base of the triangle.

In addition to deep-seated fracturing, many sizeable fragments of rock were spalled from the faces of ledges and low cliffs, apparently owing to rebound as the shock wave caused by the blast traveled to and was reflected from the ground surface. The most extensive breakage of this sort was in the portal area where about 70 feet of the cliff face, with a maximum height of about 15 feet, spalled off along an old but tight fracture. Boulders fallen from the cliff face damaged the portal to the extent that the cap timbers and the lagging on the cap had to be replaced, and boulders that dropped on the access road in Portal Draw were of such size as to require drilling and blasting before they could be handled by a bulldozer. Some of these boulders had estimated weights of 50 tons or more. Additional spalling of lesser magnitude was common on the east slope of the hill, 225 feet or so from ground zero. Impact marks were made on ledges hundreds of feet downslope in the amphitheatre by rolling boulders spalled from the east side of the hill,

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APPENDIX

Table 1.--Composite section USGS Tunnel area, Nevada Test Site

Top of Section

Bed No.	Description	Thickness (in feet)
Unit Tos_4		
24 h	Tuff, light grayish brown, fine grained, massive; pumice and ash shards; crystals of plagioclase; alkali feldspar, quartz, biotite and amphibole	2.0
24 g	Mostly covered; forms sloping bench. Probably similar to bed 24 c.	17.5
24 f	Tuff, light gray, fine grained; shard and pumice fragments. Crystals of plagioclase and quartz (sand size) are moderately abundant; scattered crystals of biotite, alkali feldspar, amphibole and an opaque oxide. Dense, good ledge former, jointed. (Chemical analyses in tables 2 and 3). . . .	7.0
24 e	Mostly covered; forms sloping bench. Resistant beds 1 to 2 feet thick crop out about every 6 feet of section; beds consist of medium-grained tuff; fragments of pumice, shards, greenish yellow porcellanite, and small brown quartzite	30.0
	Total thickness of beds 24 h to 24 e. . . .	56.5
24 d	Tuff, mostly light brownish gray. Forms prominent rough-surfaced ledge. Contains many altered pumice fragments as much as	

Bed No.	Description	Thickness (in feet)
	one inch long mostly less than one-half inch and moderately abundant dark quartzite fragments; crystals of biotite and amphibole. Eleven feet above base is a one-inch thick white friable bed that divides unit into two benches.	16.7
24 c	Mostly covered but probably similar to bed below except more friable. Forms gentle slope.	21.6
24 b	Tuff. Lower 7 feet of unit is red with light-gray pumice fragments up to one inch and subangular quartzite fragments up to 1½ inches but mostly less than one-half inch; crystals of quartz, alkali feldspar, biotite, pyroxene, and an opaque oxide. Upper part is mottled light brown and is a good ledge former	11.8
24 a	Mostly covered but basal one inch exposes tuff, fine grained, hard, porcellanitic with some brown quartzite fragments; breaks into angular small blocks and slabs.	10.0
23 p	Tuff, chalky white, fine grained groundmass but contains fragments of pumice one-half long, shards, and scattered brown quartzite fragments up to three-fourths inch.	

Bed No.	Description	Thickness (in feet)
	Scattered crystals of quartz, alkali feldspar, plagioclase, amphibole, and an opaque oxide. Good ledge former.	4.5
23 o	Poorly exposed but appears to be light gray tuff containing shard and pumice fragments. In central part of interval is a one-inch porcellanitic grit containing many fragments of greenish-yellow porcellanite and a few crystals of sanidine	8.1
23 n	Tuff, light gray; shard and pumice fragments; a few crystals of sanidine and sand-size quartz	6.0
23 m	Tuff, light gray; pumice fragments; scattered crystals of quartz, alkali feldspar, plagioclase, hornblende, and an opaque oxide. One-inch thick pink bed 10 feet above base; one-foot thick porcellanite bed above pink bed. Fifteen feet above base is one-foot thick medium-coarse bed containing large brown quartzite fragments. Twenty-three feet above base is a resistant gritty bed consisting of dark gray and brown quartzite, shard, and pink porcellanite fragments. Gradational upper contact.	25.6
	Total thickness of beds 24 d to 23 m	104.3

Bed No.	Description	Thickness (in feet)
23 1	Tuff, light gray, fine grained, resistant, ledge former; massive. Abundant fragments of small medium-size brown quartzite fragments, pumice and shards. Scattered crystals of alkali feldspar, quartz, and plagioclase; a few crystals of titanite(?).	5.0
23 K	Tuff, light gray mottled with pink indistinctly bedded. Consists mostly of ash shards, but also pumice and quartzite fragments	11.9
23 j	Covered; forms definite bench. Exposures to northeast indicate an upper white friable tuff underlain by 4 to 5 feet of very light pink tuff.	7.0
23 i	Tuff, light gray, fine grained, moderately bedded; a few sand-size quartz crystals. A few scattered porcellanitic layers each about one inch thick	10.0
23 h	Tuff, greenish gray with some pink; abundant quartzite fragments and moderately abundant pumice fragments. Moderately abundant to scattered crystals of alkali feldspar, plagioclase quartz, biotite, and an opaque oxide and rare titanite(?)	0.8
23 g	Tuff, sandy (especially near base), light gray	2.7
23 f	Porcellanite, light pink	0.5
23 e	Tuff, gray weathering light brown, well bedded. Fragments of pumice and obsidian. Abundant	

Bed No.	Description	Thickness (in feet)
	crystals of quartz, alkali feldspar, and plagioclase; crystals of hornblende moderately abundant; scattered crystals of an opaque oxide.	8.0
23 d	Tuff, pink; abundant ash shards.	1.5
23 c	Tuff, light gray. Alternating beds 6 to 10 inches thick of medium-coarse fragments of pumice, porcellanite, and brown quartzite fragments. Scattered crystals of quartz, alkali feldspar, plagioclase, and an opaque oxide	7.5
23 b	Tuff, coarse, gritty, very dense; much greenish-yellow porcellanite. Indistinctly stratified	3.5
23 a	Tuff, gray, fine grained; alkali feldspar, plagioclase and quartz crystals. Stringers of porcellanite.	2.0
22 k	Tuff, pink mottled with white. Moderately abundant pumice, ash shards, and small shark-tooth-shaped black obsidian fragments; abundant quartz and alkali feldspar crystals, scattered to rare phenocrysts of plagioclase, biotite, and an opaque oxide	3.8
22 j	Tuff, similar to bed 22 h except locally darker. Small polygonal fracture patterns (3 to 4 inches across) developed on flat surfaces .	9.0

Bed No.	Description	Thickness (in feet)
22 i	Tuff, same as bed 22 h except it is pink with white haloes around small black obsidian(?) fragments.	2.5
22 h	Tuff, light gray, very massive, medium grained. Pumice and ash shards moderately abundant. Abundant alkali feldspar and quartz crystals; moderately abundant to scattered crystals of plagioclase, biotite, and an opaque oxide. Polygonal fracture patterns, 3 to 4 inches across, developed on flat surfaces	13.0
22 g	Tuff, light gray, very friable	0.5
22 f	Tuffaceous grit, well bedded	1.5
22 e	Tuff, pink; massive, numerous white pumice and ash shards. Abundant phenocrysts of quartz, alkali feldspars, and plagioclase; scattered phenocrysts of biotite, pyroxene(?) and an opaque oxide. (Chemical analyses in tables 2 and 3).	1.7
22 d	Tuff, light gray medium-coarse grained, friable; brown to black subangular fragments (mostly quartzite)	5.0
22 c	Tuff, alternating pink and gray bands.	1.0
22 b	Tuffaceous grit, gray, resistant; good ledge former	1.7

Bed No.	Description	Thickness (in feet)
22 a	Tuff, pink; fragments of pumice, ash shards and obsidian. Moderately abundant phenocrysts of quartz, alkali feldspar, and plagioclase; scattered biotite and an opaque oxide.	4.4
21	Tuff, mostly light gray, resistant, gritty. Moderately abundant fragments of pumice, ash shards, and obsidian. Moderately abundant phenocrysts of quartz, alkali feldspar, and plagioclase. Lower 3 to 4 feet are well bedded with grit bed at base (thin resistant beds at base), alternate with coarse tuffaceous beds. Sixteen feet above base is a 2-foot thick bed of light gray very friable tuffaceous grit. One-foot thick pink bed 14 feet above base. Upper 3 feet is light gray resistant tuff with porcellanite at base	20.5
	Total thickness of beds 23-1 to 21	125.0

Unit Tos_3

20	Tuff, light red (5 R 6/6) to light pink (5 R 7/4), abundant cream-colored ash shards as much as one inch long and moderately abundant brown limonite(?), pumice, and obsidian fragments. Abundant phenocrysts of alkali feldspar and	

Bed No.	Description	Thickness (in feet)
	moderately abundant to scattered quartz, plagioclase, and biotite. Hard, massive; breaks into sharply angular fractures. Sharp upper contact; gradational lower contact. This bed is referred to as the "portal bed." (Chemical analyses in tables 2 and 3).	7.7
19 d	Tuff; lower 1.5 feet is dense, fine grained, dark pink grading upward into successively lighter pink; contains moderately abundant pumice fragments, abundant phenocrysts of alkali feldspar and moderately abundant quartz and plagioclase and scattered biotite. Top 10 feet is nearly white. About 3 feet above base the tuff is medium-coarse grained and contains abundant pumice fragments; phenocrysts of alkali feldspar are abundant, quartz and plagioclase moderately abundant, and scattered biotite and an opaque oxide. Upper 10 feet has abundant pumice fragments and is fairly friable.	27.0
19 c	Tuff, yellowish gray, gritty at base. Moderately abundant pumice and ash shards and scattered foreign fragments; scattered phenocrysts of quartz, alkali feldspar, plagioclase, and biotite	3.3

Bed No.	Description	Thickness (in feet)
19 b	Tuff, porcellanitic, white, glassy, with open texture (loosely cemented, one-half to one-inch flat aggregates with cavities between). Abundant ash shards and a few foreign fragments; scattered phenocrysts of quartz, alkali feldspar, and plagioclase. (Chemical analyses in tables 2 and 3).	1.5
19 a	Tuff, porcellanitic, light gray, mottled with pink. Tuffaceous grit bed about 0.5 foot thick 8½ feet above base of unit. Abundant fragments of pumice, moderately abundant fragments of obsidian, and scattered foreign fragments; scattered to rare phenocrysts of quartz, alkali feldspar, plagioclase, biotite, amphibole, and an opaque oxide.	15.0
	Total thickness of beds 20 to 19	54.5
18	Tuff, light gray with thin pink bands, fine grained, moderately friable. Sand-size brown quartzite grains moderately abundant. Top bed is about 2 feet thick, fine grained at top and contains scattered pumice and ash shards, and scattered quartz and alkali feldspar phenocrysts. Lower bed contains abundant ash shards, moderately abundant obsidian, and scattered pumice and foreign	

Bed No.	Description	Thickness (in feet)
	fragments; scattered phenocrysts of quartz, alkali, feldspar, and biotite.	19.0
17	Covered.	5.0
16	Gritty porcellanite. Yellowish green at base with abundant quartzite fragments; overlain by gray and mottled pink stringers; quartzite fragments up to one inch at top of unit. Abundant pumice and moderately abundant obsidian fragments; moderately abundant quartz and alkali feldspar phenocrysts and scattered plagioclase, biotite	4.6
15	Tuff, fine-grained, well bedded; light gray alternating with some pink bands in upper part. Thin porcellanite bed one foot from top. Moderately abundant fragments of pumice, obsidian, and ash shards; moderately abundant phenocrysts of quartz, alkali feldspar, plagioclase, biotite and scattered opaque oxide.	28.0
	Total thickness of beds 18 to 15 . .	56.6
14	Tuff, divisible into three units. Lowest unit is about 4 feet thick, dark brick red, very dense, generally massive; breaks into sharply angular pieces. Middle unit is pinkish red and fine grained. Upper unit similar to middle unit except it is tan. Bed contains	

Bed No.	Description	Thickness (in feet)
	moderately abundant pumice, obsidian (black, hollow, pipe-shaped bodies), and ash shards, and scattered foreign fragments; quartz, alkali, plagioclase, and biotite phenocrysts moderately abundant, and a scattered opaque oxide; many brown limonite(?) inclusions	22.2
	Total thickness of bed 14	22.2
Unit Tos_2		
13	Covered.	14.0
12	Tuff, yellowish green, fine grained. Few blebs of white porcellanite up to 2 inches. Moderately abundant pumice and ash shards; moderately abundant phenocrysts of quartz and alkali feldspar and scattered to rare plagioclase, biotite, and an opaque oxide. . . .	6.0
11	Tuff, brick red lower half and light gray upper half, generally fine grained and dense. Scattered large fragments of quartzite. Very good ledge former	4.7
10	Tuff, coarse, fragments of pumice and tuff up to one inch; mottled light red and green.	2.2
	Total thickness of beds 13 to 10. . .	26.9
9	Tuff, light gray beds interbedded with three yellowish green porcellanitic beds. Light gray unit has abundant pumice fragments,	

Bed No.	Description	Thickness (in feet)
	moderately abundant obsidian and a few foreign fragments.	7.1
8	Tuff, reddish orange. Fragments of pumice, quartzite and porcellanite	2.2
7	Tuffaceous grit and thin brownish-gray porcellanite beds. Abundant pumice and quartzite fragments; moderately abundant phenocrysts of quartz, alkali feldspar, and plagioclase and scattered biotite and an opaque oxide.	2.5
6	Tuff, intermittent exposures of dense, fine-grained gray and pink beds. Some mottled pink and gray beds near middle of unit. Lower 6 feet mostly covered forming dip-slope bench.	20.5
5	Tuff, pink with thin dark red bands, well bedded, dense porcellanite layers but generally fine to medium grained. Abundant pumice fragments and moderately abundant obsidian; scattered phenocrysts of quartz, alkali feldspar, plagioclase and an opaque oxide. At base is one-foot thick pisolite layer, mottled pink and gray, dense.	9.0
4	Tuff, white, fine grained, dense except for for small cavities, bedded. Abundant pumice	

Bed No.	Description	Thickness (in feet)
	fragments and a few quartzite fragments; moderately abundant phenocrysts of quartz, alkali feldspar, and plagioclase and scattered biotite and an opaque oxide.	3.5
3	Tuff, top 0.5 foot is a grit which is underlain by light gray, fine-grained tuff with small brown quartzite fragments near top	4.0
2	Tuffaceous grit, yellowish brown. Abundant pumice fragments and large quartzite fragments. Moderately abundant phenocrysts of quartz, alkali feldspar, and plagioclase; scattered biotite, pyroxene and an opaque oxide. Good ledge former.	2.0
1	Tuff, alternating beds of yellowish gray and pink. Yellowish gray beds are fine (porcellanitic) to medium-grained. Abundant pumice fragments moderately abundant obsidian and ash shards and scattered brown quartzite fragments, and blebs of porcellanite. Moderately abundant phenocrysts. Pink beds are mottled with light gray (greenish cast), fine grained and dense. Unit is a good ledge former	10.5
	Total thickness of beds 12 to 1	61.3

Table 2.--Semiquantitative spectrographic analyses of representative samples, USGS Tunnel Site. Sample numbers correspond to bed numbers. Figures are given to the nearest number in the series 10, 3, 1, .3, etc. in percent. Symbols used are: - not looked for; 0 looked for, but not detected; M major constituent (greater than 10 percent). Katherine V. Hazel, analyst.

Sample No.	B-19b	B-20	B-22e	B-24f	No.	B-19b	B-20	B-22e	B-24f
Si	M	M	M	M	La	0.001	0.003	0.003	0.001
Al	3.0	10	10	10	Li	0	0	0	0
Fe	0.3	1.0	1.0	.3 - 1.0	Lu	0	0	0	0
Mg	0.1	0.3	0.3	0.3	Mo	0	0	0	0
Ca	0.3	1.0	1.0	1.0	Nb	0.01	0	0	0
Na	1.0	1.0	3.0	3.0	Nd	0	0	0	0
K	3.0	3.0	3.0	1.0	Ni	0.001	0.001	0.001	0.001
Ti	0.03	0.1	0.1	.03 - 0.1	Os	0	0	0	0
P	0	0	0	0	Pb	0.001	0.001	0.001	0.001
Mn	0.01	0.01	0.003	0.01	Pd	0	0	0	0
Ag	0	0	0	0	Pr	0	0	0	0
As	0	0	0	0	Pt	0	0	0	0
Au	0	0	0	0	Rb	0	0	0	0
B	0	0	0	0	Re	0	0	0	0
Ba	0.003	0.01	0.03	0.03	Rh	0	0	0	0
Be	0.00003	0.0001	0.0001	0.00003	Ru	0	0	0	0
Bi	0	0	0	0	Sb	0	0	0	0
Cd	0	0	0	0	Sc	0	0	0.0003	0.0003
Ce	0	0	0	0	Sn	0	0	0	0
Co	0	0	0	0	Sr	0.003	0.01	0.01	0.03
Cr	0.0003	0.001	0.001	0.001	Sm	0	0	0	0
Cs	0	0	0	0	Ta	0	0	0	0
Cu	0.0001	0.0003	0.0001	0.0001	Tb	0	0	0	0
Dy	0	0	0	0	Te	0	0	0	0
Er	0	0	0	0	Th	0	0	0	0
Eu	0	0	0	0	Tl	0	0	0	0
F	-	-	-	-	Tm	0	0	0	0
Ga	0.001	0.001	0.001	0.001	U	0	0	0	0
Gd	0	0	0	0	V	0	0	0	0
Ge	0	0	0	0	W	0	0	0	0
Hf	0	0	0	0	Y	0.001	0.003	0.003	0.001
Hg	0	0	0	0	Yb	0.0001	0.0003	0.0003	0.0001
Ho	0	0	0	0	Zn	0	0	0	0
In	0	0	0	0	Zr	0.003	0.01	0.01	0.01
Ir	0	0	0	0					

Table 3.--Rapid rock analyses, in percent, and specific gravity determinations of representative samples, USGS Tunnel Site. Sample numbers correspond to bed numbers. P. L. D. Elmore, S. D. Botts, and M. D. Mack, analysts.

Sample No.	B-19b	B-20	B-22e	B-24f
SiO_2	71.5	70.3	67.8	65.0
Al_2O_3	11.4	11.8	13.2	13.4
Fe_2O_3	.83	1.7	2.3	1.9
FeO	.04	.22	.02	.30
MgO	.22	.51	.52	1.2
CaO	.63	1.4	1.6	3.7
Na_2O	1,8	1.5	2.1	1.4
K_2O	4.2	4,4	4.0	1.5
TiO_2	.12	.20	.26	.30
P_2O_5	.00	.00	.00	.03
MnO	.03	.03	.03	.04
H_2O	8.8	7.4	6.8	10.6
Co_2	.18	.09	.15	.16
	100	100	99	100
Sp. G. (lump)	1.68			
Sp. G. (powder)	2.28	2.26	2.31	2.24

Table 4.--Stratigraphic section of Oak Spring formation, Rainier Tunnel Area

(Description of units 8 and 7 taken from log of drill hole No. 3. Description of units 2 and 3 based largely on stratigraphic section measured and described by Ernest Dobrovolny, and J. M. Cattermole.)

TERTIARY

Oak Spring formation

Unit Tos_8

Bed No.	Description	Thickness (in feet)
83	Rhyolitic welded tuff, pale red purple (5 RP 7/2--wet). Abundant phenocrysts of sanidine, oligoclase, quartz, biotite, an opaque oxide, and rare augite in a groundmass of moderately compacted devitrified shards. Elongated cavities as much as one inch long. Slightly to moderately porous. Some jointing and staining along parting planes in first 10 feet; below 10 feet rock is firm. Gradational lower contact	28.0
82	Quartz-latitic (or rhyolitic) welded tuff, pale red purple at top of grading downward into mottled gray to banded, very dark gray. At top are large angular to subrounded fragments of tuff as much as 2 inches long	

Bed No.	Description	Thickness (in feet)
	and elongated cavities partly filled with opal(?) and limonite. Toward bottom fragments are smaller, cavities are less common, white phenocrysts are abundant and there are dark bands of obsidian	6.4
81	Quartz-latitic (or rhyolitic) welded tuff, dark gray. About one-half of rock consists of phenocrysts of sanidine (much embayed), andesine, biotite, quartz (a few embayed), opaque oxide, and rare augite. Groundmass is cryptocrystalline, feebly birefringent and crowded with tiny opaque trichite rods; some suggestion of fluxion structure, but could be true liquid flow. Sharp lower contact.	20.5
80	Quartz-latitic (or rhyolitic) welded tuff, grayish red purple (5 RP 5/2). Abundant phenocrysts of sanidine, oligoclase-andesine, quartz, biotite, an opaque oxide, and rare augite in a groundmass of compacted devitrified shards. Prominent schlieren (wavy lenses) and elongated flattened cavities (some opal in cavities). Smaller and less conspicuous schlieren toward base. Locally fractured.	156.0

Bed No.	Description	Thickness (in feet)
79	Quartz-latitic welded tuff (5 RP 7/2), grayish red purple. More friable and more fragments than above; spherulites. Many more cavities than above. Minerals are sanidine, quartz and rare biotite; pumice fragments, dense, brown inclusions (not quartzite). Abundant white pumice schlieren, flattened, less than one-half inch long. Locally fractured; less cavities toward bottom. Gradational lower contact.	38.0
78	Welded tuff, light gray, pale violet tinge, fine grained, abundant flattened pumice, few angular dark inclusions, minor quartz and biotite. Gradational lower contact.	4.0
77	Quartz-latitic(?), welded tuff, light gray red purple, abundant schlieren of pumice as much as 1½ inches long, very flattened; sanidine phenocrysts, biotite, quartz, similar to above but coarser. Locally fractured. More friable and more easily broken near base	19.0
	Total thickness of beds 83 to 77. . .	271.9

Unit Tos_7

76	Tuff, granular, light brownish gray (5 YR 6/1). Abundant fragments of pumice (as much as one inch; mostly less than one-half inch) and ash	

Bed No.	Description	Thickness (in feet)
	shards; some fragments of obsidian. More friable than above. Phenocrysts of sanidine, very little biotite, some quartz, little limonite. Scattered stony volcanic fragments. . . .	28.0
75	Tuff, granular, moderate reddish orange (10 R 6.5/5). Abundant pumice fragments mostly less than one-fourth inch (maximum one-half inch); rare biotite, sanidine, some quartz; large tan fragments (devitrified pumice) and a few small dark stony fragments. Grades to pale brown 12 feet above base and to light brownish gray 8 feet above base. Very friable 6 feet above base	27.5
74	Pumiceous-tuffaceous sandstone, moderately light brown (5 YR 4.5/5); very friable. Sand-size quartz grains, pumice fragments, altered biotite, feldspar(?). Grains subangular. Poorly sorted. There is a dark band (altered biotite?) one-foot thick 10 feet above base	22.5
73	Tuff, granular, loosely cemented, light brown (5 Y 6/4), fine grained. Abundant fine sand-size subangular to subrounded quartz and less abundant grains of feldspar in a friable chalky matrix. A few black grains. Seams one-sixteenth inch or less of white chalcedony. .	10.0

Bed No.	Description	Thickness (in feet)
72	Tuff, granular, light gray to nearly white, medium-coarse grained, friable. Made up mostly of subangular to subrounded grains (sand size) of quartz (probably predominates) and feldspar weakly cemented with a chalky binder. Scattered biotite and unidentified pink, orange, and lavender grains. In a few places there are pumice and ash shards and rock is lightweight.	231.0
71	Tuff, granular, light brown specked with white (small pumice fragments) subangular to subrounded quartz and feldspar; more abundant biotite than above and relatively abundant hornblende(?). Appears "dirty" in comparison to clean sand above due to brown chalky binder. Sharp upper contact	10.0
70	Tuff, granular, light gray flecked with black grains. Subangular to subrounded grains of quartz, feldspar, minor biotite and hornblende(?), very little binder	0.5
69	Tuff, granular, light brown flecked with white pumice. Same as bed above except more friable; gradational change to gray near base and more abundant pumice.	78.5

Bed No.	Description	Thickness (in feet)
68	Tuff, granular, light gray. Similar to bed above except locally finer grained and generally has more soft clay binder.	57.0
67	Tuff, granular, light gray. Mostly sand-size granular white feldspar, some quartz, scattered biotite, quartzite fragments. Weakly cemented . . .	3.0
66	Tuff, granular, brown. Weakly cemented rounded to subrounded grains mostly quartz and lesser feldspars. Few small green grains, biotite grains, and a black unidentified mineral	19.0
65	Tuff, granular, light gray. Mostly weakly cemented clean rounded fine-grained quartz and minor feldspar. Few small black grains. . . .	6.0
64	Tuff, granular, light gray. Granular weakly cemented sand-size feldspar (probably most abundant) and quartz. Scattered biotite, hornblende(?), scattered sand-size quartzite fragments. Pumice fragments near top.	10.0
63	Tuff, pumiceous, light gray to nearly white. Abundant fragments of fibrous pumice about one-fourth to one-third inch long. Phenocrysts of feldspar and quartz, and scattered biotite. Locally abundant rounded black grains.	35.0
62	Tuff, granular, gray to brown. Mostly weakly cemented fine-grained quartz, minor feldspar,	

Bed No.	Description	Thickness (in feet)
	subrounded to well rounded. Some rounded black grains	2.5
61	Tuff, granular to pumiceous, light gray. Pumice fragments one-eighth to one-fourth inch long moderately abundant. Granular, subrounded. White and clear feldspar and quartz; scattered biotite. Fragments of quartzite, sand-size and somewhat larger, moderately abundant. Porcellanite layer about 0.3 foot thick about half way up from the base.	43.5
60	Tuff, light gray to nearly white. Granular, subrounded, subangular, sand-size grains of quartz and colorless (sanidine?) to white feldspar held together with an earthy white cement. Small (mostly less than one-eighth inch) fragments of white pumice and sand-size to slightly larger brown fragments of quartz. Scattered biotite and some small unidentified subrounded black grains. Two inches of yellowish-green porcellanite 16 feet above base.	43.5
59	Tuff, gritty, light gray spotted with brown to dark gray subangular to subrounded fragments. Tuff is same as above except contains numerous	

Bed No.	Description	Thickness (in feet)
	brown dark-gray fragments of quartzite. Moderately sharp lower contact	7.0
58	Tuff, pumiceous, light brown (with possibly a reddish or pinkish cast) specked with white (pumice fragments). Very abundant white fragments of pumice mostly one-eighth to one-fourth inch long. Subrounded to subangular, mostly sand-size quartz and feldspar (clear and also white). Much more biotite than in bed above. Sand-size fragments to fragments one-fourth inch of brown to bluish gray quartzite. Some small grains of yellowish green mineral and also unidentified black grains.	38.5
57	Tuff, yellowish green, chalky, fairly soft. Abundant pumice and ash shards; moderately abundant quartzite fragments one-fourth to one-third inch long. Scattered feldspar and rare quartz. Some scattered brown bands similar to above	10.0
56	Tuff, white to light gray, fine grained.	35.0
	Total thickness of beds 76 to 56. . .	718.0

Unconformity

Bed No.	Description	Thickness (in feet)
Unit Tos_6		
55	Tuff, welded, rhyolitic; mostly olive brown to purplish red. Lenticular. Many phenocrysts of quartz and sanidine, scattered biotite, rare red crystals (rusted olivine?) and clumps of a fine-grained opaque oxide in a groundmass of compacted devitrified dusty shards. Scattered fragments of quartzite and volcanic rocks. Elongated cavities and lenses of collapsed pumice and coarsely devitrified zones. Rock is hard, comparatively heavy, and stands in near vertical ledges. Locally, basal part consists of 2 to 3 feet of nearly black perlitic (rhyolitic?) welded tuff; contains rare phenocrysts(?) of plagioclase and quartz and xenoliths of quartzite, granite, etc. in a groundmass of welded glass shards with perlitic cracks along which alteration has started. Local basal conglomerate, as much as 5 feet thick, and consisting chiefly of quartzites and volcanic rocks.	75.0 (max.)
	Total thickness of bed 55	75.0

Unconformity

Bed No.	Description	Thickness (in feet)
Unit Tos_5		
54	Tuff, yellowish green to greenish gray, pumiceous; well bedded. A few resistant bands contain scattered fragments as much as one inch long of volcanic rocks and quartzites	17.2
53	Tuff, yellowish green to greenish brown, pumiceous; medium to coarse grained, well bedded. Lightweight because of high porosity.	25.2
52	Tuff, pale-moderate yellowish green (10 Y 7.5/3). Generally fine grained, moderately well bedded (beds are a few inches to about 4 feet thick). Fine sugary texture; numerous bands, each about 0.5 foot thick that contain numerous dark-brown fragments of quartzite mostly less than one-eighth inch thick. Abundant to moderately abundant altered ash shards, pumice and obsidian, only sparse phenocrysts of quartz and feldspar	55.6
	Total thickness of beds 54 to 52	98.0*

*Probably because of the unconformity at top of unit, thickness of unit ranges from about 98 feet to 125 feet in mapped area.

Bed No.	Description	Thickness (in feet)
Unit Tos_4		
51	Tuff, mostly light gray but pink bed at base and at 7.5 feet above base. Fairly fine grained, pumiceous, fairly massive	18.0
50	Tuff, yellowish green. Abundant brown fragments of quartz and pumice fragments	2.0
49	Tuff, mostly light gray but with thin stringers and mottlings of pink (pink at top). Abundant pumice.	7.0
48	Tuff, pink (light at bottom). Abundant pumice fragments. Scattered quartzite fragments and obsidian(?).	13.0
47	Covered.	2.0
46	Tuff, gritty, yellowish green. Abundant quartzite and pumice fragments	1.0
45	Tuff, light pink, pumiceous; scattered quartzite fragments.	4.0
44	Tuff, yellowish green at base (especially lowest one foot) grading up into greenish gray. Very pumiceous in basal part. Moderately well bedded. Scattered fragments of quartzite up to one-half inch becoming fairly gritty 3 feet from top.	15.0
45	Tuff, pumiceous, pink mottled with white. Quartz and feldspar phenocrysts moderately	

Bed No.	Description	Thickness (in feet)
	abundant and scattered to rare biotite, amphibole, and an opaque oxide. Abundant white altered pumice fragments commonly one-half inch but up to 1½ inches and altered ash shards. Scattered obsidian and quartzite fragments. Bed is soft (breaks easily), punky and lightweight. Upper part is gray with pink mottling (blebs of pink 0.3 to 0.8 feet long). Red at the base. Gradational upper contact. White bed at about 21 feet at break in slope. (Bed 24 b of USGS Tunnel area)	35.0
42	Mostly covered. Tuff, light gray. Phenocrysts of alkali and plagioclase feldspar moderately abundant, scattered quartz, biotite, and an opaque oxide. Abundant altered pumice and few fragments of altered ash shards and obsidian; some quartzite fragments; only lower 2 feet exposed.	17.0
41	Tuff, light gray, fairly massive. Abundant pumice fragments especially in basal part. Indistinct pink bed at 8 feet above base. Gritty bed about 0.5 foot starting at 11.5 feet above base, greenish yellow, resistant; quartzite fragments up to one-half inch. (Correlates with base of bed 24 a at USGS Tunnel area.)	12.0

Bed No.	Description	Thickness (in feet)
40	Mostly covered. Two beds exposed between 10 to 15 feet above base (lower pumiceous; upper porcellanitic). Pink bed about 16 feet above base.	40.0
39	Tuff, light gray, generally massive pumiceous. Top forms good bench 50 feet wide.	10.0
38	Tuff, light gray, massive, fine grained and dense at base. Two feet thick pink pumiceous bed starting at 10 feet above base	12.0
37	Tuff, light gray at base with pink bed at 10 feet above base; well bedded especially near top. Pumice fragments. Gritty at about 10.5 feet above base	16.5
36	Tuff, pale pink. Pumice fragments; somewhat porcellanitic.	1.0
35	Tuff, light gray, coarser grained than below with pumice and quartzite fragments locally up to one-half inch. Rougher surface than below.	7.5
34	Tuff, light gray except for 2-inch thick pink band at 5.5 feet and 12.5 feet above base (3 inches thick). Dense, hard, generally massive with small quartzite fragments at top. Pink bed at 12.5 feet above base has small black obsidian fragments and small pumice fragments. . .	12.5

Bed No.	Description	Thickness (in feet)
33	Tuff, porcellanitic, yellowish green, gritty, well bedded. Abundant cemented pumice and quartz fragments	10.0
32	Tuff, light gray. Abundant fine-grained pumice. . .	12.0
31	Tuff, pink. Soft and pumiceous. Moderately abundant quartzite fragments	1.5
30	Tuff, light gray, generally fine grained. Small pumice and quartzite fragments	4.5
29	Tuff, pink. Abundant pumice and quartzite fragments. Gradational lower contact.	1.5
28	Tuff, light gray; abundant pumice and moderately abundant large quartzite fragments (up to 1 inch). Scattered pumice fragments up to 3 inches. Yellowish-green blebs (devitrification). Two to 6 inches of pink 12 feet above base. Some pink mottling (blebs 6 inches long) about 17 feet above base	28.5
	Total thickness of beds 51 to 28. . .	283.3

Unit Tos_3

27	Tuff, pink at base grading to red at top. Large fragments (commonly 1 to 2 inches and up to 4 inches) of pumice and elongated black obsidian. Obsidian commonly rimmed with white haloes and white in places has rind of black. Some shark-tooth-shaped black fragments, scattered	

Bed No.	Description	Thickness (in feet)
	quartzite. Pumice more abundant in lower part which is softer and more erodable. (Bed 20 of USGS Tunnel area).	35.5
26	Tuffaceous sandstone, salmon red and purple, locally cliff to ledge forming, locally coarse grained, beds ± 2.0 feet thick.	11.7
25	Tuffaceous sandstone, buff, mottled purple, thin bedded.	18.7
24	Tuffaceous sandstone, brick red to buff with some purple, locally well bedded, locally massive. Distinctive feature of bed is presence of channel and truncation by higher beds. Some of the channel fillings appear to be mudflows. (Bed 14 of USGS Tunnel area)	34.3
	Total thickness of beds 27 to 24. . .	101.4
Unit Tos_2		
23	Tuffaceous sandstone, occurring in beds 0.1 foot to ± 1.0 foot thick, well bedded, alternating bands of buff and purple, but most beds are buff. Local conglomerate beds with glassy pebbles less than 0.1 foot in diameter. Alternate ledge and recessions ± 2.0 feet thick. Clay fragments, buff with mottling in purple beds. Local strike N. 73° E., dip 42° N.	36.5

Bed No.	Description	Thickness (in feet)
22	Tuff, buff with some lavender; well bedded, beds 0.1 to 1.0 foot thick. Locally upper 4 feet pale purple. .	8.9
21	Tuff, buff; massive coarse.	5.1
20	Tuffaceous sandstone, coarser grained than Bed 19. Purple and buff beds ± 0.1 foot thick	2.5
19	Tuffaceous sandstone, well bedded, thin bedded, weak, forms undercut. Lower ± 0.1 foot is dense, fine grained red bed. Locally absent. Weathers to shalelike chips. Local channel or "pot hole" fillings. Above lowest 0.1 foot bed is a ± 0.2 foot of coarse grained sandstone	4.1
18	Tuffaceous sandstone, mottled lavender to buff; sharp contacts.	5.0
17	Tuffaceous sandstone; brick red to salmon, cliff forming in many places, local lenses and rolls, massive, occurring in beds 0.5 to 2.0 feet thick	9.1
16	Tuff, mainly concealed; probably a light-colored crossbedded tuffaceous sandstone.	14.0
15	Tuffaceous sandstone, red mottled; glassy grains and tuff, crossbedded. Locally conglomeratic with pebbles of obsidian and glass.	5.1
14	Tuff, buff with red lenses; soft, thin bedded. Also pink beds with buff stringers, crossbedded.	

Bed No.	Description	Thickness (in feet)
	Locally disseminated angular fragments of obsidian and tuff up to 1½ inches in greatest observed diameter. Sandstone, yellow at top of unit.	7.7
13	Tuff, pink to red; thick-bedded, slightly crossbedded.	2.9
12	Tuffaceous sandstone, pink, crossbedded, lenticular, lower 1.7 feet is dense, cryptocrystalline red tuff	14.0
11	Tuff, light gray to buff; some one-eighth inch greenish mineral, soft and earthy. Lower ± one inch vertically fractured with joints crossing bedding plane, pink to red	3.7
	Total thickness of beds 23 to 11. . .	118.6

Unit Tos_1

10	Tuff (intermittently exposed). Just above base is a thin-slabbed brown float of dense very fine grained tuff (bed location not known definitely but tuff is quite distinctive). One bed exposed about midway in section is very dense, dark red. At top is about 5-foot ledge of reddish brown tuff; has abundant altered pumice, and ash shards, some obsidian fragments, relatively abundant phenocrysts of	

Bed No.	Description	Thickness (in feet)
	feldspar, some quartz and an opaque oxide. Porous structure	19.0
9	Tuff; pinkish red at base to red at top, generally fine grained, hard. Plentiful golden brown biotite and cream-colored (some yellowish green) blebs of sugary material (altered pumice); also quartz and sanidine(?).	3.0
8	Covered.	27.0
7	Tuff (intermittently exposed), purplish red, generally fine grained, well bedded (bedding planes commonly one-fourth to one-half inch apart). Contains abundant golden-brown biotite and cream-colored altered(?) pumice fragments. Also contains quartz and sanidine(?).	10.0
6	Tuff, orange red, dense, fine grained, generally massive; phenocrysts of plagioclase and alkali feldspar, scattered quartz, biotite and limonite blebs. Moderately abundant altered pumice and ash shards; scattered altered obsidian; scattered foreign fragments. Forms conspicuous ledge.	12.0
5	Covered. Twenty-five feet above base is indistinct bench covered with cream-colored granular float.	

Bed No.	Description	Thickness (in feet)
	About 40 feet above base and continuing up to top of covered unit is a cream-colored float consisting of fine-grained tuff containing small subangular fragments of dark gray quartzite .	68.0
4	Intermittently exposed. Similar to below but somewhat finer grained and no conspicuous rounded aggregates on weathered outcrops. Some small, less than one-eighth inch, pumice fragments. . . .	35.0
3	Covered but float seems to be same as below.	15.0
2	Tuff, silicified; pale red purple (5 RP 6/2), coarse grained, well bedded. Weathers to conspicuous rounded aggregates less than one-fourth inch in diameter. Few thin dense fine-grained beds less than one foot thick. Good ledge former.	15.0
1	Basal conglomerate. Abundant subangular fragments less than one inch of Paleozoic rocks (light blue limestone, argillite, quartz). Conglomerate is local and probably fills channels	5.0
	Total thickness of beds 10 to 1 . . .	209.0
	Total thickness of Oak Spring formation	1,875.2

Unconformity

DEVONIAN

Nevada limestone

Table 5--Log of Rainier (UCRL) Drill Hole No. 1

By W. L. Peterson

(Petrographic work by R. E. Wilcox)

Interval No.	Description	Depth (in feet)
	Overburden, no core.	0 - 61
Unit Tos_7		
1	Tuff, rhyolite(?). Pale pinkish gray. Composed of gray, white, and pink ash shards commonly less than one-sixteenth inch in diameter. Scattered fragments one-eighth to one-fourth. Scattered biotite, quartz(?) and feldspar(?) crystals less than one-eighth inch in diameter. Scattered small fragments of quartzite(?). Porous, somewhat friable. Hard greenish porcellaneous knots at 62, 62.5, 67.5 feet. At 65.5 feet, 2-inch bed of soft white coarse-grained pumiceous tuff with quartzite fragments. Contact gradational over 4 inches.	61 - 71
2	Tuff breccia, rhyolite(?), pale pinkish gray. Matrix of fine-grained ash including scattered biotite, quartz and feldspar. Numerous white pumice fragments and fragments of quartzite one-sixteenth to one-half inch in diameter. Firm, porous. Contact gradational over one inch.	71 - 73
3	Same as Unit 1. Hard, greenish porcellaneous knots at 73.5 and 74 feet. Contact sharp.	73 - 75.5

Interval No.	Description	Depth (in feet)
4	Tuff, rhyolite(?), pinkish white mottled with pale green. Matrix of fine-grained ash and scattered crystals of biotite, quartz, and feldspar. Numerous pink and white earthy cinders one-sixteenth to one-fourth inch in diameter. Numerous pale green porcellaneous fragments one-eighth to one-half inch in diameter. Scattered quartzite fragments less than one-fourth inch in diameter. Rock is generally hard and porcellaneous. Contact gradational over 2 inches.	75.5 - 76.5
5	Similar to Interval 1.	76.5 - 85.5
6	Similar to Interval 2 except matrix is light reddish brown.	85.5 - 87.0
7	Tuff, rhyolite(?), soft white earthy matrix of altered pumice cinders. Matrix contains scattered colorless crystals and biotite less than one-sixteenth inch in diameter. Fragments of quartzite one-sixteenth to one-half inch in diameter scattered through rock. Core is very soft and friable. Contact gradational over 6 inches	87.0 - 88.5
8	Similar to Interval 2. Rather sharp lower contact.	88.5 - 89.5
9	Similar to Interval 4. Gradational lower contact.	89.5 - 92.0

Interval No.	Description	Depth (in feet)
10	Tuff breccia similar to Interval 2. Rather sharp contact.	92.0 - 95.5
11	Similar to Interval 4. Contact gradational over one inch.	95.5 - 96.5
12	Similar to Interval 1. Gradational contact.	96.5 - 99.5
13	Similar to Interval 4. Gradational contact.	99.5 - 103.0
14	Similar to Interval 7. Gradational contact. . . .	103.0 - 112.5
15	Similar to Interval 4. Sharp contact. Bedding attitude is 9° off of normal to the core axis. .	112.5 - 116.0
16	Tuff, rhyolite(?), fine grained, grayish pink. Matrix of earthy material with colorless crystals and biotite commonly less than one-sixteenth of an inch in diameter. Numerous white earthy angular pumice fragments one-sixteenth to one inch in diameter. Few fragments of quartzite one-eighth to one-half inch. White fragments become larger toward bottom. Firm. Sharp contact	116.0 - 119.0
17	Similar to Interval 4.	119.0 - 119.5
18	Similar to Interval 2. Tuff breccia, grayish pink with large white fragments. White fragments make up 30 to 60 percent of rock. Soft but commonly cannot be broken by hand. Gradational contact.	119.5 - 128.0
19	Similar to Interval 16. Gradational contact. Sample taken at 134 feet	128.0 - 143.5

Interval No.	Description	Depth (in feet)
20	Similar to Interval 19 except friable, can be broken by hand. Contains bigger percentage of white fragments than unit 19. Gradational lower contact.	143.5 - 147.5
21	Tuff breccia. Matrix of white earthy material made of faintly discernible fragments one-fourth to one-half inch in diameter. Matrix includes some colorless crystals less than one-sixteenth inch in diameter. No biotite. Some dark brown stains less than one-sixteenth inch in diameter. Fragments of angular quartzite one-eighth to one-half inch in diameter scattered through rock. Soft but cannot be broken by hand. Sharp contact	147.5 - 151.0
22	Tuff (similar to Interval 4), rhyolite(?). White, very light gray, white mottled with pale pink. Matrix is earthy to porcellaneous. Material of faintly discernible fragments one-eighth to three-eighths inch diameter, some flattened with bedding. Matrix contains scattered colorless crystals less than one-sixteenth inch in diameter and irregular dark brown stains less than one-sixteenth inch in diameter. Fragments of quartzite scattered through rock one-sixteenth to one-half inch in diameter. As a whole, rock is porcellaneous, hard, and firm. Several precore fractures at 62 feet. Contact sharp. Sample taken at 154 feet	151.0 - 165.0

Interval No.	Description	Depth (in feet)
23	Tuff breccia (rhyolite?), grayish pink groundmass. Fifty to 75 percent of rock composed of white earthy angular fragments one-sixteenth to one inch in diameter. Scattered quartzite fragments one-sixteenth to three-fourths inch in diameter. White porcellaneous bed at 170 to 170.5 feet. Several pores one-thirtysecond to one-sixteenth inch thick and 1 to 2 inches long in white bed. Core too broken up to observe contact.	165.0 - 173.0
24	Sandstone, light brownish gray, medium grained, generally well sorted. Composed of angular to subangular colorless grains, tan to red brown translucent grains (may be in part limonite stained quartz), and black opaque grains. Scattered fragments of quartzite, quartz, and tuff one-sixteenth to one-fourth inch in diameter. Appears to be cemented with thin films of white material which is probably altered ash (clay). Massive but faintly bedded on minute scale. Bedding attitude inclined 15° to normal to core axis at 177 feet (may be crossbedding). Numerous fractures, some cemented with brown clay. In places rock appears to be sheeted on minute scale, parallel to core. Rather friable, can be broken in places with fingers. Probably	

Interval No.	Description	Depth (in feet)
24 (cont')	reworked from tuff, either wind or water deposited. Sample taken at 176 feet. (Note: below 184 feet core is rather scattered in boxes. Core seems to be missing from 184 to 198 feet.)	173.0 - 184≠
25	(Depths may be off 10 feet.) Apparently tan to gray tuff breccia and conglomeratic sandstone (the pebbles being of tuff).	198.0 - 215.0
Unit Tos_6		
26	(Depths may be off 10 or more feet.) Welded tuff, dense dull red groundmass with black schlieren one-fourth to 2 inches long and one-sixteenth to one-half inch thick. Scattered black angular fragments with white haloes. Some angular to rounded white earthy fragments. Small percentage of core has gray groundmass. Scattered crystals feldspar and quartz. Schlieren consistently inclined to core but angles not consistent. Sample taken at 220 feet. Description of thin section of sample: rhyolitic welded tuff containing scattered phenocrysts of quartz and alkali feldspar, and rare biotite. Rock fragments are collapsed masses of pumice, devitrified and marginally stained with hematite, and scattered masses of foreign rocks such as siliceous shales and quartzites. Groundmass is composed of devitrified shards, much compacted, imbricated and welded.	215.0 - 236.0

Interval No.	Description	Depth (in feet)
27	(Depths here are not reliable.) Tuff, gray to tan. Coarse grained, some black schlieren, some of which appear to be obsidian. In part tuff breccia.	236.0 - 250.0

Table 6--Log of Rainier (UCRL) Drill Hole No. 2

By W. L. Peterson

(Petrographic work by R. E. Wilcox)

Interval No.	Description	Depth (in feet)
	Overburden, no core.	0 - 12
Unit Tos_7		
1	Tuff, rhyolite(?), composed of pink and white earthy fragments, one-sixteenth to three-sixteenths of an inch. Scattered biotite less than one-sixteenth inch, minor quartzite fragments. Rather friable. Sharp contact.	12.0 - 13.5
2	Tuff, rhyolite(?), matrix of pale greenish yellow (10 YR 8/2) to white (N 9) earthy fragments one-sixteenth to three-sixteenths inch in diameter. One-sixteenth to one-fourth inch fragments of gray and brown quartzite, and dense volcanics, minute flecks of biotite. Firm. Wavy, sharp contact.	13.5 - 14.5
3	Tuff, rhyolite(?), fine grained, grayish orange pink (5 YR 7/2) matrix. Numerous white fragments up to three-fourths inch. Scattered biotite and quartz crystals less than one-sixteenth inch, some feldspar crystals less than one-eighth inch; some minute black crystals (hornblende?). Some quartzite fragments less than one-sixteenth inch. Firm. Gradational contact.	14.5 - 17.5

Interval No.	Description	Depth (in feet)
4	Tuff, rhyolite(?). Matrix in upper foot is grayish orange pink (5 YR 7/2), below is white to very light gray. Numerous white earthy fragments up to three-fourths inch; scattered biotite (usually minute but up to three-sixteenths inch); some feldspar and quartz crystals and quartzite fragments. Firm. Sharp inclined contact.	17.5 - 24.5
5	Tuff, rhyolite(?). Fine grained, grayish orange pink (5 YR 7/2) matrix pale reddish brown (10 R 5/4) from 26.0 to 26.5 feet. Scattered white earthy fragments up to three-eighths inch; small biotite and quartzite fragments; quartz and feldspar crystals less than one-sixteenth inch. Firm	24.5 - 26.5

Interval No.	Description	Depth (in feet)
6	Tuff, rhyolite(?) grayish orange pink (10 YR 7/2) to light brown (5 YR 6/4). Fine-grained matrix of altered ash with some colorless crystals andrare biotite less than one-sixteenth inch in diameter. White to grayish yellow angular to rounded pumice fragments one-sixteenth to one-half inch in diameter composes 30 to 50 percent of rock. Scattered quartzite fragments. Firm. Gradational contact. Sample at 38 feet. Thin section of sample shows crystals to be of quartz, alkali feldspar and plagioclase with some biotite and amphibole and minor opaque oxides. The matrix is composed of altered shards with lesser altered pumice and some perlite and obsidian.	26.5 - 50.0
7	Tuff breccia; yellowish gray. Composed almost entirely of coarse pumice fragments, one-eighth to one inch in diameter. Some scattered quartzite fragments. Some small colorless crystals and biotite. Fragments cemented by films of brown clay(?). Firm. Sharp contact	50.0 - 54.0

Interval No.	Description	Depth (in feet)
8	Tuff breccia, pale greenish yellow. Composed almost entirely of pumice fragments varying in color from pale greenish yellow to light greenish gray, one-eighth to three-fourths inch in diameter. Thinly scattered quartzite fragments and colorless crystals. Friable. Very lightweight. Firm grayish orange pink bed at 64.5 to 65.5 feet. Apparently sharp contact. Sample at 59 feet. Thin section of sample shows crystals to be composed of alkali feldspar with minor quartz, plagioclase, amphibole and opaque oxide. The matrix is composed almost entirely of pumice.	54.0 - 75.0
9	Tuff. Very fine grained; grayish orange pink with few scattered white fragments. Dense. Sharp contact.	75.0 - 76.0
9a	Tuff, rhyolite. Fine grained, grayish orange pink (10 YR 7/2) to light brown (5 YR 6/4) matrix of altered glass with some colorless crystals and rare biotite less than one-sixteenth inch in diameter. White to grayish yellow, angular to rounded pumice fragments, one-sixteenth to one-half inch in diameter composes 30 to 50 percent of the rock. Scattered quartzite fragments. Firm. Gradational contact.	76.0 - 85.0

Interval No.	Description	Depth (in feet)
10	Sandstone, medium grained. Well sorted. Very pale orange (10 YR 8/2). Composed of colorless and black crystalline grains and tan, brown, and white earthy pumice grains. Scattered white pumice fragments one-sixteenth to three-eighths inch in diameter. Generally massive but bedded on minute scale in parts, bedding rather irregular. Probably water or wind deposited. Sharp contact. Sample at 92 feet. Thin section of sample shows crystals to be of alkali feldspar with some quartz and plagioclase and minor opaque oxides, Ash shards are composed of altered pumice and shards with lesser altered perlite and obsidian.	85.0 - 97.0
11	Same lithology as Interval 8. Sharp contact	97.0 - 100.0
12	Tuff breccia, grayish yellow (5 Y 8/4). Dark yellowish orange (10 YR 6/6) from 106 to 107 feet and 103 to 105 feet. Composed of pumice fragments generally one-eighth to three-fourths inch in diameter. Scattered fragments of quartzite generally less than one-eighth inch in diameter. Although firm, rock has earthy appearance as though much altered to clay. Core is broken into short segments. Orange zones friable. Gradational contact. Sample at 122 feet. Thin section of smaple shows crystals to be of alkali feldspar with some quartz and	

Interval No.	Description	Depth (in feet)
12 (cont'd)	plagioclase and minor opaque oxides. The matrix is composed of altered shards and pumice with altered perlite and obsidian	100.0 - 125.0
(Unit Tos_6 lacking from this drill hole)		
Unit Tos_5		
13	Tuff, grayish yellow to yellowish gray. Composed of pumice fragments flattened across core at small angle to normal. Scattered through rock are fragments of crystalline rocks up to 1.5 inch in diameter. Whole rock speckled with small manganese(?) stains. Rock hard and firm but with earthy appearance. Contact gradational over several inches.	125.0 - 127.0
14	Similar to overlying unit but with fewer fragments of crystalline volcanic rocks.	127.0 - 134.0

Interval No.	Description	Depth (in feet)
15	Tuff breccia, yellowish gray (5 Y 8/4) with dark fragments. Composed of mixture of yellowish gray and dark gray pumice fragments from one-eighth to three-fourths inch in diameter. Dark fragments usually larger than light ones. Yellowish gray fragments more altered and composed of probably 80 to 90 percent of rock. Between 134 and 145 feet rock is generally friable, below firm. General earthy appearance. Three-eighths inch thick sand of dark minerals at 145.5 feet inclined to 22° to the normal to core axis. Several thin sand layers between 154 and 155.5 feet	134.0 - 161.0
16	Tuff, grayish yellow; much altered. Probably originally composed of pumice fragments one-fourth to three fourths inch in diameter. Now a yellowish gray earthy material with original fragments faintly discernible in parts. Scattered through rock are fragments of dark dense rock usually less than one-fourth inch in diameter, probably in part quartzite. From 161 to 212 feet core is much broken and in part friable. Sharp contact. Sample at 212 feet. Thin section of sample shows crystals to be rare, those present are alkali feldspar, quartz and plagioclase. The matrix is composed of altered pumice with some obsidian and perlite and rare shards.	161.0 - 243.0

Interval No.	Description	Depth (in feet)
Unit Tos_4		
17	Tuff, fine grained, white to grayish orange pink. Composed of altered tuff fragments usually less than one-eighth inch in diameter with scattered colorless crystals and biotite less than one-sixteenth inch in diameter. Scattered quartzite fragments usually one-thirtysecond to one-eighth inch in diameter. Grayish orange pink above 262 feet, white below. Rock firm. Gradational contact. Sample at 265 feet. Thin section of the sample shows crystals to be of quartz and plagioclase with minor alkali feldspar, biotite and opaque oxides. The matrix is composed of altered pumice and shards with some altered obsidian and perlite.	243.0 - 265.0
18	Tuff, white to moderate pink. Fine-grained matrix with scattered white pumice fragments one-sixteenth to one-half inch in diameter. Few scattered quartzite fragments one-eighth inch. Scattered biotite and colorless crystals in matrix. Rock is firm. Good core. Pink from 275 to 295 feet, rest is white. Sample at 283 feet. Thin section of the sample shows crystals to be composed of plagioclase with some quartz, alkali feldspar, biotite and opaque oxides. The matrix is composed of altered pumice and shards with a little altered obsidian and perlite	265.0 - 305.0

Interval No.	Description	Depth (in feet)
19	Tuff breccia, pale greenish yellow. Composed of pumice fragments ranging from one-eighth to one-half inch in diameter. Scattered quartzite fragments. Pumice is much altered with earthy appearance	305.0 - 314.0
20	Tuff, pale greenish yellow (10 YR 8/2) to grayish yellow (5 Y 8/4). Composed of altered pumice fragments usually less than one-sixteenth inch but ranging up to one-fourth inch in diameter. Large percentage of rock composed of colorless crystals and small grains of quartzite, up to 50 percent or more in parts where rock resembles sandstone. Probably in part water worked. Firm.	314.0 - 321.5
21	Tuff (in part tuff breccia), grayish orange pink (5 YR 7/2). Moderate reddish brown (10 R 4/6) from 353.5 to 361 feet. Color is gradational generally becoming deeper red downward. Fine-grained matrix of pumice and colorless crystals with coarser white pumice fragments and quartzite (usually one-sixteenth to three-eighths inch in diameter) which make up 30 to 60 percent of the rock. Gradational contact over 3 inches. Firm rock. Correlates with bed 24b of USGS Tunnel area (WRH). Samples at 356 and 336 feet. Thin section of sample from 336 feet shows crystals	

Interval No.	Description	Depth (in feet)
21 (cont'd)	of quartz and plagioclase with rare alkali feldspar. The matrix is composed of altered shards and pumice with some altered obsidian and perlite. Thin section of sample from 356 feet shows crystals to be of quartz with some alkali feldspar and plagioclase. The matrix is composed of altered pumice and shards with some altered perlite and obsidian	321.5 - 361.0
22	Tuff; predominantly white, small percentage pink. Fine to medium grained. Commonly composed of altered pumice one-sixteenth to one-fourth inch in diameter with colorless crystals and rare biotite less than one-sixteenth inch in diameter. Scattered quartzite fragments. Pink layers at 398 to 400, 444 to 447, 470.5 to 471, 480 to 480.5, 513 to 514, 523 to 524, 547 to 548 feet. Top of red bed at 480 feet inclined 17° to normal to core axis. Bedding plane in gray tuff at 527 feet inclined 25° to normal to core axis. Firm rock. Gradational contact. Samples at 504 and 530 feet. Thin section of sample from 504 feet shows crystals to be of quartz and alkali feldspar with some plagioclase and opaque oxides. The matrix is composed of altered shards with lesser altered pumice, obsidian and perlite. Thin section of	

Interval No.	Description	Depth (in feet)
22 (cont'd)	sample from 530 feet shows crystals to be composed of quartz, alkali feldspar, plagioclase, biotite and opaque oxides, none of which are abundant in the thin section. The matrix is composed of altered pumice with lesser altered obsidian, perlite, and shards.	361.0 - 562.0
23	No Interval 23.	
Unit Tos_3		
24	Tuff, moderate orange pink. Lithologically similar to Interval 21, becomes lighter pink toward base. From 583 to 590.5 feet much thin streaking of deep pink and red across core inclined at about 30° to normal to the core axis. Correlates with bed 20 (portal bed) of USGS Tunnel area.	562.0 - 590.5
25	Firm rock. Similar to Interval 22	590.5 - 674.0
26	Tuff. Fine grained. Composed of pumice and colorless crystals, almost entirely less than one-sixteenth inch in diameter. From 674 to 684 feet moderate orange pink mottled with white, from 684 to 708 feet moderate reddish orange, from 708 to 715 feet moderate orange pink speckled with white. Firm rock. Gradational contact.	

Interval No.	Description	Depth (in feet)
26 (cont'd)	Correlates with bed 14 of USGS Tunnel area. Sample at 689 feet. Thin section of sample shows crystals to be composed of plagioclase with lesser quartz and alkali feldspar and minor biotite and opaque oxides. The matrix is composed of altered pumice and shards with minor altered perlite and obsidian	674.0 - 715.0
Unit Tos_2		
27	Tuff. Fine grained. Similar to Interval 22. White with much thin cross streaking of red inclined 24° to normal of the core axis. Firm rock, except lower 5 feet. Gradational contact.	715.0 - 735.0
28	Tuff. Fine to medium grained. Grayish orange pink. Gradational contact	735.0 - 744.0
29	Gradational contact. Similar to Interval 27 . . .	744.0 - 760.0
30	Tuff, medium grained. Generally white with pinkish cross streaks. Scattered quartzite and white pumice fragments one-eighth to one-fourth inch in diameter. Firm	760.0 - 775.0
31	Tuff. Fine grained; white, with some pink cross streaking. Firm	775.0 - 798.0

Interval No.	Description	Depth (in feet)
32	Tuff, composed of interlayered fine, medium and rarely coarse grained beds a few inches to a few feet thick. Quartzite fragments rare except in coarse phases. Much of rock is streaked and banded across core with pale red. Generally firm, though core is broken into 2-inch lengths. Sample at 844 feet. Thin section of sample shows crystal to be of plagioclase with lesser alkali feldspar, quartz, biotite and opaque oxides. The matrix is composed of altered pumice with lesser altered shards, obsidian and perlite	798.0 - 880.0
33	Similar to Interval 31	880.0 - 903.0
34	Similar to Interval 33	903.0 - 909.0
35	Tuff; fine to medium grained. Moderate orange pink 909 to 925 feet, moderate orange pink to pale red (10 R 6/2) below. Phenocrysts of quartz, feldspar, and biotite. Six inches of altered tuff at 946 feet (waxy clay). Sample at 930 feet. Thin section of sample shows crystals to be composed of quartz, alkali feldspar and plagioclase with some biotite and opaque oxides. The matrix is composed of altered pumice and shards with some obsidian and perlite.	909.0 - 955.0

Interval No.	Description	Depth (in feet)
36	Tuff, granular, fine-grained, pinkish gray. Phenocrysts of quartz, feldspar and biotite. . . .	955.0 - 958.7
37	Tuff; reddish pink with some white bands. Medium to coarse grained and granular except for thin bands and blebs of pink porcellanitic to hard clayey material (probably siliceous). Phenocrysts of quartz, feldspar, and relatively abundant golden to brown biotite. Scattered fragments, mainly quartzite. Gradational lower contact.	958.7 - 967.7
38	Tuff, granular; light gray to nearly white with thin stringers of red in lower 2 feet. Medium to coarse grained. Phenocrysts of subangular to subrounded quartz, feldspar, and biotite (more abundant than above), very few foreign fragments. Bedding planes inclined 8° to normal to core axis. Sample at 969 feet. Thin section of sample shows crystals to be composed of quartz, alkali feldspar and plagioclase with lesser biotite and opaque oxides. The matrix is composed of altered pumice and shards with minor altered perlite and obsidian	967.7 - 972.7

Interval No.	Description	Depth (in feet)
39	Tuff, dark red, generally fine grained, dense porcellanitic (good core recovery). One dark grayish red band 0.3 feet thick. Phenocrysts of feldspar, quartz, relatively abundant biotite, and a few grains of a honey-yellow mineral. Grains are in a siliceous clay or porcellanite (waxy surface). Sample at 989 feet. Thin section of sample shows crystals to be of quartz, alkali feldspar, plagioclase, biotite and opaque oxides, none of which are abundant	972.7 - 999.0
40	Tuff, granular. Pink and gray. Phenocrysts of quartz, feldspar and biotite with little binder (sand with no core recovery).	999.0 - 1000.5
41	Tuff, pumiceous; reddish pink specked with white. Abundant fragments one-fourth to 1 inch long, of white devitrified(?) waxy pumice and scattered quartzite fragments up to one-half inch but mostly less than one-fourth inch. Phenocrysts of quartz, feldspar, and biotite. Sample at 1,010 feet. Thin section of sample shows crystals to be composed of plagioclase, alkali feldspar with lesser quartz, biotite and opaque oxides	1000.5 - 1035.5

Interval No.	Description	Depth (in feet)
42	Tuff, pumiceous, pinkish gray. Abundant fragments of white waxy devitrified(?) pumice. Scattered small (mostly less than one-eighth inch) fragments of quartzite. Phenocrysts of feldspar, quartz and abundant black euhedral crystals of biotite. Bedding inclined 28° to normal to the core axis. Sample at 1,042.5 feet. Thin section of sample shows crystals to be composed of plagioclase, alkali feldspar and biotite with lesser quartz and opaque oxides.	1035.5 - 1043.0

Table 7--Log of Rainier (UCRL) Drill Hole No. 3

(Top of mesa near Point Mabel)

Petrographic work by R, E. Wilcox on selected samples; his lithologic descriptions have been incorporated into the description of the beds from which the samples were taken.

Interval No.	Description	Depth (in feet)
	Oak Spring formation	
Unit Tos_8		
1	Rhyolitic welded tuff, pale red purple (5 RP 7/2--wet). Abundant phenocrysts of sanidine, oligoclase, quartz, biotite, an opaque oxide, and rare augite in a groundmass of moderately compacted shards, devitrified. Partly filled elongated cavities as much as one inch long. Slightly to moderately porous. Some jointing and staining along parting planes in first 10 feet; below 10 feet core is firm and recovery good. Gradational lower contact. Sample taken at 13.5 feet.	0 - 28.0
2	Quartz-latitic (or rhyolitic) welded tuff, pale red purple at top grading downward into mottled gray to banded, very dark gray. At top are large angular to subrounded fragments of tuff as much as 2 inches long and elongated cavities partly filled with opal(?) and limonite. Toward bottom fragments are smaller, cavities are less common,	

Interval No.	Description	Depth (in feet)
2 (cont'd)	white phenocrysts are abundant and there are dark bands of obsidian(?). Rough fracture intersects core at 28 to 29 feet	28.0 - 34.4
3	Quartz latitic (or rhyolitic) welded tuff, dark gray. About one-half of rock consists of phenocrysts of sanidine (much embayed), andesine, biotite, quartz, (a few embayed), opaque oxide, and rare augite. Groundmass is cryptocrystalline, feebly birefringent and crowded with tiny opaque trichite rods; some suggestion of fluxion structure but more likely true liquid flow. Sharp lower contact. Sample taken at 45 feet. . .	34.4 - 55.0
4	Quartz latitic (or rhyolitic) welded tuff, grayish red purple (5 RP 5/2). Abundant phenocrysts of sanidine, oligoclase-andesine, quartz, biotite, an opaque oxide, and sparse augite in a groundmass of compacted shards, devitrified. Prominent schlieren (wavy lenses) and elongated flattened cavities (some opal in cavities). Smaller and less conspicuous schlieren between 86 to 115 feet. Fractures between 75 and 78 feet, 104 and 106 feet; 144 and 145 feet, at 174 feet, 199 and 200 feet, and 208 and 210 feet	55.0 - 211.0

Interval No.	Description	Depth (in feet)
5	Quartz latite, (5 RP 7/2), grayish red purple. More friable and fragmental than above; spherulites. Many more cavities than above. Minerals are sanidine and quartz and rare biotite; pumice fragments, dense, brown inclusions (not quartzite). Abundant white pumice schlieren, flattened less than one-half inch. Fractures at 222 to 225 feet and at 245 feet, fewer cavities toward bottom. Gradational lower contact.	211.0 - 249.0
6	Welded tuff, light gray, pale violet tinge, fine grained, abundant flattened pumice, few angular dark inclusions, minor quartz and biotite. Gradational lower contact.	249.0 - 253.0
7	Quartz latitic(?) welded tuff, light gray, red purple, abundant schlieren of pumice as much as 1½ inches long, very flattened; sanidine phenocrysts, biotite, quartz, similar to above but coarser. Fractures between 258 and 264 feet. Softer (breaks easier) near base. Gradational lower contact.	253.0 - 272.0

Interval No.	Description	Depth (in feet)
Unit Tos_7		
8	Tuff, light brownish gray (5 YR 6/1). Abundant pumice fragments (up to 1 inch; mostly less than one-half inch) moderately abundant ash shards and a little obsidian and perlite. More friable than above (can be broken by hand). Phenocrysts mostly alkali feldspar, some quart, little biotite, and limonite. Scattered and stony volcanic fragments. Samples at 275, 288, and 298 feet. Good core recovery to 279.5 feet below where core becomes very friable. Good core again at 292 to 300 feet below where material becomes too soft to core (mostly granular sand-size material recovered); has a slight pinkish cast.	272.0 - 300.0
9	Tuff, moderate reddish orange (10 R 6.5/5). Abundant pumice fragments mostly less than one-fourth inch (maximum one-half inch), ash shards and a little obsidian and perlite. Large tan fragments (devitrified pumice) and a few small dark stony fragments. Moderately abundant phenocrysts of quartz and alkali feldspar, scattered plagioclase and biotite; a few grains of zircon noted at 312 feet. Grades to pale brown at 315 feet and to light brownish gray at 319. Very friable at 321. Samples at 312, and 327 feet. Good core recovery but very friable	300.0 - 327.5

Interval No.	Description	Depth (in feet)
10	Tuff, pumiceous, moderately light brown; (5 YR 4.5/5). Sand-size phenocrysts of alkali feldspar and quartz. Grains subangular. Poorly sorted. Moderately abundant altered pumice and ash shards. Between 339 and 340 feet there is a dark band (altered biotite?) Bedding planes dip 23°. Sample at 346 feet. Mostly uncored (sand-size) because it is very friable.	327.5 - 350.0
11	Tuff, granular, light brown (5 Y 6/4), fine grained. Sand-size subangular to subrounded quartz and feldspar in a friable chalky matrix (altered ash shards). A little biotite, pyroxene, and amphibole. Seams one-sixteenth inch or less of white chalcedony. Abundant altered ash shards and moderate unaltered pumice fragments. Sample at about 355 feet. Nearly all sand; only scattered core recovered in pieces about 0.1 foot long	350.0 - 360.0

Interval No.	Description	Depth (in feet)
12	Tuff, granular, light gray to nearly white, medium-coarse grained, friable. Made up mostly of subangular to subrounded phenocrysts (sand size) of quartz and feldspar (alkali feldspars predominate). Scattered biotite, rare pyroxene, and a few pink, orange, and lavender grains of sphene. Abundant to moderately abundant pumice and ash shards, and local obsidian and perlite; where very abundant core is light. Samples taken at 355, 369.5, 405, 428, 462, 471, 482, and 577 feet	360.0 - 591.0

Core recovery as follows:

Depth (in feet)		Core recovery (in feet)
360-386	Sand; no core except for 2 inch - 3 inch pieces containing abundant altered shards	0.5
386-392	Sand except for core at beginning . .	0.5
392-406	Mostly sand consisting of abundant pumice fragments, moderate amounts of shards and alkali feldspar	0.5
406-429	Mostly sand consisting of abundant pumice fragments and moderately abundant shards	0.7

Interval No.	Description	Depth (in feet)
12 (cont'd)	Core recovery as follows:	

Depth (in feet)		Core recovery (in feet)
429-441	(Nothing recovered)	0.0
441-451	About half sand and half broken core.	5.0
451-461	About half sand and half broken core.	5.0
461-471	Soft core 0.2 to 0.5 foot long; some sand. Consists of abundant shards and moderate amounts of pumice.	7.0
471-481	Soft core 0.1 to 0.3 foot long. . . .	3.5
481-488	Soft core 0.1 to 0.4 foot long. Sample at 482 feet contains abundant phenocrysts of quartz, moderate amounts of alkali and plagioclase feldspar, and scattered biotite as well as many primary rock fragments of obsidian and perlite, moderately abundant pumice and a few ash shards.	4.0
488-511	Soft core 0.2 to 0.4 foot long. . . .	4.0
511-551	Soft core 0.2 to 0.4 foot long. . . .	4.0
551-560	Soft core 0.2 to 0.5 foot long. . . .	2.3
560-571	Soft core 0.3 to 0.5 foot long. . . .	2.7

Interval No.	Description	Depth (in feet)
12 (cont'd)	Core recovery as follows: Depth (in feet) — Core recovery (in feet) 571-577 Sand (except for core) consisting of phenocrysts of quartz and alkali feldspar and moderately abundant pumice fragments . . . . 1.0 577-591 Soft core 0.3 to 0.5 foot long. . . . 2.0	
13	Tuff, granular, light brown specked with white (moderately abundant small pumice fragments), scattered subangular to subrounded quartz and abundant plagioclase feldspar; scattered biotite and amphibole. Appears "dirty" in comparison to clean sand above due to brown chalky binder (altered shards). Sample at 592 feet. Many pumice, obsidian and perlite fragments. Sharp upper contact based on core recovery (might be some missing between units). 2.7 feet soft core 0.1 to 0.8 foot long pieces recovered.	591.0 - 601.0
14	Tuff, granular, light gray flecked with black grains. Abundant phenocrysts of plagioclase; scattered biotite and amphiboles. Much obsidian and perlite, moderate amounts of pumice and sparse altered ash shards. Sample at 601 feet	601.0 - 601.5

Interval No.	Description	Depth (in feet)
15	Tuff, granular, light brown flecked with white pumice. Same as 591 to 601.5 feet except more friable; gradational change to gray near base and more abundant pumice. Core recovery 601 to 607 feet is mostly sand with a few broken pieces at the beginning of the interval; 607 to 664 feet only sand recovered except for scattered pieces of core 0.1 to 0.3 foot long. Seven feet soft core recovered between 664 to 680 feet; sand at base	601.5 - 680.0
16	Tuff, granular, light gray. Similar to Interval 12 except locally finer grained and generally has more soft clay binder. Samples at 685 and 712 feet	680.0 - 737.0

Interval No.	Description	Depth (in feet)
16 (cont'd)	Core recovery as follows:	

Depth (in feet)		Core recovery (in feet)
680-685	Sand except for broken chips containing scattered phenocrysts of plagioclase, biotite, and amphibole; moderately abundant to many fragments of pumice, obsidian, perlite, and ash shards	0.0
685-691	Soft core in pieces 0.4 to 0.8 foot long.	5.0
691-721	Mostly sand but scattered soft core 0.1 to 0.3 foot long. Sample at 712 feet contains phenocrysts of plagioclase, abundant fragments of pumice, and moderate amounts of obsidian and perlite.	1.0
721-731	Soft core, 0.2 to 0.5 foot long pieces. Sample at 725 feet contains scattered phenocrysts of quartz, alkali feldspar, and plagioclase; abundant pumice fragments	7.5
731-737	Soft core in pieces 0.1 to 0.5 foot long	5.5

Interval No.	Description	Depth (in feet)
17	Tuff, granular, light gray. Mostly sand-size granular white feldspar and quartz; scattered biotite and rare pyroxene. Abundant pumice fragments and a few sand-size quartzite fragments. Very little core recovery (mostly granular sand). Sample at 738 feet.	737.0 - 740.0
18	Tuff, granular. Brown sand (no core recovery). Rounded to subrounded grains mostly of quartz and alkali and plagioclase feldspars; few biotite grains. Abundant ash shards and a few black obsidian fragments. Sample at 747 feet.	740.0 - 759.0
19	Tuff, granular, light gray. Mostly clean rounded fine-grained quartz and alkali and plagioclase feldspar. Pumice fragments and ash shards. No core recovery (only sand) except for very easily broken core (uncemented) last 0.5 foot. Sample at 764 feet	759.0 - 765.0
20	Tuff, granular, light gray. Sand-size phenocrysts of alkali and plagioclase feldspar and quartz. Scattered sand-size quartzite fragments. Scattered biotite, amphibole, and pyroxene. Pumice and ash shards 768 to 769 feet. Only scattered easily crushed core (mostly sand). Sample at 767 feet.	765.0 - 775.0

Interval No.	Description	Depth (in feet)
21	Tuff, pumiceous, light gray to nearly white. Abundant fragments of fibrous pumice about one-fourth to one-third inch long and ash shards, Phenocrysts of feldspar; scattered quartz and biotite. Abundant rounded black grains of obsidian at 794.5 feet. Samples at 777 and 794,5 feet. Moderately good core recovery; pieces 0.3 to 0.5 foot common and some one foot long; core is fairly soft (can be broken with difficulty by hand) and light in weight. Some sand at about 793, 795-799, and 803 feet. ,	775,0 - 810,0
22	Tuff, granular, gray to brown. Mostly small phenocrysts of plagioclase feldspar, minor quartz, subrounded to well-rounded. Scattered biotite and amphibole. Abundant ash shards, Sample at 811 feet. No core recovery (all sand).	810.0 - 812.5
23	Tuff, granular to pumiceous, light gray. Pumice fragments one-eighth to one-fourth inch moderately abundant. Granular subrounded, White and clear feldspar and quartz; scattered biotite. Fragments of quartzite, sand size and somewhat larger are moderately abundant. Porcellanite bed at 836,0 to 836,3 feet. Samples at 826 feet and 846 feet	812,5 - 856.0

Interval No.	Description	Depth (in feet)
23 (cont'd)	Core recovery as follows:	

Depth (in feet)		Core recovery (in feet)
810-815	Mostly sand	0.5
815-826	Only one short piece of core; no sand.	0.3
826-832	Pieces of core 0.1 to 0.2 foot long. (Change to smaller core size.) Sample at 826 feet contains phenocrysts of feldspar, quartz, and mica, abundant fragments of pumice and some obsidian and ash shards	4.5
832-836	Pieces of core 0.1 to 0.2 foot long. .	3.0
836-846	Mostly sand (small partial pieces of core).	---
846-848	Sand, sample of sand contained phenocrysts of quartz and feldspar and fragments of pumice and ash shards.	0.0
848-854	Sand except for last 3 feet which contains partial pieces of core . . .	---
854-856	Broken core	2.0

Interval No.	Description	Depth (in feet)
24	Tuff, light gray to nearly white. Granular subrounded to subangular sand-size phenocrysts of quartz and colorless to white feldspar (mostly plagioclase) held together with an earthy white cement (altered pumice). Scattered biotite and amphibole. Small (mostly less than one-eighth inch) fragments of white (altered) pumice and sand-size to slightly larger brown fragments of quartz. Two inches of yellowish-green porcellanite at about 883 feet. Sample at 861 feet. The core that is present is mostly firm and cannot be broken without a hammer. One foot is maximum length of any individual piece and most are 0.3 to 0.5 foot long.	856.0 - 899.5

Core recovery as follows:

Depth (in feet)	Core recovery (in feet)
856-861.5	5.5
861.5 - 866.5.	3.3
866.5 - 868	1.3
868 - 874	5.5
874 - 877 Broken 0.2 to 0.3 foot pieces of core.	3.0
877 - 880 Broken core.	3.0
880 - 890 Core missing, probably in upper 5 feet.	4.5
890 - 894	2.0
894 - 899	3.7

Interval No.	Description	Depth (in feet)
25	Tuff, grit, light gray spotted with brown to dark gray subangular to subrounded fragments. Moderately abundant phenocrysts of quartz and feldspar, scattered biotite and amphibole. Altered fragments of obsidian, ash shards and pumice. Contains numerous brown dark-gray fragments of quartzite. Moderately sharp lower contact. Sample at 905 feet. Two feet of hard core recovered in pieces 0.3 to 0.5 foot long.	899.5 - 906.5
26	Tuff, pumiceous, light brown specked with abundant white fragments of altered pumice mostly one-eighth to one-fourth inch long. Abundant altered ash shards and scattered altered obsidian and perlite. Subrounded to subangular, mostly sand-size plagioclase and alkali feldspars (clear and also white), a little quartz and amphibole and much more biotite than in interval above. Fragments from sand size to one-fourth inch long of brown to bluish-gray quartzite. Samples at 910 and 936 feet. Core is fairly lightweight and is in pieces mostly 0.2 to 0.5 foot long.	906.5 - 945.3

Interval No.	Description	Depth (in feet)
27	Tuff, yellowish green, chalky, fairly soft. Abundant altered ash shards; moderately abundant quartzite fragments one-fourth to one-third inch. Moderate amounts of phenocrysts of feldspar and a few of quartz. Sample at about 947 feet. Core was recovered in pieces 0.2 to 0.3 foot long	945.3 - 955.0
28	Tuff, white to light gray, fine grained; poor core recovery	955.0 - 990.0
Unit Tos_6		
29	Welded tuff. Two layers of obsidian; 0.5 foot at 1,046 feet and 2 feet between 1,054 and 1,057. Poor core recovery between 1,046 and 1,049 feet	990.0 - 1061.0
Unit Tos_5		
30	Tuff, buff to brown, nonwelded	1061 - 1074

End of hole