Stratigraphy and Structure of the Rainier and USGS Tunnel Areas Nevada Test Site

GEOLOGICAL SURVEY PROFESSIONAL PAPER 382-A

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By W. R. HANSEN, R. W. LEMKE, J. M. CATTERMOLE, *and* A. B. GIBBONS

GEOLOGIC INVESTIGATIONS RELATED TO NUCLEAR EXPLOSIONS

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Thomas B. Nolan, *Director*

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FOREWORD

The papers that follow this foreword constitute a series of reports on the geologic aspects of underground tests of nuclear devices for military and peaceful purposes. These papers are progress reports on segments of a continuing investigation that includes studies in some phases of the earth sciences. Later papers in the series may reinterpret and refine observations reported in the earlier ones, and undoubtedly will present new facts.

The first large deep underground nuclear explosion in the United States, known as the Rainier test, was detonated by the U.S. Atomic Energy Commission on September 19, 1957, at the Commission's Nevada Test Site, about 70 miles northwest of Las Vegas, Nev. More than a year before the actual detonation, the Albuquerque Operations Office of the Atomic Energy Commission's Division of Military Applications requested the U.S. Geological Survey to provide advice on the geologic, hydrologic, and geophysical factors involved in large underground nuclear explosions. Originally the Geological Survey's part in the program was assisting in the choice of sites and in location and design of underground workings, in prediction of the seismic effects of deeply buried detonations, and in assessment of possible contamination of ground water. As the program developed, the Survey was called upon to act in an advisory capacity to the Commission in a broad range of activities in the fields of earth science.

The development and operation of a program for testing nuclear devices, particularly in a new medium, is obviously a complex undertaking that requires the coordinated efforts of many groups and individuals. Solution of the many problems encountered in the Test site program required the skills of many units and individuals within the Survey, and it was essential that the effort be coordinated in time and place to a most exacting degree. The results of the Survey's studies were made available, in whole or in part, to a large number of scientific and technical groups that participated in the tests. In addition to the Atomic Energy Commission and the Department of Defense, this group included scientific and technical laboratories under contract to these agencies and a number of consultants. The Survey's contributions have also been aided by advice from and consultation with many of these groups, particularly the Commission's Board of Consultants which has continuously reviewed the progress of the test program. Insofar as possible the data obtained by these other organizations have been correlated with those obtained by the Survey.

The general area within the test site most suitable for underground muclear tests was selected without much difficulty, and indeed with a minimum of geologic guidance. The requirement of all the agencies involved—that the tests be conducted under several hundreds of feet of cover—narrowed the choice to one of the higher hills or mesas in the test site. A flat-topped spur of the Belted Range in the northwest corner of the test site, which became known as Rainier Mesa after detonation of the first test, was eventually selected. Even though it was chosen largely on the basis of topography, the fact that topographic features reflect the underlying rocks and their geologic history resulted in the choice of a medium—tuff of the Oak Spring formation of Tertiary age—that was nearly ideal for the purpose.

After the general site, Rainier Mesa, had been selected, the local geology was studied and mapped in sufficient detail to permit choice of specific sites for the planned series of tests. Soon after geologic studies on Rainier Mesa were started, the Geological Survey suggested that, as a preliminary to the nuclear tests, a few tests should be made with conventional explosives. Despite the obvious differences between the effects of nuclear explosions and those of dynamite, it seemed reasonable that much-needed information as to the possible effects of nuclear tests could be gained by dynamite tests. These could also be expected to provide a few points near the bottom of a curve that would be useful in checking the depth of cover that theoretically was necessary to provide containment of nuclear blasts of various yields. The Commission concurred in the Survey's suggestion and furnished all necessary support for carrying out the high-explosive tests under the Survey's supervision. The site chosen for the preliminary tests, which has become generally known as the USGS Tunnel area, is about a mile east of Rainier Mesa. The rocks are the Oak Spring formation of Tertiary age, the same unit exposed in the mesa. A deliberate effort was made, however, to select a site at which the rocks were rather severely faulted and jointed, so that the tests would be made under unfavorable geologic conditions.

The high-explosives test consisted of 2 explosions, one of 10 tons and the other of 50 tons of conventional

60 percent dynamite, fired in separate drifts from the main USGS Tunnel. Numerous small explosions in drill holes of various depths were also set off. These tests, small as they were in comparison with nuclear standards, provided much of the data needed to evaluate the feasibility and safety of the proposed nuclear tests. Moreover, the results are of direct value to engineers who work with conventional explosives. These tests were the first known to the Survey in which the objective was to contain the effects of an explosion within a rock mass. Earlier containment tests, in ice and rock, had used very small explosive charges; all known previous large explosions had been designed to break the rock to some free surface, such as a mine stope, a quarry face, or the ground surface. Thus, the 10-ton and 50-ton dynamite tests were of a pioneering nature, and the results are of real significance in themselves.

In evaluating the significance of the Survey's studies at the Nevada Test Site it is important to relate the time element to the state of knowledge. Today (1960) both the feasibility and the limitations of underground testing of nuclear devices are well recognized. It is well to keep in mind that until the Rainier test was made in the autumn of 1957 grave doubts existed in many minds as to whether nuclear explosions could be contained within rock, and whether the rests could be adequately instrumented and evaluated. There even were very real fears that the blasts might trigger destructive earthquakes, and that the ground-water supplies might be dangerously contaminated for decades to come. The Rainier detonation in 1957 followed by a series of tests in 1958 resolved many of the problems, at least for nuclear explosions conducted in geologic settings and under conditions similar to those of the early tests. The Geological Survey's contribution, through its investigations in geology, hydrology, and geophysics, was thus of considerable importance in finding the answers to many of the questions that were posed in the early stages of the test program.

Thomas B. Nolan *Director*

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STRATIGRAPHY AND STRUCTURE OF THE RAINIER AND USGS TUNNEL AREAS, NEVADA TEST SITE

By W. R. Hansen, R. W. Lemke, J. M. Cattermole and A. B. Gibbons

ABSTRACT

The Rainier and USGS Tunnels in 1957 were the sites of experimental explosions designed to test the feasibility of deep-underground detonation as a method of testing nuclear devices. Ten- and fifty-ton dynamite charges fired in chambers of the USGS Tunnel were followed by a relatively low yield (1.7 *kt*) nuclear detonation in the Rainier Tunnel. Before these explosions the geology of both areas was mapped in detail so that geologic effects of the blasts could be fully evaluated.

The Rainier Tunnel area is on the east margin and slope of Rainier Mesa, which is an outlier of the Belted Range in the northwestern part of the Nevada Test Site. The USGS Tunnel area is at the foot of a ridgelike salient of Rainier Mesa about 2½ miles to the east. Rocks exposed in the Rainier Tunnel area include dolomites and limestones of the Nevada formation of Devonian age, various rhyolitic and quartz-latitic tuffs and tuffaceous sandstones of the Oak Spring formation of Tertiary age, and various unconsolidated rubbly surficial deposits of Quaternary age. In the Rainier Tunnel area the Oak Spring formation is divided into 8 map units numbered in ascending order 1 to 8. Only three of these units crop out in the USGS Tunnel area, but higher and lower units of the formation occur nearby. Parts of the Oak Spring formation seem to have been deposited by direct fallout from volcanic ash clouds supposedly into the standing waters of a large lake, parts by reworking of ash fall material by streams, and parts by huge hot ash flows. Some of the latter have produced welded tuffs, which occur at three stratigraphic horizons in Rainier Mesa. These tuffs must have been deposited on dry land, because the quenching effect of water would have prevented welding.

The nonwelded parts of the Oak Spring formation are characterized, for the most part, by rhythmically alternating intervals of well-bedded tuff and poorly bedded or massive tuff. Each bedded interval overlies a minor stratigraphic break, or diastem. Major stratigraphic breaks, or unconformities, occur at the base of units 6 and 7.

Welded tuffs in units 2 and 6 occur as relatively small discontinuous lenses in the axial parts of synclines. The synclinal structure clearly antedates the emplacement of the welded tuffs; the suggestion is made, therefore, that this structure is initial, caused by the deposition of tuffaceous material on a preexisting surface of moderate relief.

The Rainier and USGS Tunnel areas lie within a region that has had a long history of structural deformation. The Paleozoic rocks were folded, faulted, and eroded before the overlying Oak Spring formation was deposited. Folding and faulting also followed deposition of the Oak Spring formation, and may have occurred intermittently during its deposition. Over most of its outcrop area the Oak Spring formation is gently folded. A large broad synclinal fold underlies Rainier Mesa and adjoining areas; the axes of several smaller superimposed folds pass through the Rainier Tunnel area. Within the small USGS Tunnel area the dip is mainly in one direction, to the east or northeast.

Abundant small normal faults in the USGS Tunnel area fall into two well-defined sets—one that trends northeast, dips northwest, and is upthrown on the southeast; the other that 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 with a predominant northeast trend and a subsidiary northwest trend. Joints are relatively fewer at the Rainier Tunnel area, except in the welded tuffs where they are very abundant. In the lower part of unit 8 well-formed columnar joints are the result of contraction during the cooling of the ash flow.

INTRODUCTION

The Rainier [1] and USGS Tunnel areas are near the southern end of the Belted Range in the northwestern part of the Tippipah Spring 15-minute quadrangle, which is in the northwestern part of the Nevada Test Site. The Rainier Tunnel area covers slightly more than 2 square miles (fig. 1) within Army Map Service grid units 14–18 N. and 70–73 E., Tippipah Spring quadrangle; the smaller USGS Tunnel area, about 1 mile to the east, covers about 21 acres in grid unit 17–18 N., 74–75 E. These areas are reached from Camp Mercury, Nev., over all-weather roads across Frenchman and Yucca Flats, a mean distance of about 40 miles. Camp Mercury, reached in turn from U.S Highway 95, is about 70 miles northwest of Las Vegas, Nev. Access to the Nevada Test Site, including the

[1] The name Rainier Tunnel, as used throughout this report and in prior publications of the University of California Radiation Laboratory, is synonymous with the name UCRL Tunnel and U12b Tunnel. After the Rainier underground test, however, when it became evident that several additional tunnels would be dug into the mesa, the serial designation U12b largely supplanted the name Rainier among workers at the Nevada Test Site. Tunnels dug later were designated U12c, U12d, and U12e.

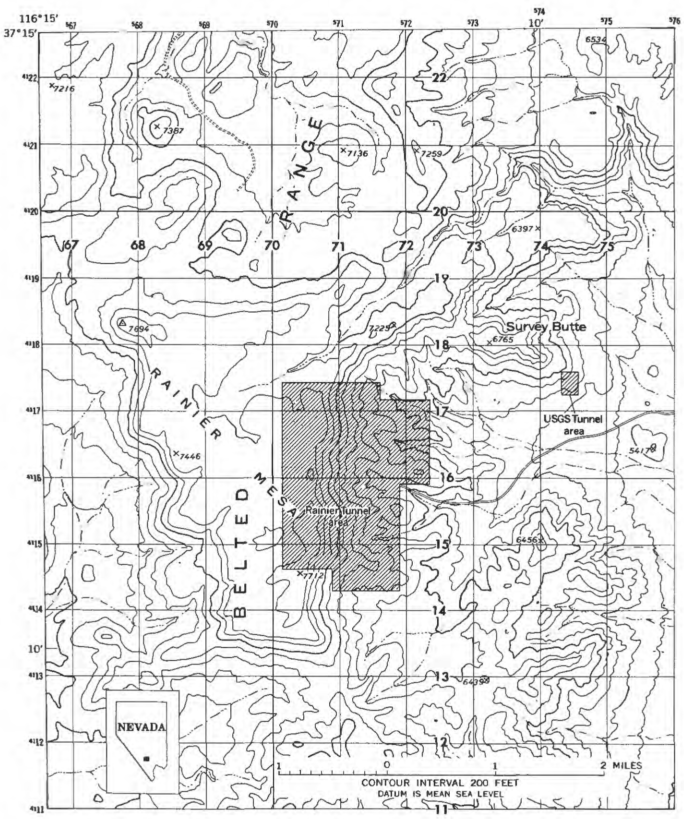

FIGURE 1.—Map showing location of northwest corner of Tippipah Spring quadrangle, Nevada Test Site.

Rainier and USGS Tunnel areas, is restricted and permission to enter must be obtained in advance from the U.S. Atomic Energy Commission.

In the winter and spring of 1957, 10-ton and 50-ton dynamite charges were exploded underground in the USGS Tunnel, and numerous much smaller charges of various size were exploded in shallow holes drilled from the ground surface. The purpose of these tests was to determine the amount of rock cover needed to contain blasts of various magnitudes, to determine the geologic and geophysical effects of the blasts on the rocks, and thus to gain information forecasting the behavior of the much larger Rainier underground atomic explosion on September 19, 1957.

With a rated energy yield equivalent to 1.7 thousand tons of TNT, the Rainier explosion greatly exceeded in size any deep-underground contained explosion previously attempted by the Atomic Energy Commission. By nuclear standards, however, the explosion was small. One of its chief purposes was to demonstrate the feasibility of deep-underground detonation as a method of testing atomic devices and to afford a basis for predicting the behavior of larger underground tests.

The purpose of the following report is to outline briefly the geologic background of the Rainier and USGS Tunnel areas. New tunneling and drilling are in progress in these areas, particularly in the Rainier Tunnel area, as this report is being written (1958); the geological data presented here probably will be expanded and modified in the near future. Much additional geological information undoubtedly will become available as the area of investigation widens.

FIELDWORK

Fieldwork on which the following report is based began in the fall of 1956 and extended over a period of several months. The surface geology of the USGS Tunnel (pl. 3) was mapped in January and February of 1957 by Lemke and Hansen assisted by Warren L. Peterson, using planetable methods with telescopic alidade and stadia, at a scale of 50 feet per inch. The topographic base for the geological map was prepared by Holmes and Narver, Atomic Energy Commission contractors, with modifications by the U.S. Geological Survey. The underground geology (pl. 2) was mapped concurrently by J. M. Cattermole, assisted part time by Peterson, using planetable methods and tape measurements and control established by Holmes and Narver and the U.S. Geological Survey; both the sides and the back of the underground workings were mapped at a scale of 10 feet per inch.

Surface geology of the north half of the Rainier Tunnel area (north of departure 888,000 N.) was mapped in March 1957 by Hansen and Lemke by plotting the geology 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 (pl. 1) on a topographic base prepared photogrammetrically by Hycon Aerial Surveys, Inc. The scale of the multiplex compilation was 100 feet per inch for areas along the rim of the mesa and was 166 feet per inch for the lower ground to the east. The south half of the Rainier Tunnel area was mapped by Hansen in October 1957, using the same field and compilation methods. The underground geology of the Rainier Tunnel (pl. 4) was mapped by A. B. Gibbons and E. B. Eckel in July and August 1957, at a scale of 50 feet per inch, using Brunton compass and tape and control by Holmes and Narver.

Stratigraphic sections were measured mainly by means of a modified Jacob's staff fitted with clinometers and spirit levels, supplemented by steel tape and by information taken from the logs of drill holes.

Several exploratory holes were drilled at both tunnel sites to obtain lithologic, stratigraphic, and structural data. Logs of these holes are given on pages A21 to A30 in this report. Physical and petrographic studies of cored samples and geophysical interpretations of the drill holes are still in progress and will be described in separate reports by several other authors.

Three core holes were drilled over the USGS Tunnel (pl. 3). Drill hole 1 was abandoned when it intersected a wide fault zone that could not be cemented off adequately. Drill hole 1A was located directly above room B, the 50-ton explosion chamber; it passed through the chamber and bottomed at a depth of 252 feet. Drill hole 2 was located above room A, the 10-ton chamber. Because of terrain conditions, the drill rig could not be placed directly over room A; therefore, the drill hole was inclined 5° to the vertical in order to penetrate the center of the chamber. (See also pl. 5.)

Four exploratory holes were drilled in the immediate vicinity of the Rainier Tunnel (pl. 1). Drill hole 1 (table 1), located about 500 feet to the right (northeast) of the tunnel was drilled to a depth of 250 feet. Drill hole 2 (table 2), at station 3+82 on the centerline of the tunnel, was drilled to a depth of 1,043 feet. Drill hole 3 (table 3), near Point Mabel, was drilled to a depth of 1,074 feet. This hole was to pass through the site of the explosion chamber, but, owing to adverse rock conditions, the position of the chamber was relocated after the hole was completed. Drill hole 4, about 350 feet east of the portal, bottomed in limestone at a depth of 633 feet. Additional special-purpose holes were drilled above and near the explosion chamber by the University of California Radiation Laboratory before and after the Rainier test, but these holes were not logged or studied by the U.S. Geological Survey and are not shown on plate 1. An additional hole about a mile west of the area shown on plate 1, the so-called Hagestad hole, was drilled to obtain data on stratigraphy, structure, physical properties, geophysics, ground water, and thermometry. The drill entered limestone at a depth of about 1,900 feet and bottomed at a depth of 1,919 feet.

ACKNOWLEDGMENTS

This report was prepared under the general supervision of Ernest Dobrovolny, geologist in charge of the U.S. Geological Survey activities at the Nevada Test Site at the time the high-explosive tests were fired in the USGS Tunnel in the winter and spring of 1957. Extensive preliminary geologic studies in 1956 by Messrs. Dobrovolny and E. B. Eckel paved the way for the authors and greatly facilitated fieldwork.

Much credit is due Warren L. Peterson who was instrumentman for most of the planetable work in the USGS Tunnel area and who logged a considerable part of the core of the Rainier Tunnel area (tables 1, 2).

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. The authors also profited from discussions with Wilcox in the office and in the field.

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

PHYSIOGRAPHIC SETTING

In southern Nevada the Basin and Range physiographic province is characterized by short isolated mountain ranges separated by broad interior-drainage basins or bolsons. Several such basins and ranges occur within or partly within the Nevada Test Site. Yucca and Frenchman Flats are notable examples of the bolsons of the province. The Belted Range, which bounds Yucca Flat on the northwest and is the site of the Rainier and USGS Tunnels, is not typical of the basin ranges as a whole, however, although it is fairly representative of most of those within the test site. It is a heterogeneous cluster of hills and mesas (fig. 3) that extends into the test site from the northwest.

The Rainier and USGS Tunnels were dug in the southern part of the Belted Range near the margin of Yucca Flat in an area of moderate to strong local relief and dissection. The USGS Tunnel is in a low south-facing bedrock spur about 500 feet high at the foot of Survey Butte (figs. 1, 7). Survey Butte is an east-trending ridgelike salient of Rainier Mesa, which contains the Rainier Tunnel and is the southernmost extensive highland mass in the Belted Range.

Rainier Mesa has a relief of about 2,100 feet. From its east base at an altitude of about 5,600 feet above sea level it rises to a height of 7,712 feet at its highest point just south of the area shown on the map (pl. 1). Within the mapped area, altitude ranges from a low point of about 5,810 feet in the ravine bottom near the northeast corner of the area to a high point of about 7,630 feet at the rim of the mesa just south of EGG Point. Viewed from the alluvial flats below to the east, Rainier Mesa presents an even flat-appearing skyline (figs. 2, 11), but its upper surface, in reality, is modified by hills and gullies and has a rolling relief of more than 200 feet.

Parts of three separate interior-drainage basins receive drainage from the piñon-covered top of the mesa—Yucca Flat to the southeast, the Amargosa desert by way of Forty Mile Canyon to the southwest, and Kawich valley to the northwest. This drainage is all ephemeral, for no permanent streams exist in the area. The broad washes that collect runoff from the east face of the mesa and trend east past the USGS Tunnel area toward Yucca Flat contain water only after prolonged or intense storms. Even in the spring, when the con-

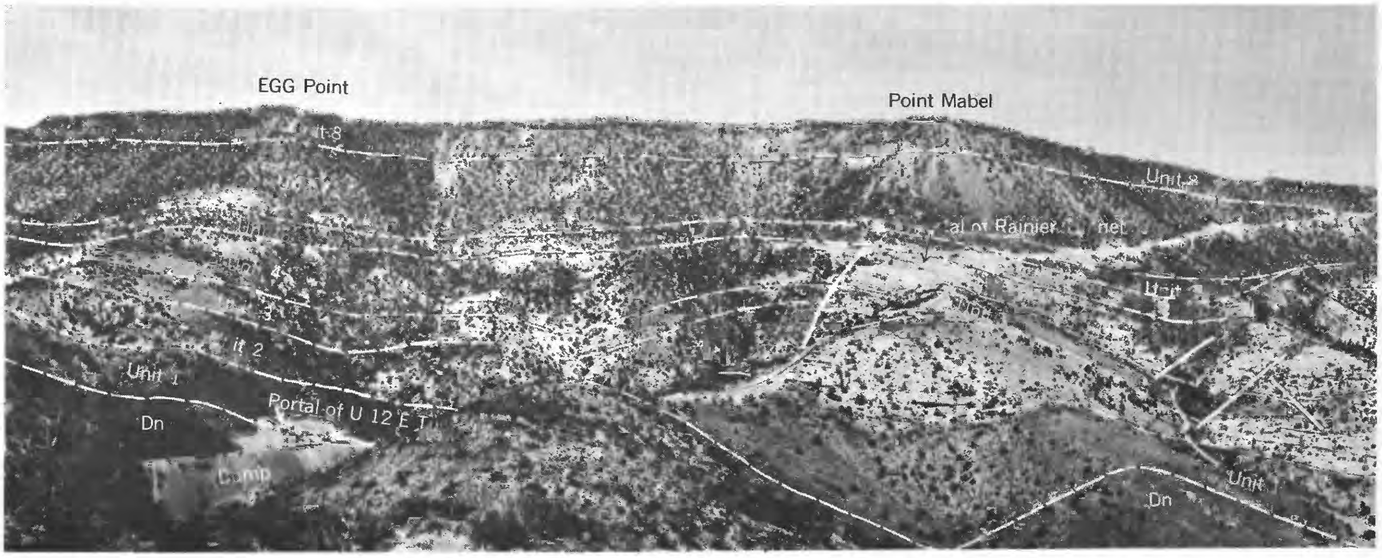

FIGURE 2.—Rainier Mesa from the east showing Nevada formation (Dn) and Oak Spring formation (units 1 to 8). U12e Tunnel and dump, lower left below EGG Point Rainier Tunnel and dump, upper right below Point Mabel. Cat Hill and False Start Draw (with road), lower right. Workings and tailings piles as of May 6, 1958.

siderable snowpack on the mesa is melting, small tricklets of water in the ravines at the front of the mesa disappear into the alluvium before reaching the flats below.

Most natural slopes in the area are between 20° and 30°. The rimrocks of the mesa form near-vertical cliffs (fig. 3) and consist of welded tuffs which probably were erupted and deposited in two separate volcanic outbursts. They form an upper and a lower palisade about 90 and 40 feet in height, respectively, separated by a steep slope about 140 feet in height. This slope and the upper part of the long slope below the lower palisade commonly are as steep as 40° (fig. 3).

Resistant beds at several intervals in the section also form low cliffs and ledges on the lower slopes of Rainier Mesa and near the USGS Tunnel. Such cliffs and ledges generally are more conspicuous on outcrops with southerly exposure than on those with northerly exposure, and the craggy aspect of many south-facing slopes contrasts with a smoother more uniform appearance of north-facing slopes. By the same token, bedrock is better exposed on south-facing slopes. Along the east front of Rainier Mesa, where ravines drain due east, the contrast between south- and north-facing slopes is particularly striking.

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 surficial deposits of Quaternary age (Johnson and Hibbard, 1957). In adjacent areas there are intrusive rocks of Cretaceous or Tertiary age and contact-metamorphosed rocks of Paleozoic age. Discounting thin veneers of overburden, the only formation exposed in the USGS Tunnel area is the Oak Spring formation of Tertiary age. A more complete section of this formation, and part of the Nevada formation of Devonian age, crop out in the Rainier Tunnel area.

NEVADA FORMATION OF DEVONIAN AGE

Paleozoic rocks of the test site range in age from Early Cambrian to probably early Permian. According to Johnson and Hibbard (1957), they have a total thickness of about 22,000 feet, of which more than 16,000 feet is dolomite and limestone. 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. The rocks within the Rainier Tunnel area probably should be assigned to unit C of the Nevada formation of Johnson and Hibbard (1957, p. 354). This unit consists of medium-gray to black, dense, finely crystalline thick-bedded massive dolomite that contains a few chert bands and nodules and some beds of lighter gray dolomite. Many beds contain small rodlike stromatoporoids, and some contain larger concentric reniform masses several inches in diameter, commonly in association with a favositid colonial coral.

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 with the beds of the Oak Spring formation that overlie it unconformably along the eastern base of Rainier Mesa, and that form the knoll into which the USGS Tunnel was dug.

FIGURE 3.—View north along rim of Rainier Mesa. Point Mabel in middle distance; palisade-forming welded tuff, unit 8 of Oak Spring formation, at left; long smooth slopes below palisades formed on unit 7; main part of Belted Range, upper right.

ENGINEERING CHARACTERISTICS

At the time of this writing no working experience in the Nevada formation was available to aid in prejudging its probable engineering behavior. A few inferences, however, can be made from observations of its outcrop habit and general field relations and from known behavior of other carbonate rocks. As the rock is hard and resistant to erosion and forms massive blocky ledges, it undoubtedly has great bearing strength and can be expected to stand unsupported in high near-vertical cuts. By the same token, it should stand well underground with a minimum of supporting timbers, although heavy ground may be expected if slabby bedding or close jointing is encountered. In any excavation involving firm rock, either above or below ground, drilling and blasting will be required.

In exploratory drilling operations the rock should core easily and well. Drill water losses, however, are almost certain to occur; and they may be high, owing to numerous joints, to partings along bedding planes and, perhaps, to scattered small solution cavities.

OAK SPRING FORMATION OF TERTIARY AGE

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 and in widespread areas elsewhere in the Nevada Test Site. This formation underlies the USGS Tunnel area and most of the Rainier Tunnel area. The following general descriptions of the Oak Spring formation are based largely on observations made in the Rainier Tunnel area, but they apply equally well to the USGS Tunnel area.

GENERAL CHARACTER AND ORIGIN

The rocks of the Oak Spring formation, including the several bedded and welded tuffs, are mainly rhyolitic to quartz latitic in composition. A few beds are dacitic. Texturally, the tuffs range widely from exceedingly fine grained rocks to coarse lapilli tuffs, tuff breccias, and agglomerates. Shards and lapilli are the chief constituents. Phenocrysts of quartz, feldspar, biotite, other ferromagnesian minerals, and opaque oxides are common in some beds and rare in others. The bulk density of the nonwelded tuffs ranges from about 1.2 to 1.9 and the corresponding porosities from 20 to 45 percent (G. V. Keller, written communication, 1957). The welded tuffs have a bulk density of about 2.2 to 2.3. This corresponds closely with the powdered density of the nonwelded tuffs.

Fragments of tubular pumice are exceedingly common, and some beds consist largely of pumice fragments. Lithic inclusions are common also, although volumetrically they comprise a relatively minor part of the rock. They consist mostly of various older volcanic rocks probably derived largely from the crater walls and vents of the erupting volcanoes; various sedimentary rocks, chiefly quartzite and chalcedony, probably derived mainly from adjacent Paleozoic terranes but possibly including material torn from the walls of the magma chamber; and rarer fragments of plutonic igneous rock. Rocks that contain abundant small lithic inclusions, such as quartzite, are referred to in measured sections and core logs as tuffaceous grit. Many of the tuffaceous grits have a hard flintlike matrix. Hard flintlike rock itself is referred to in logs and measured sections as porcelanitic material. The porcelanitic beds, however, are largely surface or near-surface features, being cemented by a zeolitic matrix that is very hard on the outcrop but is very soft underground. Thus, the physical character of a rock on the outcrop is but a poor clue to its character underground; hardening on the outcrop is observed commonly in rocks of arid regions, and appears to be a weathering phenomenon associated with loss of constituent water and precipitation of silica.

The predominant colors of the tuffs are pale shades of gray, cream, and buff to almost white. Many beds, however, are pink or red, particularly in the lower half or so of the formation. Despite considerable lateral color variation, color has proved to be one of the most reliable guides for correlation, both from place to place and from surface to underground. Colors tend to be darker underground than at the surface, partly because of a decrease in color value underground owing to greater moisture content and partly because of bleaching on the outcrop. Some beds that are decidedly brown or pink underground are monotonous gray on the outcrop.

The welded tuffs of the formation are generally darker in shade than the nonwelded tuffs, and their outcrops, accordingly, are readily distinguished in distant views. Physically and topographically, of course, their outcrops are distinctive also.

Throughout the nonwelded parts of the Oak Spring formation there is a very marked tendency for well-bedded relatively thin-bedded intervals to alternate with massive nonbedded intervals. The massive intervals are generally two to three times as thick as the adjacent bedded intervals. Each bedded interval overlies a minor stratigraphic break or diastem. Thus, as shown by many outcrops, the base of a given bedded interval commonly appears to truncate the top of the underlying massive interval, whereas the top of the bedded interval commonly grades indefinitely upward into the overlying massive one. In many places, abundant angular lithic fragments several millimeters across are concentrated in the basal part of the bedded interval. The bedded intervals tend to be grittier than the massive intervals, and are somewhat more sorted, although sorting is poor virtually everywhere. In some beds vague crossbedding may be observed, but on the whole crossbedding is rare.

Graded bedding is very common, including unusual inverse graded bedding in coarse granular pumiceous material. Inverse graded bedding of pumiceous rocks has been attributed (Bateman, 1953, p. 1499; Chesterman, 1956, p. 8) to desposition of erupted fallout in standing water—the larger lapilli, having greater air retention and hence buoyancy, settle more slowly to the bottom than the smaller particles. Some beds that contain both pumice lapilli and denser lithic fragments of quartzite or certain volcanic rocks show inverted size gradations of the pumice fragments and normal size gradations of the denser material.

The bedding habit of some of the nonwelded tuffs of the Oak Spring formation suggests deposition in standing becalmed water such as would exist in a large inland lake. Aquatic fossils in some parts of the formation support such a view. The uniformity and wide lateral extent of some beds—surprisingly wide for rapidly accumulating volcanic sediments—support such a view also, and the general paucity of current features, scour-and-fill structures, ripplemarks, and crossbedding suggest settling out in still water. Such beds, however, might conceivably accumulate on dry land. The local abundance of foreign fragments, such as quartzite, probably derived from adjacent Paleozoic terranes, together with crude size sorting and local occurrences of quartz sands, indicate transportation by streams, with mild reworking and winnowing, perhaps, by shore or bottom currents. Intermittent desiccation, or at least withdrawal of the water, is indicated by intraformational unconformities and conglomerates.

The welded tuffs of the formation present a very different mode of origin and depositional environment from the nonwelded bedded tuffs. Vitric ash that is blown high into the air during eruption loses heat quickly by adiabatic cooling and convective and radiational heat transfer to the atmosphere. It is cool and solid by the time it drops to the ground and its transformation to rock is accomplished slowly by the usual processes of compaction and cementation. In large part, the coherency of the bedded nonwelded tuffs of the Oak Spring formation is due to the conversion of the vitric constituents—shards and pumice—to zeolite and to the cementation of fragmental material by interstitially deposited zeolite and opaline material (Ray E. Wilcox, written communication, 1958). The welded tuffs, on the other hand, are not blown aloft but are erupted as highly heated glowing avalanches or ash flows (Smith, 1960, p. 795), similar to, but probably on an even larger scale than, the spectacular nuées ardentes or peléan clouds of some modern eruptions (Perret, 1937, p. 3, 84).

Ash flows possess vast energy and great mobility. Their almost frictionless motion seems to be made possible by spontaneous disaggregation of the gas-charged lava on ejection from the vent and by mechanical suspension of the individual particles in the hot expanding gas. Characteristically, therefore, they move rapidly over great distances, even on slopes of very low gradient (Perret, 1937). Commonly, also, they flow streamlike under the influence of gravity down valleys and into depressions, coming to rest in low places as still-hot incandescent masses. The thicker deposits retain their heat for a long time, and under the weight of the superincumbent load the individual particles are flattened and welded tightly together into a hard coherent rock. Obviously such rocks cannot form under water; a subaerial environment is required, in contrast with the lacustrine environment in which at least part of the bedded nonwelded tuffs of the formation presumably accumulated.

Correlations and age.—Johnson and Hibbard left open the question of the relation of the Oak Spring formation to similar rocks in adjacent areas. Ball (1907, p. 33) earlier had mapped the nonwelded tuffs of the formation as the Siebert lakebeds, which have their type exposure in the Tonopah district (Spurr, 1905, p. 51–55) about 100 miles northwest of Oak Spring Butte. As defined by Johnson and Hibbard (1957, p. 367), the Oak Spring formation contains some rocks—notably welded tuffs—not included in the Siebert lakebeds by Ball or by Spurr. A broad correlation between the two formations is otherwise probable, even though physical tracing between typical Oak Spring and the type Siebert tuff is impossible owing to a wide gap of unrelated rock types—a gap of 50 miles or more, judging from Ball's map (1907, pl. 1).

The Siebert lakebeds are correlated in part with the Esmeralda formation (Ransome, 1909, p. 98; Buwalda, 1914, p. 335–363); the probability seems good, therefore, that the Oak Spring is equivalent to part of the Esmeralda. As the name Esmeralda has priority in the literature, the U.S. Geological Survey restricts usage of the name Siebert tuff to its type area in the Tonopah district (Ferguson, 1924, p. 42).

No definite age has been assigned to the Oak Spring formation, owing to a lack of diagnostic fossils (Johnson and Hibbard, 1957, p. 369), but a late Miocene or an early Pliocene age is probable. Merriam (1916, p. 161–198) assigned a late Miocene age to the vertebrate-bearing beds of the Esmeralda formation, and Stirton (1932, p. 60) found faunas of both late Miocene and early Pliocene age. According to Nolan (1943, p. 166), "the name Esmeralda, as commonly used, probably applies to beds that contain the younger of the two faunas, but it has also been used as a group name for both units." No fossils have yet been found in the Rainier or USGS Tunnel areas, but well-preserved fish, gastropods, and several genera of plants have been discovered in the lower part of the Oak Spring formation in other parts of the Nevada Test Site (Ernest Dobrovolny, oral communication, 1956). With further study some of these remains might yield a more precise age determination than has yet been made.

SUBDIVISIONS OF THE OAK SPRING FORMATION

In the Rainier Tunnel area the Oak Spring formation is divisible into eight units that can be traced throughout the mapped area (fig. 2). It is not expected that all these units can be recognized at any great distance from the mapped area, but some of them have remarkable continuity and can be traced for considerable distances with confidence. Their delineation has greatly assisted in the solution of various structural problems involving the Oak Spring formation. From bottom to top, the units are numbered 1 to 8. Units 6 and 8 consist largely of welded tuff; the remaining units are largely nonwelded tuff, although lenticular bodies of welded tuff occur also at the top of unit 2. In units 1 through 4 the glass of the shards and pumice fragments is largely altered. In unit 5, the shards and pumice are altered in some beds and are fresh and glassy in others. In unit 7, alteration is confined largely to the lower 180 feet or so. Only units 2, 3, and 4 crop out in the small USGS Tunnel area, but higher and lower units are recognized nearby (fig. 7). To bring out better the geologic structure at the map scale used for that area (pl. 3), it was convenient to further subdivide units 2, 3, and 4 into smaller map intervals consisting of a few beds per interval (pl. 5).

Of special interest is the unusual mode of occurrence of the welded tuffs in units 2 and 6. These welded tuffs occur as relatively small discontinuous lenses in the axial parts of synclines (fig. 11). The synclinal structure clearly antedates their emplacement, and its possible structural and genetic implications are discussed further under "Origin of folds and tectonic significance" in the section of this report on geologic structures.

Comparative partial sections of the Oak Spring formation are shown on plate 6. Plate 6 was composed from data taken from measured sections and well logs; it is most useful, therefore, if used in conjunction with the detailed descriptions of the various measured sections and well logs given in the text.

UNIT 1

At Rainier Mesa, unit 1 consists of nonwelded bedded tuffs totaling about 210 feet in thickness. Most beds of the unit contain abundant altered pumice fragments in a fine-grained zeolitic matrix. Phenocrysts of quartz, feldspar, and biotite, and blebs of rusty limonite occur in virtually all beds; in some beds they are abundant, in others they are abundant only locally and form a mottling on the outcrop.

Unit 1 is distinguished by its predominantly red color, ranging from pink to nearly purple. A few beds are nearly white, but these do not crop out well and are rarely seen at the surface. Most beds of the unit, in fact, crop out poorly and form scree-mantled slopes, although resistant ledge-forming members at the base and top of the unit and 20 to 30 feet below the top, have near-continuous outcrops. Thin resistant members also crop out here and there throughout the unit. Probably the best exposed section of the unit in the mapped area is along the ridgeline 1,000 feet south of portal of the U12e Tunnel, extending west from latitude N. 886,900, departure E. 638,300. The resistant basal beds of the unit are further characterized, on weathered surfaces, by a distinctive texture like that of fish roe, which is formed by aggregates of small pellets, each a few millimeters in diameter. On continued weathering the rock disaggregates into a coarse pelletal sand.

In some places unit 1 has a basal conglomerate composed chiefly of material derived locally from the underlying rocks. At latitude N. 888,200, departure E. 637,570, it consists of subangular fragments of blue dolomite, gray argillite, and white vein quartz, mostly less than an inch across, in a gray tuffaceous matrix. This conglomerate probably filled shallow channels in the old surface on which unit 1 was deposited. Its discontinuity of outcrop is caused partly by local nondeposition and partly by concealment beneath dislodged slabs of basal tuff.

Detailed sections.—Unit 1 is rarely well exposed, and completely exposed detailed sections are unavailable. One of the most nearly complete sections is as follows:

Section of unit 1 of Oak Spring formation of Tertiary age measured along ridgeline 1,000 feet south of the portal of U12e Tunnel, extending west from latitude N. 886,900, departure E. 638,300

[Bed numbers assigned to this and other measured sections correspond with numbers that appear on plate 6. Measured by A. B. Gibbons and W. R. Hansen]

	Thickness (feet)
Unit 1:	
6. Tuff, medium-brick-red; many white pumice fragments ¼ to ½ in. across. Rare small crystals of quartz and feldspar mostly less than one thirty-second inch across	5.2
5. Tuff, fine-grained, thin-bedded, purplish-red and red-orange interlayered	23.9
4. Tuff, medium-reddish-brown (10*R* 4/6), fine-grained, pumiceous, fragmental. Rusty spots about one-fourth inch across. Bricklike texture. Irregular mottling of crystal-rich tuff; crystals very small. Forms conspicuous ledge	7.3
3. Tuff, mostly covered. Whitish fine-grained pumiceous tuff at base; moderate red-orange float	45
2. Tuffs, pink. Near-white bed at 15 to 16 ft. Pumiceous; contains considerable quartz. Near-white bed 40 ft above base contains abundant quartz; overlies a distinctive dark-red bed. At 48 ft above base is a crystal-rich (quartz and feldspar) purplish-red tuff which contrasts with underlying pumice tuffs. At 78 ft is a bed of well-indurated crystal tuff. At 111 to 113 ft is a ledge-forming pink pumiceous lapilli tuff (fragments 1/32 to 1/16 in. across)	113
1. Tuff, dark-red (5*R* 5/4 to 5*R* 6/6) stained darker by weathering and desert varnish. Slabby beds 2 to 6 in. thick. Small ovoid aggregates less than one-fourth inch across on weathered surfaces. Dip is 21° W.	13
Total thickness of beds 6 to 1	207.4

The following section, less well exposed than than that above, was measured across the Cat Hill road:

Section of unit 1 of Oak Spring formation of Tertiary age measured near Cat Hill, extending west from latitude N. 891,000, departure E. 639,500.

[Measured by R. W. Lemke and W. R. Hansen]

Unit 1:	Thickness (feet)
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 ledge about 5 ft. thick of reddish-brown tuff; has abundant altered pumice and ash shards, some obsidian fragments, relatively abundant phenocrysts of 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. Contains abundant 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 ¼ to ½ in. 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. About 40 ft 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 bed 2 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 tuff 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 across. Few thin dense fine-grained beds less than 1 ft thick. Good ledge former	15.0
1. Basal conglomerate. Abundant subangular fragments less than 1 in. derived from underlying 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

Unconformity.

Nevada limestone of Devonian age.

UNIT 2

Unit 2 of the Oak Spring formation conformably overlies unit 1. It consists of nonwelded bedded tuffs similar mineralogically to unit 1 but dissimilar in color and bedding habit. It totals about 125 feet in thickness, crops out well, and forms conspicuous angular ledges. Good near-complete sections may be seen on the south-facing slopes of the principal ravines along the front of Rainier Mesa.

In overall color unit 2 contrasts markedly with the units above and below. Most beds are light gray to buff with perhaps the faintest suggestion of color, although pink, red, and purplish beds and stringers are common and are fairly well distributed throughout the unit. Individual beds range in thickness from a fraction of an inch to 15 feet or more and in texture from very fine grained to very coarse. There is a rhythmic alternation of relatively thin bedded sequences 3 to 4 feet thick and much more massive sequences commonly about twice as thick. Most of the thin-bedded sequences are more resistant to erosion than their massive counterparts; hence, they generally form the tops of slope breaks. In some places the unit displays microfolds that appear unrelated to any other structures and seem to have formed penecontemporaneously—perhaps by slumping during deposition. Their amplitudes range from a few inches to a few feet.

The pisolitic bed.—About two-thirds of the way up from the base of the unit is an interesting and distinctive pisolitic bed which, because of its unmistakable appearance and widely exposed outcrop, provides an excellent horizon marker. It is equally well exposed near the USGS Tunnel (bed 5, pls. 5, 6) and near the Rainier Tunnel (bed 12 of measured section 1, pl. 6).

Near the USGS Tunnel, where it is about a foot thick, the pisolitic bed contains gritty stringers composed of yellow pumice fragments, gray and tan quartzite fragments, dark-gray chert, and brown, gray, and tan volcanic rock fragments. The bed itself is blocky, hard, and for tuffaceous rock, relatively dense; except for the cited stringers, it is fine grained.

Individual pisolites average about 5 mm in longest diameter and range from about 1 mm to more than 1 cm; a very few pisolites are as large as 2 cm across. They are somewhat flattened in the plane of bedding but are subcircular in plan. Each pisolite commonly has a light-colored massive core enclosed by several darker colored concentric shells which superficially resemble minature Liesegang rings but which consist of finer grained material than either the core or the matrix. The shells evidently contain much ferric oxide, if their color is any indication. Some pisolites contain nuclei of pumice, quartzite, or other material, but the majority of them lack obvious nuclei. When the rock is broken, some pisolites break across; others break around and stand out like hobs on the sole of a boot.

At the Rainier Tunnel area the pisolitic bed is basically the same as at the USGS Tunnel area, but it differs in detail. The bed is thicker, totaling about 3½ feet, with hard purplish intervals about 1 foot thick at the top and base and a mottled cream and purple interval between. The bed is pisolitic throughout, although pisolites are more abundant in the upper and lower intervals than in the central part. They are less closely packed than at the USGS site, the bed is somewhat softer, and the rock breaks across the pisolites. Some of the pisolites have been broken and fragmented, and the fragments are scattered through the enclosing rocks. The color contrast between the pisolites and the matrix is marked; the shells are dark grayish red or grayish purple, the matrix is grayish pink. In some specimens a dark-colored massive core is enclosed by alternate shells of dark and light material—the outermost shell invariably is dark. Some specimens have as many as 15 shells.

The origin of the pisolites can only be conjectured. Plainly, they are syngenetic and were formed as discrete solid particles before the enclosing bed was lithified. No other explanation is possible because of the breakage and scattering of fragments through the bed. Several modes of origin have been attributed to various pisolites and their smaller homologs, oolites, particularly those formed in sedimentary rocks. Relatively little attention, however, has been given to pisolites in tuffaceous rocks. Most volcanic pisolites described in the literature (summarized by Wentworth and Williams, 1932, p. 37) are attributed to accretion—mainly segregation of tuff particles by condensing steam or by the action of rain and wind on newly fallen ash. Rain falling through airborne ash clouds might achieve identical results. During a very light rain shower at Parícutin Volcano in Mexico, Ray E. Wilcox (oral communication, 1958) observed that rain drops falling on fresh ash formed small pellets which rolled downslope and snowballed into larger mud balls. Ideally the layering of such mud balls should be helical.

Mechanical accretion does not seem to explain satisfactorily the delicately laminated shells of the pisolites of the Rainier and USGS Tunnel areas nor the color contrast of the shells with the cores and matrix. Moreover, some of the fragmented pisolites show slight regrowth after fragmentation in that new shells have formed about broken fragments; hence, the process of formation was still active during the fragmentation. Rather special conditions seem to be required, for in a section of nonwelded tuffs nearly 1,600 feet thick, only one other bed—20 feet above the base of unit 2—contains pisolites, and they are rare.

A hypothesis detailed by Bradley (1929, p. 221) to explain certain inorganic calcareous oolites deposited in the Eocene lake of the Green River formation, modified to fit the differences in chemistry and environment, may account for the origin of the tuffaceous pisolites of unit 2. Although the oolites described by Bradley are calcareous and are much smaller than the pisolites, they are similar in that they are darker than the matrix in which they are embedded, they lack radial structure, they possess concentric bands that contain much ferric oxide, and some, but not all, possess nuclei, such as minute quartz grains. According to Bradley, the concentric bands probably formed from a gel of ferric hydroxide coagulated by negative ions of carbonate or chloride. Citing experiments of Heinrich Schade, who was investigating the origin of gall stones, Bradley further pointed out that minute coagulating particles tend to coalesce into spheres and that "concentric lamination * * * is characteristic property of coagulated colloids that contain admixtures of foreign material."

To adapt Bradley's hypothesis to the origin of the pisolites, silicate ion is called upon as a coagulant in place of carbonate or chloride. Silica is a major constituent of the Oak Spring tuff, and it probably occurred in relatively soluble form in the newly erupted ash. The tuff also contains relatively large proportions of the soluble alkalies soda and potash in whose presence silica is readily soluble in water. The rock before lithification may be visualized as a soupy slurry of fine volcanic ash fallen in shallow water, partly suspended in a thin gel of positively charged ferric hydroxide but possibly kept in suspension mainly by the gentle agitation of waves. Silica derived from the ash, and probably also in a colloidal state, on reaching a suitable ionic concentration would coagulate the ferric hydroxide which, at the same time, would entrap part of the suspended ash.

Coagulation would stop when the ferric hydroxide was consumed, or more probably, when the concentration of silicate ion fell out of balance by rising above or dropping below an optimum level. At the USGS Tunnel locality, where the pisolitic bed is very hard and appears to be highly siliceous, the pisolites are much crowded, so that individuals are touching on all sides. The matrix, moreover, seems to contain more iron than the cores, but less than the dark concentric shells. Apparently an excess of ferric hydroxide existed until the rock finally lithified—probably by saturation and precipitation of silica. At the Rainier Tunnel locality, however, where the bed is relatively soft and apparently is appreciably less siliceous, the pisolites are not crowded; very few are even in contact, although the matrix contains appreciable iron, especially in the upper and lower parts of the bed. Pisolite formation stopped well before the bed lithified, as indicated by the distribution of pisolite fragments through the bed. It is suggested that the silicate-ion concentration dropped below effective levels before the bed began to lithify. In conclusion, the pisolites seem to have formed by precipitation under water rather than by accretion in air.

Detailed section.—Unit 2 is well exposed in many places; one of the best places for viewing and measuring the section is on the south exposure of the high ridge south of U12e Tunnel as follows:

Section of unit 2 of Oak Spring formation of Tertiary age measured along ridgeline 1,000 feet south of portal of U12e Tunnel, extending west from latitude N. 886,800, departure E. 637,840

[Measured by A. B. Gibbons and W. R. Hansen]

	Thickness (feet)
Unit 2:	
15. Pumiceous tuff, pale, fine-grained with scattered foreign inclusions. Red bands 1 to 2 in. thick, pinch, swell, follow bedding in general way only. Less biotite than in base of unit 2. Some horizons of red tuff with pumice fragments	30.1
14. Tuff; coarser beds are grit size with considerable bronze biotite; some quartz and feldspar. No coarse pumice fragments	9.0
13. Tuff; medium red purple in layers 1 to 6 in. thick	6.5
12. Pisolite bed 3½ ft thick with 1-ft ledge of hard purple slightly mottled pisolite-riddled tuff at base; 1½ ft of pale-cream and purple mottled pisolitic tuff; 1 ft upper ledge like that at base. Pisolites have dark-purple rims. Slightly sandy or altered pale-tan cores are less than one-half inch in longest diameter (in plane of bedding) and are round in plan. Matrix of pisolite beds uniformly very fine; few crystals	3.5
11. Tuff, pale, nonresistant; fine grained in massive layers about 6 ft thick; separated by fine-bedded slightly more resistant sequences of pale tuff about 4 ft thick. A few lenses as much as 6 in. thick in massive phase have volcanic fragments to three-eighths inch. Massive phase has common very fine black biotite. Ten feet above base begins 2-ft layer of coarse pale pumice-breccia with a few three-eighths inch subangular fragments of dark volcanic rock. Alternation of coarse massive and fine-bedded phases is 3 to 4 ft fine, then 6 to 8 ft massive. At 29 to 37 ft is a massive ledge-forming layer, pale purple mottled at base grading up to medium red purple at top. Contains pumice fragments less than one-fourth inch. This layer is topped by 2-ft laminated sequence, thence massive pale tuff	53.0
10. Tuff, pale-purple (10R 6/2), hard, fine-grained, mottled, massive; patchy distribution of pumice fragments as much as one-half inch, sparse biotite. Good ledge former. Unit has rare three-eighths inch pale-lavender pisolites	3.7
Unit 2—Continued	
9. Tuff, very pale, pumiceous with many tiny biotite flakes. Layers about 1 in. thick. Bedding very faint, effect massive; resistance slight. At 5 ft above base is top of 1½-ft resistant fine-grained purplish layer, which is topped by 1 in. of pumice-breccia; pumice fragments to one-half inch; breccia has fragments of dark volcanic rocks less than one-half inch	9.2
8. Tuff, in layers 1 to 10 in. thick. Rich in pumice fragments, color cream to pale purple, crystals few and small, include bronze biotite. Forms moderately strong ledge. A 1-in.-thick mottled purple pumice fragment sequence near top	6.7
7. Tuff, pink to cream, poorly bedded. Pumice fragments less than one-half inch, crystals few and small, color irregularly distributed	5
Total thickness of beds 15 to 7	126.7

Welded tuff at top of unit 2.—At the top of unit 2, but occurring only at the northern boundary of the Rainier Tunnel area in the keel of the Point Mabel syncline, is a lenticular body of rhyolitic welded tuff. This rock also crops out as a lens about 1,000 feet to the southeast of the USGS Tunnel area, where it also occupies the keel of a syncline.

At the Rainier area locality, the welded tuff has a maximum exposed thickness of about 15 feet. Its top forms a flat shelf, and its face forms a low vertical cliff. Except for the lower 3 feet, which is gray perlite, the rock is grayish red (5*R* 5/2 to 5*R* 3/4), dense, hard, and stony, and contains scattered flattened cavities mostly less than half an inch across. Its appearance is unlike that of any other rock in the area.

As examined by Ray E. Wilcox (written communication, 1957), this welded tuff contains many phenocrysts of quartz and alkalic feldspar. These phenocrysts are visible megascopically and range in length from about 1 to 3 mm. The rock also contains scattered phenocrysts of biotite and rare undetermined red crystals, possibly rusted olivine. Elongate masses of devitrified collapsed pumice are common. The groundmass is compacted devitrified shards with dusty shard inclusions. Megascopically, the compacted-shard structure is plainly visible in some specimens but is undiscernible in others. Lithic inclusions of foreign rock material are rare, but masses of brown material that looked like devitrified glass of possible andesitic composition are noted.

UNIT 3

Unit 3 of the Oak Spring formation overlies unit 2 with an apparently conformable contact. It consists

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FIGURE 4.—General view of portal area, USGS Tunnel, before 10-ton explosion. Portal is just behind sedan in center. Sandbags to left of sedan were used for stemming charge in room A. Unit 3 of Oak Spring formation crops out at and below portal; unit 4 crops out above tunnel.

chiefly of nonwelded bedded tuffs similar in general appearance to those of unit 2 but different in color and detail. In outcrops south of the portal of the Rainier Tunnel, its predominant red color sets it apart from the units below and above. Northward from the Rainier Tunnel, in UCRL drill hole 2, and toward the east at the USGS Tunnel, the medial greater part of the unit is gray.

Throughout the area, unit 3 maintains a near-uniform thickness of about 135 to 140 feet. It crops out well and forms very conspicuous generally rounded ledges and low cliffs. It is further distinguished by well-defined marker beds at its base and top.

The basal bed is a dark-brownish-red (about 10*R* 5/3) very massive relatively hard dense tuff 4 to 7 feet thick. It forms a distinctive blocky readily identified outcrop; downslope from the outcrop, large subequidimensional blocks commonly litter the hillsides. The basal bed is further distinguished by an abundance of small rounded lithic inclusions and scattered subrounded fragments of partly devitrified pumice in a porous groundmass of devitrified shards and crystal fragments. The pumice fragments, which may be 5 mm or more across but are mostly smaller, are stained brown by iron oxide and commonly have dark-brown limonitic shells.

Between the basal and the topmost bed of the unit is the familiar alternation of bedded and massive tuffs, much the same as previously noted lower in the section in unit 2, but redder and generally in thicker intervals. The rhythmic alternation of bedded and massive intervals characterizes nearly all the nonwelded tuffs of the Oak Spring formation.

The uppermost bed of unit 3 is referred to as the portal bed for its occurrence at the portal of the USGS Tunnel (fig. 4). Because the portal bed is resistant to erosion and hence crops out very well throughout both tunnel areas, it is an excellent horizon marker. Its thickness is about 7 to 9 feet, but together with the beds that immediately underlie it, it commonly forms a ledge or low cliff 15 to 40 feet high. The resistant overlying basal beds of unit 4, which are gritty and porcelanitic, further accentuate the outcrop, and the light-red to moderate-red color (about 5*R* 7/4 to 5*R* 5/5) helps to identify the outcrop in distant views.

In detail, the portal bed is fine to medium grained and contains scattered light-colored pumice fragments as much as 10 cm across locally but generally much smaller (<10 mm). Small dark lithic inclusions are abundant. Phenocrysts of quartz, feldspar, and biotite are relatively inconspicuous, but small black ferromagnesian(?) grains enclosed in white reduction halos are eye catching and noteworthy.

Measured section.—The following section of unit 3 is exposed about 400 feet west-northwest of U12e Tunnel. An additional section was measured at the USGS Tunnel area (pl. 5), and the unit was penetrated by UCRL drill hole 2 (table 2).

Section of unit 3 of Oak Spring formation of Tertiary age measured along ridgeline 400 feet west-northwest of U12e Tunnel, extending west from latitude N. 888,200, departure E. 637,060

[Measured by A. B. Gibbons and W. R. Hansen]

	Thickness (feet)
Unit 3:	
22. Tuff, (portal bed, No. 20, in USGS Tunnel area) massive, moderate red (5*R* 5/5) when fresh; when weathered is moderate reddish brown (10*R* 4/6). Tuff is fine grained with pumice fragments mostly less than one-fourth inch, a few more than one-half inch. Has distinctive small white halos which appear to surround slightly altered mafics. Portal bed forms strong cliff with help of beds below it (the 16-ft and 15-ft beds). Cliff (capped by portal bed) may be 25 to 30 ft high in favorable exposures	9.3
21. Tuff, massive, very pale cream purple to dull pinkish-red. Color in 2 to 3 ill-defined zones, roughly parallel to bedding as marked by layers of varying resistance and by 1-in. thick bands of deep purple which appear to follow irregular horizons in bed and suggest erosion planes of slight relief with perhaps slight winnowing of surface during erosion interval. Top of bed (like base) is a 3-ft-thick irregular white to purple-pink mottled layer. Pumice fragments as much as 1 in. and foreign volcanic fragments to one-half inch resemble the underlying 16-ft bed	15.0
Unit 3—Continued	
20. Tuff, massive, pink basal phase with coarse pumice fragments, grading up within 3 ft of top into medium-brick-red tuff with fine pumice fragments. Phenocrysts of rare quartz and feldspar, ultrafine common black biotite. A wavy bed or band, 1-in. thick, of very deep red-purple tuff lies at the top of this bed. Scattered subangular fragments of dark volcanic rocks as much as three-fourths inch are commonest in the middle of this bed	16.0
19. Tuff, in layers 1 ft. to 4 in. thick. Laminae marked by thin bands of purple-red color. Many white pumice fragments, 1 in. across. Definite truncation of massive tuff at base. Bedding appears especially at base to be fine, low-angle crossbedding, with mutual truncation of beds. At top of unit is a massive layer, 2 ft. thick, of medium to coarse brick-red tuff with conspicuous pumice fragments. Pumice fragments greenish, few phenocrysts. A few layers toward middle of unit are entirely of fine material and are red and white banded	10.0
18. Tuff, basal unit is 1.2 ft. thick, laminated in layers 3 to 4 ins. thick which are purple red to tan red to cream banded. Next laminated ledge is 5 ft. above top of this unit. Laminated sequences separated by massive red and cream mottled phase. Blocky ledge at 17.5 to 19.5 ft. of pinkish massive tuff, weathering orange red. Grain fine, dominated by fine pumice fragments. Red color above this ledge becomes more purple, like that of unit 2 (but more of the tuff has this color here than in unit 2). At about 20 ft. above the base of bed, pumice fragments as much as one-half inch noted. General continuation of 1 ft. to 6-in. laminated sequences at 4 to 6 ft. intervals in massive tuff. Coarser and coarser pumice fragments, become increasingly common above this point in darker colored beds of section. At about 30 ft. above base, change in spacing of laminated sequences 1 ft. to 6 in. thick drops to 1 to 3 ft. in place of 4 to 6 ft. of lower part of section	56.8
17. Tuff, massive, medium-red to cream, mottled; has crude obscure banding parallel to bedding. Pumice fragments to one thirty-second inch notable in redder phases (10*R* 6/4); considerable inconspicuous fine crystalline material consists of quartz and clear feldspar, a little biotite. Ledges ill defined, not strong nor blocky	23.2
16. Tuff, pale-reddish-brown, weathered (10*R* 5/4), unweathered (10*R* 5/3), dark-brick-red ledge. (Bed 14 of USGS site.) Grain, fine both for pumice and for abundant very fine quartz and clear feldspar. Mafics fine, rare, and obscure. Roundish limonite balls to one-half inch. Base of bed obscure here. Bed forms a very blocky ledge	7.0
Total thickness of beds 22 to 16	137.3

UNIT 4

The basal bed of unit 4 overlies the portal bed of unit 3 with a sharp and well-defined contact. The contact probably represents no greater stratigraphic break, however, than any of the other contacts between the usual alternating massive and bedded intervals of the formation. The unit is more heterogeneous than any of the units below, and it ranges more widely in thickness and other characteristics.

From a thickness of about 365 feet in the slopes above the U12e Tunnel, it ranges down to about 285 feet at the Rainier Tunnel and 290 feet at the USGS Tunnel. Much of the thickness variation is due to initial differences in bed thicknesses from place to place, especially in the upper half or so of the unit; but part of the variation appears to be due to local truncations and crosscutting within the body of the unit. Sizable unconformities, in fact, occur within unit 4 in nearby areas, outside the areas mapped.

By and large, the unit crops out well (figs. 4, 7). It forms broad ledges that have a generally rounded massive appearance. In some places single outcrops with virtually no overburden extend over several acres of ground, as for example, on the south slope of Cat Hill. The usual cyclic alternation of bedded and massive tuffs leads to a somewhat stairlike arrangement of ledges—the more resistant bedded intervals form the treads, the less resistant massive intervals form the risers.

The color of unit 4 is mostly gray, in contrast to the red of unit 3 and the yellow-green of overlying unit 5; but red beds are common, and some beds are greenish. Several thin red beds crop out persistently in the lower 100 feet of the unit. Some of these can be traced with confidence from the USGS Tunnel area, where they were first studied, to the Rainier Tunnel area; with others, the correlation is more doubtful. Taken as a group they lend character to the stratigraphic section and provide a good general correlation over a wide area.

About two-thirds of the way up from the base of unit 4 is a red bed of outstanding stratigraphic significance, owing to its distinctive appearance, widespread occurrence, and good outcrop development. In the Comparative Partial Sections (pl. 6) this bed is numbered 31 in section 1, 21 in section 2, 43 in section 3, and 24b in section 4. It forms the portal of the Rainier Tunnel. This bed averages 35 to 40 feet in thickness and forms a bold clifflike outcrop. From its base it grades upward from deep red orange through mottled light pink to gray or light brown at the top. It is topped by a well-bedded gritty porcelanitic band. Throughout its full thickness and constituting probably half of the bed by volume are abundant light-gray to cream and pink subangular pumice fragments; these are mostly less than 5 mm across, but many are 10 mm across and some are as much as 25 mm across. They are especially conspicuous because of their marked color contrast with the darker colored matrix, and together with the singular color gradation from bottom to top, they set the bed apart in the stratigraphic section. The rock also contains many small (± 1 mm) lithic inclusions and scattered inconspicuous phenocrysts.

The upper 50 to 90 feet of unit 4, overlying the red bed, exhibits marked and rapid lateral lithologic and color variations. Just above the portal of the Rainier Tunnel it contains much red and pink material, but a few hundred yards south and at the USGS Tunnel also, it is largely gray or light greenish gray. It passes upward—indefinitely in some places, sharply in others—into unit 5.

Measured section.—Sections of unit 4 were measured at locations about 800 feet due south of the portal of the Rainier Tunnel, along the centerline of the tunnel just east of the portal, and at the USGS Tunnel site (pl. 5). This unit was also penetrated by UCRL drill hole 2 (pl. 6; table 2).

Section of unit 4 of Oak Spring formation of Tertiary age measured about 800 feet south of Rainier Tunnel extending west from latitude N. 888,200, departure E. 636,760

[Measured by A. B. Gibbons and W. R. Hansen]

	Thickness (feet)
Unit 4:	
32. Tuff, pale-colored; begins with 3 ft of pale slightly greenish ledge former. At 6.7 ft base of 2-ft ledge of definitely greenish-brown fairly resistant tuff with lithic volcanic inclusions very common and as much as one-half inch across. At 18.5 ft top of a 6-in. porcelanitic conglomerate bed overlying zone (8.5 ft to 18.5 ft) of pale pumiceous nonresistant tuff with many one-fourth inch lithic volcanic fragments. Top of this bed, under porcelanitic band, is faintly red for 2 to 3 ins. Shows pumice fragments as much as three-fourths inch. Poorly defined 2-ft pinkish zone at 35 ft occurs in pale tuff that has big pumice fragments to 1 in., and very fine abundant lithic volcanic inclusions to one-thirty-second inch. Matrix mottled or spotted with red on very fine scale, surrounds a few phenocrysts of quartz and clear feldspar, some biotite. A finely laminated sequence at 46 to 48.5 ft consists of pale-cream to gray layers 2 to 6 in. thick. From 48.5 to 70 ft tuff is similar to that below 46 ft, but shows a few obscure bands as much as 8 in. thick of faint red	90.0

Unit 4—Continued *Thickness (feet)*

31. Tuff, at base of subunit, a coarse red pumice-breccia with white pumice fragments in dull deep-red matrix. Pumice fragments still rounded and look little altered. This bed, numbered as 24b at USGS site, marked by transition from red base to gray top; foreign dark lithic volcanic fragments as much as one-fourth inch very common. At 30 ft, some of pumice fragments show pale-greenish alteration. By 35 ft bed has lost most of color, and it is completely without red color at top where it is overlain by a 2- to 3-in. layer of fine laminated tuff. This 40-ft sequence has lithic volcanic rock fragments of same size, type, and abundance from bottom to top ---------------------------- 40. 0
30. Tuff, fine-grained; slightly greenish when fresh; roughly massive bedded; weathers reddish tan. Pumiceous matrix has many fragments of dark volcanic rocks under one-sixteenth inch and many blebs the same size of dark-dull-green alteration products. Weathers to indistinct ledges ------------------------- 19. 0
29. Tuff, pale-gray, massive; fine grained with few phenocrysts. A 1-foot thick, thin-bedded sequence of same lithology about 10 ft above base, then massive phase to about 20 ft. At 20 ft, appearance of well-sorted layers of dull pale-red-purple tuff with coarse pumice fragments and very fine white tuff; forms distinct ledges. A strong ledge of this banded sequence at 28 ft, 28 to 40 ft covered. At 40 ft, a ledge of fine-grained pale-cream tuff, with many lithic volcanic fragments as much as three-eighths inch. At 46 ft, top of a very pale red tuff grading to cream at bottom. This part of section continues to be rich in lithic volcanic fragments. Tuff begins to be obviously composed of pumice fragments about one-fourth inch and has pebbly or gritty surface. At 60 ft yellow porcelanitic material with lithic volcanic fragments abundant and as much as one-half inch, becoming definitely finer toward base. Top porcelanitic material at 61 ft--------------------------------- 61. 0
28. Tuff. Base sequence of finely laminated orange-red fine-grained pumiceous tuff; poorly exposed. Basal fine-bedded sequence about 8 ft thick, thence to mottled red-purple to white tuff with pumice fragments in layers 3 in. or more thick. (Layers of basal sequence are thinner, down to one-fourth inch.) ---------- 20. 0
27. Tuff, finely laminated case hardened, pale-cream, pumiceous, fine-grained. A red tuff with pale reduction spots (correlated with bed 23d of USGS Tunnel site) is 14 ft up in bed and two-thirds up prominent ledge locally as much as 12 ft high. Bed of hard red porcelanitic tuff, 9 in. thick and 23.4 ft from base of unit, is equivalent to USGS bed 23f. Above this, section continues as sequence of cream-colored layers 2 to 6 in. thick unmarked by color banding, but weathering to small ridges and ledges across the outcrop. This lithology extends in this subunit from 0 to 35 ft, with exceptions as noted above. At 35 ft occurs a change to heavier layers, here ill-exposed, of same color and lithology; this to 55 ft--------------------------------- 55. 0

Unit 4—Continued *Thickness (feet)*

26. Tuff, fine-grained, pale, as in underlying bed; at 3 to 5 ft above base, a poorly defined 2-ft pink layer. Bed 26 is mostly massive and lacks bedding, locally is mottled pink, has fairly common sand-sized phenocrysts of quartz and feldspar, is not very resistant. At the top of bed 26 is 3.5-ft red bed riddled with reduction spots and blotches. At the top of the red bed is a slightly porcelanitic fine-grained, hard ledge. Top of the red bed corresponds to top of bed 22k of USGS site---- 22. 5
25. Tuff, fine-grained; almost white when fresh, tan when weathered; nonresistent. Few phenocrysts. Top is a 4-ft red tuff with white spots (USGS bed 22i). Like all red beds of this part of section, this one makes distinct low ridge. White spots as much as one-half inch and pumice fragments as much as three-eighths inch- 22. 8
24. Tuff, fine-grained, pale, cream-purple with a few fine pumiceous bands about one-half way up. Top is 3-ft bed of red-purple fine-grained tuff (compare bed 22e of USGS Tunnel) with a few scattered reduction spots about one-half inch across------------------------------- 11. 0
23. Tuff. Massive basal layer is 5 ft thick, overlain by 3 ft finely laminated tuff; both are creamy, case hardened. Matrix of fine pumice and ash with rather plentiful scattered fragments of dark volcanic rocks as much as 1 in. At 14 ft a faint irregular pink layer 4 to 6 in. thick overlain by 6 in. of very pale yellow porcelanitic pumice-breccia. Top is a blotchy red bed 3 ft thick (compare bed 22a of USGS Tunnel) with pumice fragments three-eighths inch; bed has irregular base and a sharp well-defined top overlain by 8 in. of yellow porcelanitic pumice-breccia. Identifiable phenocrysts rare. Definite pale reduction spots in places run together into large irregular blotches-------------------------- 22. 0

Total thickness of beds 32 to 23-------- 363. 6

Section of unit 4 of Oak Spring formation measured along centerline of Rainier Tunnel just east of the portal

[Measured by R. W. Lemke and W. R. Hansen]

Unit 4:		Thickness (feet)
51.	Tuff; mostly light gray but pink bed at base and at 7.5 ft 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 1 ft) grading up into greenish gray. Very pumiceous in basal part. Moderately well bedded. Scattered fragments of quartzite as much as one-half inch becoming fairly gritty 3 ft from top	15.0
43.	Tuff, pumiceous, pink mottled with white. Quartz and feldspar phenocrysts moderately abundant and scattered to rare biotite, amphibole, and an opaque oxide. Abundant white altered pumice fragments, commonly ½ in. but as much as 1½ in., and altered ash shards. Scattered obsidian and quartzite fragments. Bed is soft (breaks easily), punky and light weight. Upper part is gray with pink mottling (blobs of pink 0.3 to 0.8 ft long). Red at the base. Gradational upper contact. White layer at about 21 ft at break in slope. Equivalent to bed 24b of USGS Tunnel area)	35.0
42.	Mostly covered. Light-gray tuff. 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 ft exposed	17.0
41.	Tuff, light-gray, fairly massive. Abundant pumice fragments especially in basal part. Indistinct pink bed at 8 ft above base. Greenish-yellow resistant gritty bed about 0.5 ft thick starting at 11.5 ft above base; quartzite fragments as much as one-half inch. (Correlates with base of bed 24a at USGS Tunnel area)	12.0
40.	Mostly covered. Two beds exposed between 10 to 15 ft above base (lower pumiceous; upper porcelanitic). Pink bed about 16 ft above base	40.0
39.	Tuff, light-gray, generally massive, pumiceous. Top forms good bench 50 ft wide	10.0
Unit 4—Continued		
38.	Tuff, light-gray, massive; fine-grained and dense at base. Pink pumiceous layer, 2 ft thick, starting at 10 ft above base	12.0
37.	Tuff; light-gray at base with pink layer at 10 ft above base; well bedded especially near top. Pumice fragments. Gritty at about 10.5 ft above base	16.5
36.	Tuff, pale-pink. Pumice fragments; somewhat porcelanitic	1.0
35.	Tuff, light-gray; coarser grained than bed 34 below with pumice and quartzite fragments locally up to one-half inch. Rougher surface than bed 34 below	7.5
34.	Tuff; light-gray except for thick pink band, 2 in. thick, at 5.5 ft and 12.5 ft above base (3 in. thick); dense, hard, generally massive with small quartzite fragments at top. Pink bed at 12.5 ft above base has small black obsidian fragments and small pumice fragments	12.5
33.	Tuff, porcelanitic, 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, 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 (as much as 1 in.). Scattered pumice fragments as much as 3 in. Yellowish-green blebs (devitrification). Some pink mottling (blobs 6 in. long) about 17 ft above base. Two to six inches of pink 12 ft above base	28.5
	Total thickness of beds 51 to 28	283.3

UNIT 5

Although the boundary between units 4 and 5 is indefinite in some places and must be drawn arbitrarily, unit 5 is the most distinctive nonwelded unit in the Oak Spring formation. Not only does it crop out over comparatively long distances—far beyond the limits of the area mapped—but its color is unmistakably different from that of any other part of the formation. Even where its outcrop is poor, unit 5 generally is distinguished by a yellowish color band or by yellowish patches of earth on the side of the mesa.

In detail the beds of the unit range through several shades of yellow and green. Grayish yellow (about 5*Y* 8/4) predominates in the Rainier Tunnel area. Pale greenish yellow (near 10*Y* 7/3) is a common hue, also, and some beds are as dark as dusky yellow (5*Y* 6/4). The unit is incomplete in the USGS Tunnel area, but it forms conspicuous pale-blue-green (5*BG* 7/2) outcrops on the slope of Survey Butte to the northwest. Where both yellow and blue-green color phases occur in the same stratigraphic sequence, the blue-green phase overlies the yellow.

Unit 5 is also distinctive in lithology. There is a rather wide range of textures, but the most characteristic rock type is a very lightweight medium-grained pumice-lapilli tuff which commonly contains subordinate perlite fragments and various small lithic inclusions. The yellowish color phase of the unit is earthy and devitrified. The bluish-green color phase is relatively fresh and vitreous. Some rocks contain glassy black obsidian in flattened streaky lenses an inch or two long and a fraction of an inch thick. There is generally a coarse but well-defined stratification characterized by distinct textural layering and indistinct or obscure bedding planes.

Unit 5 varies widely in thickness in short distances, partly because of its indefinite base, perhaps, but largely because it is cut by an unconformity. In a surface section measured near the centerline of the Rainier Tunnel it is about 100 feet thick; in UCRL drill hole 2 on the centerline it is about 110 feet thick, as corrected for dip in the cored section; but the cored section is faulted, and an undetermined thickness of beds is subtracted by faulting. (In the Rainier Tunnel this fault has a throw of about 7 ft.) South along the face of the mesa, rough calculations based on cross sections drawn from the map (pl. 1) indicate thicknesses for unit 5 greater than 200 feet. Just north of the USGS Tunnel area it is about 120 feet thick; to the east, it is only about 45 feet thick.

Section of unit 5 of Oak Spring formation of Tertiary age measured along the centerline of Rainier Tunnel starting just above and back of the portal

[Measured by R. W. Lemke and W. R. Hansen]

	Thickness (feet)
Unconformity.	
Unit 5:	
54. Tuff, yellowish-green to greenish-gray, pumiceous, well-bedded. A few resistant bands contain scattered fragments as much as 1 in. long of lithic volcanic rocks and quartzite	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 (layers are a few inches to about 4 ft thick). Fine sugary texture; numerous bands, each about 0.5 ft 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

UNIT 6

Unit 6 of the Oak Spring formation is a discontinuous body of welded tuff that was erupted onto the eroded surface on unit 5. It is present in many parts of the test site, and in some places it forms broad benches or rimrocks. North and east of Yucca Flat, unit 6 is correlated with the upper rhyolite flow [map unit rh_2] of Johnson and Hibbard (1957, pl. 32). In the mapped area, however, it is lenticular and has surface expression only north of the Rainier Tunnel, where it fills a shallow swale or valley in the old preexisting topography. This swale coincides with the axis of a major syncline; hence, it is structural as well as topographic. Although unit 6 does not occur at the USGS Tunnel area, it caps a small mesa about 1,200 feet to the east where it also fills a synclinal swale. It also crops out discontinuously between the USGS Tunnel area and the Rainier Tunnel area.

At Rainier Mesa, centering at Cat Hill, unit 6 crops out for a distance of about 1,300 feet along the face of the mesa (pl. 1). Its greatest exposed thickness there, about 125 feet, is just north of Cat Hill, from which point it tapers gradually north and southward. Its Westward extension underground is intersected by the Rainier Tunnel between stations 5+49 and 6+74, where it is about 40 feet thick, including a basal conglomerate 4 to 5 feet thick (pl. 4). It also is cut by UCRL drill hole 3 at 1,029-foot depth near the zero point of the Rainier test.

At Cat Hill unit 6 is hard and dense, and stands in sharply outlined near-vertical cliffs. It is purplish red or pink where oxidized, mostly olive brown where not. Its character above ground and underground is the same. It contains scattered phenocrysts of quartz and alkalic feldspar, sparse biotite, and clumps of opaque oxide in a groundmass of compacted devitrified shards. Partly filled elongated cavities and dark-gray inclusions of collapsed pumice 2 to 3 inches long and a quarter to half an inch across give the rock a distinctive striking appearance (fig. 5). Numerous lithic inclusions are enveloped by interesting compaction structures—flattened pumice and other planar features are draped over and indented under the inclusions. Some inclusions are several inches across, but most are much smaller. They consist chiefly of accessory fragments of granitic material, quartzite, and other rock types. In most places the lower 2 to 3 feet of the unit is dark-gray to olive-brown perlite or pitchstone.

In exposures just south of Cat Hill a discontinuous basal conglomerate contains, in order of decreasing abundance, subrounded pebbles and cobbles of lava rock, quartzite, and biotite-bearing granitic rock in a yellow tuffaceous matrix. In the Rainier Tunnel the conglomerate contains boulders as large as 1½ feet in

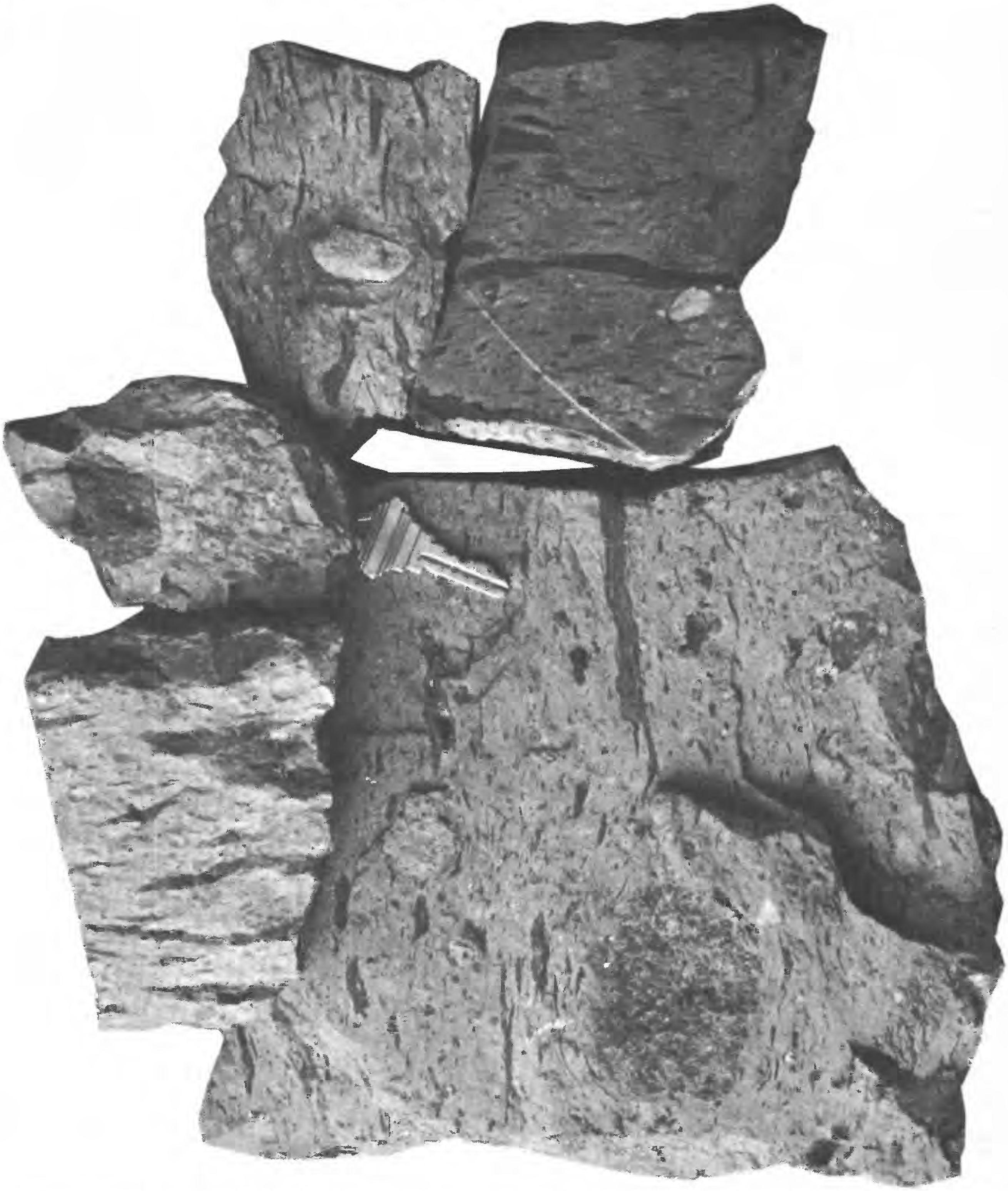

FIGURE 5.—Hand specimens of welded tuff, unit 6 of Oak Spring formation, Cat Hill. Dark streaks are collapsed devitrified pumice. Note lithic inclusions enveloped by compaction structures.

diameter. (What apparently is the same conglomerate also lies at the base of unit 7 in areas where the lenticular welded tuff of unit 6 is lacking.) Overlying the conglomerate is a layer of vitreous perlitic welded tuff 2 to 3 feet thick, which, in turn, is overlain by stony olive-brown devitrified welded tuff 13 feet thick that contains abundant dark flattened inclusions and abundant flattened vesicles. Six feet of nonvesicular welded tuff is next succeeded by several feet more of vesicular welded tuff. Boundaries between these rock types are gradational over a narrow vertical distance. The perlitic welded tuff at the base of the lens owes its glassy texture to rapid chilling by conduction of heat into the underlying rocks. Slower heat loss higher in the lens enabled the overlying welded tuff to devitrify.

Just north of Cat Hill the lower several feet of welded tuff is strongly brecciated and is recemented by milky white opal. Brecciation in that position, at the bottom of the thickest part of the lens, suggests slight, viscous flowage after emplacement—following compaction and welding but preceding complete loss of plasticity. The occurrence of opal as crack fillings and as linings of vesicles or other openings in the welded tuff is not unusual, although nothing comparable to its large-scale development north of Cat Hill has been observed elsewhere in the area. It probably formed during cooling of the entrapped gasses, and brecciation in the base of the lens may have aided its concentration.

Laterally, at the limbs of the syncline, the welded tuff grades into a wedge of friable nonwelded tuff where the ash flow apparently was too thin to weld or compact itself. This nonwelded tuff is identical in many respects to the welded part of the flow in that it contains large somewhat flattened pumice inclusions, lithic fragments, and the same mineral suite; but it is of open texture, and hence of lower density than the more typical welded portion. It is well exposed in a roadcut about 100 feet northwest of the portal of the Rainier Tunnel; natural exposures are uncommon.

Rapid rock analyses, specific gravity determinations, and semiquantitative spectrographic analyses of samples of welded tuff from unit 6 are shown in columns 5 and 6, table 34.

UNIT 7

Unit 7 of the Oak Spring formation lies unconformably on units 6 and 5. It consists of a highly variable suite of light-gray, light-brown, pink, and greenish bedded nonwelded tuffs totaling about 720 feet in thickness in the slopes above the Rainier Tunnel. North and south along the face of the mesa the thickness varies markedly. The unit overlies a discontinuously exposed conglomerate which consists of pebbles of lava rock, quartzite, and scattered granitic fragments in a yellow tuffaceous sandstone matrix. This conglomerate appears to be continuous laterally and identical with the basal conglomerate of unit 6. The lower 180 feet or so of the unit is composed of distinctly pink and greenish beds. This zone, which also contains many brownish beds, has appreciably greater induration and strength than the overlying beds; unlike the overlying beds it much resembles the nonwelded tuffs of unit 5 and lower; it is zeolitized, and the zeolite and opaline material provide an intergranular cement that increases the strength and coherency of the rock (Ray E. Wilcox, written communication, 1958).

Samples from the lower part of unit 7 were collected from UCRL drill hole 3, at horizons near to the Rainier explosion chamber, for rapid rock analysis and semiquantitative spectrographic analysis. The results are shown in columns 3 and 4, table 4.

The overlying several hundred feet of the unit is relatively fresh and vitreous, lacks cohesion, and has very low mechanical strength. Some of it approaches loose sand in consistency. It cores poorly, if at all, in a drill hole, and it caves badly in an uncased drill hole. Much difficulty was encountered in penetrating it in UCRL drill hole 3, centered near Point Mabel at the top of the mesa. Expectably, therefore, it crops out poorly in most places and commonly forms rubble-covered slopes. For the same reason, the details of its lithology and structure are incompletely understood.[2]

The uppermost 35 feet or so of unit 7 is a variably coarse textured vitreous pumice-lapilli tuff-breccia. It is genetically related to the overlying welded tuff of unit 8, and it grades upward imperceptibly into it through a transition zone about 4 feet thick (fig. 6). The transition is marked by a gradual increase in rock density, coupled with a flattening, attenuation, and welding of the constituent shards and pumice fragments into a hard brittle dense rock. The nonwelded tuff-breccia is characterized by lack of bedding and a related peculiar teepeelike erosional form; in fact, it shows only the faintest suggestion of a gross horizontal fabric. The overlying welded tuff is marked by palisade-forming large-scale columnar jointing which increases in geometric regularity upward and fades out indefinitely downward in the nonwelded material.

Genetically, the nonwelded pumice-lapilli tuff-breccia at the top of unit 7 unquestionably is more closely related to unit 8 than to the lower part of unit 7. In terms of engineering, physical, and seismic properties, however, it is more akin to the underlying rocks. Mindful of these disparities, the authors felt impelled by the latter considerations to map the boundary between

[2] After geologic mapping of the Rainier Tunnel area was completed, a roadway across unit 7 was constructed on a long upward traverse to the top of the mesa. Cuts along this roadway afford excellent opportunities to examine the unit in detail, and studies not possible during the fieldwork for this report, therefore, are in progress at the time of this writing (1958).

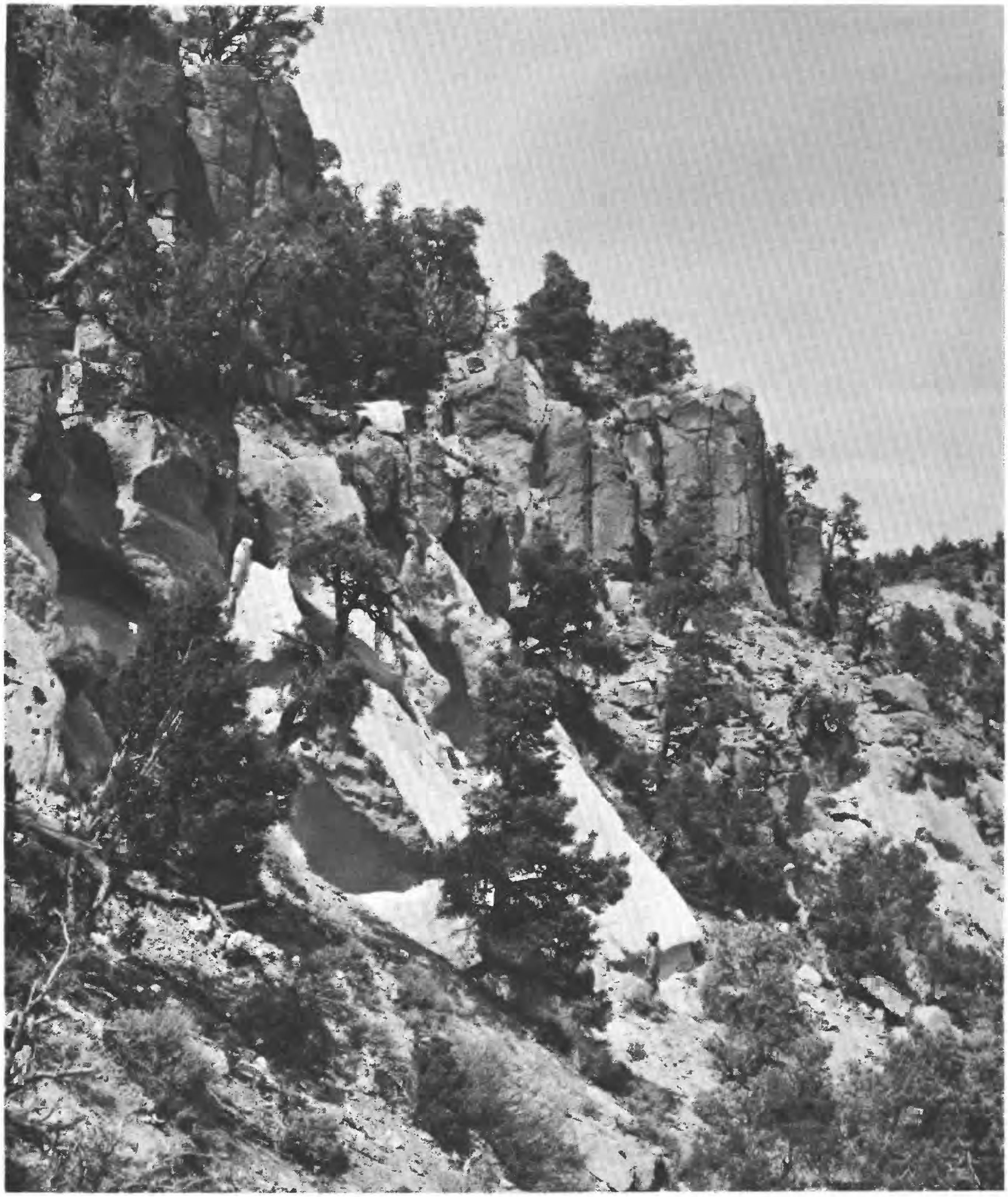

FIGURE 6.—Upward gradation of upper part of unit 7 of Oak Spring formation, lower half of picture, into unit 8 near north end of Rainier Mesa. Note massive character of unit 7, and columnar jointing in unit 8. Note figure to right of lower center for scale.

the units as shown on the map (pl. 1) and to describe the units in the same terms. Moreover, the base of the conspicuous, well-exposed palisade provides a far better mapping horizon than the base of the underlying tuff-breccia, which in most places is concealed by overburden.

UNIT 8

Unit 8 of the Oak Spring formation, about 270 feet thick below Point Mabel, forms the caprock of Rainier Mesa and the high spur just northwest of the USGS Tunnel area (figs. 3, 7). It consists chiefly of welded tuffs emplaced as two separate ash flows probably in two distinct volcanic outbursts. The lower ash flow is chiefly rhyolite, the upper is chiefly quartz latite. At the base, the lower ash flow grades downward from welded into nonwelded tuff of unit 7 (fig. 6). The upper ash flow grades upward from welded into porous and nonwelded but coherent tuff. Chemical differences between the two ash flows are readily apparent from rapid rock analyses and semiquantitative spectrographic analyses shown in columns 1 and 2 of table 4.

The two ash flows are distinguished readily by their topographic discontinuity. Each flow forms a clifflike palisade, one above the other. The lower palisade is about 40 feet high, the upper is about 90 feet, and they are separated by a steep slope about 140 feet high (fig. 3). Columnar jointing characterizes both palisades, but it is coarser and less perfectly formed in the upper one. Medially located in the upper palisade is a conspicuous dark-colored band of vitrophere 10 to 15 feet thick. The actual contact between the two ash flows, even viewed at close range, is difficult to discern, largely because it is generally poorly exposed in the steep slope between the palisades; in many places it is completely concealed by mantle rock.

Thin sections of representative core samples of unit 8 have been examined by Ray E. Wilcox. In the most general terms, the sections show a dense groundmass of tightly packed welded shards and collapsed pumice characterized by irregular spherulitic devitrification. About 30 feet below the top of the welded tuff there are streaky bands of obsidian containing many opaque microlites. Abundant flattened elongated cavities at some levels are lined with tridymite or cristobalite.

Unit 8 contains abundant feldspar and quartz phenocrysts. The feldspar phenocryst are mostly fragmental and include both alkali feldspar (anorthoclase) and plagioclase (oligoclase to labradorite). The plagioclase in the upper ash flow generally is more calcic than in the lower ash flow. The quartz is the high-temperature variety and in the upper flow it commonly is euhedral; in the lower ash flow it tends to be rounded. Phenocrysts of biotite, clinopyroxene, and magnetite are sparse in the upper ash flow and rare in the lower. The devitrified groundmass of both flows consists chiefly of extremely fine grained crystals of quartz and feldspar. The groundmass of the upper nonwelded part of the upper ash flow is not compacted and hence has a duller luster than the underlying welded tuff; it consists mostly of devitrified shards and pumice with abundant minute acicular crystals crowding the cavities.

In contrast with the welded tuff of unit 6, those of unit 8 contain many more phenocrysts but far fewer lithic inclusions. Large inclusions are exceedingly rare, and even small ones a few millimeters in diameter are relatively uncommon.

TABLE 1.—*Log of UCRL drill hole 1*

By Warren L. Peterson

[Thin-section description by Ray E. Wilcox]

Bed	*Description*	*Depth (feet)*
	Overburden, no core	0–61
	Unit 7 of the Oak Spring formation:	
1.	Tuff, rhyolitic(?) pale-pinkish-gray. Composed of gray, white, and pink ash shards commonly less than one-sixteenth inch across. Scattered fragments ⅛ to ¼ in. Scattered biotite, quartz(?), and feldspar(?) crystals less than one-eighth inch across. Scattered small fragments of quartzite(?). Porous, somewhat friable. Hard greenish porcelaneous knots at 62, 62.5, and 68.5 ft. At 65.5 ft, 2-in. bed of soft white coarse-grained pumiceous tuff with quartzite fragments. Upper contact gradational over distance of 4 in	61–71
2.	Tuff-breccia, rhyolitic(?), pale-pinkish-gray. Matrix of fine-grained ash including scattered biotite, quartz, and feldspar. Numerous white pumice fragments and fragments of quartzite(?) ¹⁄₁₆ to ½ in. across. Firm, porous. Contact gradational over distance of 1 in	71–73
3.	Same as bed 1. Hard greenish porcelaneous knots at 73.5 and 74 ft. Upper contact sharp	73–75. 5
4.	Tuff, rhyolitic(?); pinkish white mottled with pale green. Matrix of fine-grained ash and scattered crystals of biotite, quartz, and feldspar. Numerous pink and white earthy pumice fragments ¹⁄₁₆ to ¼ in. across. Numerous pale green porcelaneous fragments ⅛ to ½ in. across. Scattered quartzite(?) fragments less than one-fourth inch across. Rock is generally hard and porcelaneous. Upper contact gradational over distance of 2 in	75. 5–76. 5
5.	Similar to bed 1	76. 5–85. 5
6.	Similar to bed 2, except matrix is light reddish brown	85. 5–87. 0

TABLE 1.—*Log of UCRL drill hole 1*—Continued

Bed	Description	Depth (feet)
	Unit 7 of the Oak Spring formation—Continued	
7.	Tuff, rhyolite(?); soft white earthy matrix of altered pumice cinders. Matrix contains scattered colorless crystals and biotite less than one-sixteenth inch across. Fragments of quartzite 1/16 to 1/2 in. across scattered through rock. Core is very soft and friable. Upper contact gradational over distance of 6 in	87. 0–88. 5
8.	Similar to bed 2. Rather sharp lower contact	88. 5–89. 5
9.	Similar to bed 4. Gradational lower contact	89. 5–92. 0
10.	Tuff-breccia similar to bed 2. Rather sharp contact	92. 0–95. 5
11.	Similar to bed 4. Contact gradational over distance of 1 in	95. 5–96. 5
12.	Similar to bed 1. Gradational contact	96. 5–99. 5
13.	Similar to bed 4. Gradational contact	99. 5–103. 0
14.	Similar to bed 7. Gradational contact	103. 0–112. 5
15.	Similar to bed 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 inch across. Numerous white earthy angular pumice fragments 1/16 to 1 in. across. Few fragments of quartzite 1/8 to 1/2 in. across. White fragments become larger toward bottom. Firm. Sharp contact	116. 0–119. 0
17.	Similar to bed 4	119. 0–119. 5
18.	Similar to bed 2. Grayish-pink tuff-breccia; contains large white fragments, which 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 bed 16. Gradational contact. Sample taken at 134 ft	128. 0–143. 5
20.	Similar to bed 19 except friable; can be broken by hand. Contains bigger percentage of white fragments than bed 19. Gradational lower contact	143. 5–147. 5
21.	Tuff-breccia. Matrix of white earthy material made up of faintly discernible fragments 1/4 to 1/2 in. across. Matrix includes some colorless crystals less than one-sixteenth inch across. No biotite. Some dark-brown stains less than one-sixteenth inch across. Fragments of angular quartzite 1/8 to 1/2 in. across scattered through rock. Soft but cannot be broken by hand. Sharp contact	147. 5–151. 0
22.	Tuff (similar to bed 4), rhyolite(?); white very light gray, white mottled with pale pink. Matrix is earthy to porcelaneous. Material of faintly discernible fragments 1/8 to 3/8 in. across; some flattened with bedding. Matrix contains scattered colorless crystals less than one-sixteenth inch across and irregular dark-brown stains less than one-sixteenth inch across. Fragments of quartzite scattered through rock 1/16 to 1/2 in. across. As a whole, rock is porcelaneous, hard, and firm. Several precore fractures at 62 ft. Contact sharp. Sample taken at 154 ft	151. 0–165. 0
23.	Tuff-breccia (rhyolite?); grayish-pink groundmass. Fifty to seventy-five percent of rock composed of white earthy angular fragments 1/16 to 1 in. across. Scattered quartzite fragments 1/16 to 3/4 in. across. White porcelaneous bed at 170 to 170.5 ft. Several pores 1/32 to 1/16 in. thick and 1 to 2 in. 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 1/16 to 1/4 in. across. 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 ft. (may be crossbedding). Numerous fractures, some cemented 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 reworked from tuff, either wind or water deposited. Sample taken at 176 ft. NOTE—below 184 ft. core is rather scattered in boxes. Core seems to be missing from 184 to 198 ft.)	173–184+
25.	(Depths may be off 10 ft.) Apparently tan to gray tuff-breccia and conglomeratic sandstone with pebbles of tuff	198–215

TABLE 1.—*Log of UCRL drill hole 1*—Continued

Bed	Description	Depth (feet)
	Unit 6 of the Oak Spring formation:	
26.	(Depth may be off 10 ft or more.) Welded tuff; dense dull-red groundmass with black schlieren ¼ to 2 in. long and 1/16 to ½ in. thick. Scattered black angular fragments with white halos. 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 ft. 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	215–236
27.	(Depths here are not reliable.) Gray to tan coarse-grained tuff. Contains some black schlieren, some of which appear to be obsidian. In part tuff-breccia	236–250

TABLE 2.—*Log of UCRL drill hole 2*

By Warren L. Peterson

[Thin-section description by Ray E. Wilcox]

Bed	Description	Depth (feet)
	Overburden, no core	0–12
	Unit 7 of the Oak Spring formation:	
1.	Tuff, rhyolite(?); composed of pink and white earthy fragments, 1/16 to 3/16 in. across. Scattered biotite less than one-sixteenth inch; minor quartzite fragments. Rather friable. Sharp contact	12–13. 5
2.	Tuff, rhyolite(?), matrix of pale-greenish-yellow (10*YR* 8/2) to white (*N* 9) earthy fragments 1/16 to 3/16 in. across. Fragments of gray and brown quartzite 1/16 to ¼ in. across and dense volcanic rocks; 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 as much as three-fourths inch across. 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

TABLE 2.—*Log of UCRL drill hole 2*—Continued

Bed	Description	Depth (feet)
	Unit 7 of the Oak Spring formation—Continued	
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 as much as three-fourths inch; scattered biotite (generally minute but as much as three-sixteenths inch); some feldspar and quartz crystals and quartzite fragments. Firm. Sharp inclined contact	17. 5–24. 5
5.	Tuff, rhyolite(?). Fine-grained gray-orange-pink (5*YR* 7/2) matrix (pale reddish brown (10*R* 5/4) from 26.0 to 26.5 ft.). Scattered white earthy fragments as much as three-eighths inch; small biotite and quartzite fragments; quartz and feldspar crystals less than one-sixteenth inch. Firm	24. 5–26. 5
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 and rare biotite less than one-sixteenth inch across. White to grayish yellow angular to rounded pumice fragments 1/16 to ½ in. across composes 30 to 50 percent of rock. Scattered quartzite fragments. Firm. Gradational contact. Sample at 38 ft. Thin section of sample shows crystals 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
7.	Tuff-breccia, yellowish-gray. Composed almost entirely of coarse pumice fragments, ⅛ to 1 in. across Some scattered quartzite fragments Some small coloress crystals and biotite. Fragments cemented by films of brown clay (?). Firm. Sharp contact	50–54
8.	Tuff breccia, pale-greenish-yellow Composed almost entirely of pumice fragments varying in color from pale greenish yellow to light greenish gray, ⅛ to ¾ in. across. Thinly scattered quartzite fragments and colorless crystals. Friable. Very lightweight. Firm grayish orange-pink bed at 64.5 to 65.5 ft. Apparently sharp contact. Thin section of sample at 59 ft shows crystals of alkali feldspar with minor quartz,	

Table 2.—*Log of UCRL drill hole 2*—Continued

Bed	Description	Depth (feet)
Unit 7 of the Oak Spring formation—Continued		
	plagioclase, amphibole, and opaque oxide. The matrix is composed almost entirely of pumice	54–75
9.	Tuff, very fine grained; grayish orange pink with few scattered white fragments; dense. Sharp contact	75–76
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 across. White to grayish-yellow angular to rounded pumice fragments, 1/16 to 1/2 in. across composes 30 to 50 percent of rock. Scattered quartzite fragments. Firm. Gradational contact	76–85
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 1/16 to 3/8 in. across. Generally massive but bedded on minute scale in parts, bedding rather irregular. Probably water or wind deposited. Sharp contact. Thin section of sample at 92 ft shows crystals 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	85–97
11.	Same lithology as bed 8. Sharp contact	97–100
12.	Tuff-breccia, grayish-yellow (5*Y* 8/4); dark yellowish orange (10*YR* 6/6) from 106 to 107 ft and 103 to 105 ft. Composed of pumice fragments generally 1/8 to 3/4 in. across. Scattered fragments of quartzite generally less than one-eighth inch across. Although firm, rock has earthy appearance as though much altered to clay. Core is broken into short segments. Orange zones friable. Gradational contact. Thin section of sample at 122 ft shows crystals of alkali feldspar with some quartz and plagioclase and minor opaque oxides. The matrix is composed of altered shards and pumice with altered perlite and obsidian	100–125
Unit 6 lacking from this drill hole.		
Unit 5 of the Oak Spring formation:		
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 as much as 1.5 in. across. Whole rock speckled with small manganese(?) stains. Rock hard and firm but with earthy appearance. Contact gradational over several inches	125–127
14.	Similar to overlying bed but with fewer fragments of crystalline volcanic rocks	127–134
15.	Tuff-breccia, yellowish-gray (5*Y* 8/4) with dark fragments. Composed of mixture of yellowish-gray and dark-gray pumice fragments from 1/8 to 3/4 in. across. Dark fragments generally larger than light ones. Yellowish-gray fragments more altered and composed of probably 80 to 90 percent of rock. Between 134 and 145 ft rock is generally friable, below firm. General earthy appearance. Sand, three-eighths inch thick, of dark minerals at 145.5 ft inclined to 22° to the normal to the core axis. Several thin sand layers between 154 and 155.5 ft	134–161
16.	Tuff, grayish-yellow; much altered. Probably originally composed of pumice fragments 1/4 to 3/4 in. across. Now a yellowish-gray earthy material with original fragments faintly discernible in parts. Scattered through rock are fragments of dark dense rock generally less than one-fourth inch across, probably in part quartzite. From 161 to 212 ft core is much broken and in part friable. Sharp contact. Thin section of sample at 212 ft 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	161–243
Unit 4 of the Oak Spring formation:		
17.	Tuff, fine-grained, white to grayish orange-pink. Composed of altered tuff fragments generally less than one-eighth inch across with scattered colorless crystals and biotite less than one-sixteenth	

Table 2.—*Log of UCRL drill hole 2*—Continued

Bed	Description	Depth (feet)
Unit 4 of the Oak Spring formation—Continued		
	inch across. Scattered quartzite fragments generally 1/32 to 1/8 in. across. Grayish orange pink above 262 ft, white below. Rock firm. Gradational contact. Thin section of the sample at 265 ft shows crystals 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	243–265
18.	Tuff, white to moderate-pink. Fine-grained matrix with scattered white pumice fragments 1/16 to 1/2 in. across. Few scattered quartzite fragments one-eighth inch. Scattered biotite and colorless crystals in matrix. Rock is firm. Good core. Pink from 275 to 295 ft, rest is white. Thin section of the sample at 283 ft shows crystals 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	265–305
19.	Tuff-breccia, pale-greenish-yellow. Composed of pumice fragments ranging from 1/8 to 1/2 in. across. Scattered quartzite fragments. Pumice is much altered with earthy appearance	305–314
20.	Tuff, pale-greenish-yellow (10*YR* 8/2) to grayish-yellow (5*Y* 8/4). Composed of altered pumice fragments generally less than 1/16 in. but as much as one-fourth inch across. Large percentage of rock composed of colorless crystals and small grains of quartzite, as much as 50 percent or more in parts where rock resembles sandstone. Probably in part water worked. Firm	314–321. 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 ft. Color is gradational generally becoming deeper red downward. Fine-grained matrix of pumice and colorless crystals with coarser white pumice fragments and quartzite (generally 1/16 to 3/8 in. across) which make up 30 to 60 percent of the rock. Gradational contact over distance of 3 in. Firm rock. Correlates with bed 24b of USGS Tunnel area (WRH). Samples at 356 and 336 ft. Thin section of sample from 336 ft shows crystals 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 ft shows crystals 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
22.	Tuff; predominantly white, small percentage pink; fine to medium grained. Commonly composed of altered pumice 1/16 to 1/4 in. across with colorless crystals and rare biotite less than 1/16 in. 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 ft. Top of red bed at 480 ft inclined 17° to normal to core axis. Bedding plane in gray tuff at 527 ft inclined 25° to normal to core axis. Firm rock. Gradational contact. Samples at 504 and 530 ft. Thin section of sample from 504 ft shows crystals 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 sample from 530 ft shows crystals 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	361–562
23.	No bed 23.	
Unit 3 of the Oak Spring formation:		
24.	Tuff, moderate orange-pink. Lithologically similar to bed 21, becomes lighter pink toward base. From 583 to 590.5 ft 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	562–590. 5
25.	Firm rock. Similar to bed 22	590. 5–674
26.	Tuff, fine-grained. Composed of pumice and colorless crystals, almost entirely less than one-sixteenth inch across. From 674 to 684 ft moderate orange-pink	

TABLE 2.—*Log of UCRL drill hole 2*—Continued

Bed	Description	Depth (feet)
Unit 3 of the Oak Spring formation—Continued		
	mottled with white, from 684 to 708 ft moderate reddish orange, from 708 to 715 ft moderate orange-pink speckled with white. Firm rock. Gradational contact. Correlates with bed 14 of USGS Tunnel area. Thin section of sample at 689 ft shows crystals 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	674–715
Unit 2 of the Oak Spring formation:		
27.	Tuff, fine-grained. Similar to bed 22. White with much thin cross streaking of red inclined 24° to normal of the core axis. Firm rock, except lower 5 ft. Gradational contact	715–735
28.	Tuff, fine to medium-grained, grayish orange-pink. Gradational contact	735–744
29.	Gradational contact. Similar to bed 27	744–760
30.	Tuff, medium-grained, generally white with pinkish cross streaks. Scattered quartzite and white pumice fragments ⅛ to ¼ in. across. Firm	760–775
31.	Tuff, fine-grained; white, with some pink cross streaking. Firm	775–798
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-in. lengths. Thin section of sample at 844 ft shows crystals 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	798–880
33.	Similar to bed 31	880–903
34.	Similar to bed 33	903–909
35.	Tuff, fine- to medium-grained; moderate orange pink 909 to 925 ft, moderate orange pink to pale red (10*R* 6/2) below. Phenocrysts of quartz, feldspar, and biotite. Six inches of altered tuff at 946 ft (waxy clay). Thin section of sample at 930 ft shows crystals 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	909–955
36.	Tuff, granular, fine-grained, pinkish-gray. Phenocrysts of quartz feldspar, and biotite	955–958. 7
37.	Tuff; reddish pink with some white bands. Medium to coarse grained and granular except for thin bands and blebs of pink porcelanitic 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 ft; 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. Thin section of sample at 969 ft. 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
39.	Tuff, dark-red, generally fine grained, dense, porcelanitic (good core recovery). One dark grayish-red band 0.3 ft thick. Phenocrysts of feldspar, quartz, relatively abundant biotite, and a few grains of a honey-yellow mineral. Grains are in a siliceous clay or porcelanite (waxy surface). Thin section of sample at 989 ft shows crystals of quartz, alkali feldspar, plagioclase, biotite, and opaque oxides, none of which are abundant	972. 7–999
40.	Tuff, granular, pink and gray. Phenocrysts of quartz, feldspar, and biotite with little binder (sand with no core recovery)	999–1, 000. 5
41.	Tuff, pumiceous; reddish pink specked with white. Abundant fragments, ¼ to 1 in. long, of white devitrified(?) waxy pumice and scattered quartzite fragments as much as ½ inch but mostly less than ¼ inch. Phenocrysts of quartz, feldspar, and biotite.	

TABLE 2.—*Log of UCRL drill hole 2*—Continued

Bed	Description	Depth (feet)
Unit 2 of the Oak Spring formation—Continued		
	Thin section of sample at 1,010 ft shows crystals of plagioclase, alkali feldspar with lesser quartz, biotite, and opaque oxides	1,000.5–1,035.5
42.	Tuff, pumiceous, pinkish-gray. Abundant fragments of white waxy devitrified(?) pumice. Scattered small (mostly less than 1/8 inch) fragments of quartzite. Phenocrysts of feldspar, quartz, and abundant black euhedral crystals of biotite. Bedding inclined 28° to normal to the core axis. Thin section of sample at 1,042.5 ft shows crystals of plagioclase, alkali feldspar, and biotite with lesser quartz and opaque oxides	1,035.5–1,043

TABLE 3.—*Log of UCRL drill hole 3*

[Top of mesa near Point Mabel. Thin-section descriptions by Ray E. Wilcox have been incorporated into the description of the beds from which the samples were taken]

Bed	Description	Depth (feet)
Unit 8 of Oak Spring formation:		
1.	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 1 in. long. Slightly to moderately porous. Some jointing and staining along parting planes in first 10 ft; below 10 ft core is firm and recovery good. Gradational lower contact. Sample taken at 13.5 ft	0–28
2.	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 in. long. Elongated cavities are less common, white phenocrysts are abundant, and there are dark bands of obsidian(?). Rough fracture intersects core at 28 to 29 ft	28–34.4
3.	Welded tuff, dark-gray. About one-half of sample taken at 45 ft 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. Sharp lower contact	34.4–55
4.	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. Conspicuous schlieren (wavy lenses) and elongated flattened cavaties (some opal in cavities). Smaller and less conspicuous schlieren between 86 to 115 ft. Fractures between 75 and 78 ft, 104 and 106 ft, 144 and 145 ft; at 174 ft, 199 and 200 ft, and 208 and 210 ft	55–211
5.	Welded tuff (5*RP* 7/2), grayish red-purple. More friable and fragmental than bed 4; 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 ft and 245 ft; fewer cavities toward bottom. Gradational lower contact	211–249
6.	Welded tuff, light-gray; pale-violet tinge; fine-grained; abundant flattened pumice, few angular dark inclusions; minor quartz and biotite. Gradational lower contact	249–253
7.	Welded tuff, light-gray red-purple, abundant schlieren of pumice as much as 1½ in. long, very flattened; sanidine phenocrysts, biotite, quartz, similar to above but coarser. Fractures between 258 and 264 ft. Softer (breaks easier) near base. Gradational lower contact	253–272
Unit 7 of the Oak Spring formation:		
8.	Tuff, light-brownish-gray (5*YR* 6/1). Abundant pumice fragments (as much as 1 in.; mostly less than ½ in.), moderately abundant ash shards, and a little obsidian and perlite. More friable than above (can be broken by hand). Phenocrysts mostly alkali feldspar, some quartz, little biotite, and limonite. Scattered and stony volcanic fragments. Samples at 275, 288, and 298 ft. Good core recovery to 279.5 ft below where core becomes very friable. Good core again at 292 to 300 ft below where material becomes too soft to core (mostly granular sand-size material recovered); has a slight pinkish cast	272–300
9.	Tuff, moderate reddish-orange (10*R* 6.5/5). Abundant pumice fragments mostly less than ¼ in. (maximum ½ in.), 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	

Table 3.—*Log of UCRL drill hole 3*—Continued

Bed	Description	Depth (feet)
	Unit 7 of the Oak Spring formation—Continued	
	at 312 ft. Grades to pale brown at at 315 ft and to light brownish gray at 319 ft. Very friable at 321 ft. Samples at 312 and 327 ft. Good core recovery but very friable	300–327. 5
10.	Tuff, pumiceous, moderately light brown (5*YR* 4.5/5). Sand-sized phenocrysts of alkali feldspar and quartz. Grains subangular. Poorly sorted. Moderately abundant altered pumice and ash shards. Between 339 and 340 ft there is a dark band (altered biotite?). Bedding planes dip 23°. Sample at 346 ft. Mostly uncored (sand-size) because it is very friable	327. 5–350
11.	Tuff, granular, light-brown (5*Y* 6/4), fine-grained. Sand-sized 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 ft. Nearly all sand; only scattered core recovered in pieces about 0.1 ft long	350–360
12.	Tuff, granular, light-gray to nearly white, medium-coarse grained, friable. Made up mostly of subangular to subrounded sand-sized phenocrysts 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 ft	360–591

Core recovery as follows:

Depth (feet)		Core recovery (feet)
360–386	Sand; no core except for 2- to 3-in. pieces containing abundant altered shards	0. 5
386–392	Sand except for core at beginning	. 5
392–406	Mostly sand consisting of abundant pumice fragments, moderate amounts of shards and alkali feldspar	. 5
406–429	Mostly sand consisting of abundant pumice fragments and moderately abundant shards	. 7
429–441	(Nothing recovered)	. 0
441–451	About half sand and half broken core	5. 0
451–461	About half sand and half broken core	5. 0

Table 3.—*Log of UCRL drill hole 3*—Continued

Bed	Description	Depth (feet)
	Unit 7 of the Oak Spring formation—Continued	

Core recovery as follows—Continued

Depth (feet)		Core recovery (feet)
461–471	Soft core 0.2 to 0.5 ft long; some sand. Consists of abundant shards and moderate amounts of pumice	7. 0
471–481	Soft core 0.1 to 0.3 ft long	3. 5
481–488	Soft core 0.1 to 0.4 ft long. Sample at 482 ft 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 ft long	4. 0
511–551	Soft core 0.2 to 0.4 ft long	4. 0
551–560	Soft core 0.2 to 0.5 ft long	2. 3
560–571	Soft core 0.3 to 0.5 ft long	2. 7
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 ft long	2. 0

Bed	Description	Depth (feet)
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 ft. Many pumice, obsidian, and perlite fragments. Sharp upper contact based on core recovery (might be some missing between units). 2.7 ft of soft core, in pieces 0.1 to 0.8 ft long, recovered	591–601
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 ft	601–601. 5
15.	Tuff, granular; light brown flecked with white pumice. Same as 591 to 601.5 ft except more friable; gradational change to gray near base and more abundant pumice. Core recovery 601 to 607 ft is mostly sand with a few broken pieces	

Table 3.—*Log of UCRL drill hole 3*—Continued

Bed	Description	Depth (feet)
	Unit 7 of the Oak Spring formation—Continued at top of bed; 607 to 664 ft only sand recovered except for scattered pieces of core 0.1 to 0.3 ft long. Seven feet soft core recovered between 664 to 680 ft; sand at base	601.5–680
16.	Tuff, granular, light-gray. Similar to 360 to 591 ft except locally finer grained and generally has more soft clay binder. Samples at 685 and 712 ft	680–737

Core recovery as follows:

Depth (feet)	Core recovery (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 ft long	5.0
691–721 Mostly sand but scattered soft core 0.1 to 0.3 ft long Sample at 712 ft contains phenocrysts of plagioclase, abundant fragments of pumice, and moderate amounts of obsidian and perlite	1.0
721–731 Soft core in pieces 0.2 to 0.5 ft long. Sample at 725 ft 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 ft long	5.5

Bed	Description	Depth (feet)
17.	Tuff, granular, light-gray. Mostly sand-sized 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 ft	737–740
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 ft	740–759
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 ft. Sample at 764 ft	759–765
20.	Tuff, granular, light-gray. Sand-sized phenocrysts of alkali and plagioclase feldspar and quartz. Scattered biotite, amphibole, and pyroxene. Scattered sand-size quartzite fragments. Pumice and ash shards 768 to 769 ft. Only scattered easily crushed core (mostly sand). Sample at 767 ft	765–775
21.	Tuff, pumiceous, light-gray to nearly white. Abundant fragments of fibrous pumice about ¼ to ⅓ in. long and ash shards. Phenocrysts of feldspar; scattered quartz and biotite. Abundant rounded black grains of obsidian at 794.5 ft. Samples at 777 and 794.5 ft. Moderately good core recovery—pieces 0.3 to 0.5 ft common and some 1 ft long; core is fairly soft (can be broken with difficulty by hand) and light in weight. Some sand at about 793, 795 to 799, and 803 ft	775–810
22.	Tuff, granular, gray to brown. Mostly small phenocrysts of plagioclase feldspar; minor subrounded to well-rounded quartz. Scattered biotite and amphibole. Abundant ash shards. Sample at 811 ft. No core recovery (all sand)	810–812.5
23.	Tuff, granular to pumiceous, light-gray. Moderately abundant granular subrounded pumice fragments ⅛ to ¼ in. White and clear feldspar and quartz; scattered biotite. Fragments of quartzite; sand size and somewhat larger are moderately abundant. Porcelanitic layer at 836.0 to 836.3 ft. Samples at 826 and 846 ft	812.5–856

Core recovery as follows:

Depth (feet)	Core recovery (feet)
810–815 Mostly sand	0.5
815–826 Only 1 short piece of core; no sand	.3
826–832 Pieces of core 0.1 to 0.2 ft long. (Change to smaller core size.) Sample at 826 ft 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 ft 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
848–854 Sand except for last 3 ft which contains partial pieces core	-----
854–856 Broken core	2.0

Table 3.—*Log of UCRL drill hole 3*—Continued

Bed	Description	Depth (feet)
Unit 7 of the Oak Spring formation—Continued		
24.	Tuff, light-gray to nearly white. Granular subrounded to subangular sand-sized 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-sized to slightly larger brown fragments of quartz. Two inches of yellowish-green porcelanitic material at about 883 ft. Sample at 861 ft. 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 ft long	856–899. 5
24.	Core recovery as follows:	

Depth (feet)	Core recovery (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-ft pieces of core	3. 0
877–880 Broken core	3. 0
880–890 Core missing, probably in upper 5 ft	4. 5
890–894	2. 0
894–899	3. 7

Bed	Description	Depth (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 ft. Two feet of hard core recovered in pieces 0.3 to 0.5 ft long	899. 5–906. 5
26.	Tuff, pumiceous, light-brown specked with abundant white fragments of altered pumice mostly ⅛ to ¼ in. long. Abundant altered ash shards and scattered altered obsidian and perlite. Subrounded to subangular, mostly sand-sized plagioclase and alkali feldapars (clear and also white), a little quartz and amphibole, and much more biotite than in bed above. Fragments from sand size to one-fourth inch long of brown to bluish-gray quartzite. Samples at 910 and 936 ft. Core is fairly lightweight and is in pieces mostly 0.2 to 0.5 ft long. At 943 ft apparent dip in core is 6°	906. 5–945. 3
27.	Tuff, yellowish-green, chalky, fairly soft. Abundant altered ash shards; moderately abundant quartzite fragments ¼ to ⅓ in. Moderate amounts of phenocrysts of feldspar and a few of quartz. Sample at about 947 ft. Core was recovered in pieces 0.2 to 0.3 ft long	945. 3–955
28.	Tuff, white to light-gray, fine-grained; apparent dip of 5° at 960 ft; poor core recovery	955–990
Unit 6 of the Oak Spring formation:		
29.	Welded tuff. Apparent dips as follows: 20° at 994 ft, 25° to 30° at 995 ft, 35° at 1,023 ft and 25° at 1,037 ft. Two layers of obsidian: 0.5 ft at 1,046 ft and 2 ft between 1,054 and 1,057. Poor core recovery between 1,046 and 1,049 ft	990–1, 061
Unit 5 of the Oak Spring formation:		
30.	Tuff, buff to brown, nonwelded. Apparent dip is 23° at 1,068 ft, 15° at 1,070 ft	1, 061–1, 074

The following table shows rapid rock analyses, specific gravity determinations, and semiquantitative spectrographic analyses of selected samples collected from the Oak Spring formation at Cat Hill and from cores taken from UCRL drill hole 3.

TABLE 4.—*Analyses and specific gravity determinations of selected samples from the Oak Spring formation, Rainier Tunnel area*

Rapid rock analyses and specific gravity determinations

Nos. 1, 2, and 6 analyzed by P. L. D. Elmore, S. D. Botts, and M. D. Mack. Nos. 3, 4, and 5 analyzed by Dorothy F. Powers. Analyses based on methods of Shapiro and Brannock (1956)]

	1	2	3	4	5	6
SiO_2	66. 4	75. 6	69. 82	63. 49	74. 10	75. 2
Al_2O_3	16. 6	12. 2	12. 09	14. 35	11. 59	10. 8
Fe_2O_3	2. 0	. 58	1. 33	3. 51	3. 36	3. 3
FeO	. 60	. 11	. 15	. 26	. 03	. 06
MgO	. 58	. 36	. 93	1. 18	. 08	. 19
CaO	1. 8	. 54	2. 58	2. 89	. 14	. 44
Na_2O	4. 4	3. 2	1. 55	2. 02	4. 00	4. 1
K_2O	5. 3	4. 4	2. 44	2. 64	5. 54	4. 4
TiO_2	. 48	. 10	. 18	. 52	. 22	. 21
P_2O_5	. 11	. 00	. 03	. 10	. 02	. 01
MnO	. 07	. 06	. 05	. 12	. 15	. 16
H_2O	. 41	2. 9	8. 59	8. 61	. 57	. 84
CO_2	$<$. 05	. 06	. 00	. 04	. 02	. 12
	[1]98. 80	100. 11	99. 74	99. 73	99. 82	99. 83
Sp gr (lump)	2. 24	2. 16				2. 34
Sp gr (powder)	2. 50	2. 42				2. 47

See footnotes at end of table.

TABLE 4.—*Analyses and specific gravity determinations of selected samples from the Oak Spring formation, Rainier Tunnel area—Con.*

	1	2	3	4	5	6
Semiquantitative spectrographic analyses [2]						
[Nos. 1, 2, and 6 analyzed by Katherine V. Hazel. Nos. 3, 4, and 5, analyzed by Raymond G. Havens]						
Ag	0	0	0	0	0	0
As	0	0	0	0	0	0
Au	0	0	0	0	0	0
B	.001	.003	0	0	0	.001
Ba	.1	.001	.07	.07	.007	.003
Be	.00003	.0001	Trace	.00015	.0003	.0001
Bi	0	0	0	0	0	0
Cd	0	0	0	0	0	0
Ce	0	0	.015	.03	.03	0
Co	.001	0	0	.0003	0	0
Cr	.0003	.0003	Trace	.0003	0	.0003
Cs	0	0	--	--	--	0
Cu	.0001	.0001	.00015	.0007	.00015	.0001
Dy	0	0	0	0	0	0
Er	0	0	0	0	0	0
Eu	0	0	0	0	0	0
F	--	--	--	--	--	--
Ga	.003	.001	.0003	.0007	.0015	.003
Gd	0	0	0	0	0	0
Ge	0	0	0	0	0	0
Hf	0	0	0	0	0	0
Hg	0	0	0	0	0	0
Ho	0	0	0	0	0	0
In	0	0	0	0	0	0
Ir	0	0	0	0	0	0
La	.003	0	.003	.007	.015	.003
Li	0	0	0	0	0	0
Lu	0	0	0	0	0	0
Mo	0	0	0	0	0	.0003
Nb	0	0	.0015	.003	.007	0
Nd	0	0	0	.007	.015	0
Ni	.001	.001	0	.00015	0	.001
Os	0	0	0	0	0	0
Pb	.001	.001	.0015	.0015	.0015	.001
Pd	0	0	0	0	0	0
Pr	0	0	0	0	0	0
Pt	0	0	0	0	0	0
Rb	0	0	--	--	--	0
Re	0	0	0	0	0	0
Rh	0	0	0	0	0	0
Ru	0	0	0	0	0	0
Sb	0	0	0	0	0	0
Sc	.0003	.0003	0	.0007	0	.0003
Sn	.001	0	0	0	0	.001
Sr	.03	.001	.07	.07	.0007	.003
Sm	0	0	0	0	0	0
Ta	0	0	0	0	0	0
Tb	0	0	0	0	0	0
Te	0	0	0	0	0	0
Th	0	0	0	0	0	0
Tl	0	0	0	0	0	0
Tm	0	0	0	0	0	0
U	0	0		0	0	0
V	.001	0	.0007	.003	0	.001
W	0	0	0	0	0	.03
Y	.001	.003	.003	.007	.015	.003
Yb	.0001	.0003	.00015	.0007	.0015	.0003
Zn	0	0	0	0	0	0
Zr	.03	.003	.015	.03	.15	.1

[1] Sample contains organic matter.

[2] Figures are given, in percent, to the nearest number in the series 7, 3, 1.5, 0.7, 0.3, 0.15, and so on. 60 percent of the reported results may be expected to agree with the results of quantitative methods.

Symbols used are—

--, not looked for

0, looked for, but not detected

Trace, near threshold amount of element.

UCRL drill hole 3:	Depth (feet)
1. Unit 8, quartz latitic welded tuff	45
2. Unit 8, rhyolitic welded tuff	251
3. Unit 7, altered nonwelded tuff	889
4. Unit 7, altered nonwelded tuff	916–917
5. Unit 6, rhyolitic welded tuff	1,029
Cat Hill:	
6. Unit 6, rhyolitic welded tuff.	

ADDITIONAL NOTES ON THE TUFFS OF THE USGS TUNNEL AREA

The tuffs of the USGS Tunnel area all fall within units 2, 3, and 4 of the Oak Spring formation (pl. 2 and fig. 7). All of them are rhyolitic or quartz latitic except possibly beds 24f and 24h, which on the basis of their phenocrysts, may be dacitic. Most beds consist chiefly of altered pumice and ash shards; about half contain small obsidian fragments, also largely devitrified. The predominant alteration product is heulandite (possibly clinoptilolite), a silica-rich zeolite which acts here as a cementing material between shards and other fragments; it also lines cavities. Of the lithic inclusions, subangular to subrounded gray to dark-brown quartzose material predominates. Older volcanic fragments, granitic, gneissic, and schistose fragments are subordinate. On the average, the medial size of lithic fragments at the USGS and Rainier Tunnel areas seems to be about the same; unit 4 at the Rainier Tunnel area, however, contains fragments considerably larger than any noted in any part of the section in the USGS Tunnel area.

All beds contain phenocrysts. Quartz and alkalic feldspar range from sparse to abundant, although in no bed are they abundant enough to warrant use of the term "crystal tuff." Wilcox's preliminary studies (written communication, 1957) indicate that the alkalic feldspar is a sodic sanidine. Phenocrysts of plagioclase (largely oligoclase or oligoclase-andesine) are less abundant than either quartz or sanidine in most beds, but they are present in all but a few beds. Altered biotite and an opaque oxide—probably magnetite—were noted in more than half the beds sampled. Wilcox noted crystals of green hornblende in several beds of unit 4 and found rare crystals of pyroxene in beds 2, 22e, and 24b. Rare crystals of titanite (?) were found in beds 23l and 23h.

Measured section.—Following is a composite measured section of rocks exposed in the USGS Tunnel area. For a comparison with rocks of the Rainier Tunnel area, see plate 6. A comparison with the subsurface section at the USGS Tunnel, as shown by well logs, is given on plate 5.

Composite partial section of the Oak Spring formation exposed in the USGS Tunnel area

[Measured by R. W. Lemke and W. R. Hansen]

		Thickness (feet)
Unit 4:		
24h.	Tuff, light-grayish-brown, fine-grained, massive; pumice and shard fragments; crystals of plagioclase; alkali feldspar, quartz, biotite and amphibole	2.0
24g.	Mostly covered; forms sloping bench. Probably similar to bed 24c	17.5
24f.	Tuff, light-gray, fine-grained; shard and pumice fragments. Crystals of plagioclase and	

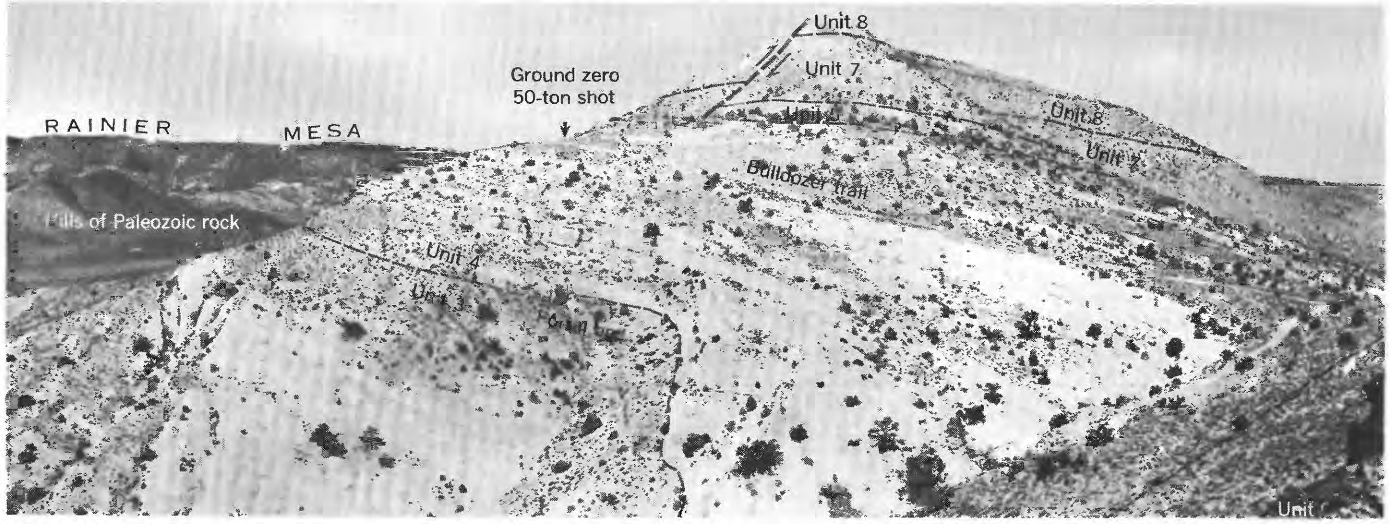

FIGURE 7. —View west toward Survey Butte showing general appearance of Oak Spring formation in vicinity of USGS Tunnel area. Unit 6 forms ledges at lower right, but it is not present in middle distance. Note ledgy outcrop habit of unit 4.

Unit 4—Continued	Thickness (feet)
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 table 5)	7. 0
24e. Mostly covered; forms sloping bench. Resistant layers 1 to 2 ft thick crop out about every 6 ft of section. Layers consist of medium-grained tuff; fragments of pumice, shards, greenish-yellow porcelanite, and small brown quartzite	30. 0
Total thickness of beds 24h to 24e	56. 5
24d. Tuff, mostly light brownish-gray. Forms conspicuous rough-surfaced ledge. Contains many altered pumice fragments as much as 1 in. long but mostly less than one-half inch and moderately abundant dark quartzite fragments; crystals of biotite and amphibole. Eleven feet above base is a white friable layer, 1 in. thick that divides bed into two benches	16. 7
24c. Mostly covered but probably similar to bed below except more friable. Forms gentle slope	21. 6
24b. Tuff. Lower 7 ft of bed is red with light-gray pumice fragments as much as 1 in. and subangular quartzite fragments as much as 1½ in. 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
24a. Mostly covered but basal 1 in. exposes fine-grained hard, porcelanitic tuff, with some brown quartzite fragments; breaks into angular small blocks and slabs	10. 0

Unit 4—Continued	Thickness (feet)
23p. Tuff, chalky white, fine-grained groundmass, but contains fragments of pumice one-half inch long; shards, and scattered brown quartzite fragments as much as three-fourths in. Scattered crystals of quartz, alkali feldspar, plagioclase, amphibole, and an opaque oxide. Good ledge former	4. 5
23o. Poorly exposed but appears to be light-gray tuff containing shard and pumice fragments. In central part of bed is a 1-in. porcelanitic grit containing many fragments of greenish-yellow porcelanitic material and a few crystals of sanidine	8. 1
23n. Tuff, light-gray; shard and pumice fragments; a few crystals of sanidine and sand-sized quartz	6. 0
23m. Tuff, light-gray; pumice fragments; scattered crystals of quartz, alkali feldspar, plagioclase, hornblende, and an opaque oxide. Pink layer, 1 in. thick, 10 ft above base; porcelanitic layer, 1 ft thick, above pink layer. Fifteen ft above base is medium-coarse layer, 1 ft thick, containing large brown quartzite fragments. Twenty-three ft above base is a resistant gritty layer consisting of dark-gray and brown quartzite, shards, and pink porcelanitic fragments. Gradational upper contact	25. 6
Total thickness of beds 24d to 23m	104. 3
23i. Tuff, light-gray, fine-grained, resistant, ledge former; massive. Abundant shards, small to medium-size fragments of brown quartzite, and some fragments of pumice. Scattered crystals of alkali feldspar, quartz, and plagioclase; a few crystals of titanite(?)	5. 0

Unit 4—Continued		Thickness (feet)
23k.	Tuff, light-gray mottled with pink indistinctly bedded. Consists mostly of shard fragments, but also some pumice and quartzite fragments	11.9
23j.	Covered; forms definite bench. Exposures to northeast indicate an upper white friable tuff underlain by 4 to 5 ft of very light pink tuff	7.0
23i.	Tuff, light-gray, fine-grained, moderately bedded; a few sand-size quartz crystals. A few scattered porcelanitic layers each about 1 in. thick	10.0
23h.	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
23g.	Tuff, sandy (especially near base), light-gray	2.7
23f.	Porcelanite, light-pink	0.5
23e.	Tuff, gray weathering light-brown, well-bedded. Fragments of pumice and obsidian. Abundant crystals of quartz, alkali feldspar, and plagioclase; crystals of hornblende moderately abundant; scattered crystals of an opaque oxide	8.0
23d.	Tuff, pink; abundant shards	1.5
23c.	Tuff, light-gray. Alternating layers 6 to 10 in. thick of medium-coarse fragments of pumice, porcelanitic material, and brown quartzite fragments. Scattered crystals of quartz, alkali feldspar, plagioclase, and an opaque oxide	7.5
23b.	Tuff, coarse, gritty, very dense; much greenish-yellow porcelanitic material. Indistinctly stratified	3.5
23a.	Tuff, gray, fine-grained; alkali feldspar, plagioclase and quartz crystals. Stringers of porcelanitic material	2.0
22k.	Tuff, pink mottled with white. Moderately abundant pumice, ash shards, and small black obsidian fragments; abundant quartz and alkali feldspar crystals, scattered to rare phenocrysts of plagioclase, biotite, and an opaque oxide	3.8
22j.	Tuff, similar to bed 22h except locally darker. Small polygonal fracture patterns (3 to 4 in. across) developed on flat surfaces	9.0
22i.	Tuff, same as bed 22h except it is pink with white halos around small black obsidian(?) fragments	2.5
22h.	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 in. across, developed on flat surfaces	13.0
22g.	Tuff, light-gray, very friable	0.5
22f.	Tuffaceous grit, well-bedded	1.5
22e.	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 table 5)	1.7
22d.	Tuff, light-gray, medium-coarse grained, friable; brown to black subangular fragments (mostly quartzite)	5.0
22c.	Tuff, alternating pink and gray bands	1.0
22b.	Tuffaceous grit, gray, resistant; good ledge former	1.7
22a.	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 ft 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-ft thick layer of light-gray very friable tuffaceous grit. Pink layer 1 ft thick, 14 ft above base. Upper 3 ft is light-gray resistant tuff that is porcelanitic at base	20.5
	Total thickness of beds 231 to 21	125.0
Unit 3:		
20.	Tuff, light-red (5*R* 6/6) to light-pink (5*R* 7/4), abundant cream-colored ash shard fragments as much as 1 in. long and moderately abundant brown limonite(?), pumice, and obsidian fragments. Abundant phenocrysts of alkali feldspar and 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 table 5)	7.7
19d.	Tuff; lower 1.5 ft 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 ft is nearly white. About 3 ft above base the tuff is medium coarse grained and contains abundant pumice fragments; phenocrysts of alkali feldpsar are abundant, quartz and plagioclase moderately abundant, and scattered biotite and an opaque oxide. Upper 10 ft has abundant pumice fragments and is fairly friable	27.0

Unit 3—Continued	Thickness (feet)
19c. 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
19b. Tuff, porcelanitic, white, glassy, with open texture (loosely cemented, ⅛ to 1-in. flat aggregates with cavities between). Abundant ash shards and a few foreign fragments; scattered phenocrysts of quartz, alkali feldspar, and plagioclase. (Chemical analyses in table 5)	1. 5
19a. Tuff, porcelanitic, light-gray, mottled with pink. Tuffaceous grit bed about 0.5 ft thick 8½ ft 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 19a	54. 5
18. Tuff, light-gray with thin pink bands, fine-grained, moderately friable. Sand-sized brown quartzite grains moderately abundant. Top layer is about 2 ft thick, fine grained at top, contains scattered pumice and ash shards and scattered quartz and alkali feldspar phenocrysts. Lower layer contains abundant ash shards, moderately abundant obsidian, and scattered pumice and foreign fragments; scattered phenocrysts of quartz, alkali, feldspar, and biotite	19. 0
17. Covered	5. 0
16. Tuff, gritty, porcelanitic. Yellowish green at base with abundant quartzite fragments; overlain by gray and mottled pink stringers; quartzite fragments up to 1 in. 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 porcelanitic tuff 1 ft 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 parts. Lowest part is about 4 ft thick, dark brick red, very dense, generally massive; breaks into sharply angular pieces. Middle part is pinkish red and fine grained. Upper part similar to middle unit except it is tan. Bed contains moderately abundant pumice, obsidian (black hollow pipe-shaped bodies), and ash shards and scattered foreign fragments; quartz, alkali, feldspar plagioclase, and biotite phenocrysts moderately abundant, and a scattered opaque oxide; many brown limonite(?) inclusions	22. 2
Thickness of bed 14	22. 2
Unit 2:	
13. Covered	14. 0
12. Tuff, yellowish-green, fine-grained. Few blebs of white porcelanitic material as much as 2 in. 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 as much as 1 in.; mottled light red and green	2. 2
Total thickness of beds 13 to 10	26. 9
9. Tuff, light-gray layers interbedded with three yellowish-green porcelanitic layers. Light-gray phase has abundant pumice fragments, moderately abundant obsidian, and a few foreign fragments	7. 1
8. Tuff, reddish-orange. Fragments of pumice, quartzite, and porcelanitic tuff	2. 2
7. Tuffaceous grit and thin brownish-gray porcelanitic layers. Abundant pumice and quartzite fragments; moderately abundant phenocrysts of quartz, alkali feldspar, and plagioclase; scattered biotite and an opaque oxide	2. 5
6. Tuff; intermittent exposures of dense fine-grained gray and pink layers. Some mottled pink and gray layers near middle of bed. Lower 6 ft mostly covered forming dip-slope bench	20. 5
5. Tuff; pink with thin dark-red bands; well bedded; dense porcelanitic 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 dense pisolite layer, 1-ft thick, mottled pink and gray	9. 0
4. Tuff, white, fine-grained; dense except for small cavities; bedded. Abundant pumice fragments and a few quartzite fragments; moderately abundant phenocrysts of quartz, alkali feldspar, and plagioclase; scattered biotite and an opaque oxide	3. 5
3. Tuff; top 0.5 ft is a grit which is underlain by light-gray fine-grained tuff with small brown quartzite fragments near top	4. 0
2. Grit, tuffaceous, yellowish-brown. Abundant pumice fragments and large quartzite fragments. Moderately abundant phenocrysts of quartz, alkali feldspar, and plagioclase;	

Unit 2—Continued	*Thickness (feet)*
scattered biotite, pyroxene, and an opaque oxide. Good ledge former	2.0
1. Tuff, alternating beds of yellowish-gray and pink. Yellowish-gray layers are fine (porcelanitic) to medium grained. Abundant pumice fragments, moderately abundant obsidian and ash shards, scattered brown quartzite fragments, and blebs of porcelanitic material. Moderately abundant phenocrysts. Dense fine-grained pink beds are mottled with light gray (greenish cast). Bed is a good ledge former	10.5
Total thickness of beds 9 to 1	61.3

Rapid rock analyses, semiquantitative spectrographic analyses, and specific gravity determinations were made of samples from beds 19b, 20, 22e, 24f (table 5). These analyses show only a small range in chemical composition among the beds sampled. These samples, moreover, are fairly representative of the whole of units 2, 3, and 4 of the Oak Spring formation. 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, manganese, phosphorus, and titanium are minor constituents. Minor amounts of barium, beryllium, chromium, copper, gallium lanthanum, manganese, nickel, lead, scandium, strontium, titanium, yttrium, ytterbium, and zirconium were detected spectrographically.

ENGINEERING CHARACTERISTICS OF THE OAK SPRING FORMATION

The rocks of the Oak Spring formation may be grouped into three general classes based on their engineering behavior and expressed in terms of relative rock strength and competence. Rocks of class 1 possess relatively high strength and competence, rocks of class 2 moderate strength and competence, and rocks of class 3 very low strength and competence. The following notes are based on observations made in the field at the test site and, hence, are largely qualitative.

TABLE 5.—*Analyses and specific gravity determinations of selected samples from the Oak Spring formation, USGS Tunnel area*

[Sample numbers correspond to bed numbers]

Rapid rock analyses and specific gravity determinations

[P. L. D. Elmore, S. D. Botts, and M. D. Mack, analysts. Analyses based on methods of Shapiro and Brannock (1956)]

	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 gr (lump)	1.68	----	----	----
Sp gr (powder)	2.28	2.26	2.31	2.24

TABLE 5.—*Analyses and specific gravity determinations of selected samples from the Oak Spring formation, USGS Tunnel area*—Con.

[Sample numbers correspond to bed numbers]

Semiquantitative spectrographic analyses [1]

[Katherine V. Hazel, analyst]

	B-19b	B-20	B-22e	B-24f
Ag	0	0	0	0
As	0	0	0	0
Au	0	0	0	0
B	0	0	0	0
Ba	.003	.01	.03	.03
Be	.00003	.0001	.0001	.00003
Bi	0	0	0	0
Cd	0	0	0	0
Ce	0	0	0	0
Co	0	0	0	0
Cr	.0003	.001	.001	.001
Cs	0	0	0	0
Cu	.0001	.0003	.0001	.0001
Dy	0	0	0	0
Er	0	0	0	0
Eu	0	0	0	0
F	--	--	--	--
Ga	.001	.001	.001	.001
Gd	0	0	0	0
Ge	0	0	0	0
Hf	0	0	0	0
Hg	0	0	0	0
Ho	0	0	0	0
In	0	0	0	0
Ir	0	0	0	0
La	.001	.003	.003	.001
Li	0	0	0	0
Lu	0	0	0	0
Mo	0	0	0	0
Nb	0	0	0	0
Nd	0	0	0	0
Ni	.001	.001	.001	.001
Os	0	0	0	0
Pb	.001	.001	.001	.001
Pd	0	0	0	0
Pr	0	0	0	0
Pt	0	0	0	0
Rb	0	0	0	0
Re	0	0	0	0
Rh	0	0	0	0
Ru	0	0	0	0
Sb	0	0	0	0
Sc	0	0	.0003	.0003
Sn	0	0	0	0
Sr	.003	.01	.01	.03
Sm	0	0	0	0
Ta	0	0	0	0
Tb	0	0	0	0
Te	0	0	0	0
Th	0	0	0	0
Tl	0	0	0	0
Tm	0	0	0	0
U	0	0	0	0
V	0	0	0	0
W	0	0	0	0
Y	.001	.003	.003	.001
Yb	.0001	.0003	.0003	.0001
Zn	0	0	0	0
Zr	.003	.01	.01	.01

[1] Figures are given, in percent, to the nearest number in the series 10, 3, 1, 0.3, and so on.

Symbols used are—
--, not looked for.
0, looked for, but not detected.

ROCKS OF CLASS 1

Rocks of class 1 include only the welded tuffs of units 2, 6 and 8. These rocks, owing to their hardness, density, and complete induration, possess great bearing strength. In natural exposures they form vertical to near-vertical cliffs (figs. 3, 6). In artificial excavations they likewise should form unsupported near-vertical cuts; their shear resistance appears to be adequate to withstand large artificial loads.

Because of their hardness and resistance to the drill, rocks of class 1 are difficult to excavate. Fieldwork on Rainier Mesa also showed that high water losses in drilling are to be expected, owing chiefly to the relative abundance of water-permeable joints and other natural fractures caused by the brittleness of the rocks. The rocks core well; one unbroken segment of *nx* core (2-in. approximate diameter) 10 feet long, for example, was obtained from unit 8 in UCRL drill hole 3 on Rainier Mesa. Excellent core recovery was also obtained from unit 6 in UCRL drill hole 1.

In summary, class 1 rocks can be expected to possess high compressive, shear, and tensile strength except where weakened by natural or induced fracturing. Drilling and blasting are required for all excavations.

ROCKS OF CLASS 2

Rocks of class 2 include most of the altered bedded nonwelded tuffs of units 1 through 5 and include the lower 180 feet or so and the upper 35 feet of unit 7. Most of the excavation and engineering works to date in the Oak Spring formation have been in rocks of this class. The vitric constituents of these rocks (except those at the top of unit 7) have been zeolitized, and the zeolite has increased their strength by acting as a bonding agent between grains and fragments.

Natural exposures of these rocks form low cliffs (figs. 4, 7) that range in height from 10 to 30 feet in many places and stand at inclinations of 60° to nearly vertical; in some places they even overhang. In a grosser way, that is, in terms of slopes several tens or hundreds of feet in height, inclinations of more than 30° are rare. In most artificial excavations, cuts 10 to 30 feet high should be stable at slopes of 1 horizontal to 2 vertical. Higher cuts probably should be sloped further back to assure stability or should be provided with berms. The bearing strength of class 2 rocks is much less than that of class 1.

In practically all surface excavations into fresh rock, as, for example, along the switchbacks to the Rainier Tunnel portal, drilling and blasting are required before the rock can be handled; the rock is easily drilled with airhammers. On north-facing slopes mechanical weathering products and regolith accumulations commonly extend to a depth of several feet, and shallow cuts are possible with a bulldozer or power shovel without recourse to explosives.

Both the Rainier and USGS Tunnels are dug in rocks of class 2. Tunneling conditions in these rocks are highly satisfactory when tunnels of moderate-size cross section are employed; the USGS Tunnel is about 4 by 7 feet in section (figs. 8, 9). Before the underground explosive tests the walls and backs of both tunnels stood well without the aid of supporting timbers except in one or two areas of heavy ground, as, for example, a fault zone at station 2+65 in the USGS Tunnel. The U12e Tunnel, under construction at this writing (1958), is supported throughout its length because of less favorable rock conditions. The part of the tunnel completed at the time of this writing is entirely in the beds of unit 1. The tuffs of this unit are very soft, as suggested at the surface by their poor outcrop, and they have a slabby bedding habit. Because of the relatively large cross section of the tunnel (about 11 by 12 ft) support was used as insurance against rock falls. In a smaller tunnel the stability of unit 1 undoubtedly would be greater, though it probably would not equal that of higher units.

Core drilling is relatively easy in class 2 rocks, and good core recovery is generally obtained with *nx* bits. The several holes drilled in these rocks have stood well without casing except in faulted or fractured zones, where in addition, water loss is high. Drill tools have been jammed, on occasion, in beds containing gritty lithic inclusion, such as quartzite; these inclusions tend to pluck out from the sides of the hole and bind against the drill stem.

ROCKS OF CLASS 3

The friable nonwelded vitric tuffs of unit 7 are grouped into class 3. These loosely cemented tuffs possess very low mechanical strength. Although natural slopes apparently are stable at fairly steep inclinations (locally as much as 35° or 40°) along the face of Rainier Mesa at present, large landslides involving these rocks have been widespread in the mesa area in the geologically recent past. Little attention has been given to this problem, however, and the specific factors that led up to past slope failures are undetermined. Slopes steeper than 1 to 1 even in shallow cuts seem unadvisable and probably would require frequent maintainance. Slopes of 2 horizontal to 1 vertical probably are stable under most conditions. Most cuts can be excavated without recourse to drilling or explosives.

Much difficulty has been met with in drilling through class 3 rocks of unit 7 on Rainier Mesa, using rotary and coring equipment. Many stoppages were caused by water loss, and very poor core recovery was obtained using *nx* bits. Tunneling has not yet been attempted in

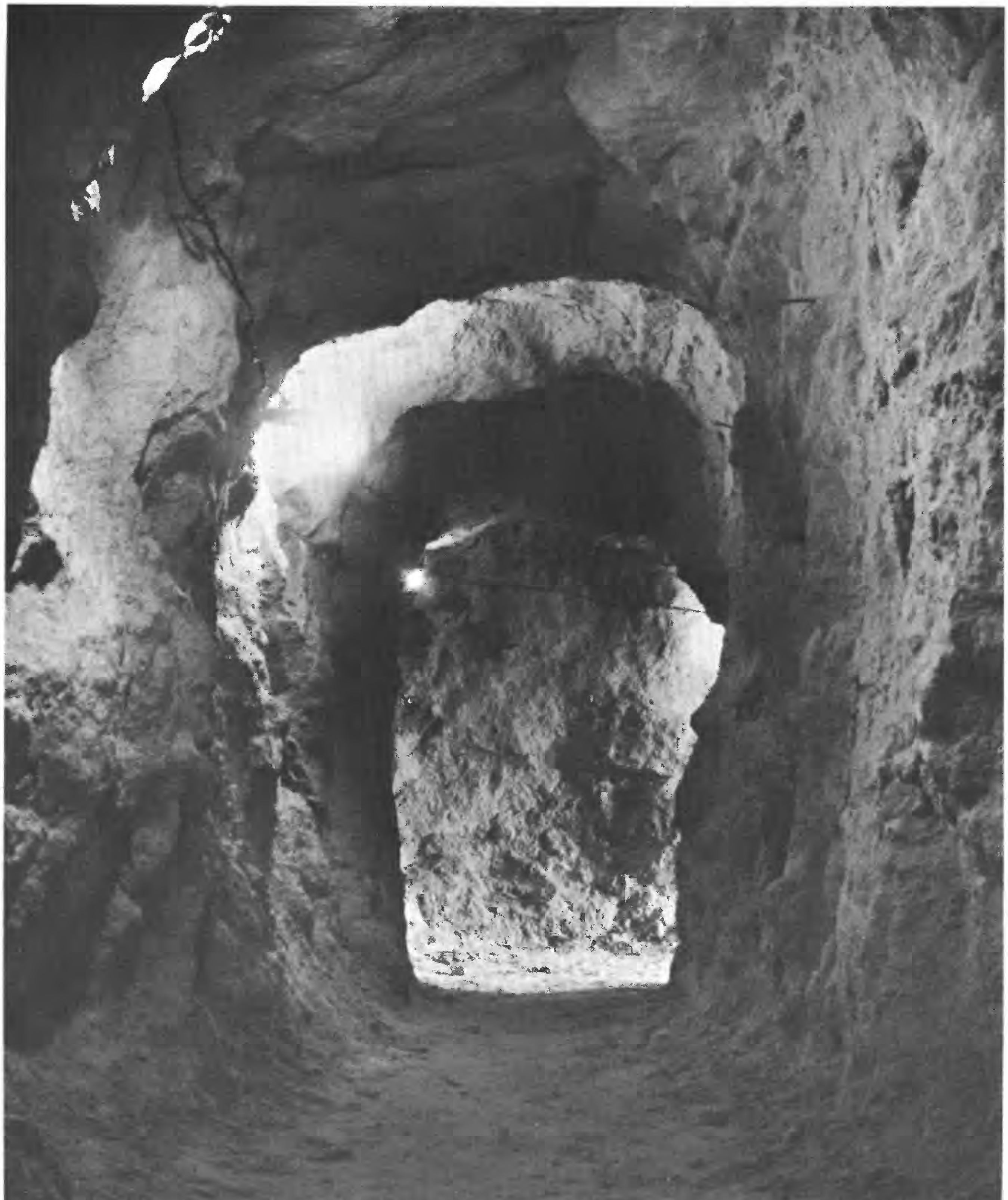

FIGURE 8.—USGS Tunnel viewed from room B toward station 4+50 showing excellent rock and tunnel conditions before high-explosive tests.

FIGURE 9.—USGS Tunnel viewed into room A showing excellent rock and tunnel conditions before high-explosive tests. Tunnel stands very well without bracing. Top of bed 20 (P) at grade line in room A.

these rocks; but in the event of future tunneling, it is expected that continuous support of the back and possibly of the sides would be required.

SURFICIAL DEPOSITS

Mapped surficial deposits in the Rainier Tunnel area consist chiefly of coarse bouldery poorly sorted rubbles in the form of talus, slope wash, and alluvium along the face of the mesa and in the ravines below. These deposits are all of like physical character and have not been differentiated on the map. Finer grained deposits of sand- and silt-sized material are confined to the shallow valleys on top of the mesa back from Point Mabel. Little time was available for mapping or considering surficial deposits, and considerably more of such material exists in the Rainier Tunnel area than is shown on the map. In a large part the outlines that are shown on the map are sketchy and approximate, but they indicate in a general way the shape and distribution of the more significant deposits.

There seems little doubt that surficial deposits were much more extensive in the Rainier Mesa area in the geologically recent past than at present and that the existing deposits are largely inactive remnants of formerly more widespread accumulations. It also seems probable that the deposits are of more than one age. The oldest deposits are mainly blanketlike veneers that mantle the broad slopes of the interdrainage areas where they have survived the attacks of erosion; younger deposits form partly dissected ravine fillings that lie close to the grade lines of the present drainages and form long sinuous rubble piles down the face of the mesa; the very youngest deposits, mainly alluvium, are still accumulating in the bottoms of the larger ravines.

In terms of engineering use, these deposits have little value. On the contrary, they pose a problem that is at least a nuisance. Thick accumulations, which may exceed 60 or 70 feet, must be avoided in selecting tunnel sites, owing to the cost of clearing the debris from the portal area or of collaring a portal through it. The deposits are too heterogeneous for any but the coarsest backfills, and they are utterly unusable as aggregate. Many of the boulders, which are derived chiefly from the caprock of the mesa, are too large for handling even by bulldozer without first being reduced with dynamite. On the steeper slopes, some of the material is susceptible to sliding under the ground motion of an underground test. Many small slides, in fact, were caused by the Rainier explosion.

In the USGS Tunnel area a thick accumulation of slope wash and alluvium fills the bottom of Portal Draw. After the tunnel was started the surface of this accumulation was all but completely reworked in connection with tunneling operations; it also was contaminated with, and largely buried beneath, muck and tailings removed from the tunnel. A small patch of windblown sand extends across the northern part of the USGS Tunnel area. This deposit had no part in the test program at the tunnel site, but it was mapped because it obscured a sizable area of bedrock. Elsewhere in the USGS Tunnel area surficial deposits are of little consequence and consist only of thin unmapped screes and colluvial mantles.

GEOLOGIC STRUCTURE

STRUCTURAL SETTING

The Frenchman Flat-Yucca Flat area of the Nevada Test Site lies within a region that has had a long history of structural deformation (Nolan, 1943, p. 171). Here strongly deformed Paleozoic rocks are overlain unconformably by gently folded Tertiary rocks of the Oak Spring formation. Folding and faulting also followed deposition of the Oak Spring formation, and possibly occurred intermittently during its deposition. Unconformities occur within the Oak Spring formation at the tops of units 5 and 6.

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 the West. 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 and south of the flat more so than those to the north and west (Johnson and Hibbard, 1957, p. 375). 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 sizable ones are present.

STRUCTURE OF THE RAINIER TUNNEL AREA

FOLDS

In the Rainier Tunnel area the Oak Spring formation is modified structurally by a series of broad shallow anticlines and synclines (pl. 1) superimposed on the more complexly deformed Nevada formation. Within the small area of the map, however, the Nevada formation is homoclinal—dipping 10° to 25° or so toward the west—and its grosser complexities involving areas outside the map are not evident. Quite by chance, therefore, its bedding and that of the overlying unconformable Oak Spring formation are almost concordant.

Folds of the Rainier Mesa area range widely in size and can be grouped into several orders of magnitude. Discounting the structure of the Paleozoic basement, the major (first order) structure beneath Rainier Mesa is a broad north-trending syncline, here referred to as the Rainier Mesa syncline. The axis of this fold nearly bisects the mesa into subequal east and west counterparts. The Rainier Tunnel area is located well to the east of the syncline axis; hence, most dips have a a westerly component.

Superimposed on the east limb of the Rainier Mesa syncline are several smaller folds that trend northeastward or eastward obliquely across the larger structure. These folds, which plunge toward the major syncline axis, range in size from mere bowings caused by minor strike deflections to well-defined structures several thousand feet long. 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 (pl. 1). Additional unnamed warps occur farther south along the front of the mesa, but these are poorly expressed.

The Point Mabel syncline and the UCRL anticline are larger scale folds (second order) than the Cat Hill anticline and the False Start syncline. The latter two structures may be visualized as third-order features modifying the limbs of the second-order structures; their trends, about N. 80° W. are oblique to the northeasterly trends, of the second-order structures. The Point Mabel syncline extends northeast far beyond the limits of the mapped area. The second- and third-order folds are cut off by erosion on the east, and the folds are unrecognized in the Paleozoic rocks east of the outcrop of the Oak Spring formation. It is doubtful that these folds ever extended much beyond their present limits.

The fourth-order folds of the area are very small, rather uncommon structures measuring a few feet or yards across the limbs. It is doubtful whether or not these structures are even related to the larger ones. Some of them apparently are penecontemporaneous

FIGURE 10.—Axis of False Start syncline as exposed on north slope of False Start Draw showing the sharp asymmetrical keel typical of the synclines of the area. Hammer (upper left) rests on a thin bed of unit 3 of the Oak Spring formation; a massive bed underlies it to the left.

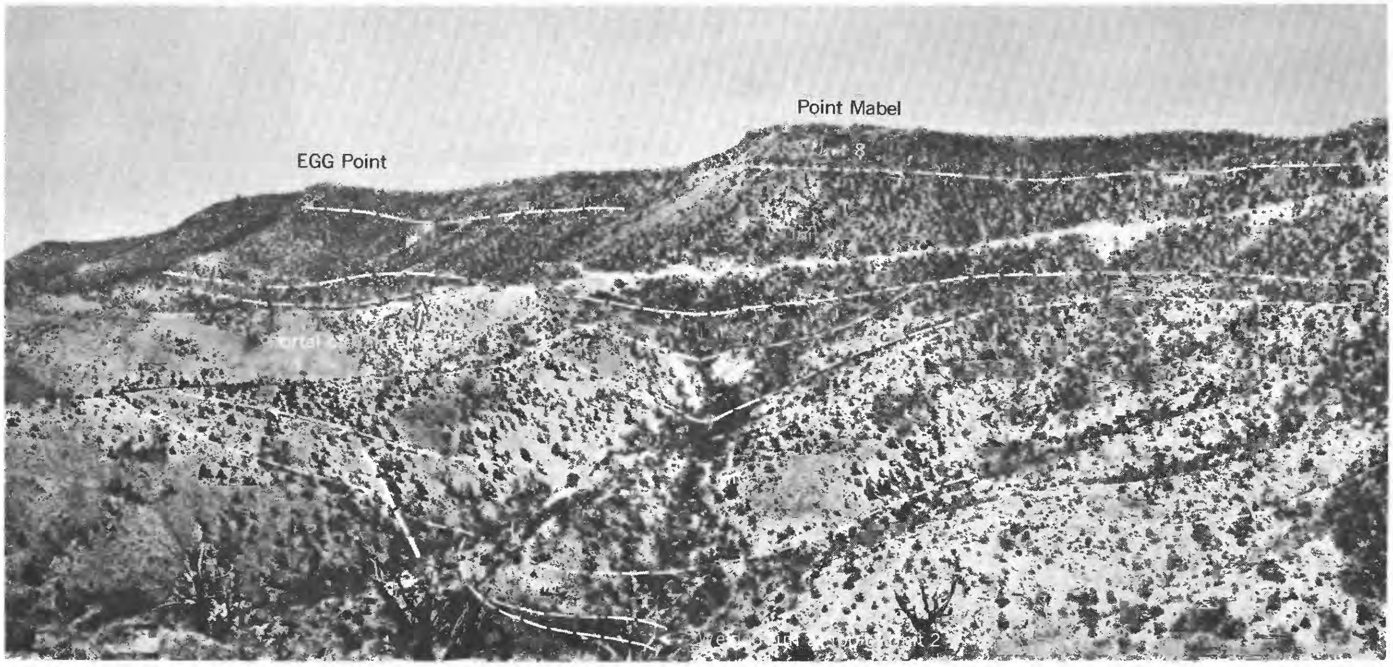

FIGURE 11.—View southwest along axis of Point Mabel syncline toward Rainier Mesa showing lens-shaped section of unit 6 of Oak Spring formation lying in fold axis and truncated by base of unit 7. Road below Point Mabel (skyline, center) leads to top of Rainier Mesa.

features formed by slumping down slopes of initial dip.

Most folds of the Rainier Tunnel area plunge gently westward toward the axis of the Rainier Mesa syncline. Along the face of the mesa, therefore, nearly all dips have a westerly component. Although the amount of plunge varies appreciably from fold to fold and along the axis of any given fold, it ranges on the average between 10° and 15° westward at the face of the mesa. A few thousand feet to the east, however, the axes of the UCRL and Point Mabel folds reverse and plunge eastward. The UCRL fold, therefore, although basically a plunging anticlinal nose, has a local closure of about 75 feet and a point of culmination that approximately underlies the third switchback of the road to the Rainier Tunnel. The Point Mabel syncline, in effect, is crossfolded, since from the point of reversal its axis plunges in opposite directions. Viewed in a section parallel to its axis, it would appear as a broad arch.

Folds of the Rainier Tunnel area are asymmetrical. In section their north-dipping limbs are two to three times as long as their south-dipping limbs (pl. 1) and generally are steeper by several degrees of dip. The crests of the anticlines are broad and open, but the keels of the synclines are narrow and sharply delineated (fig. 10).

The folds increase in amplitude downward. Folding is more pronounced beneath the unconformity at the top of unit 5 than above it; in fact, the Cat Hill and False Start folds lack expression in rocks younger than unit 5 and the UCRL and Point Mabel folds are much subdued in the higher units. In a large part the change in amplitude is due to beveling of unit 5 at the unconformity. The Point Mabel syncline is further reduced in amplitude, however, by lens-shaped (in cross section) masses of welded tuff along the syncline axis, especially unit 6 (fig. 11). The base of unit 6 in the Point Mabel syncline has a maximum structural relief of about 250 feet; the top of the unit, however, has a relief of only about 125 feet; thus, between the base and top of unit 6 the Point Mabel syncline has a net loss of structural relief of about 125 feet, which is equal to the total maximum thickness of the welded-tuff lens in that area. A similar but much smaller net loss of structural relief occurs between the base and top of the thinner welded tuff in unit 2.

A map and section of the Rainier Tunnel before the atomic test are shown on plate 4. Plate 1 also shows a less detailed section along the tunnel centerline at a reduced scale. As shown by these diagrams, the portal of the tunnel is collared in unit 4 (bed 31 of section 1, pl. 6). At tunnel level the structure is homoclinal. Dips diminish gradually from about 29° at the portal to 5° or 6° near the explosion chamber. The tunnel successively passes through units 4, 5, and 6 and terminates in unit 7 at the chamber.

Owing to the unconformity at the base of unit 7, the structure below tunnel level differs appreciably from that at tunnel level. As reconstructed from information taken from tunnel, drill hole, and surface observations the structure below the unconformity is synclinal.

The axis of the Point Mabel syncline seems to pass diagonally beneath the tunnel near station 15+00. Above the unconformity at tunnel level the axis passes approximately through the Rainier explosion chamber. As indicated by UCRL drill hole 3 (table 3), dips below the unconformity are much sharper than those above it.

ORIGIN OF FOLDS AND TECTONIC SIGNIFICANCE

The welded tuffs of units 2 and 6 commonly occupy the axial portions of synclines, not only in the Rainier Tunnel area, but in other adjacent parts of the Nevada Test Site also (p. A17). Thus, welded tuffs occur at 2 horizons on the axis of the Point Mabel syncline in the Rainier Tunnel area, at the same 2 horizons farther east just beyond the USGS Tunnel area, and at the same or similar horizons at other nearby localities in the test site. The synclinal structure clearly antedates the emplacement of the welded tuffs and undoubtedly was an important factor in their localization. At the time of emplacement the synclines must have been topographic troughs as well as structural ones.

The question follows, therefore, as to how much of the fold structure in the Oak Spring formation is tectonic and how much of it is due to other factors, such as initial dip or differential compaction of unconsolidated beds on an initial surface of strong relief. The following evidence favors the conclusion that a large part of the structure is initial:

1. The often-observed ability of pyroclastic rocks to accumulate at unusually steep initial dips, owing chiefly to the angularity of the individual rock fragments.
2. The upward decline in amplitude of the folds.
3. The repeated occurrence of welded tuffs along synclinal axes.
4. The apparent lack of continuity of folding between the Oak Spring formation and the older underlying rocks—the folds are superposed upon a dissimilar buried structure and they seem to be molded to a buried prevolcanic topography.
5. The similar molding of folds in higher tuffaceous units to dissectional topography in lower tuffaceous units. This relationship, which seems unequivocal in its implications, does not occur in the Rainier Tunnel area but is well defined in adjacent parts of the test site.
6. The broad-crested anticlines and sharp-keeled synclines are geometric forms that would be expected to result from burial of predepositional sharp relief.

On the other hand, postdepositional structure superposed on initial structure is indicated by warping in the welded tuffs. Unlike nonwelded tuffs, which are airborne and accumulate on the ground as all-concealing blankets, welded tuffs spread outward like fluids and tend to fill depressions; hence they have irregular bases and flattish upper surfaces. Relief on the upper surface of a welded tuff, therefore, suggests postdepositional warping either by tectonic movements or by differential compaction of the welded tuff itself or possibly of the interbedded and subjacent nonwelded tuffs. Differential compaction of most sediments is most operative before and during lithification—compaction, in fact, helps promote lithification. Marked compaction follows emplacement of most welded tuffs. It seems probable that the small-scale warpings noted in the welded tuffs of units 2 and 6 (the 125-odd ft of structural relief on the top of unit 6, for example) are due mainly to their own differential compaction and partly, perhaps, to that of the underlying beds after emplacement of the welded tuffs. Large-scale regional warpings, such as the first-order Rainier Mesa syncline, probably are true tectonic effects inasmuch as structures of their magnitude can hardly be explained by any of the processes outlined above.

Further evidence of tectonic movement, aside from regional warping and faulting, is indicated locally by slippage, shearing, and rock granulation on the contact between the Oak Spring and Nevada formations, as, for example, in exposures at the portal of the U12e Tunnel. In addition, bedding attitudes that seem excessively steep even for pyroclastic rocks—a dip of 36° at one point—probably indicate postdepositional warping superimposed on initial dip.

In summary, fold structure of the Oak Spring formation seems to be due to a combination of three factors: (1) deposition on an initial surface of strong relief that localized most of the smaller higher order folds; (2) differential compaction that further accentuated these folds, as shown by differential warping of successive welded-tuff lenses; and (3) regional warping that still further accentuated the folding and produced broad first-order folds typified by the Rainier Mesa syncline.

FAULTS

Faults are not abundant in the Rainier Tunnel area and most of those present are small—that is, their surface traces commonly extend but a few hundreds of feet and their throws measure mostly a few tens of feet of less. One sizable fault in the southeastern part of the area extends south nearly 1,800 feet from its northward termination to the south border of the mapped area, and it extends an undetermined distance beyond the border. Where it displaces unit 1, its throw is on the order of 200 feet.

Only one fault of any consequence intersects the Rainier Tunnel below ground. This fault crosses the tunnel centerline at station 3+85. It appears to be the underground continuation of a northwest-trending fault whose surface trace passes between the portals of the Rainier and the U12c Tunnels. In the tunnel its throw is about 7 feet (pl. 4); above ground its maximum measured throw is 22 feet.

A small fault was mapped in the Rainier Tunnel at station 17+15 before the Rainier explosion (Gibbons, A. B., and Eckel, E. B., unpublished map, 1957). This fault has no surface indication. Its throw underground, before the explosion, was only about a foot. It was of special interest, however, because natural openings existed along the fault plane.

Most of the faults of the Rainier Tunnel area trend northwesterly. A few, including the largest, trend almost due north. The faults are too few in number to warrant any definite conclusions as to their possible interrelations and habits; but they all seem to be normal in displacement, and they seem to fall into two sets or families. Faults of one set range in trend from about due north to about N. 35° W., are upthrown on the northeast, and probably dip southwest; faults of the other set trend from about N. 45° to about N. 70° W., are upthrown on the southwest, and dip northeast. The displacement habits of the two sets and the relation of one set to the other are similar to those of the faults at the USGS Tunnel area, described on page A45. 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

Joints are inconspicuous, except locally, in the nonwelded tuffs of the Rainier Tunnel area, but they are very conspicuous in the hard welded tuffs that cap the mesa. In unit 4 on the south side of Cat Hill conspicuous widely spaced joints more than 100 feet long have been accentuated by weathering and erosion so as to form steep-sided miniature canyons. Those joints are exceptional, however, and some outcrops are virtually free of joints or at least of well-defined ones. Some of the harder beds, such as the basal bed of unit 3, have a blocky outcrop habit caused by conjugate dip and strike joints—two sets arranged normal to the bedding plane in the directions of dip and strike.

The hard welded tuffs of unit 8 are much jointed. Shocks and vibrations caused by the Rainier explosion dislodged numerous large boulders from the rimrocks by failure along joint planes. The lower rhyolitic welded tuff of unit 8 is characterized by large-scale well-formed columnar joints caused by contraction during the cooling of the ash flow (fig. 6). These joints, which terminate abruptly downward in the nonwelded tuffs below, strongly influence the appearance and outcrop behavior of the welded tuff by producing near-vertical cliffs.

In the upper quartz-latitic ash flow of unit 8, which forms the caprock of the mesa, columnar joints are much less regular in form and spacing. Numerous lineaments in the caprock, however, are visible on air photographs and form a striking pattern on the map (pl. 1). Many of these lineaments are inconspicuous at close range on the ground, owing chiefly to the soil mantle and to vegetation. Undoubtedly most of them are large joints, but some may be faults. Two sets are readily discernible; one set trends generally northward but ranges through several degrees of bearing both east and west of north. The other set trends about N. 45° W. and departs only a few degrees from that bearing. The lineaments of the northerly set seem to be much longer and more continuous on the average than those of the northwesterly set, but they are much less abundant. A genetic relationship between the lineaments of the caprock and the faults of the rocks below seems probable because of the similarity in the trends of the sets of the two types of fractures.

STRUCTURE OF THE USGS TUNNEL AREA

The Oak Spring formation on the map of the USGS Tunnel area (pl. 3) includes only one segment of a fold. A short distance to the north of the mapped area the axis of a broad low anticline trends east-northeast and plunges gently eastward. About 1,200 feet to the east of the mapped area the axis of a small syncline trends and plunges generally north. These folds are comparable in size to the UCRL anticline of the Rainier Tunnel area. Between them the rocks of the USGS Tunnel area dip mostly to the east or northeast at angles of 5° to 15°. Local departures from the general attitude are common, especially along and near to faults

The portal of the USGS Tunnel is collared in bed 20, and the tunnel rises in the section away from the entry (pls. 2, 3, 5 and fig. 4). Underground, the strike of the bedding is variable, but it has a persistent northerly component; dips are 7° to 15° eastward. The main tunnel, oriented N. 22° E., therefore, cuts progressively higher beds in the stratigraphic section from the portal to station 2+65 [3] where bed 19c is brought to tunnel level against bed 22d by normal faulting. The fault at station2 +65, with a throw of about 65 feet, is one of the largest faults in the USGS Tunnel area (fig. 12). It strikes about north and dips 65° W. The east side is upthrown, bringing bed 19c on the east wall against bed 22d on the west at tunnel level. The hanging wall for about 20 feet west from the fault plane is broken and disturbed by criss-cross fractures; the footwall is relatively unfractured, but is marked by red-brown gouge 1 to 3 inches thick. Beyond the

[3] All stationing is measured from a zero point at the tunnel portal; thus, station 2+65 is 265 ft from the portal in the main tunnel, station 2+16 W. is 16 ft from station 2+00, main tunnel, measured to a point in the west lateral to room A.

FIGURE 12.—Footwall of fault at station 2+65, USGS Tunnel, before the 10-ton blast in room A. Plaster of paris was dabbed across fractures to help bring out any movement resulting from blast. Subsidiary shears to left.

fault, in the upthrown block, the main tunnel and the east lateral again rise through the section from bed 19c, station 2+65, to the base of bed 20 (portal bed) which is exposed in the back at station 4+50 (fig. 8).

From station 2+00 the west lateral to room A cuts down in the section to the top of bed 20 (portal bed) which is at grade line at the entrance to room A (fig. 9). At station 2+00 and in the first 8 to 10 feet of the west lateral, there was evidence of preexplosion interbed slippage between the top of bed 21 and the base of bed 22a. The upper 0.5 foot of bed 21, underground, is a soft plastic clay grit which is overlain by about 2.5 feet of porcelanitic tuff of bed 22a. This bedding plane subsequently had an important part in both explosions.

Small faults with vertical displacements of a few inches to 50 or 60 feet, and nearly all normal in habit, are abundant in the USGS Tunnel area. Room A, where the 10-ton dynamite explosion was detonated, was intentionally located in a highly fractured area near several faults to test the behavior of high explosives in fractured rock. Room B, the 50-ton chamber, was located in sounder, less fractured rock (Dobrovolny, Ernest, and Eckel, E. B., written communication, 1957). In both locations, preexisting fractures strongly influenced the fracture pattern imposed on the rocks by the explosions.

The only fault of any consequence observed in the underground workings is the one that crosses the tunnel at station 2+65 (fig. 12). Three minor faults with displacements of a foot or less were cut by the east lateral to room B. In addition, a shear zone in the northeast corner of room B contained four main vertical fractures striking north to northeast. A manganese-stained bedding plane was not displaced from one side of this shear zone to the other, but was displaced upward 6 inches to 1 foot within the shear zone. The apparent net displacement of the entire zone, therefore, was nil. In the main tunnel between stations 1+11 and 1+19, as well as in the west lateral to room A between stations 2+37 W. and 2+44 W., the rock was sheared, but displacements were negligible.

In the tunnel 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. The two sets of faults diverge less in strike than their respective traces, as shown on plate 3, at first suggest. Part of the divergence is due to the effect of topography on the dipping fault planes. Faults of the northeast set are upthrown to the southeast; 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 pattern of two mutually opposed sets of normal faults, dipping mostly from 50° to 70°, suggests a west to east tensional condition in the earth's crust at the time of faulting. The faults may be regarded as rock failures parallel to the shear component of the tensional stress, and the divergence in their strikes suggests tilting since faulting. To better visualize the probable stress relation at the time of faulting and the subsequent modifications due to tilting, in qualitative terms, it is convenient to use the strain ellipsoid. In such a visualization an imaginary sphere is distorted into a triaxial ellipsoid by the stresses involved (fig. 13). Thus viewed, the greatest strain axis (*A-A′*) is the direction of tensional stress and may be visualized as extending horizontally west to east. The intermediate strain axis (*B-B′*), which contains the intersection of any two opposed fault planes, plunges gently to the north; the least strain axis (*C-C′*) plunges steeply to the south and before tilting coincided with the downward force of gravity.

The ellipsoid, therefore, is tilted to the north on the *A-A′* axis. In any section cut parallel to *B-B′* the traces of the faults would be parallel; in any other section, as, for example, a horizontal plane (which would include the lines of strike), the traces would diverge. Thus, the reconstructed stress field that existed at the time of faulting tilts gently toward the north; if the tensional stresses that produced the faulting were originally applied horizontally, as seems probable, and the gravitative stress (equal to *C-C′*) was vertical, the rocks have since been tilted toward the north. The probability that such has indeed occurred gains substance from a general northward structural inclination in the northwestern part of the test site—that is, in the southern part of the Belted Range. In other words, the area to the south of the USGS Tunnel is structurally higher than the area to the north.

For their relatively small displacements, most of the faults in the Oak Spring formation have relatively wide zones of breakage between walls (fig. 14). This condition may reflect a relative shallowness of cover at the time of faulting and hence relatively low confining pressures on the walls of the faults, which permitted relief of stress by fracturing and expansion. It also probably reflects the low crushing strength of the rocks. At the same time, the widths of fault zones vary widely within single faults and in short distances, owing apparently

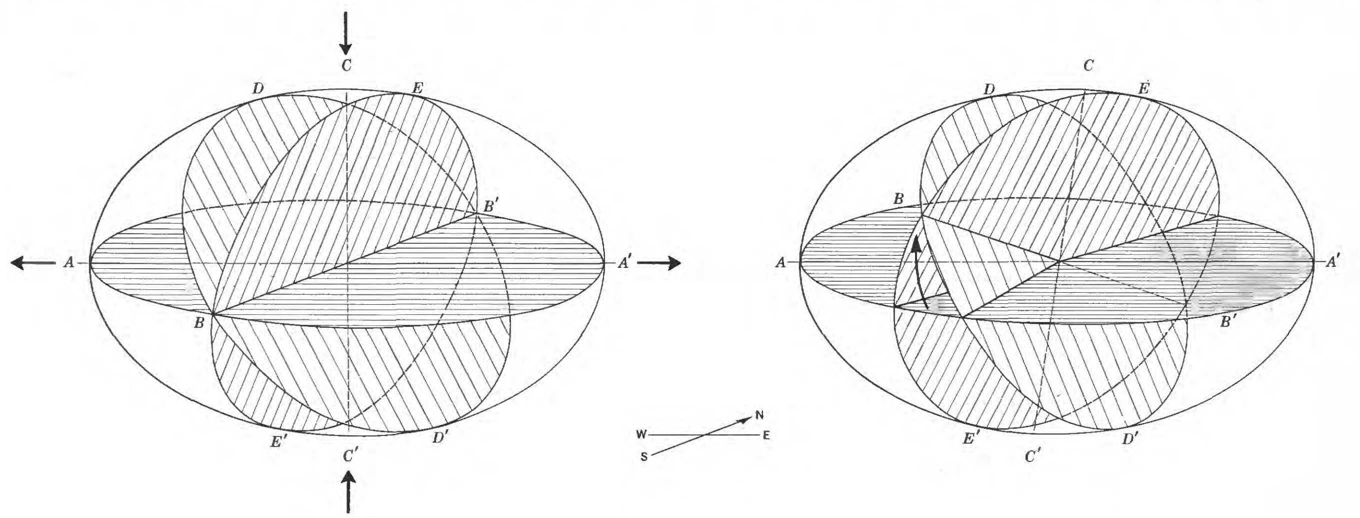

FIGURE 13.—Strain ellipsoid diagrams showing (left) probable stress relation in USGS Tunnel area at time of faulting and (right) subsequent northward tilting of ellipsoid by rotation approximately on *A-A′*. *A-A′* is the greatest strain axis; *B-B′*; is the intermediate strain axis and coincides with the intersection of the two shear components of stress *BDB′D′* and *BEB′E′*; *C-C′* is the least strain axis and coincides with the downward force of gravity. Faults of the area are parallel to the shear components *BDB′D′* and *BEB′ E′*. In both diagrams the plane containing *A-A′* is horizontal.

FIGURE 14.—Fault zone exposed 130 feet west-southwest of USGS Tunnel portal showing intense fracturing in hanging wall (left) and moderate fracturing in footwall. Near-vertical fractures (±80°) are gash (tension) fractures; flatter fractures (about 50° to 60°) are shear fractures and are subparallel to fault plane. Note drag in bedding in hanging wall. Hanging wall moved down relative to footwall. Top of portal bed in footwall (at survey station 116) is opposite top of bed 21 in hanging wall; vertical displacement is about 25 feet; width of fault zone is 48 inches.

to differences in competence and behavior of the particular beds truncated by the faults. In general, fracturing is both more extensive and more intensive 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.)

Wallrock fractures in faults of the USGS Tunnel area take three common forms: shear fractures, gash or feather (tension) fractures, and bedding-plane fractures. All three types are well illustrated by exposures 130 feet west-southwest of the tunnel portal (fig. 14). Shear fractures either are subparallel to the fault plane or they dip less steeply than the fault plane at angles that flatten with distance from the fault plane. Gash fractures dip more steeply than the fault plane, or even dip in the opposite direction. Where they dip in the same direction as the fault plane, their angle of dip commonly steepens away from the fault plane. The angle between gash fractures and the fault plane points in the direction of relative movement of the wall containing the fractures; conversely, the angle between shear fractures and the fault plane points opposite the direction of movement. Bedding-plane fractures are caused by differential movement between beds as a result of drag in the wall. They are a special type of shear fracture and hence bear the same dip relation to the fault plane as the shear fractures already described.

Joints are abundant in the USGS Tunnel area, especially close to faults, and although they range widely in orientation, the great majority of them trend northeastward (fig. 15) subparallel to the northeast fault trend. Like the faults, the northeast-trending joints dip mostly northwest, and the northwest-trending joints dip mostly northeast. Generally steeper than the faults, however, their dips range mostly from 70° to vertical.

Before the high-explosive tests, joints were stronger and were more closely spaced at the surface in the vicinity of room A than they were in the vicinity of room B. Few joints at that time had been traced

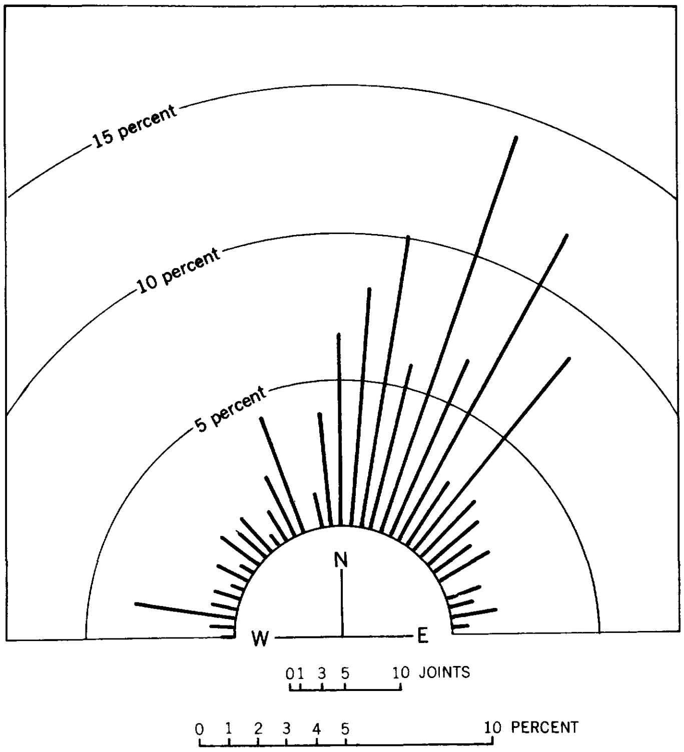

FIGURE 15.—Diagram showing percentage distribution of high-angle joints in the USGS Tunnel area. Compiled from 266 determinations.

much more than 40 feet along any single fracture, but after the explosions, when many 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.

Before the tests, joints were conspicuous in some parts of the underground workings but not in others. The factors controlling jointing apparently were related to the lithology and competence of the beds involved. The stronger, more brittle, beds were jointed upon deformation; the weaker beds, especially those altered to a zeolitic matrix, absorbed the stresses of deformation without visible fracturing. The strikes of joints vary considerably in direction, but most of them are northeasterly. Consequently, the majority of the joints are subparallel to, or are at a slight angle to, the main tunnel, and are about perpendicular to the laterals. Most of the joints seen underground are steep or vertical, and most of them are bordered by slightly altered zones one-fourth inch or so wide caused probably by percolating ground water.

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